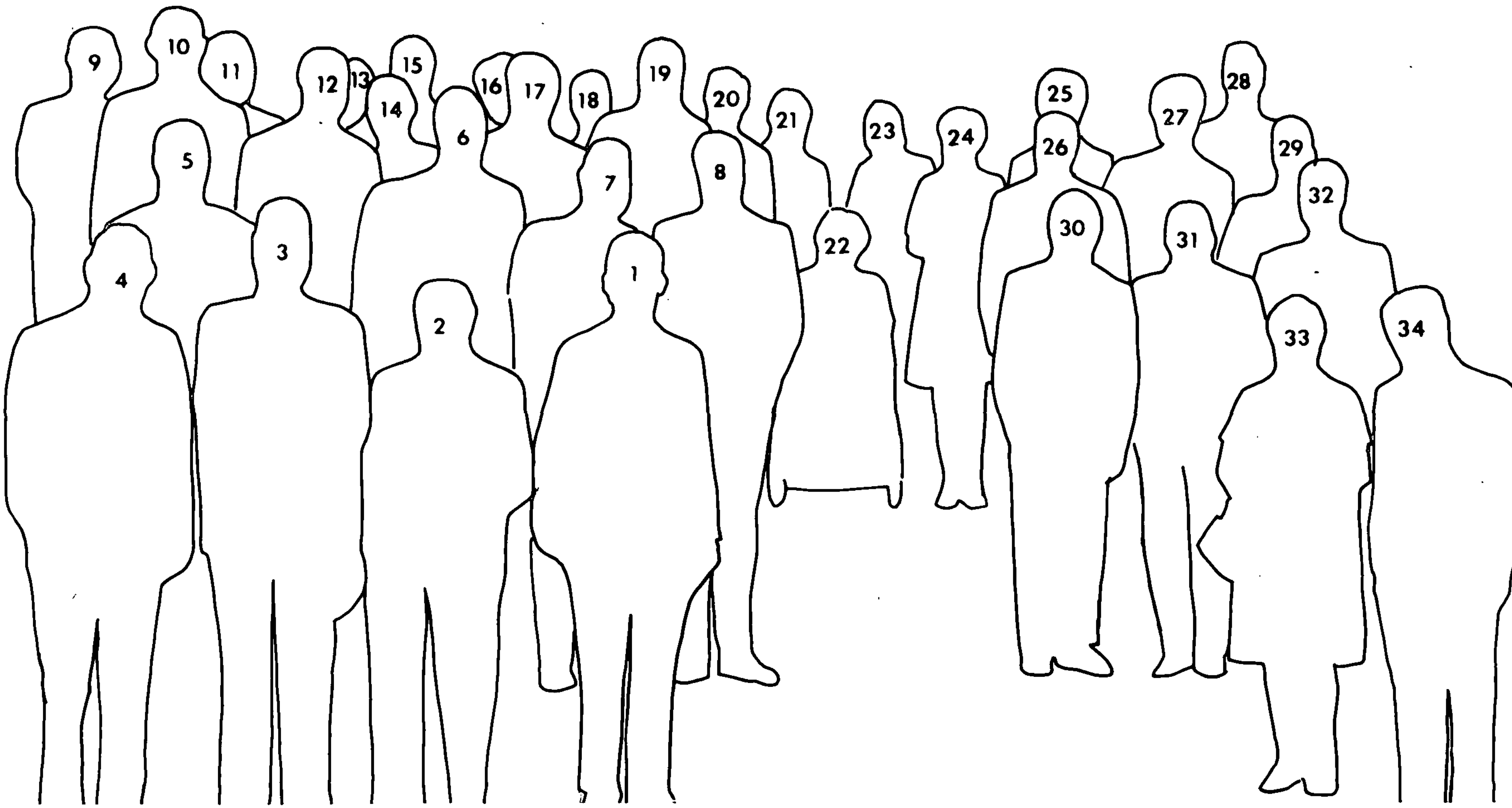
COMETS
SCIENTIFIC DATA AND MISSIONS
PROCEEDINGS OF THE TUCSON COMET CONFERENCE

EDITED BY G. P. KUIPER AND E. ROEMER

Tucson, Arizona, 1 July 1972

Conference Photograph



1. Delsemme, U. Toledo
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13. Schmidt, Max Pl. I.
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Part-time participants not in photograph: Code, Gehrels, O'Dell, D. Roberts, IITRI.

Foreword

This Volume contains the proceedings of a Conference on Comets organized by the Editors at the suggestion and with the support of NASA. The Conference took place in the Space Science Building, University of Arizona, April 8-9, 1970. There were about 36 participants, including representatives of NASA Hq. and JPL. A group photograph of the participants is reproduced.

The editorial steps were the following: the verbal presentations and discussions were all tape-recorded. The tapes were transcribed after the meetings by Mrs. M. Wilson, assisted by Dr. E. Roemer for sections of the tapes that were not clear. The transcribed presentations were submitted to the authors for correction and updating. Some authors submitted a completely new text. On 7 January 1971, a "preliminary partially-edited version" was sent to Dr. W. Brunk of NASA Hq. before one major chapter had been received; this chapter arrived May 1971. The text was then about 320 typed pages not counting figures, three-fourths of it still basically the spoken versions. The Editors then decided that a much more thorough editing and condensation of the texts was needed before publication because of the informal conversational style of the tape records and the lengthy discussions. This work was done by Dr. Kuiper during the first part of 1972. Mrs. I. Edwards assisted with this complete revision of text and references. Thereupon, the texts were resubmitted to the authors for final verification and updating. We are much indebted to Dr. Delsemme who, during a special visit to Tucson, graciously agreed to assist us in these last stages. He read the entire manuscript and suggested many improvements; and added in Paper 25 an up-to-date Summary.

Since the Tucson Conference occurred during a prominent display of Comet Bennett, which led to much discussion of this object and a display of photographs by this Laboratory, it was deemed appropriate to add in these Proceedings a summary of the LPL photographic results with a brief accompanying text (Paper 26); an approximate period of rotation for the nucleus is derived.

We are indebted to Mrs. M. Wilson for retyping the final manuscript for offset, to Mrs. M. Matthews for making the Index, and to the University of Arizona Mimeo Bureau for the production of this Volume.

The editors regret the delays resulting from the unexpectedly large editorial task, at a time of often too-heavy work loads. They wish to acknowledge the interest of NASA in sponsoring the Conference and the publication cost of the Proceedings.

Lunar and Planetary Laboratory
University of Arizona
July 25, 1972

Gerard P. Kuiper
Elizabeth Roemer
Editors

TUCSON COMET CONFERENCE

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NO. 1

INTRODUCTION: MISSION OPPORTUNITIES AND MODES

by N. Sirri

Office of Space Science and Applications - NASA-JPL

I would like to welcome you on behalf of NASA and say a few words about comet missions.

The basic ideas about sending a spacecraft to a comet have not changed much over the past few years. For example, although there is obviously great scientific interest in sending a spacecraft to a new non-periodic comet, this type of mission is not included in the first flights because of the technical difficulty of accomplishing it. However, we have made progress in some areas: (1) we have conducted studies on both fly-thru and rendezvous missions to periodic comets, and (2) we have formulated a more definitive plan for actual launches of spacecraft on comet missions. In the process several questions came up, and as a result this meeting was arranged.

I would now like to cover briefly three points: (a) NASA's current plans and priorities; (b) the new study results to be presented later; and (c) typical questions we would like to hear discussed here.

(a) NASA has projected plans through the first half of the 1980's or some 15 years into the future. In the first plan is a fly-thru mission to Comet d'Arrest in 1976. This d'Arrest mission is currently being proposed for FY-72 "new start". Two other new starts have been proposed for FY-72, the Grand-Tour missions to the outer planets, and the Venus Explorer program. Comet d'Arrest was selected first because it is the only predicted comet having a favorable fly-thru trajectory geometry in the mid-1970's. An early comet mission is very desirable, both as a "reconnaissance" mission in preparation for a possible Halley's mission, and in order to take advantage of procuring a modified Mariner spacecraft in connection with the Mariner Venus-Mercury 1973 Project.

The single fly-thru mission would be followed by a rendezvous mission. Plans for such missions are not yet definitive, but there are interesting possibilities. These are the 1980 apparition of Comet Encke, d'Arrest 1982, Kopff 1983, and Halley 1986. Those are currently of greatest interest, but your views are desired in selecting future missions. Comet missions have been given quite high priority by NASA's Planetary Office. However, funds are short and as Drs. Kuiper and Roemer pointed out in their letter of invitation, the future of comet missions depends largely on how scientists view them.

(b) The new study results cover two subjects. Dr. Gardner of JPL will summarize their still incomplete study of the d'Arrest '76 fly-thru mission. It is based on using a modified Mariner spacecraft in order to reduce costs. The spacecraft would carry about 180 lbs of scientific instruments, would fly through the coma and would pass from 3,000-10,000 km from the nucleus, if one exists. The relative speed between spacecraft and comet would be about 13 km/sec, so it would pass through the coma in a couple of hours. Further, Mr. Friedlander of the IIT Research Institute will describe the work that IITRI has done on rendezvous opportunities with comets. They have identified a number of interesting missions selected primarily on payload and trajectory considerations, and on certain ground-based viewing criteria. They have also considered two different flight modes: the ballistic mode using conventional chemical propulsion, and the low-thrust mode using electric propulsion. These were further subdivided, the ballistic into a so-called three-impulse ballistic mode, and a Jupiter gravity-assist mode. The low-thrust electric-propulsion mode was divided into a solar-electric and a nuclear-electric mode. It is difficult to make comparisons because there are so many variables; but it appears that the solar-electric mode is the most desirable.

Typical features of solar-electric missions are: Net spacecraft payload weight (total spacecraft without propulsion), 900-1,100 lbs; the scientific instruments, 150 or 200 lbs; flight times, 2-3 years. A Titan 3C launch vehicle is required. For the ballistic modes the characteristics vary. On some the payload gets down as low as 500 lbs; and on others the flight time is 5-6 years. The launch vehicle required for the ballistic mode is, in some cases, a 7-segment Titan/Centaur.

(c) There are questions which came up in our current work, to be discussed at this meeting. They concern three areas: (i) general, (ii) fly-thru missions, and (iii) rendezvous missions.

For instance, what is the relationship between fly-thru and rendezvous missions? What experiments should one have on the fly-thru mission that enhance a later rendezvous mission? What is the relative scientific value of a fly-thru and a rendezvous mission? How should the mission comets be selected? What about the comets tentatively selected already? How important is it to send a mission to Halley's comet around 1986? Is it really worthwhile here to overcome the rendezvous problems with a comet in a retrograde orbit? Of course, we have seen some answers, but we would like to get the integrated opinion of this group of scientists interested in comets.

On fly-thru missions, some of the questions are: What is the micrometeorite hazard due to impact, as the spacecraft flies through the coma? Since it is possible to have a second spacecraft for a relatively small cost increment, the question arises: Should the fly-thru mission be a dual-launch mission, with one spacecraft sent through the coma and another sent through the tail? What should be the resolution of the visual imaging? What is the effect on visual imaging of light scattered by particles in the coma? What should be the resolution of the spectrometer? Is there a preferred time prior to perihelion when the rendezvous should occur? What would be the scientific value of extending the rendezvous missions and having the spacecraft stay with the comet for an entire orbit of the comet? What aspects of the spacecraft presence in the comet would disturb the scientific measurements?

In closing, I want to express my appreciation and NASA's appreciation to Dr. Kuiper and Dr. Roemer for setting up this conference.

NO. 2

COMETARY NUCLEI - MODELS

by F. L. Whipple

Director, Smithsonian Astrophysical Observatory

ABSTRACT

Arguments for the existence of some kind of icy-conglomerate cometary nucleus are put forward, and the role of clathrates in the condensation of comets from the solar nebula is discussed. The division of cosmic materials into three types is described, and it is suggested that whereas Jupiter, and to a large extent Saturn, condensed directly from gas and the terrestrial planets and asteroids collected from planetesimals of earthy material, the comets were formed as snow balls in the vicinity of Uranus and Neptune, with these two planets themselves representing accumulations of comets. The evidence for the existence of a comet belt beyond Neptune is considered, and it is concluded that at 50 A.U. from the sun the mass of such a belt cannot be more than that of the Earth. Some attention is paid to the question as to whether cometary nuclei eventually turn into inert objects, indistinguishable from small asteroids in appearance. Finally, some of the problems associated with the mission to periodic Comet d'Arrest are discussed, in particular those concerned with the detectability of the nucleus and the hazards of a close encounter.

The general concept of the icy comet model is one that seemed obvious back in the 1940's. We then knew that many tons of material per second were coming out of comets and there was no way of maintaining such rates by desorption of gases. With any diffuse or gravel-bank model it was quite impossible to replenish the gases, as was evident even in early calculations, using the upper limit of solar wind number density of 1,000 electrons/cm^3 at the earth's distance. This limit is now reduced a factor of 20. Also, the density must fall with increasing solar distance. Further, there is the evidence for nuclear integrity from sun-grazing comets: there must be a nucleus. The fact that the comets sometimes split into discrete nuclei also shows that the nucleus is solid with a huge reservoir of material releasable by solar heat. On these grounds I went to the concept of the icy comet model. The model was able to account also for the non-Newtonian motion of comets, which was already reasonably well established in several cases. Some comets showed a reduction of orbital angular momentum, others an increase.

The detailed structure of the model nucleus was still vague. Dr. Levin has commented that in my earlier papers there were three different models: particles embedded in ices, a molecular mass stuck together, and ices frozen in earthy particle structures. Actually, one could not be certain, nor can one today, which model is most appropriate, though there certainly are particles, seen as meteors in our atmosphere.

The elements and molecules identified in comets are shown in Table 2-I; near the sun cometary spectra show compounds of carbon, nitrogen, oxygen with hydrogen, and earthy atoms. The observed radicals suggest the presence of water, ammonia, and methane. Delsemme's clathrate hydrates

TABLE 2-I

SPECTRAL IDENTIFICATIONS IN COMETS

Head:	C_2, C_3, CH, CN, $C^{12}C^{13}$
	NH, NH_2, [OI], OH, H
	Na, Si, Ca, Cr, Mn, Fe, (Ni, Cu)
Tail:	CH^+, CO^+, CO_2^+, N_2^+, OH^+, (CN)
Tail:	Continuum

solve an important problem, as otherwise very low temperatures are needed to produce the solid carbon compounds. This is seen from Table 2-II. In-

TABLE 2-II

CONDENSATION T(°K) AT VAPOR PRESSURE 10^{-10} TORR

H_2	3.2	CH_4	28.2
He	<1	CO	23.8
Ne	6.5	CO_2	68.4
A	23.7	NH_3	81.5
Kr	32.7	NO	43.4
Xe	45.1	H_2O	130.0

creasing the pressures to 1 mb does not increase the temperatures greatly. Carbon dioxide would seem acceptable as a condensate except that this is not suited chemically; ammonia would do if the temperatures were around 100°K; but the methane temperature is too low for condensation and that is serious because of the abundance of CH. Delsemme's concept is attractive because clathrates can be condensed out of the solar nebula at much higher temperatures. We now have information on interstellar clouds and infrared stars developing "solar nebulae". It is found that regions in space where stars are forming rarely have temperatures below 100°K. Even 100°K may be rare because the heat release due to collapse must be radiated away. It is therefore unrealistic to consider frozen hydrogen and helium as sources. Clathrate hydrates are needed.

Continued observation is very important. Comets represent the most primitive material in the solar system. The moon was quite active in its early days. We may have lost the records of perhaps the first 100 million years of lunar history, when the sun was extremely active in the Hayashi phase and just afterwards. As yet we see no evidence of the period when the solar wind and solar flares were very strong and new radioactive elements like I^{129} and Pu^{244} existed. Such records seem to be missing from the lunar surface but are present in meteorites. The cometary material will surely lead even farther back, to the very early history of the solar system.

Harrison Brown (1949) was the first to state clearly the concept of three types of cosmic materials, based fundamentally on melting temperature, cf. Table 2-III: (a) earthy materials, Si, Mg, Fe, S, O, which are solid at high temperatures; (b) the ices of C, N, O, combined with H to form compounds that vaporize at room temperatures; and (c) the enormously abundant

TABLE 2-III

A DIVISION OF COSMIC MATERIALS

Material	Earthy	Icy	Gaseous
Elements	Si, Mg, Fe etc. plus O	C, N, O plus H (Ne?)	H, He
Mass available	1	4-7	300-600
Melting point	~2000°K	≲273°K	≲14°K

gaseous elements which vaporize already at extremely low temperatures. These properties have an important bearing on the evolution of the solar system. Consider these elements and look at the solar system forming in a Laplacian-type nebula. The planetary compositions (cf. Table 2-IV) show that Jupiter and Saturn have an almost entirely gaseous composition. A solar mix would condense directly into these large planets, without much

TABLE 2-IV

THE GROSS COMPOSITIONS OF THE PLANETS

Material	Earthy	Icy	Gaseous
Terrestrial planets	1.00	<0.01	0
Jupiter	<0.01	0.1	0.9
Saturn	0.01	0.3	0.7
Uranus	0.1	0.8	0.1
Neptune	0.1	0.8	0.1
Comets	0.15	0.85	0

differentiation of materials. Uranus, Neptune, and the comets appear to be much alike if you use the icy comet model and freeze out those likely substances at temperatures on the order of 100°K or less, particularly with clathrates. Here we have mostly icy material enriched with the earthy material available and practically no hydrogen, helium or noble gases. The terrestrial planets and the asteroids are earthy, with only traces of icy or gaseous materials, except for oxygen in compounds.

At temperatures 1000-2000°K one loses from a solar mix the ices and the gases; and if one collects the planetesimals according to the Chamberlain-Moulton concept, he can produce the terrestrial planets and the asteroids. Jupiter can be collected directly from the solar mix; and if one adds a little heavier material, Saturn can be formed. But if one freezes the solar mix and just accumulates comets, he comes out essentially with Uranus and Neptune. Cameron looked at the problem in exactly this way, as I was doing. Kuiper (1951) has long held that comets were formed out in that part of space and showed that snowballs roughly 1 km in diameter would form outside the Neptune orbit, consistent with Oort's (1950) hypothesis of a distant comet reservoir of 10^{11} members with total mass ~10^{27} grams. The planetesimals of the outer part of the solar system appear to be the comets; a huge number of comets collected together to make Uranus and Neptune in the same way as a huge number of planetesimals made the inner planets.

Interestingly enough, the minimum quantities of solar mix required to produce Jupiter, Saturn, Uranus, and Neptune, the terrestrial planets, and the comets are comparable; less than 1% of a solar mass in each case, as shown in Table 2-V. The problem of eliminating the unused material is fascinating and apparently solvable, but it is too involved for this discussion.

TABLE 2-V

MINIMAL MASSES REQUIRED TO FORM THE SOLAR SYSTEM BODIES

Objects	Present mass (earth = 1)	Factor	Original material (sun = 1)
Terrestrial	1.9	500	0.0028
Jupiter	317	10	0.0095
Saturn	95	30	0.0086
Uranus & Neptune	32	75	0.0072
Comets	1	90	0.0003
Minimum original mass			0.0284

There may still be a comet belt beyond Neptune near the fundamental plane of the solar system. Presumably there were a great many comets formed in the region beyond Neptune, as I assume it was cold enough beyond Saturn to form comets. After Uranus and Neptune were formed the remaining comets inside Neptune's orbit were perturbed - some of them to infinity, many of them into the inner part of the solar system where they were vaporized, as occurs today, or captured. Saturn probably picked up quite a few comets, perhaps some 10% of its mass. Many may have been left in the belt (cf. Fig. 2-1). Perhaps 1% went into the Öpik-Oort cloud extending to many thousands of astronomical units (Öpik 1932, Oort 1950).

Can one prove or disprove the existence of the outer comet belt? We cannot see it from the Earth and probably not from deep space probes. One question is whether the high mass derived for Pluto, 0.18 of the Earth (Duncombe et al. 1968), is actually due to the comet belt.

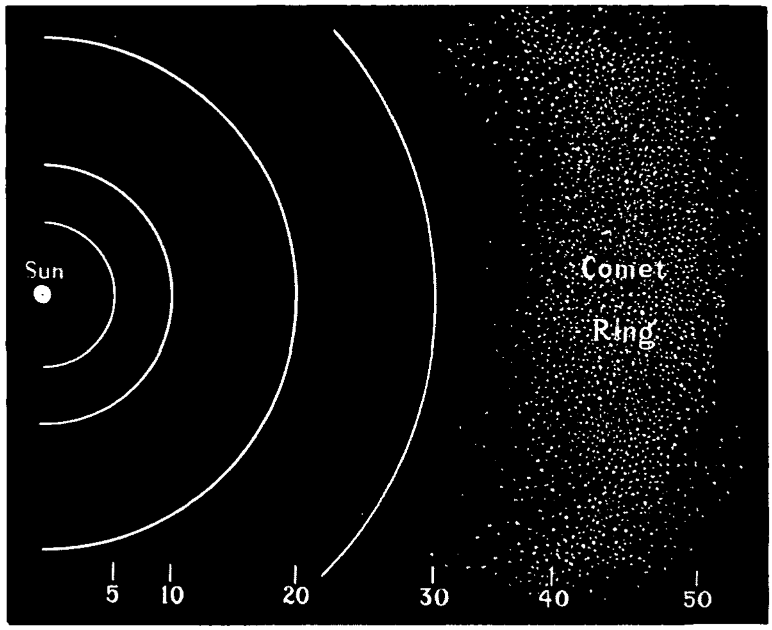

Fig. 2-1. Concept of a comet belt still existing near the plane of the solar system beyond Neptune

Fig. 2-2 shows the pole of the ecliptic and of planetary orbits. If the pole of a comet belt is properly located, the belt could account for the perturbations that implied the excessive mass of Pluto. It appears most likely (Kovalevsky 1971; Ash, Shapiro, Smith 1971), however, that we are still dealing largely with observational errors, as was the case in the earlier mass determination of Pluto, 1.0 ± 0.1 Earth mass (Wylie 1940).

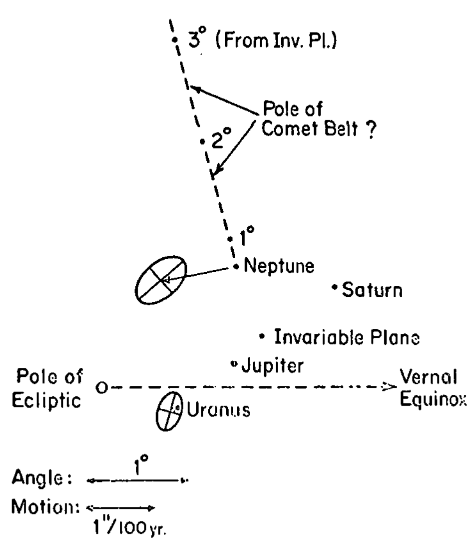

Fig. 2-2. Poles of planet orbits (ellipses represent m.e. of spread)

There is another method of getting at the problem of the comet belt. Some comets have aphelia not far from the region of appreciable perturbations by a comet belt. Halley's comet (Fig. 2-3) is an excellent example and has been well observed. Hamid, Marsden, and I (1968) examined the old apparitions to see whether perturbations by a comet belt could have affected the comet's motion. We found a rather negative result, setting an upper limit to the comet belt of 1 Earth mass to 50 A.U. So the direct verification of a comet belt remains unproven.

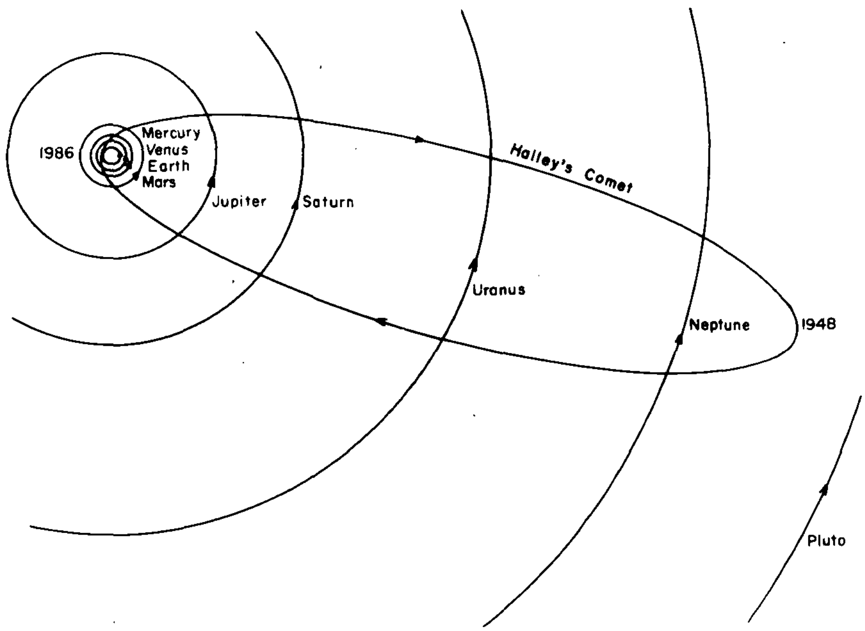

Fig. 2-3. Orbits of the planets and of Halley's Comet.

The problem of the meteoritic constituents of comets is difficult (Whipple 1965). We observe them as meteors (or meteoroids in space) but never identify them as meteorites on the ground. An old comet like Encke's shows many larger bodies (Taurid meteors and fireballs) which appear to be very friable; they destroy themselves rapidly in the atmosphere, and they seem to be of low density (Whipple 1950). Dr. McCrosky discusses the Prairie Network data, which have a bearing on this subject.

There remains the question as to whether old comet nuclei die away to nothing or to solid meteoritic cores. Is the inside solid enough, perhaps heated by radioactivity soon after formation or even formed from earthy materials before the ices froze, that a very old comet is a dead body, indistinguishable in appearance from an asteroid? Öpik (1963) has argued that the Apollo earth-crossing asteroids are mostly the nuclei of old comets, only a fraction being true asteroids. Only one line of evidence bears on the question. Dr. Sekanina (1970) has an indication of radio meteors stemming from Apollo asteroids, including Apollo, Icarus, Adonis, Hermes, and 1968AA - five of the earth-crossing ones out of 14 all together (he found no meteors from Geographos). The case is not yet definitive; but if sustained, it would suggest that many Apollo asteroids are indeed old comet nuclei.

The problem of how the meteorites attained their present orbits is not yet well understood. We have some information on the cosmogenic ages, which are determined by the short-lived activity of Argon 39 or 37 produced by cosmic rays, compared to Argon 38 which is stable. The ratios give ages that rarely exceed 60 million years. I believe that these stony meteorites must come from earth-crossing objects like the Apollo asteroids, which had lifetimes long enough that they could be perturbed into their present orbits.

By contrast, some of the iron meteorites may have been perturbed directly from the asteroid belt, whereas the stones were almost certainly broken off by collisions from larger bodies in earth-crossing orbits. Yet, we do not know whether they ultimately come from typical asteroids - perhaps from asteroids in orbits near Mars and perturbed by Mars into earth-crossing orbits. Perhaps they are old comet nuclei as Öpik has suggested, although I doubt this, except possibly for type I carbonaceous chondrites. Thus we now have an immense store of information about the early days of the solar system from meteorites but we are not sure what bodies they represent. The solution to this problem is extremely important. The asteroids and comets are keys to the history of the solar system.

We may take the Comet d'Arrest mission as an example and estimate the meteoritic hazards of a fly-by. The particle size distribution of Fig. 2-4 is used. Included are data from space-probe penetrations, radio meteors, and photographic meteors.

I assume that the nucleus of P/d'Arrest has a radius of 1.4 km, the value I calculated in 1950 on the basis of the period changes. If I take Dr. Roemer's measures of the comet's brightness at large distances, the 1.4 km radius corresponds to an albedo of 0.12, twice that of the moon, which seems reasonable.

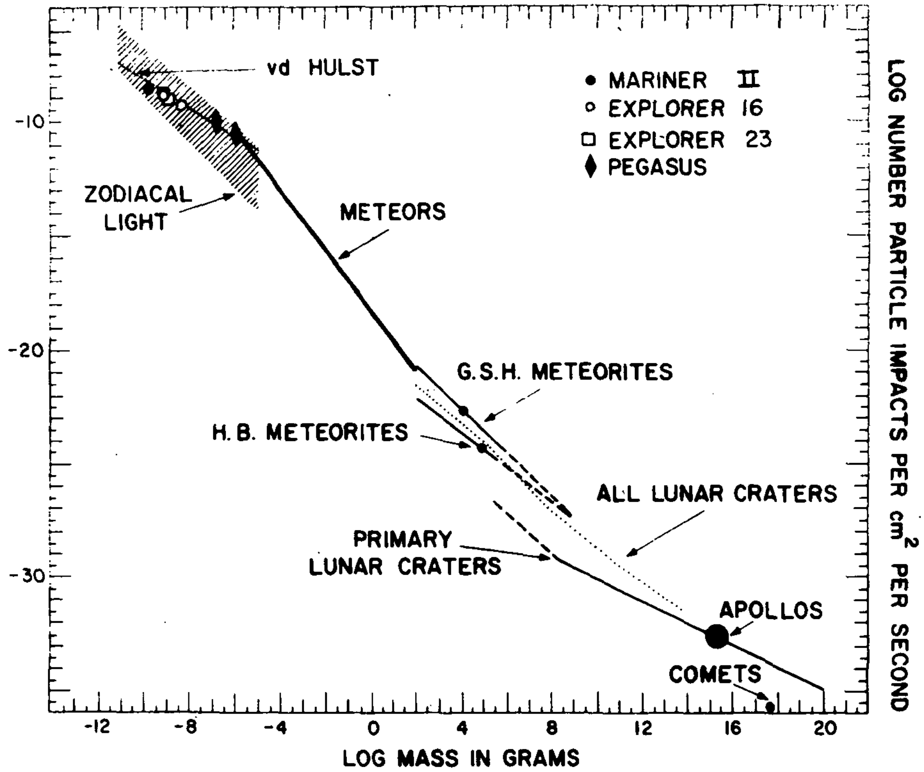

Fig. 2-4. Cumulative impact rates on a sphere in space at the Earth's distance from the Sun.

If Comet d'Arrest is receiving solar radiation at 1.1 A.U., i.e., its perihelion distance, and the efficiency is 10% for energy going into vaporization (requiring 300 calories per gram), the loss would be 7 x 10^6 g/sec, of which 1/3 may be meteoritic. The meteoritic loss would then be some 2 tons/sec. (For Comet Bennett the loss is thousands of tons/sec).

For the velocity of ejection, I adopt my 1951 value; Probstein, more recently, makes much the same assumptions. Free-molecular flow applies for a small comet. The gravity limits the masses of large particles ejected. For particle densities of 0.44 gm cm^{-3} (instead of my 1950 density of 4.0 gm cm^{-3}), the particle ejection velocity becomes approximately (Whipple 1951, eq. 9b):

$$V_\infty = \left(\frac{1}{s^{1/2}} - 0.052\ R_c\right)^{1/2} R_c^{\ 1/2} \times 320 \text{ cm sec}^{-1}$$

where s is the (spherical) particle radius (cm) and R_c the radius (km) of the comet nucleus.

For the major fraction of the zodiacal particles, of mass near 10^{-5} gm, the radius for $\rho = 0.44$ gm cm^{-3} is 350μ and their velocity V_∞ is typically 30 m/sec. The maximum ejectable particle has s ~ 190 cm or a mass exceeding 10 tons. Thus quite large fireballs in the Prairie Net class might be ejected from a comet like P/d'Arrest.

Suppose a probe passes through a cometary coma at minimum distance D, the space density of the material being ρ_o near the surface of the nucleus at distance R_c from the center of the nucleus and varying as $1/R^2$. Then the total mass encountered per unit area is $\pi\rho_o R^2/D$. In our case the space density at the comet surface calculated with 2 tons/sec escaping at 30 m/sec, is $\rho_o = 2.7 \times 10^{-9}$ gm/cm^3. The mass in the line of sight tangent to the nucleus comes out 1.6×10^{-3}gm/cm^2. At 150 cm^2 of apparent surface per gram of particles the tangential material is fairly opaque.

At a distance of 1600 km, a passing probe would encounter some 1.4×10^{-6} gm/cm^2. In near-earth space a sphere would encounter something like 2.5×10^{-16} gm/cm^2 per second. Hence the 1600-km pass by the comet would be equivalent to 6×10^9 seconds or 200 years exposure to meteors in near-earth space.

We may assume that the 1600-km encounter indicates a high probability of collision with a 10^{-7} gram-particle per cm^2 or a 5×10^{-5} gram-particle per square meter. If $\rho = 0.44$ gm/cm^3, the former particle has a diameter of 1.2×10^{-2} cm and the latter 0.12 cm. The penetrations, P, of aluminum sheets, following Bjork and Herrmann and Jones, are then in the range of $3.5\ m^{1/3}$ cm to $1.5\ m^{1/3}$ cm for mass m(gm) at 13 km/sec velocity of collision. Each cm^2 of forward surface would have a strong chance of being penetrated if it is 0.17 mm to 0.07 mm thick; each square meter would be penetrated if its thickness were 1.0 mm to 0.4 mm. I would consider such probabilities moderately hazardous.

These calculations are subject to rather large uncertainties because of the unknown distribution of sizes among the dust particles blown out by Comet d'Arrest. The assumed distribution has been compared with the brightness of the Gegenschein, leading to a modest over-estimate by a factor of 2. Some check is possible by calculating the diameter of the coma, which from the above data might be photographable to a radius of 60 arc sec. At 1 A.U. from earth and sun and phase angle 90° the magnitude of the nucleus, assumed to have a radius of 1 arc/sec, would be something like 13th magnitude, a reasonable value. The false nucleus, where the outgoing particle are over the total apparent area, would not extend beyond the true nucleus. Hence, the true nucleus could easily be observed at moderate distances by a space probe.

Discussion - Dr. Roemer commented as follows:

It might be useful to clarify the matter of "total" as opposed to "nuclear" magnitudes of comets and the question of the nuclear diameters that are under discussion here. It is the "total" magnitude that is involved in the comparison with the Gegenschein. With short-focus photographic instruments, and in extrafocal visual comparisons of comet brightnesses with stars, it is essentially the "total" brightness that is measured. With the 61-inch or 90-inch reflectors, or any large, long-focus telescope, the contribution of the light reflected from a small monolithic nucleus is nearly completely separated from that of the coma. These "nuclear" magnitudes can be used, with necessary assumptions about the reflecting properties of the surface, to obtain dimensions of cometary nuclei that are more reasonable than those based on observations in which the contribution of the nucleus is less completely resolved.

The difference between determinations of the "total" and "nuclear" magnitudes made of the same object at the same time is typically something like 6 magnitudes. That is, reflection of light from the small nucleus contributes less than 1% to the total brightness of the comet.

On the question of optical recoveries of returning periodic comets, and particularly the mission to Comet d'Arrest, it is the "nuclear" magnitudes that must be used. The early observations are almost invariably made with large, long-focus reflectors, and the brightness scale that applies to observations with such instruments is that of the "nuclear" magnitudes.

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NO. 3

REALITY OF COMET NUCLEUS

by R. A. Lyttleton
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There can be little doubt that the prime problem of a comet mission must be to settle whether the cometary nucleus has an actual tangible material existence, or whether it arises from some optical effect present only at times within comets. My impression is that the existence of an actual solid nucleus is something widely believed in these days, but I myself have been rather intransigent in not subscribing to the majority view. I have returned to, or at least not yet gone forward from, the classical view that a comet is a vast swarm of tiny particles separated by very large distances.

The absence of any large particles in a comet seems to be demonstrated by certain meteor showers. For in really intense ones, such as that of 1833 and the recent 1966 one, the Earth probably intercepted thousands of millions of meteoric particles; yet there appears to be no record of a single meteorite reaching ground level associated with the stream. This suggests that whatever particles may be injected into the stream by comets, none are large enough to penetrate the Earth's atmosphere. For some meteor streams, there is no longer any discoverable associated comet, so practically all the material of any former comet must now be in the stream, but again no meteorites occur on passage through such streams.

Accounts by observers of the general appearance of the nucleus do not suggest that it can be a permanent structure. There seems often to be a nucleus near the center of the coma, but some comets show no nucleus, while in others its place is taken by a more or less diffuse condensation of light within the coma. Moreover, in most cases the nucleus makes it appearance only when the comet nears the sun, though some have shown a sharp nucleus when at great distance. In a few cases the nucleus is double or even multiple. Dimensions of the nucleus, as recorded, range considerably. Russell himself quotes the following examples: Halley's comet when near perihelion in 1910 had a nucleus 500 miles across; Brooks' comet (1911) 750 miles; and Donati's (1858) about 900 miles. The great comet of 1882 had a nucleus 1800 miles in diameter; and if this were a solid object, it would be approaching a lunar mass, which seems impossible.

A point often made is that survival of sungrazing comets, which pass through the solar corona, seems to require the presence of large solid bodies if the comet is to withstand the intense heat of the sun near perihelion. But the conclusion may not be sound. Even if a sungrazing comet is completely vaporised at perihelion passage, the rate of its thermal expansion would only be on the order of 1 km/sec, which is negligible compared with the orbital speed; the comet will get safely by and recondense into small particles again, and not just dissipate into space.

Another feature that would seem to indicate that a comet consists primarily of a swarm of particles is that the coma in general contracts as the comet approaches the sun, roughly in proportion with the distance, and then expands again as it recedes. This property of comets has been known for centuries, but seems not widely remembered today, though Wurm has emphasised it. On the other hand, if a heating mechanism deriving from the sun were the cause of the coma being evaporated off an icy nucleus, then an expansion as it neared the sun would be the expected result; but this is just not so. Then again, there have been comets that have started in towards the sun with every promise of becoming brilliant objects, only to peter out and vanish before even reaching perihelion. Such curious behavior would seem inexplicable if the coma is produced by heating of a permanent nucleus. Halley's comet transited the disc of the sun in 1910, and any solid body as large as 50 km would have been observable. Then, there are the sudden bursts of activity that comets such as 1925II show at quite irregular intervals, and there are the seemingly explosive emissions of luminous shells from the central regions of some comets.

A number of my observing friends inform me that the central region of the great Andromeda nebula, when looked at near the limit of vision, resembles a comet and shows a sharply defined nucleus; but it seems no one has gone on to make the equally valid inference that this is an icy snowball a few kilometers in diameter controlling the galaxy. One wonders why an icy object, say 10^5-10^6 cm in diameter should develop an atmosphere extending out to 10^{10}-10^{11} cm, a factor 10^5 times the radius of the nucleus. What would settle this matter?

It seems generally to be the case that the greater the power of telescope used, the smaller the nucleus seems to be. Present-day estimates of size are inferred from measures of the apparent magnitude and an assumed albedo. The dimensions arrived at, on the order of a few kilometers, cannot be resolved optically, for at 1 A.U. it requires as great a length as 750 km to subtend only 1". For these reasons, it seems to be of the greatest importance in any comet mission to make certain that the craft passes sufficiently near the nucleus that its equipment can be sure of finding it if it is there.

I recently extracted from Vsessviatski's catalogue the accounts of the known apparitions of Comet d'Arrest, which is of special interest as possibly offering in 1976 the first suitable target for a comet mission. It was discovered in 1851, and described as a faint circular blurred object with no nucleus and in 1857, as a faint nebulous object of circular shape, brighter towards the center. Then in 1870, observers saw many luminous points in the head, with the comet very diffuse, very pale, slightly condensed, and no nucleus. In 1890, at one stage it was a very faint object with central condensation, then a few days later showed a nucleus of 13^m, while three weeks later there was a nucleus 30" in diameter. Sometimes it was seen as a faint indefinite object without a nucleus. So evidently the nucleus comes and goes observationally. These are, of course, early accounts, and usually not now taken too seriously as such; but in 1923 P/d'Arrest appeared again as a very faint circular nebula with no condensation. In 1943 a faint starlike nucleus of 16^m was seen eccentrically within the coma. Then in 1950 it was detected as a faint object of 18.5 with slight condensation; later as of photographic magnitude 16^m or 15^m (said to be obviously the nucleus); and a month later a nucleus of $12\overset{m}{.}5$ was seen, increasing in a few days to $11\overset{m}{.}5$. The diameter of the nucleus is quoted as 15", which would mean quite a large body.

Editors Comments:

The discussions that followed reiterated the points made by Dr. E. Roemer on the reality of the nucleus, which is always stellar, unresolved, as distinct from the coma which may reach values from a few arc sec to many arc minutes. The coma has an emission spectrum and is presumed to be largely gaseous, with the stellar (visible or invisible) nucleus the source of the gases.

Dr. Lyttleton also showed a slide of a JPL experiment showing the impact of dust ($v \sim 3$ km/sec) on a curtain of dust slowly falling in air at low pressure.

NO. 4

INFRARED MEASURES OF COMETS

by T. Lee

Lunar and Planetary Laboratory

ABSTRACT

Infrared observations of two comets, 1969g and 1969i, are presented. In both comets the infrared flux appears to be of thermal origin. The structure of the sources as well as the temperature, emissivity, and composition of the radiating material are discussed.

Jointly with Drs. Kleinmann and Low, I have been obtaining infrared observations of two comets, Comet Tago-Sato-Kosaka (1969g) and Comet Bennett (1969i), at wavelengths ranging from 2.2μ to 22μ. We have flux measurements centered on the nucleus for both comets; and for 1969i we have spatial scans of the cometary head and tail, as well as 70μ-flux measures of the nucleus made from an aircraft operating in the stratosphere (Kleinmann et al. 1971).

The observed energy distributions of the comets are given in Figs. 4-1 and -2. During the course of our observing of Comet 1969g, the

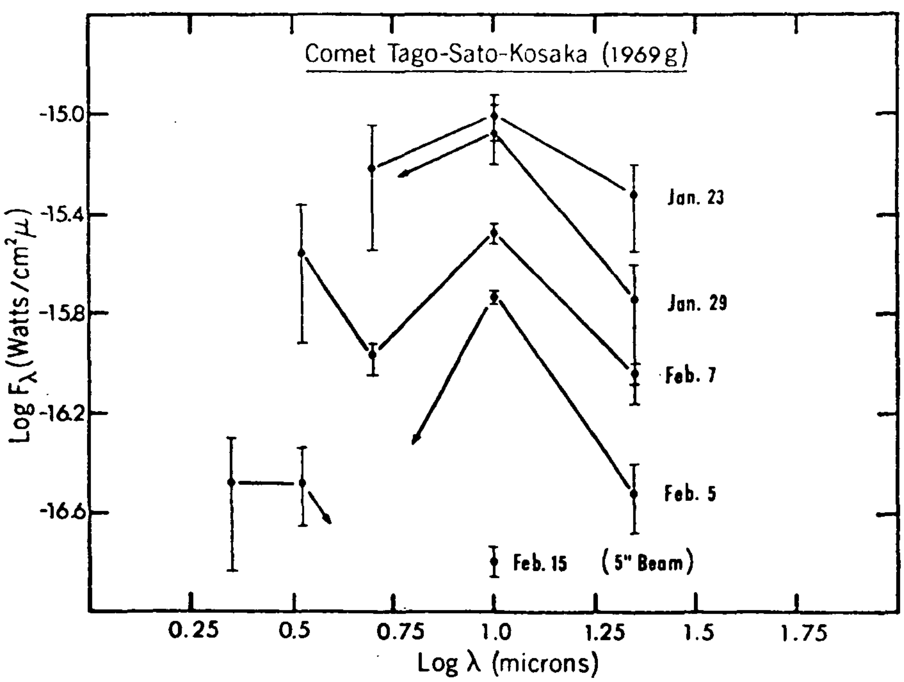

Fig. 4-1. Fluxes for Comet 1969g (Tago-Sato-Kosaka) as measured through a 6" aperture, except for February 15. Dates are all in 1970.

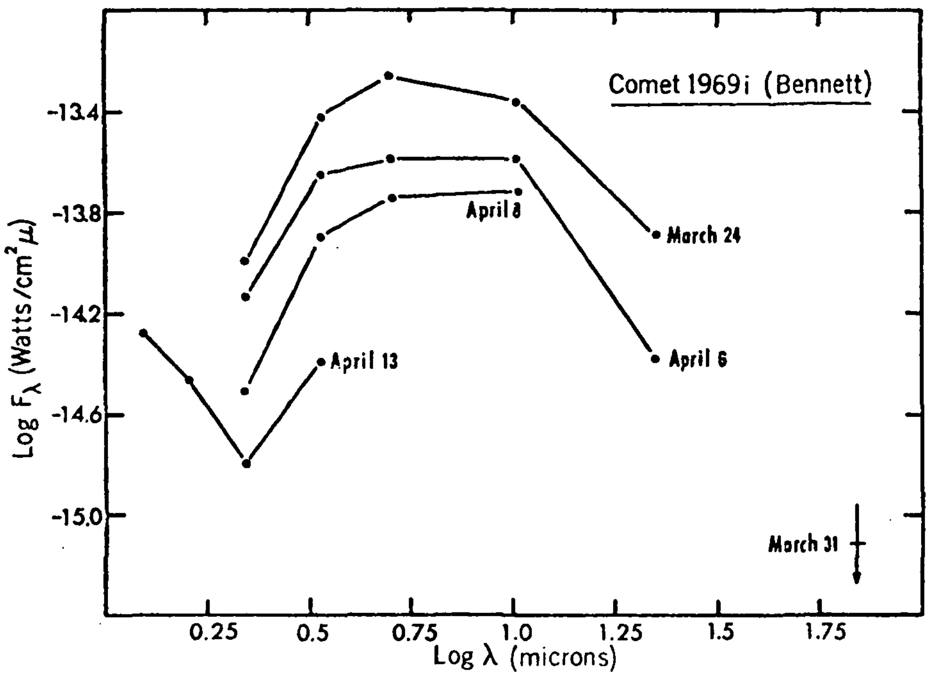

Fig. 4-2. Fluxes for Comet 1969i (Bennett). The top three curves are for measurements with a 35" aperture while the April 13 measurement was made with a 20" aperture. The airborne observational upper limit at 70μ has been corrected to an effective aperture of 35" from the actual aperture of 7" by means of a surface-brightness model. Dates are in 1970.

geocentric and heliocentric distances increased from 0.39 A.U. to 0.67 A.U. and from 0.89 A.U. to 1.16 A.U., respectively; and from 0.70 A.U. to 0.93 A.U. and 0.55 A.U. to 0.75 A.U. for Comet 1969i. The scans of Comet 1969i revealed the nuclear source to be only slightly larger than the beam size, whereas the tail is definitely much broader, 3-4 arc min. in width. The morphology of the infrared-emitting region of Comet 1969i has recently been discussed by Myer (1972), who confirms the point-like structure of the cometary nucleus. Fig. 4-1 shows that on February 7, 1970, we were fortunate to record a flare in Comet 1969g; Dr. Roemer informs us that this phenomenon coincided with the appearance of a jetlike extension (~0.8 arc min. in length) from the nucleus in the direction of the tail. The fact that the infrared energy distribution did not change after the flare indicates that neither the temperature nor the composition of the radiating particles was changed significantly by the outburst.

The spectral energy distributions for Comets 1969g and 1969i fit a black-body curve reasonably well and, therefore, the infrared radiation appears to be thermal rather than gaseous. As was found for Comet 1965f by Becklin and Westphal (1966), the 5μ-10.2μ and 10.2μ -22μ color temperatures for Comets 1969g and 1969i are higher than the equilibrium black sphere temperature at the comet's heliocentric distance. Table 4-I summarizes the color temperatures for Comet 1969g; the mean color temperature

TABLE 4-I

COLOR TEMPERATURES FOR COMET 1969g

5μ - 10.2μ	$T_c = 335 \pm 30°K$
10.2μ - 22μ	$T_c = 315 \pm 100°K$
Black (gray) Sphere 1 A.U. from Sun	$T_{eq} = 280°K$
Iron Spheres 1 A.U. from Sun	$T_{eq} = 480°K$.

325°K is greater than the equilibrium black-sphere value of 280°K, but considerably below that of iron particles favored by Becklin and Westphal (1966) for Comet 1965f. Thus, the emissivity of the radiating particles in Comet 1969g, and Comet 1969i as well, is more gray than that of iron. Finally, we note that Comet 1969i is a much stronger infrared radiator than Comet 1969g, even when allowances are made for the different geometry. This distinction is not surprising, however, since Comet 1969i is known to have been much the dustier of the two.

Thus, from infrared observations of comets we can make certain inferences regarding particle temperatures, emissivities and composition. Nevertheless, such determinations are no substitute for sampling and detailed in situ analysis that could result from a probe. Clearly, such a venture would have profound importance to other areas of astronomy, such as the interstellar medium where dust and grains somewhat akin to those of the comets may be found. Thus, we are pleased to support enthusiastically the type of mission you are considering at this Conference.

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NO. 5
INFRARED OBSERVATIONS OF COMETS IKEYA-SEKI (1965f) AND BENNETT (1969i)

by J. A. Westphal
California Institute of Technology

ABSTRACT

Measurements of Comet Bennett (1969i) from 1.2μ to 10μ indicate the presence of material at a temperature of 590°K on 6 April 1970. The excellence of the fit of the flux values to a 590°K blackbody severely restricts the possible range of materials present. Specifically it precludes simple isolated small particle models to explain the excess temperature observed.

Just prior to this Conference, we have been observing Comet Bennett every morning for the past 24 days. The results represent then only a first look at our data. I would like to review briefly our observations of the 1965 apparition of Comet Ikeya-Seki (Becklin and Westphal 1966). Fig. 5-1 shows the absolute intensities of the latter during both the approaching and receding phases. One sees a rather smooth run with heliocentric distance at λ2.2μ corresponding to a similarly smooth run observed in the visual region.

The radial distributions of emitted radiation as measured at 2μ for Comet 1965f and at 3μ for Comet 1969i (Bennett) are shown in Fig. 5-2. A nearly linear dependence on aperture diameter is found for both comets, implying a radial surface intensity distribution of r^{-1}. The maximum diameter included is 4 mm at the telescope's focal plane or 80 arc-sec. The r^{-1} surface distribution corresponds to a r^{-2} space distribution, compatible with the hypothesis of a point source emitting particles with a constant velocity, expanding out in all directions. Some variant of this hypothesis can, of course, also be considered.

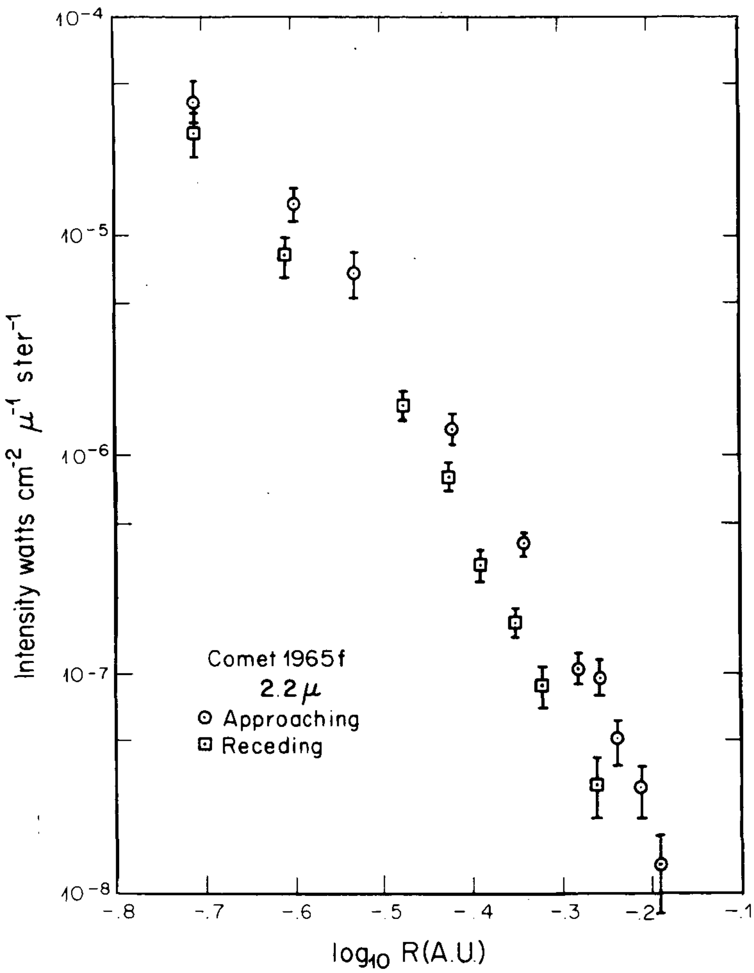

Fig. 5-1. Observed absolute intensities for Comet Ikeya-Seki, 1965f, versus heliocentric distance during approach ⊙ and recession ⊡ from the Sun.

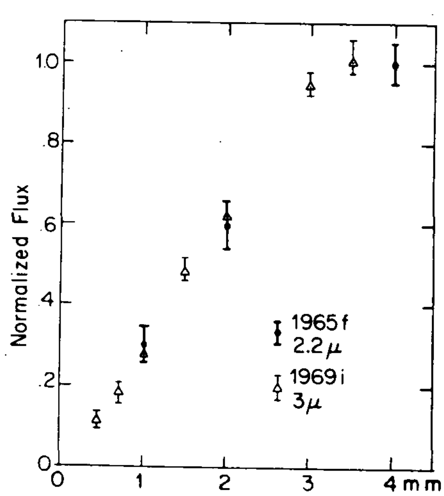

Fig. 5-2. Radial distribution of emitted radiation at 2μ for Comet Ikeya-Seki, 1965f, and at 3μ for Comet Bennett, 1969i.

Fig. 5-3 gives cross-sections across the tail for Comet Ikeya-Seki, both before and after perihelion. The observations were made at 3 microns; it will be seen later that this is all thermal flux, with no significant component of reflected sunlight. In the thermal part of the IR, there really are tails on comets; the tail has a profile roughly the same as in the visible.

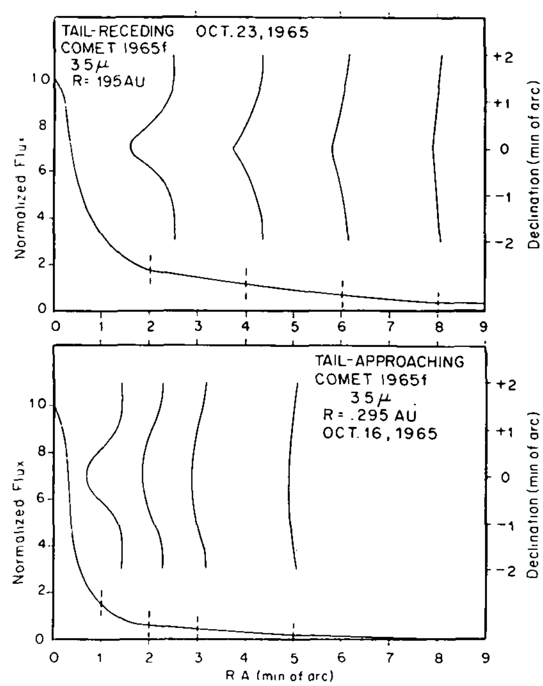

Fig. 5-3. Normalized flux measured across the tail of Comet Ikeya-Seki, 1965f, at various distances from the head: bottom - before perihelion, top - after perihelion.

At the time we observed Comet Ikeya-Seki, it all happened so quickly that we assumed that visible data would be taken elsewhere. When it was all over, no UBV measurements were found to be available. With Comet Bennett we are better prepared. Dr. McCord and co-workers from MIT have covered 3000 A to 1.2μ region*, and we at CIT covered 1.2 to 10μ, both groups using the 24-inch at Mt. Wilson.

Fig. 5-4 shows for Comet Ikeya-Seki the optical density in a 40-second-of-arc circular region centered on the head, as a function of distance from the sun. The optical density is down by about a factor

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* Johnson, et al., PASP, 83, 93.

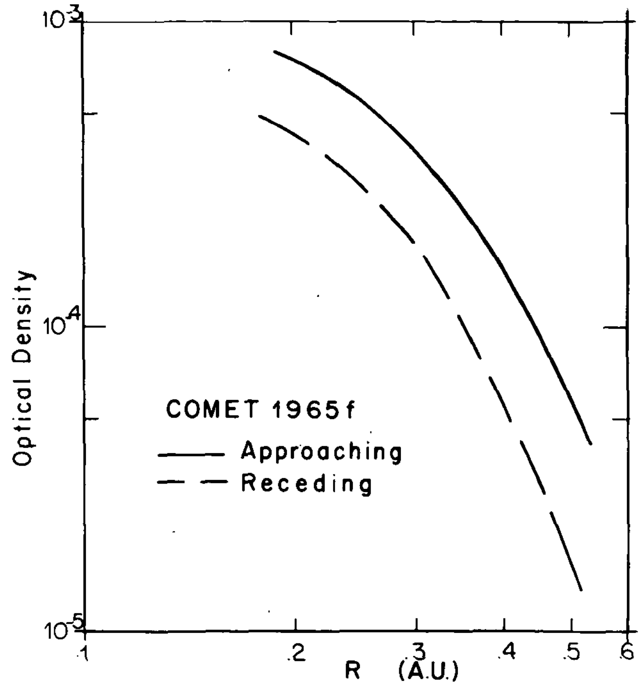

Fig. 5-4. Optical density in a 40 arcsec diameter circular region centered on the head, Comet Ikeya-Seki, versus distances of the comet from the Sun, before and after perihelion passage.

of 2 between approaching and receding. In our 1966 paper, we concluded that this reflected the size of the nucleus producing the material, and that in going around the sun it lost about half its surface area.

Fig. 5-5 shows the new data for Comet Bennett. Observations were made at 1.2, 1.6, 2.2, 3.4, 4.8, and 10μ. These are the transmission windows in our atmosphere available at Mt. Wilson. If one ignores the 2μ point and looks at 3, 5, and 10μ, a 590°K blackbody curve fits the data precisely. A change of only 15° either way disturbs the fit. If the solar energy curve is fitted to the 1.2μ point, one derives the line at the left in Fig. 5-5 assuming that the albedo is constant with λ,which cannot strictly be the case. If the albedo were constant, then the corrected 2μ point would yield the thermal 2μ component, agreeing approximately with the T = 590°K curve.

This forces us to conclude: (1) there are materials in Comet Bennett having temperatures at 590°K; (2) the emissivities of the particles at 3,

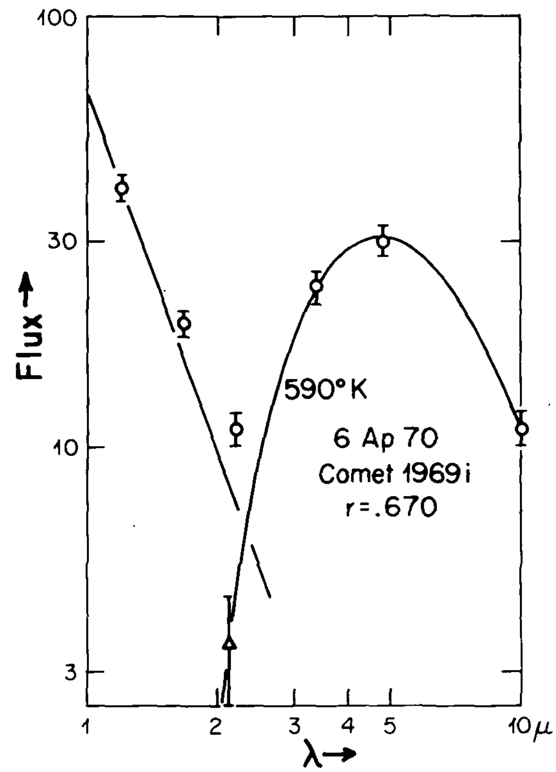

Fig. 5-5. Flux measured at wavelength of 1.2 to 10μ for Comet Bennett on 6 April 1970. The line to the left represents the solar energy curve fitted to the 1.2μ measurement, assuming albedo constant with wavelength. The measured fluxes at 3, 5, and 10μ are compared with a 590°K blackbody curve.

5, and 10μ must be very similar, within 20%. Thus, one cannot, e.g., have pure iron, because the emissivity between 3 and 10μ varies by about 2. On the other hand, some dirt could make the emissivity, already very low for iron, constant over the region. Note that the heliocentric distance is 0.67 A.U.

Fig. 5-6 shows how this compares with the data on Comet Ikeya-Seki. The color temperatures of both comets are shown with their error bars, as a function of heliocentric distance. Also given is the computed equilibrium temperature for a black conducting sphere. The comet temperatures derived seem about 300° too high. This cannot be accounted for by gray particles having the same albedo in the visible and the IR. It requires that the visible albedo be about 4X lower than the IR albedo.

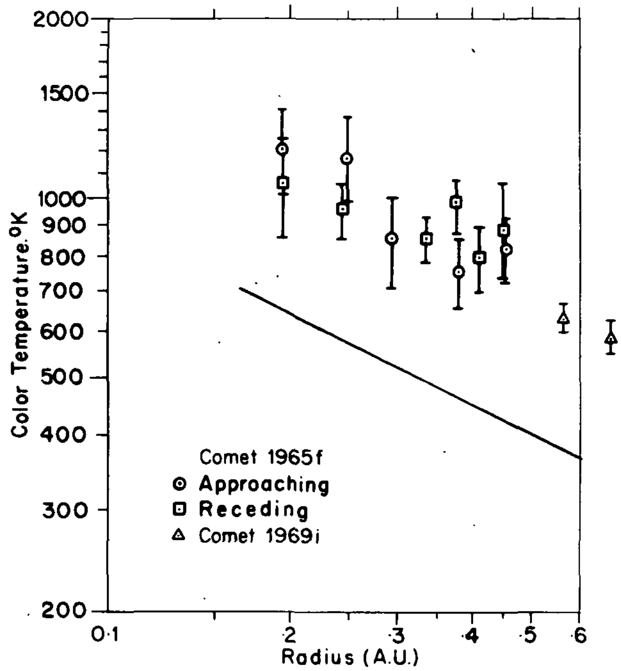

Fig. 5-6. Color temperatures of Comet Ikeya-Seki, 1965f, compared with those of Comet Bennett, 1969i, as a function of heliocentric distances of the comets. The derived comet temperatures are about 300°K higher than equilibrium temperatures expected for a black conducting sphere (solid line).

The line in Fig. 5-7 is computed with the emissivities of iron. The data on both comets are now well represented. The Comet Bennett points have actually not yet been corrected for the emissivity of iron; if this is done, these points will drop a bit. Ultimately, we should have more points, but this time the comet did not get closer to the sun than 0.4-0.5 A.U. In that sense, the Comet Bennett data are not as interesting as those of Comet Ikeya-Seki.

After our 1966 paper on Comet Ikeya-Seki, there was discussion (Krishna Swamy and Donn 1968) that our interpretation might be incorrect because there might be a molecular emission at 3μ. We had not taken any spectra there. At 2μ we had found that there was no line emission at the 10% level. For Comet Bennett we did get spectra at 3μ with a resolution of 50; there is no emission above 15%. This number may turn out somewhat smaller by further work. At 2μ the resolution is higher and there are no emission lines to the 5% level.

We are forced, therefore, to conclude that at least for Comet Bennett, this is really thermal emission, not gaseous, molecular emission; and that it fits a blackbody. What acceptable material is black in the visible and

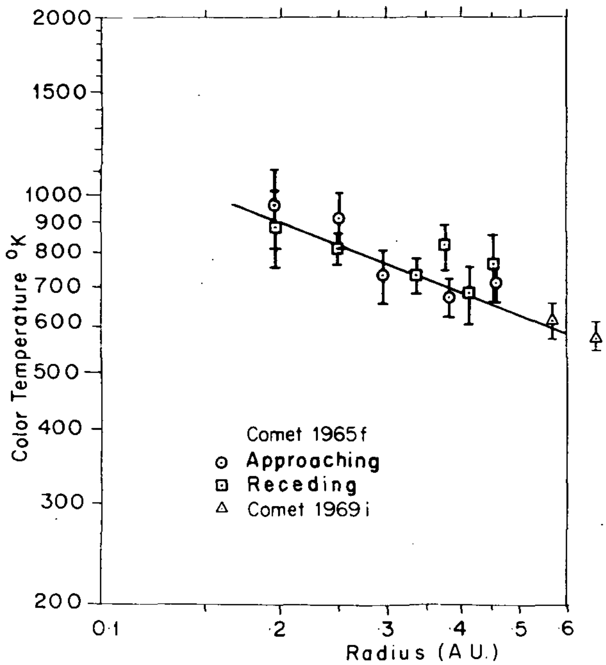

Fig. 5-7. Color temperature data of Comets Ikeya-Seki and Bennett as in Fig. 5-6, compared with equilibrium temperatures expected for an iron sphere (solid line).

shiny in the IR? In the case of Comet Ikeya-Seki, a sun-grazer, it was assumed everything might be boiled off but iron, so that the particles were iron. In the case of Comet Bennett this is difficult to believe. Where are the silicates?* How could the particles be like "iron", i.e., any metallic material having the same basic properties as iron, like chromium, nickel, tin, or lead; but not aluminum, copper, and gold, because the emissivity in the visible must be very much higher (or the albedo lower) than in the IR?

There does not yet seem to be a ready solution to this problem. Some have suggested that small particles are involved. Particles 2-3μ in size would become very poor emitters at 10μ, because they are smaller than λ. The difficulty is that the emissivity from 2 or 3μ to 10μ is nearly constant. It does not seem that any single species of small (spherical) particle can be involved. What if these particles are in fact flat plates or needles, or

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*Note added 1972 - see Maas, et al., Ap. J., 160, L101.

complex structures like fairy-castles? In fact, there is evidence that meteorite material may be fluffy, with grain sizes 2 or 3μ, contained in a fairy-castle structure. In visible light the fairy-castle is going to act like an "integrating sphere". Visible photons will get inside and bounce around and get absorbed. At 10μ however, the emissivity will probably be low. Whether such a structure will have a "sharp" emissivity cutoff near 1 micron is unknown.

References:

Becklin, E.E. and Westphal, J.A. 1966, "Infrared Observations of Comet 1965f", Ap. J., 145, 445.

Krishna Swamy, K.S. and Donn, Bertram 1968, "An Analysis of the Infrared Continuum of Comets", Ap. J., 153, 291.

Discussion:

Dr. Whipple: I am speaking now for Öpik on the subject of his "false nucleus", caused by the release of particles. As Dr. Westphal mentioned, with a constant velocity, the intensity of the nucleus will fall off with 1/r. The false nucleus will be very much larger than a true solid nucleus at the center.

In answer to questions by Drs. Donn and Dubin relating to the particle size, Dr. Westphal states: The difficulty is that thermal radiation is observed to come from the comet tail with the same color temperature, so you must have particles small enough that the radiation pressure is effective in blowing them away from the nucleus. This cannot occur for 50μ solid particles. Therefore, one cannot assume a mixture of particles to allow for the emissivities. Possibly the fairy-castle hypothesis would do.

Dr. O'Dell: Here follows the abstract of a paper on the same subject (O'Dell, C.R. 1971, "Nature of Particulate Matter in Comets as Determined from Infrared Observations", Ap. J., 166, 675-684).

"Infrared and optical wavelength photometry are combined to determine the albedo (0.3±0.15) of particles in three bright comets. The infrared data also indicate that the 10μ absorptivity is only about one-fourth that in optical wavelengths. Surface brightness distributions give particle radii of about 0.1μ. The resulting particle models are similar in these aspects to the interstellar particles".

Dr. Delsemme: When we speak about the nucleus, we still suffer from a vague terminology. For most observers, the nucleus means only the concentration of light or of material that is conspicuous in the head (10^3 to 10^4 km diameter). For the theorists, the nucleus means the icy conglomerate (1 to 10 km diameter). Dr. Whipple has rightly attracted attention to Öpik's suggestion to call the concentration of light that we see: "false nucleus". This, however, introduces a bias in favor of the icy conglomerate model; I am therefore proposing to call it the "photometric" nucleus. At any rate, the icy conglomerate cannot be responsible for a substantial fraction of the observed intensity around 10μ; instead, this must be due to dust particles that have been stripped from the nucleus by the drag of the vaporizing gases. When these grains have lost their icy cover, if any, they will reach their radiative equilibrium temperature almost instantly. It is therefore not surprising to detect a "photometric" nucleus around 10μ corresponding to the sharp maximum of the dust cloud surrounding the icy conglomerate.

NO. 6

NATURE AND ORIGIN OF COMETARY HEADS

by A. H. Delsemme
University of Toledo, Ohio

ABSTRACT

In cometary spectra the three major constituents seem to be OH, H, and O. Their common precursor is likely to be water, whose rates of evaporation and dissociation have so far not led to a major discrepancy with the observations. This type of explanation, however, has not led to a positive identification of other parent molecules. With the known solar intensities, all the molecules that have been suggested, as NH_3, CH_4, etc., would lead to lifetimes one-to-two orders of magnitude larger than needed by the coma observations.

An alternate hypothesis is that the precursors are not molecules, but icy particles stripped from the nucleus by the evaporating gases. By evaporating within an icy halo, the grains would liberate either parent molecules with very short lifetimes or some of the radicals themselves. Recent laboratory work suggests that the grains could be made of clathrate hydrates of gases or of radicals. The observations appear to indicate the presence of icy grains within the inner coma.

The radicals responsible for the emission of the molecular bands observed in comets can be classified by abundance into three groups: (a) the major constituents: OH, H, and O; (b) those having an abundance lower by two orders of magnitude: CN, C_2, C_3, CO^+; and (c) with an abundance lower by three orders of magnitude, like NH, NH_2, CH, N_2^+. The accepted explanation of the origin of the molecular bands was given by Wurm in 1943, namely, that they are due to the photodissociation of more complex parent molecules. We are not well informed on these parent molecules with the possible exception of water. Circumstantial evidence for the presence of water snows has been presented in the past (Delsemme 1965). However, the evidence for the presence of the water molecule in the cometary nucleus has been much reinforced by the discovery of the Lyman α halo of Comets 1969g and i.

Five primary processes are energetically possible for the photodissociation of the water molecule by the solar ultraviolet. They have been listed in Table 6-I in decreasing order of their wavelength cutoff.

TABLE 6-I

PHOTODISSOCIATION OF WATER BY THE SOLAR ULTRAVIOLET

A. In the first continuum (1800-1400 A)

(1) $H_2O + h\nu \rightarrow H(^2S) + OH(X^2\Pi)$

(2) $H_2O + h\nu \rightarrow H_2 + O(^1D)$

B. In the second continuum (1400-1150 A)

(3) $H_2O + h\nu \rightarrow H(^2S) + OH(A^2\Sigma^+)$

(4) $H_2O + h\nu \rightarrow 2H(^2S) + O(^3P)$

(5) $H_2O + h\nu \rightarrow 2H(^2S) + O(^1D)$

An important result (Ung and Back 1964) definitely rules out process (2) and therefore confirms only process (1) in the first continuum of water. Experiments in flash photolysis (Venugopalan and Jones 1968) suggest that several processes compete in the second continuum of water. This fact is probably linked with the well-known existence of a structure of diffuse bands (predissociation phenomena) superimposed on the second continuum. The relative production estimates of the competing processes cannot yet be unambiguously established for cometary conditions. However, the energy that can be absorbed in the solar spectrum by the first continuum of water is about ten times larger than by the second continuum. Process (1) is therefore responsible for the photodissociation of more than 90 per cent of the water molecules while less than 10 per cent could be explained by processes (3), (4) and (5).

Both the hydrogen and hydroxyl halos seem therefore explained mainly by reaction (1), producing OH and H in their ground states, with subsequent excitation of these molecular fragments by fluorescence. The further photodissociation of OH could, in this case, probably explain the intensity as well as the profile of the observed red line of [OI], because this dissociation can energetically lead to $H(^2S) + O(^1D)$ for all wavelengths shorter than 1950Å, as can be verified from the dissociation energy of OH. Some contribution from the dissociation of CO_2, if any, is however not excluded.

The brightnesses of OH and [OI] seem consistent with a production rate of water vapor of the order of 10^{30} mol/sec (Biermann and Trefftz 1964). It will be seen hereafter that this rate corresponds fairly well with what can be vaporized by the sublimation of water or of clathrate snows from an average nucleus.

The model used corresponds to the theoretical rate of vaporization of a sphere of water ice (or solid hydrates) whose radius is 10 kilometers. The production rates coincide then with a reasonably bright comet, like Comets Halley or Bennett. Of course only the orders of magnitude are significant, but no striking contradiction has appeared so far.

In particular, such a model of the cometary nucleus is the only one which predicts the onset of activity for the average incoming comet near 3 A.U. (Delsemme 1966), because water ice vaporization controls the appearance of the major molecular bands. It also predicts the right mass loss needed to explain the nongravitational forces and also the decay of activity after many perihelion passages. The loss is of the order of 10^{15} gm for a 10^{18} gm comet, which implies that the comet can sustain 100 passages but not 1000.

If water explains so easily the origin of the three major molecular fragments (OH, H, and O), one might think that it is easy to identify other parent molecules. In particular, CN, C_2, C_3, CH, NH, NH_2 . . . all seem molecular fragments originating from simple molecules that are known to exist in interstellar space, like ammonia, formaldehyde or hydrogen cyanide. An unexpected difficulty is brought by the study of the photometric profiles of the molecular bands. The deviation of these profiles from the simplest dilution law is conspicuous. The source of the radicals is therefore not a point source at the nucleus, but an extended source whose radius is of the order of 10^4 kilometers (O'Dell and Osterbrock 1962, Wurm 1963, Malaise 1966, F. Miller 1967, Vanýsek 1968 and 1969). However most of the possible molecules have been considered by Potter and Del Duca (1964). From laboratory data, it is easy to show that they will all decay by photodissociation or photoionization, but with lifetimes which are at least one order of magnitude too large. These lifetimes would lead to scale lengths larger than 10^5 km, while 10^4 km is observed. This argument is very serious, as one molecule after another has been ruled out among the possibilities.

I have proposed (Delsemme 1968) another possibility to escape from the dilemma. The observed lifetimes would not be the lifetimes of assumed parent molecules, but the lifetimes of ice grains, stripped from the nucleus and dragged away by vaporizing gases, and vaporizing themselves in the solar radiation.

The rationale of this idea is found in the laboratory studies made in Toledo to simulate cometary conditions. With David Miller, I have first been able to show that adsorption on water snows leads thermodynamically to the formation of clathrate hydrates of gas. The absorbed molecules rearrange themselves somewhat, layer after layer, to find their maximum stability in the clathrate lattice. The clathrate lattice is a peculiar water-ice lattice with many cavities where gas molecules are trapped by Van der Waals forces; it has been sometimes called the "solid hydrate" of the gas. The clathrate lattice determines the amount of adsorbed gas roughly at one gas molecule per six water if enough gas is available. If there is an excess of gas, this excess will condense without adsorption and will be the first available for evaporation, for instance in new comets. I suggested this idea of the solid hydrates of gases almost 20 years ago in collaboration with Prof. Swings (Delsemme and Swings 1952). Their thermodynamic importance in the solar system was stressed later by Stanley Miller (1961): they should always appear at low temperatures because they are thermodynamically more stable than their constituents. It does not matter if the kinetics of their reactions are slow, because in astronomical phenomena we have time.

Our results emphasize that clathrate hydrates simulate gas adsorption with very large "pseudo" specific areas; in the literature they have probably been mistaken for very large adsorption by water snows (Fig. 6-1).

David Miller and I have found a second result: Although sufficient gas may be adsorbed on cometary water snows to explain the quantity of gases emitted into the coma, the desorption decay-times rule out desorption from water snows as the regulating factor of gas production in incoming comets. The desorption should take place between 14 and 9 A.U., in stark contradiction with the observations (Table 6-II). The regulating factor of gas production remains therefore the sublimation rate of the snows, in par-

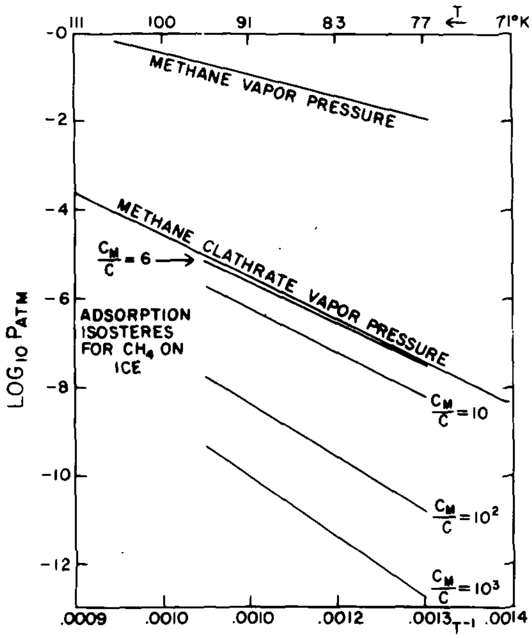

Fig. 6-1. The adsorption isostere for methane on a specific area of $500 m^2 g^{-1}$ of water ice ($\frac{Cm}{C} = 6$) coincides in a large range of temperatures with the dissociation pressure curve of the clathrate of methane.

ticular the sublimation rate of the icy lattice of the clathrates. The other gases are liberated in proportion, as the cavities of the clathrates open by evaporation. This explains the success of my 1965 model in predicting the heliocentric distance for the onset of comet activity.

TABLE 6-II

DESORPTION DECAY TIMES τ, EXPRESSED IN SECONDS, AS A FUNCTION OF TEMPERATURE AND HELIOCENTRIC DISTANCE. t IS THE TIME IN SECONDS OF FREE FALL FROM THE HELIOCENTRIC DISTANCE r.

T°K	r(A.U.)	log t	log τ_{NH_3}	log τ_{CO_2}	log τ_{CH_4}	log $\tau_{C_2H_2}$	log $\tau_{C_2H_4}$
20	225	10.3	66.9	63.3	37.3	76.9	60.3
40	56	9.3	27.0	26.3	12.3	32.3	24.0
60	25	8.8	13.9	13.0	4.3	17.3	12.0
80	14	8.5	7.3	6.3	0.9	9.8	5.8
100	9	8.2	3.3	2.9	-2.3	5.0	2.0
120	6.2	8.0	0.6	0.2	-4.2	2.3	0.6
140	4.6	7.8	-1.2	-1.7	-5.5	0.1	-2.1

The sublimation of water ice gives the law of temperature dependence, instead of Levin's law. On this interpretation the observations of Comet Arend-Roland by Liller (1960) and of Comet Rudnicki by Mayer and O'Dell (1968) point to a very high latent heat of sublimation, like water ice.

The clathrate lattice also is an excellent protection for unstable molecules. Large amounts of radicals could have been trapped in the cavities of the clathrates during the accretion process. Insulated from any outside influence by the potential well of the cavities, they can remain stored at higher temperatures than in ordinary lattices; they could be released into the coma by the evaporation of the water ice lattice only (Fig. 6-2). Donn and Urey (1956) have suggested the possibility of radical storage in lattices, but they appear to have given up the idea because of the very low concentrations of radicals reached experimentally. Actually, special radicals studied in lattices have not been studied in clathrate lattices, and most of them could not be, because they are too big to enter the cavities; the clathrate cavities have stringent steric limitations.

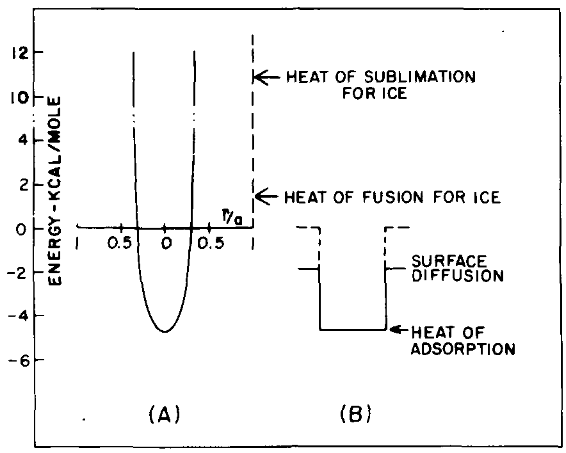

Fig. 6-2. (A) Potential well of the clathrate cavities. (B) Potential well of adsorption on ice. The radicals trapped in the clathrate cavities are much more protected from any outside influence; they can be released only by the sublimation of their icy lattice.

With another graduate student, Aaron Wenger (Delsemme and Wenger 1970), I have recently tried to duplicate a cometary environment in the laboratory, to study the behavior of different types of ices and clathrates. The clathrate hydrate of gas looks like a peculiar powder snow, made of icy grains with a sharp diameter distribution from 0.1 to 1 mm (Fig. 6-3).

When we simulate cometary conditions (Fig. 6-4), the evaporating gases strip some grains from the main body of snow. For this reason, we have suggested that a halo of icy grains builds up within the inner coma.

This leads to a new interpretation of the photometric profiles of the molecular emissions.

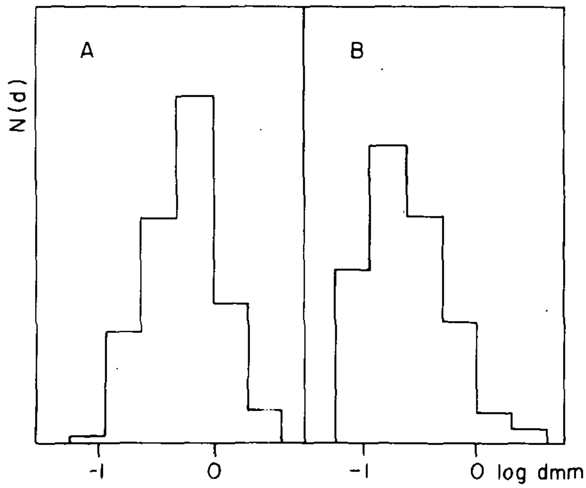

Fig. 6-3. (A) Size distribution of the grains of clathrate hydrate of methane. (B) Size distribution of the grains, after partial sublimation of the outer layers of the grains, (experimental results, Delsemme and Wenger, 1970).

The existence of a halo of a different type, limited to submicron icy particles, had been investigated by Huebner and Weigert (1966). They postulate a large optical depth, which drastically limits the particle size, because the scattering of submicron particles was needed to keep the evaporation going. They were therefore led to an icy halo that was vanishingly small. By contrast, our experimental results show that a sizeable mass can be had through a moderate number of large particles, which avoids the problem of keeping the evaporation going through an absorbing haze. The supplementary production of gases within the icy halo by its steady evaporation changes the shape of the photometric profiles of the inner coma. It also links the profile of the continuum with the profile of the molecular emissions, because the icy grains that reflect light in the continuum also act as a gas source which feeds the molecular emissions.

Examples of the new photometric profiles of molecular emissions of the model with an icy halo are shown in Fig. 6-5. The curves are normalized, with the exponential mean path of the decaying radicals taken as a dimensionless unit; the family of curves corresponds to a second parameter, which is the ratio of the exponential mean path to the radius of the icy

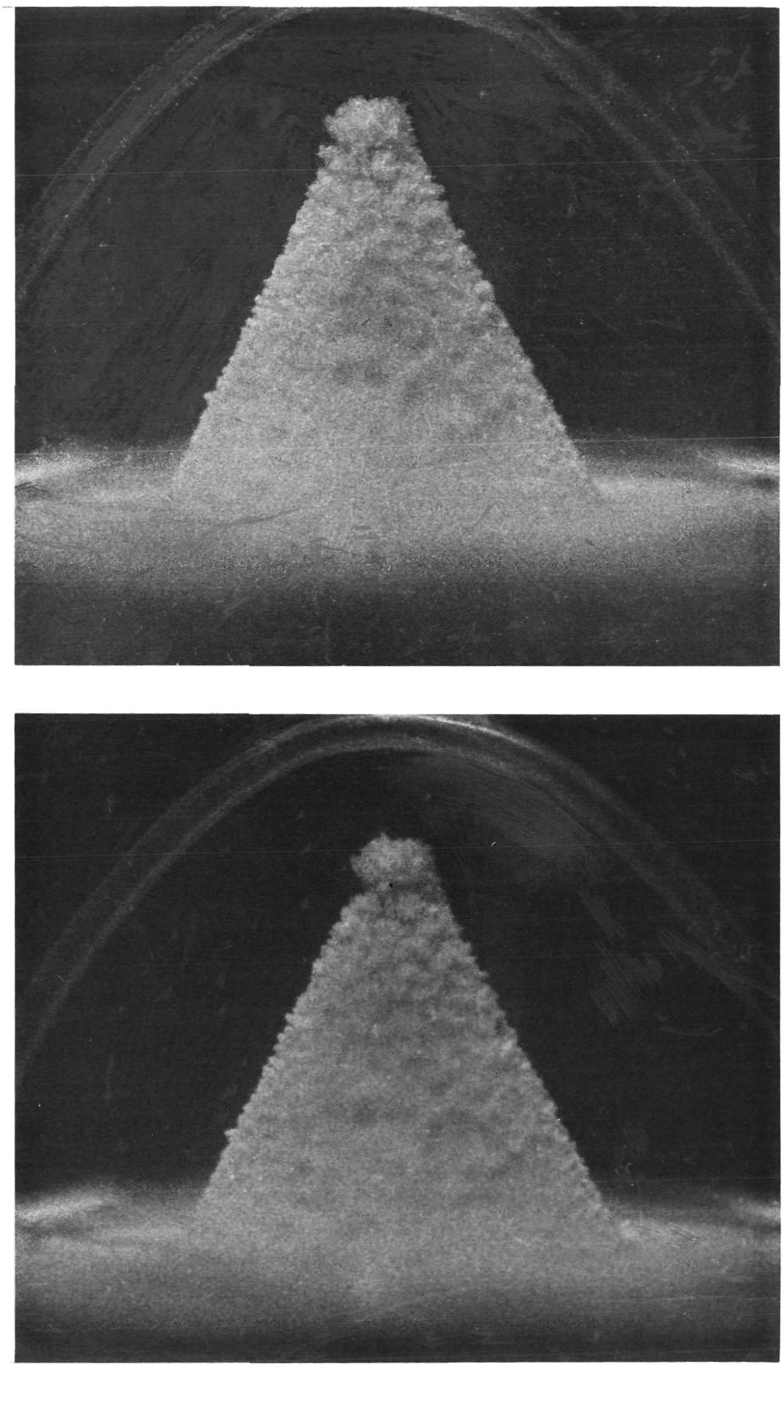

Fig. 6-4. Two photographs of the grains of clathrate hydrate of methane while simulating cometary conditions. Some grains have been stripped away in the second picture, which was taken a few seconds after the first one.

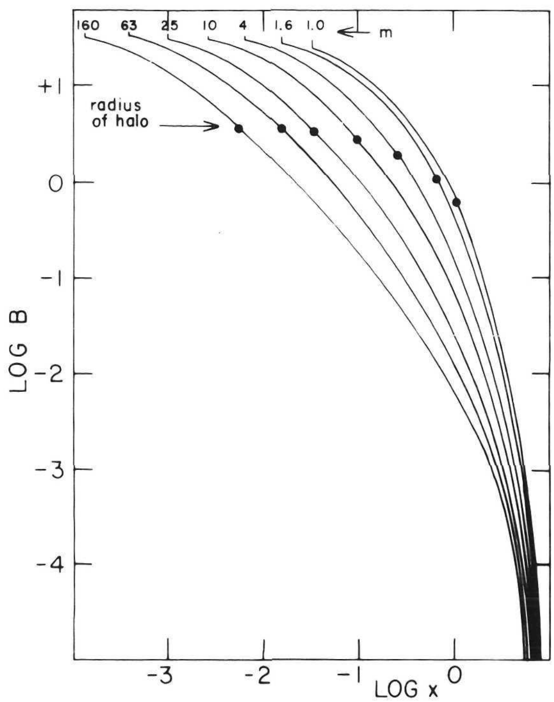

Fig. 6-5. Theoretical photometric profiles of molecular emissions for different sizes of the icy halo. The curves have been normalized for $x_o = 1$, the exponential mean path of a molecular fragment (like C_2 or CN) undergoing dissociation. B is the brightness and x the dimensionless distance from the nucleus, from Delsemme and Miller, 1970.

halo. For comparison with observations we have plotted in Fig. 6-6 the exponent of the brightness curve, or n in

$$\log B = -n(r) \log r,$$

where B is the brightness of the coma per unit area, and **r** the distance from the nucleus. The best available data on Comet Burnham have been used, three independent sets by Freeman Miller and O'Dell for the outer coma, and by Malaise for the inner coma. The interpolation proposed by Miller for the intermediate r values is not drawn here, and the Miller and O'Dell data are used only in the range where they agree. The solid curves are Haser's classical model. These dimensionless models are fitted first with the high values of the slopes observed, by a translation along the x-axis. This gives a lifetime of $10^{4.95\pm0.04}$ sec for C_2 if v = 1 km/sec. Then, the data fit with m = 9 for the ratio of the two lifetimes: C_2/ its precursor. But Malaise's observations are off the curve; they are unexplainable in Haser's model. They give a ratio around 25 for the same precursor. The technique using the derivative is exacting, and the points cannot be fitted in any other way.

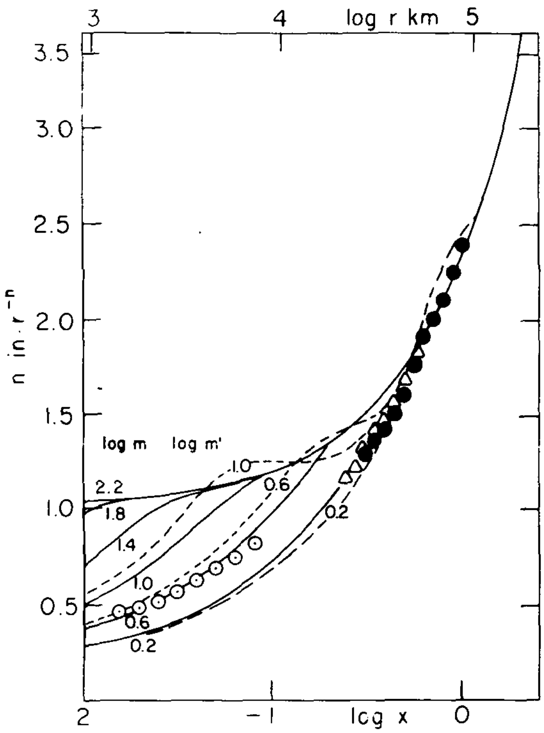

Fig. 6-6. Theoretical photometric shape of the molecular emissions in the coma. n is the exponent in log B = -n log r, where B is the brightness and r the distance from the nucleus; x is the dimensionless distance r/r_o. The family of solid curves corresponds to Haser's classical model. The family of dotted curves corresponds to Delsemme and Miller's model with an icy halo. The parameter m expresses the ratio of the exponential mean path of the precursor to the exponential mean path of the decaying radical, while the parameter m' expresses the ratio of the exponential mean path of the decaying radicals, to the radius of the icy halo. The observations of Comet Burnham by three independent observers are plotted on the two families of curves. The discrepancy with Haser's model has no possible interpretation. In Delsemme and Miller's model, the interpretation is obvious; (see text).

In our model we use the family of dotted lines, drawn in Fig. 6-6. The observations still cross individual lines, but the meaning is simple: they are average lifetimes of icy grains and the lifetimes are a function of the size of the grains; the largest lifetimes are normally observed for the grains reaching the outer halo, and the observational curve expresses the distribution of grain sizes.

The model links also for the first time the spread of the continuum reflected by the halo with the spread of the molecular emissions. Fig. 6-7 shows the computed brightness profile of the continuum reflected by the icy-

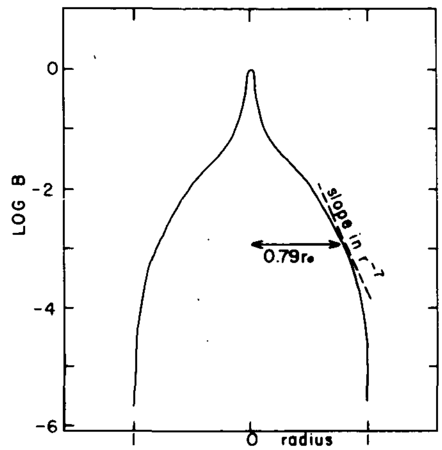

Fig. 6-7. Theoretical brightness profile of the continuum reflected by the icy grain halo. The brightness B is expressed as a function of the dimensionless radius x.

grain halo. Fig. 6-8 shows the variation of its slope with the distance r from the nucleus, compared with the best fit of the only other model that can give high values of the slope. This is Freeman Miller's model, taking into account the deformation of the coma. Miller's model shows no slope

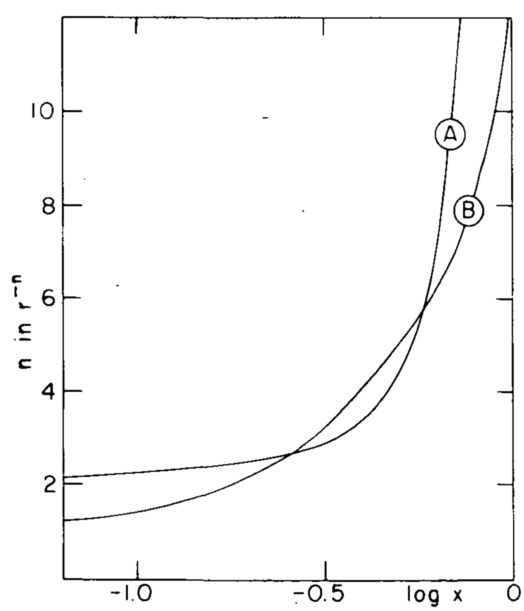

Fig. 6-8. Theoretical photometric shape of the continuum in the coma. n is the exponent in log B = -n log r, where B is the brightness and r the distance from the nucleus. (A) corresponds to the model with an icy grain halo. (B) corresponds to the deformation of a coma of non-evaporating dust which can give high values of the slope.

variation in one direction only: the direction away from the sun. This gives a ready criterion for observations along this direction. Though such do not exist, the orientation of O'Dell's observations is given. Fig. 6-9 shows the continuum of Comet Burnham as observed by O'Dell. To

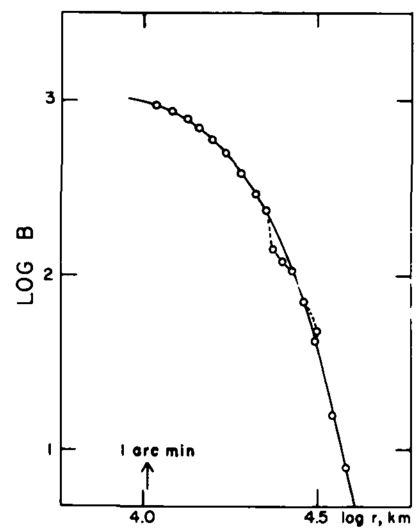

Fig. 6-9. Continuum of Comet Burnham as observed by O'Dell

compute the exponent n, I corrected for the small bump on his curve. Fig. 6-10 shows O'Dell's observations compared with the two foregoing models, A still being the evaluating ice-grain model, smoothed out by a computed

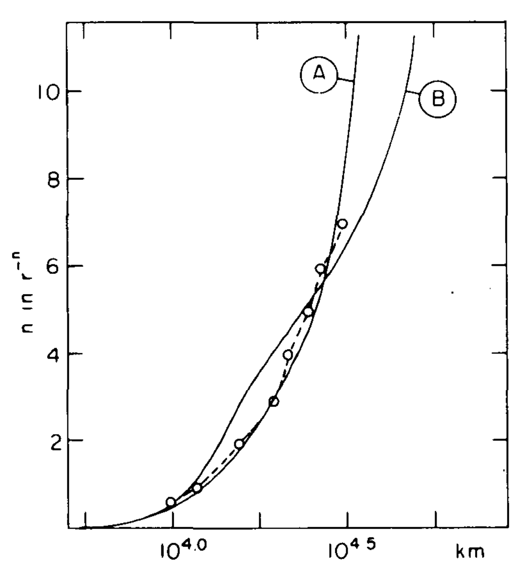

Fig. 6-10. The observations of the continuum of Comet Burnham, deduced from Fig. 6-9, are compared with the best fit of the two models of Fig. 6-8, modified to reach a space resolution comparable with the observations. (A) corresponds to a halo of evaporating ice grains. (B) corresponds to the deformation of a coma of non-evaporating dust.

space resolution of 1' (arc min) to correspond to O'Dell's photometric technique. The resolution is poor, and the continuum may be affected by some light from C_2; this should be checked with other comets. However, the existence of the icy halo has not been ruled out by this preliminary test.

Collisions in the coma and the presence of solid grains there has recently received much attention in a different context. For instance, grain interaction with gases near the nucleus was studied by Finson and Probstein (1968). The continuum in the head and its polarization have been compared with theoretical size distributions by Donn, Powell, and Remy Battiau (1967). The polarization observed is too low for iron spheres but can be explained by dielectric grains. The bulk of cometary grains cannot have sizes larger than a few microns without requiring excessive mass, but a fraction of larger particles is not ruled out. An increase in the ratio of the intensities of the continuum/molecular emission has been observed near inferior conjunction. Vanýsek (1968b) suggests that it comes from a forward scattering effect of the dust halo, which has to originate from particles whose size is at least as large as the wavelength of light. Krisna Swamy and Donn (1968) have studied grain temperatures, but they do not mention the temperature drop introduced by the latent heat of evaporation of ices for small heliocentric distances. Russian authors have also studied grain behavior: Kaimakov and Sharkov (1967) studied grain velocities, Dolginov (1967) and Egybekov (1969) studied the formation of grains in the coma.

At small heliocentric distances, less volatile grains may occur. Spinrad and Miner (1968) describe the Na I velocity field observed during the close perihelion passage of Comet 1965f. The observations are explained by the ejection of Na from the nucleus in stable compounds or in grains larger than 40μ. Huebner (1970) has studied the vaporation of sodium grains at small heliocentric distances.

Increasing concentrations are suggested within the inner coma, so the highest concentrations suggested by the snow sublimation are being accepted. Malaise (1970), by computing theoretical spectra, shows that the observed spectra are not pure fluorescent mechanisms. The observed spectra are explained by mixing linearly a fluorescent equilibrium with a Bolzmann equilibrium. To justify the latter, he needs collisions, that is, high densities. Probstein's work (Finson and Probstein 1968) also needs high densities in the evaporating gases to carry the dust.

Besides, the best photometric profiles of the inner coma are deduced from spectra, and too often the slit orientation is ignored and spherical symmetry of the coma assumed. Freeman Miller's theoretical and observational work on the coma deformations is important here, as well as perhaps the Högner and Richter Isophotometric Atlas (Högner and Richter 1969) which gives invaluable information on head shapes and symmetry for older comets, unfortunately only in white light and without photometric calibration.

For the old photographs this cannot be helped, but in the future we recommend consistent practice of photometric calibration of all cometary photographs.

Conclusions:

To explain the origin of the free radicals detected in the cometary spectra, Wurm suggested in 1943 the existence of unobservable parent molecules decaying exponentially into radicals. This hypothesis was developed by Haser to predict the shape of the photometric profiles observed along the diameter of a cometary head in the monochromatic light of the radicals. However, none of the lifetimes deduced from these shapes has led so far to a positive identification of any parent molecule.

An alternate hypothesis, namely the existence of a halo of icy grains, can also explain the photometric profiles observed in cometary heads.

The model I described favors Whipple's as far as ices are concerned, but it has aspects of Lyttleton's ideas as far as cohesion is concerned, because we do not know just where the halo stops and where the lump nucleus starts.

The recent evidence for the presence of water gives a strong support to the existence of solid hydrates in the nucleus, and to the model of the halo of icy grains surrounding the nucleus.

Discussion:

In response to questions by Dr. Jackson on the extent of the icy halo, Dr. Delsemme replied that the radius was estimated at 10^3-10^4 km, still small within the inner coma; that the grains would be large so that the halo might be quite transparent; that Dossin's (1962) observation of the occultation of a star and the work of Malaise indicate that visually at R = 600 km, the absorption is 1 $\pm$ 1/2 mag. Dr. Whipple added that 1 cm particles should go out to about 1000 km.

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NO. 7

PHOTOMETRY OF COMETS

by Freeman Miller
University of Michigan

Dr. Delsemme has indicated the usefulness of observations referred to under Isophotometry. Also, the implications of what he has said for space probes are obvious.

The programs we started and which are increasingly being done elsewhere were begun in Michigan 20 years ago with the Curtis-Schmidt telescope. It was a program of photographic surface photometry, at times augmented by photoelectric work by Dr. Liller (Miller and Liller 1956; Miller 1957). We found that two things were needed: (1) the pictures had to be carefully standardized photometrically; (2) filters, to separate the various components. In 1951 we started with glass filters and now use two interference filters: one for a C_2 band at λ5165, and one for continuum (Miller 1969). The aim is not just isophotes, but also photometric profiles.

Work such as Malaise's near the nucleus can undoubtedly be done more accurately with spectra; however, the coma in, e.g., neutral molecules, is not in general a simple circular pattern. It may be flattened or extended toward the sun (Miller 1967), so that, as Dr. Delsemme has pointed out, a single slit across it does not give the full picture.

Photometry of the tail must provide data that will check such theories as developed by Dr. Probstein, for dust tails (Finson and Probstein 1968). Photometry of the ion tails is similarly useful for verifying nature of the plasma indications (Biermann, Brosowski and Schmidt 1967). Calibrations must be provided to put the data on an absolute basis. Surprising things are found, in the shape of the neutral coma, and in the dust distribution. I refer to the kind of observations that Dr. Delsemme has indicated are needed. Photographic techniques will give the whole picture of the comet, not just a profile here and there, though photoelectric and spectrographic traces can contribute needed data for fitting theoretical models. It has been disappointing that so far the characteristics of the parent molecules are undecided. The analysis I made has not led to the proposal for the presence of clathrates. But photometric observation must be used to test any model, and that is its primary value.

Discussion:

Dr. Schmidt: Sodium should be a good tracer of the dust, and we made observations of Comet Bennett with a sodium interference filter. I now have a question for Dr. Delsemme. We did not see in Na the spiral structure very near the nucleus as observed in the continuum, only the envelopes beginning at about 20 arc-sec from the nucleus. Would this imply that the grain temperature is controlled also by the evaporation process?

Dr. Delsemme: The grain temperature is indeed entirely controlled by the vaporization process. The steady state of vaporization gives about 200°K for the temperature of the grain surrounded by an icy mantle of water or clathrate compounds. The radiative steady state is reached only when no vaporization takes place. When the icy mantle disappears and if nothing else vaporizes, the radiative steady state is reached almost instantaneously; the temperature of the grain goes up to the 600°K range for the heliocentric distances discussed here. Therefore, it makes sense to think that the sodium will be vaporized only when the icy mantle of the grains has disappeared. As the icy grain halo may reach 10^4 km, the sodium line will be produced at distances larger than this; as each grain acts as a secondary source of those particles which are going to become the parents of the atomic or molecular emissions, details and patterns visible in the emission of the dust are going to be washed out in the atomic or molecular emissions.

This is indeed a remarkable result of the observations of Comet Bennett done here in Tucson, that the spiral structure of the head is most visible in the light of the continuum, while it disappears partially or totally in the atomic or molecular emissions (cf. Paper #26). This implies that the observed spiral structure is a dust structure.

My interpretation of the disappearance of structure in the emissions is that grains are volatile, not only because of ices, but also because of less volatile materials that keep evaporating at temperatures in the range of 600°K, providing a very extended source of emitters.

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NO. 8

Lα PHOTOMETRY OF COMET BENNETT

by Maurice Dubin
Office of Space Science and Applications - NASA

I would like to report on some very recent results (Bertaux and Blamont 1970) by scanning Comet Bennett in Lα from OGO-V. The OAO-2 has not been used because the OAO is not able to see Comet Bennett until April 12 because of the solar elongation angle. I have the permission of Prof. Blamont to report these results here.

This experiment is different from OAO because the satellite orbit is different. OGO has been up about two years and the perigee has been raised to 17,000 km. OGO is a three-axis stabilized spacecraft, but has several control modes. Near apogee, above 100,000 km, the spacecraft was spun with the angle of rotation in the direction of the sun. On board is a Lα detector which has 80 Å bandpass. Blamont scans and maps the celestial sphere. He had already made two scans in September and December 1969, and has observed most of the celestial sphere. The third scan was delayed in order to observe Comet Bennett. The detector has a pointing mirror which can be controlled in angle in 40 arc-min. steps. As the satellite rotates, it scans a 40 arc-min portion of the sky that can be stepped to map out nearly the entire sky. Detailed scans of Comet Bennett were obtained.

The timing on this was unique in the sense that scattered light from the sun is a problem. One of the antennae was only 1/2° away from a critical scattering angle which would have blocked out the entire comet because of scattered light.

Blamont then made the measurements and when he saw the results coming off the Sanborn records, he became alarmed because he found that the intensity of Lα was extremely high. It saturated the Sanborn record. He was able to get scans across the comet and along the coma and across the tail. Although the angular resolution is low, it suffices for mapping this comet.

Fig. 8-1 is a plot of Comet Bennett in Lα. The abscissae and ordinates are in degrees. The contours are isophotes in Lα; the direction of the sun is shown. The visible comet is within the central contour. The intensity of this region is at least 150 x brighter than the rest of the sky. The saturation on the Sanborn was probably not in the taped signal and the telemetered read-out would be able to yield better amplitude resolution.

Dr. Blamont was able to observe the outer boundary of Comet Bennett against the Lα background of about 50 Rayleighs, from interplanetary and interstellar hydrogen. The limit of outer "envelope" of the comet is therefore approximately the 50-Rayleigh contour not shown in Fig. 8-1.

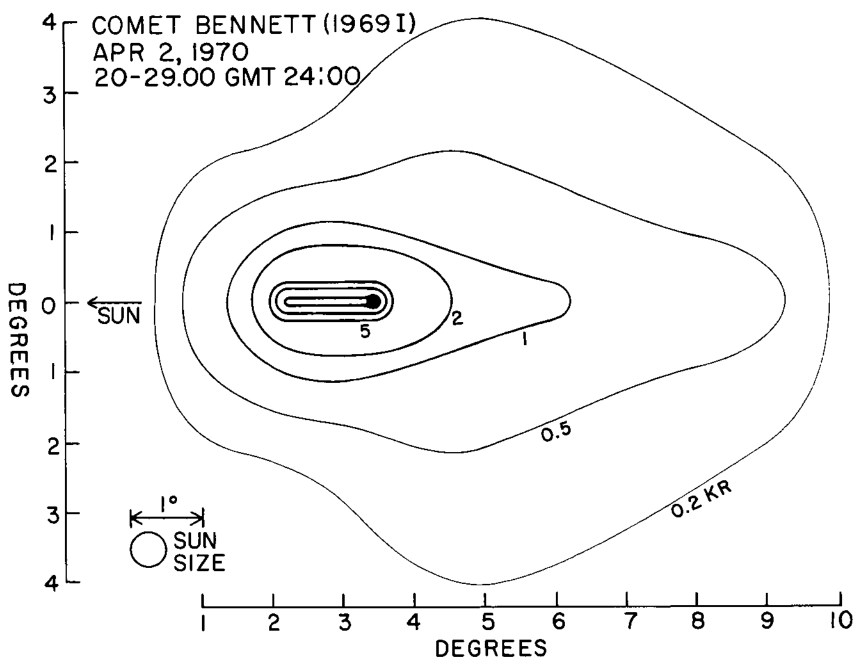

Fig. 8-1. Comet Bennett (1969I), Apr 2, 1970
20-29.00 GMT 24:00

<u>Discussion</u>:

Dr. Whipple: How bright is the comet compared with the geocorona? He must get that in these scans.

Mr. Dubin: He is outside the geocorona. It depends how far you are from it. The geocorona will go to 7 kilo Rayleighs.

Dr. Whipple: It is several times brighter than the geocorona, as you can see it looking out?

Mr. Dubin: Yes. He observes the distribution function. Dr. Lillie informed me that what the OAO sees is this inner part which Delsemme describes in terms of Comet Tago-Sato-Kosaka. The outer "envelope" is the new information in terms of the size of the neutral hydrogen cloud.

In addition to this, there are other scans. As the satellite entered into the geocorona, the scans were continued. Then the outer boundary is in the shadow of Lα, and it is possible to get isointensity contours of the comet "envelope" using the atmosphere as a filter. The OGO-V satellite will continue in this spinning mode, probably through mid-April, to study the evolution of this hydrogen cloud. Then, in conjunction with OAO, beginning maybe April 10 or 12, there will be fairly detailed study of the inner portion of the comet in Lα and OH.

Dr. Delsemme: It looks strangely like the dust distribution we see with the naked eye when we look at the comet.

Mr. Dubin: No, that halo has a different size. This is about 6°.

Dr. Biermann: What was the distance of the comet from the earth?

Mr. Dubin: 0.7 A.U., so you can get an idea of the size of the cloud.

Dr. Biermann: I did some work on the Lα distribution of the comet in 1967 (JILA Report No. 93, Jan. 30, 1968). The main conclusions were: (1) the central brightness could be determined by the width of that part of the Lα profile that was cut out, estimated at several percent of the total width of Lα; (2) the radiation pressure in Lα was comparable with the solar gravity, so that the outer shape should be distinctly non-spherical, just as now observed. The lifetime against ionization is $\sim 10^6$ sec, so that an outflow of 5-10 km/sec will suffice to achieve distances of several million km, as indeed observed. But I am surprised on one point: I was under the impression, from the work of Dr. C. Barth at Boulder, that the brightness of the geocorona was around 400 K R.

Lα pictures of Comet Bennett which we have seen can be interpreted on the basis of the total gas production of such comets as I first proposed in 1964 (Report, Commission 15, IAU 1970), on the basis of the relative proportion of molecules containing hydrogen following Dr. Whipple and others. The extent of the hydrogen atmosphere seen in Lα, of moderately bright comets, I estimated in 1967, as stated above.

Mr. Dubin: Blamont sees a background of 50 to 100 Rayleighs; in different parts of the sky, the background is different. He made a calibration and compared it to Barth's measurements; I think Blamont's numbers are quite good.

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Bertaux, J. L., Blamont, J.E. 1970, "Observation de l'émission d'hydrogène atomique de la comète Bennett", Compt.-Rend. Acad. Sci. Paris, 270, 1581-1584.

Editorial Note:

One reference is added. Note particularly the statement on P. 215, Col. 1, 2nd paragraph, re Delsemme's icy halo model:

Code, A.D., Savage, B.D. 1972, "Orbiting Astronomical Observatory: Review of Scientific Results", Science, 177, 213-221.

NO. 9

COMMENTS ON PHOTOCHEMISTRY

by B. D. Donn

Goddard Space Flight Center - NASA

Dr. Delsemme gave a good review of the general problem about photochemistry and the source of radicals that have been observed. One thing which I think is an important point is the source of the C_3; where this comes from, how it is produced, what is the parent? Its presence implies that there are fairly complex molecules in comets with at least the C_3 structure.

The more complex species, C_3 for example, are among the first molecules observed as the comet approaches the sun, and similarly for C_2 (Swings and Haser 1957). What we need badly are high resolution observations of the region near the nucleus. The 61" photographs by Larson and Fountain here on display are very interesting. They are fairly unique, showing the photographic structure near the nucleus (Rahe, Donn, and Wurm 1969). These authors point out that what is needed is near-continuous coverage, with few-hour intervals. I doubt, however, that anyone else has done this type of work. It requires good observatories, spaced in longitude. And something else which, to my knowledge, should be done; to study comets with image intensifiers, to get high spectral and spatial resolution, and keep the exposure time reasonable (Editors: this was done by R. Cromwell, E. Roemer, H.U. Schmidt on Comet Bennett).

Discussion:

Dr. Whipple: Does anyone know the source of C_3?

Dr. Kuiper: I remember that many years ago I discussed this C_3 question with Dr. Herzberg of Canada. He suggested that one should not look upon C_3 as having necessarily a parent molecule in the ordinary sense. If one has an icy mass, then anything impinging on it is likely to stick. Thereafter, under the influence of sunlight, ultraviolet, or particles, fragments will come off, so that some molecules are being formed as they come off.

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Rahe, J., Donn, B.D., and Wurm, K. 1969, "Atlas of Cometary Forms, Structures Near the Nucleus", NASA SP-198, Nat. Aero. Space Adm., Washington, D. C.

Swings, P. and Haser, L. 1957, Atlas of Cometary Spectra, Liège.

NO. 10

FURTHER COMMENTS ON PHOTOCHEMISTRY

by W. M. Jackson

Goddard Space Flight Center - NASA

The problem of C_3 or C_2 is indeed major. Is it realistic from a chemical point of view to consider that C_3 or C_2 would impinge upon the surface, be stopped, frozen, trapped, and then re-evaporate? When C_2 or C_3 hits the surface, it would probably recombine or lose its radical identity on the surface. We have seen no evidence in the laboratory except under very special conditions that one can trap radicals. I cannot envision that the astronomical conditions anywhere would be such as to enhance the free-radical trapping.

Considering Dr. Delsemme's model of clathrates, the possibility of trapping the radical inside the clathrate probably does not exist because, as he pointed out, there are kinetic barriers to making the clathrates. It is not a simple thing to do; you have to get a certain amount of rearrangement to do it, and during the rearrangement the radicals can also move and recombine with each other or react with the clathrate. There is a paper written by Prof. Jules Jackson at Wayne State University on the critical concentration of free radicals that can be trapped under ideal laboratory conditions in an inert gas matrix. The limiting thing is spontaneous warming of this matrix due to a chance recombination of radicals. This causes diffusion of radicals and more recombination, which heats the whole matrix again and allows more diffusion. So in the long run I think we are forced to rely on some kind of formation processes for the radicals.

We also need some kind of formation processes for the ion species. The situation for trapping should be much worse here since the ions should rapidly recombine with any free electron in the solid. Prof. Biermann has a picture of plasma interactions and shock fronts, and I am sure that this has a bearing on the question of CO^+, and possibly C_2 and C_3 formation. In order to analyse the problem more, we are going to need both better laboratory data on reaction cross-sections and rate constants for the formation and destruction of free radicals and ions, and primary data on the nature and identity of neutral molecule precursors in the comet. I think this is the whole reason for a cometary probe. We can sit back and look at secondary evidence for years, and this is actually what we are doing most of the time - looking at secondary evidence and building structures on that basis. A comet mission will enable us to get some information about the primary neutral parent compounds.

Lastly, I would like to mention our present program at NASA Goddard. This is primarily a laboratory program to measure rate constants for reactions of cometary interest and to study the electronic states of polyatomic molecules. We have recently completed an apparatus which allows us to look in detail at the dynamics of ion-molecule reactions down at both low and high energies, i.e., kilovolt range. One of the specific studies that is of cometary interest is the quenching of the $B^2\Sigma^+$ state of the CN radical, which has been studied and will be published in the J. of Chem. Physics.* We also have a program for trying to measure the neutral products from the electron dissociation of polyatomic molecules. This will give us some ideas about the upper excited states of polyatomic molecules. Now the problem with polyatomics is that their spectra are not as easily identified and characterized as for diatomic molecules. The spectrum is diffuse, and it is difficult to determine what the excited states of a molecule are. By looking at electron dissociation products over a range of energies, one can look at both the allowed states and the forbidden states of the molecule. This then allows us to predict which, if any, of these states are significant for comets.

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* Editor's Note:

The above reference has been published. W.H. Jackson and J.L. Faris 1972, J. Chem. Phys., 56, 95-101.

NO. 11

TYPE I TAILS - SOLAR WIND INTERACTIONS

by L. Biermann

Max-Planck Institut für Physik und Astrophysik

The cometary nucleus is the source of the gas, which we see in the coma, and of the plasma. All the gas emitted by a comet must ultimately be ionized and thus become plasma; the total plasma production is therefore equal to the total gas output of a comet.* The plasma emission is 10^3 times larger than what we see as visible plasma tails. At the current Conference we have seen the first direct evidence of the large gas output required by the Lα pictures which gives in visible form the number of H atoms. From this, within a factor of 2 or so, the number of heavier atoms emitted by the comet can be found, in essential agreement with what we previously derived for an object of this intrinsic brightness.

A small fraction of the neutral gas streaming outward is ionized close to the nucleus; this is the fraction of the gas seen in the visible plasma tails. The CO^+ ions are first seen moving towards the sun and then bent back; thus a cylindrical region, of diameter $\sim 10^5$ km, is filled with fine filaments emitting CO^+, N_2^+, CH^+, etc. by resonance fluorescence.

Since the solar wind flow is hypersonic, arguments from fluid dynamics show that there must be a contact surface with a stagnation point near the comet and therefore also a shock front somewhere upstream towards the sun. Our theoretical work has led to the conclusion that, for a medium-large comet, this bow shock front should be at a distance of several 10^6 up to 10^7 km from the comet. From hydrodynamical arguments we know that between the bow shock and the contact surface a transition region exists not unlike

* For an account of the recent history of our knowledge of the total gas output of comets, see the introductory section of the Report of Commission 15, IAU 1970.

the one we have around the earth. About the position of the contact surface which corresponds to the earth's magnetosphere we are less sure. Brosowski, Schmidt, and I (1967) believed that it is at a distance from the nucleus of either several 10^4 or somewhat over 10^5 km. A rediscussion has begun by H. U. Schmidt and co-workers.

Outside the bow shock, the solar wind is known from the measurements in interplanetary space. In the transition region the velocity of the solar ions is similar to the bulk velocity outside, but the flow velocity may be 10-100 km per sec, depending on position. One result of the calculations was that the drop in pressure from the bow shock to the stagnation point was small. Here for the gas output we used the figures which Eleanor Trefftz and I (1963) had found for the cometary nucleus on the basis of the observed intensity of the forbidden red lines of oxygen (confirmed by W. Huebner's work).

Our recent work on the atomic hydrogen density indicates that the atomic hydrogen moves considerably faster than the heavier neutral atoms. Both are sources of plasma. The lifetimes are of the same order, but the distances reached from the nucleus are different: the neutral molecules stream out at about 1 km/sec, whereas the H atoms move from 5-10 km/sec (H. U. Keller, 1971).

The pictures shown at this Conference (J. Blamont's experiment) do reach out to these distances. Photometry of the Lα pictures might show a gradient discontinuity. What we observe is the number of Lα transitions/cm^2 sec, from which one can, with some assumptions about the geometrical configuration, derive the density. In the earth's shock front the density increase is about 3X. Thus ionization by charge transfer (proportional to the number density of ionized hydrogen atoms) will be different on the two sides of the shock front. This shock front might therefore be detectable in data of the type being obtained by A. Code, J. Blamont, and co-workers. This observation can be done from an orbiting platform - no cometary probe is needed.

Let me now enumerate questions that can be answered by a cometary probe.

1. Existence and Outline of Shock Front and Transition Region:

A recent recommendation adopted by the IAU reads: "Interplanetary space offers one of the few opportunities to study in situ in a kind of cosmic laboratory the behavior of cosmic plasmas and magnetic fields, and, more generally, the applicability of magnetohydrodynamics; to be more precise, when a comet interacts with the solar wind, we can check in a specific but rather complicated case to which extent 'classical' magneto-fluid dynamics suffice or else have to be supplemented by considerations at a more refined level of plasma physics - the microscopic plasma physics, which is very important in some laboratory experiments and is being studied in that context rather intensively".

The comets are in a sense incidental, being only sources of neutral gas and plasma, which bring about an important physical situation. This might lead also to insights about interstellar space, which we cannot probe directly.

2. Densities, Composition, and Velocity Fields:

The chemical composition can be investigated at two different levels:

(a) What are the relative abundances of H_2O, NH_3, and hydrocarbons (CH_4, C_2H_2, C_2H_4 ....), that is, combinations between O, C, and N on the one hand, and hydrogen on the other? There are also other combinations of C, O, and N, for instance CO_2, (CN_2), N_2O_3 and molecules containing all three atoms.

(b) Comets are interesting as relics from the early history of the solar system. The atmosphere of a virgin comet may thus resemble the initial atmosphere of a small body in the planetary system. The isotopic abundances will thus be of special interest. One could devote 10-20% of the total of the scientific payload to this experiment.

3. Position of Contact Surface:

The rate of dissociative recombination of CO^+ as a function of the temperature has been measured by Mentzoni and Donohoe (1969); this reaction has a large cross section, the rate constant in the relevant temperature range being $10^{-7.0}$ $cm^3 s^{-1}$. (This constant is the product of the average velocity of reacting electrons, a few 10^7 cm per sec; and the cross section, several 10-15 cm^2.) Work is in progress on relating the observed number of transitions/cm^2 to the physical parameters of the comet, including the expected contours of equal intensity.

4. Processes Inside Contact Surface:

How do the CO^+ and (invisible) ions of other molecules originate? I am inclined to believe that our paper (Biermann, Trefftz 1963) is still valid; that the alternative, ascribing the primary ionization to fast electrons, is questionable because the fast electrons causing the CO^+ would be even more effective in destroying other neutral molecules in the inner coma (Biermann and Lüst 1963). The observed stability of CN, C_2, etc., is an indication that there is an upper limit to the flux of fast electrons (other than photoelectrons).

5. Magnetic Fields in the Transition Region:

   The general remarks made under (2) apply here also.

6. Measurements of Rays and Filaments and of Plasma Velocity Field:

   The plasma tails appear made up of rays of a few 1000 km diameter. These narrow filaments have a tendency to be displaced towards the main body of the tail, as discussed by Wurm (1963). Stumpff discussed whether the time dependence of the angle between a ray and the tail axis can be understood as due to the lateral gradient of the plasma flow velocity. We consider that the changes of the motion of the visible plasma exhibit the convective part in the Eulerian formulation of fluid dynamics. These convective accelerations contain information on the structure of the velocity field. This concept should be checked by measurements. Alternatively, we may be dealing with a wave.

In closing, I would direct attention between what one can do from the ground, or by means of a cometary probe, or from an orbiting observatory. In 5 years a platform orbiting the earth may carry a Lα telescope suitable to do cometary work as well as a good optical telescope. Then a comet probe can be supported continuously by such observations.

Discussion:

Dr. Jackson: You mentioned that the hydrogen atoms come, I presume, from the dissociation of water, since that's supposed to be the main component of the comet head. Are the velocities of the H atoms of the order of 10^6 cm per sec?

Dr. Biermann: Yes; this is based on evidence collected by Keller, the details of the dissociation process and how the excess energy is being distributed.

Dr. Jackson: In the case of one laboratory study in which one is looking at the excited OH, where you can measure the amount of energy going into vibration and rotation, a large amount of excess energy goes into the excited OH and excited vibrational and rotational levels. As for the partition of the energy for the translational modes, especially for ground-state of OH, I had not previously been aware of any direct laboratory data.

Dr. Suess: I think isotopic composition is one of the most important problems one should attack; but the evidence may be difficult to interpret. We have much information from meteorites on isotopic variations and they are difficult to interpret. I should then like to make a remark about the chemical composition of comets. There is always the idea that comets consist of water, ammonia and methane essentially. These will be there because they occur in the solar system. Other materials that occur are in carbonaceous chondrites. Somehow these must be derived from a substance that contained water, ammonia, and methane after undergoing chemical reactions, e.g. by ionizing radiation. Thus, what we should look for in comets is something between the clean substances and the very dirty stuff of the carbonaceous chondrites. We know for example that CO_2 should be there, but then you have CO_2 and CH_4 at the same time. This implies a variety of organic stuff as well, including hydrogen compounds.

Dr. Schmidt: I would comment on the distances from the nucleus of: (a) the features near the contact surface, and (b) the shock front. My calculations indicate that the equilibrium position, at least with stagnation equilibrium, can come very near to the nucleus, inside 10^4 km to 10^3 km.

Dr. Biermann: I used a similar argument recently (Biermann 1970) to show that from the new value of the rates constant of dissociative recombination of CO^+ one can deduce a lower limit to the distance from the nucleus at which the CO^+ can appear. If you go very near to the nucleus (<500-1000 km) the density, going up as r^{-2}, becomes so high that the time scale of dissociative recombination is shorter than the convective time scale. So the plasma would disappear before it reaches any distance.

Dr. Arpigny: Do you know in which state the oxygen atom is formed in this dissociative recombination from the CO^+?

Dr. Biermann: The CO^+ as an oxygen atom source is probably very inefficient because the total production of CO^+ in a medium-bright comet is only of the order of 10^{28} per sec, so it is by something like a factor of some 10^2 or 10^3 less than that of other molecules. Even if half the CO^+ which was originally produced would give rise to excited O atoms, it wouldn't add more than 0.05% or 0.1% to the O. So this contribution to the [O] emission is minor.

Dr. Delsemme: I am still at a loss to understand the mechanism sending CO^+ sunwards as it leaves these filaments. Have you got an explanation for that, for this high velocity?

Dr. Biermann: Not really. Our earlier publications contain ideas that might help but no full explanation is at hand.

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NO. 12

TYPE I TAILS - FURTHER COMMENTS

by J. C. Brandt
Goddard Space Flight Center - NASA

The study of comets is fascinating in itself, but it leads to many other things, including the study of the plasma in which the comet is immersed. If there were no solar wind, we would not have the comets familiar to us. A comet probe studies the properties of solar wind along the way.

I have been occupied for some years with discussing cometary structure on the gross scale. The ionized comet tail flows away from the sun; but in what precise direction does it flow? I think it is in the direction of the local momentum field, and this can be verified from the aberration angles which, in turn, give the parameters of the solar wind. The average azimuthal velocity comes out to agree with the space probes. One can also study the fluctuations in solar wind, important in the discussion of a solar-wind model; it may be responsible for some fine structure in the ionized tails.

It is not commonly realized how good the agreement is between comet analysis and space-probe results. Fig. 12-1 is a histogram showing dispersions in angle of the direction of the solar wind. With comets one can do it in two ways: calculate an aberration angle (ε), which the tail makes with the radius vector. This has to be adjusted statistically because there are projection factors which make it appear too large. The fluctuations in solar wind direction can also be found from a comet with the earth exactly in its orbital plane; one then gets fluctuations in the direction perpendicular to the observing plane. This was done for Comet Daniel (1907d). Reference is made to a more detailed study (Brandt and Hardorp, 1970).

All of these comparisons are statistical, with comets used from the present to 1889. It would be desirable, if on a probe going through a comet, we could make one detailed comparison. This would require that we have a

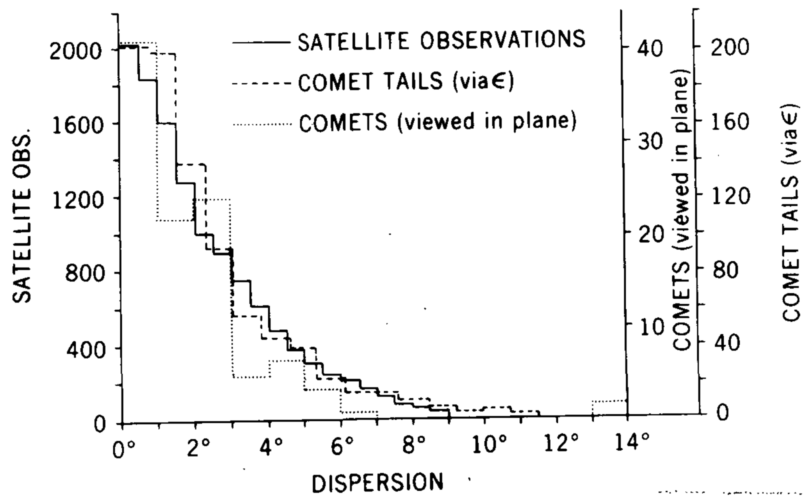

Fig. 12-1. The distribution of solar-wind directions as determined by satellite and comet observations.

plasma probe which can accurately determine the angles of flow. Actually, it is difficult to tell, as a function of time, in which direction the plasma probe of a spinning satellite is pointing. So it may be easier to measure the angles with comets!

The best kind of plasma probe, taking into account the need for both solar wind and directional data, is probably a rotating electrostatic analyzer; this can be made to have a fairly narrow field of view, and this is what has been used on the Vela experiment.

Incidental to this I have been able to calculate the e-folding time of solar rotational braking entirely on the basis of comet observations (Brandt and Heise 1970). This may well be emphasized when funding a probe to a comet is considered. The comets are a very useful tool for probing of the velocity field of the solar wind, and, except for some radio observations, are our only data source of the solar wind velocity field outside the plane of the ecliptic. It is extremely valuable to get this calibration point.

Our effort is continuing and I might add that we have just put a new comet telescope into operation. The field appears to be excellent; we have examined images 6° from the center, and they are round and compact as specified. It is also important that we consider how ground-based observations are to be correlated with a comet-probe effort. We could lose a great deal of information if we do not tie in with ground-based observations.

Discussion:

Dr. Kuiper: Is the average spread of the solar-wind beam meant to be at a given time over space; or is it at a given point in space over time?

Dr. Brandt: It is in fact an average at a discrete number of points in space taken at different times. It is not the preferred way, but it is all we have. It would be beautiful to have one firm calibration point on this distribution.

Dr. Donn: At Goddard we tried to see whether one could correlate the available information on the two bright comets taken by present satellite probes. It turned out that neither came close enough to the earth-sun line to use the earth satellites. However, we tried to get solar wind data from the various satellite observers and make use of the Comet Tago-Sato-Kosaka and Comet Bennett observations to obtain a sequence to search for a correlation between changes in the ion tail with the solar wind.

Dr. Lyttleton: The pictures shown seem to refer to an average comet. Individual comets may differ. For instance, Comet Ikeya-Seki went inside the Earth orbit close to the sun before any activity began; Comet Humason showed this phenomenon without coming inside the orbit of Mars. Also, the activity is stronger after perihelion than before, whereas the velocity relative to the solar wind is higher before perihelion than afterward.

Dr. Whipple: I thought generally the activity was less after perihelion.

Dr. Lyttleton: No, I think the activity is greater after perihelion.

Dr. Schmidt: I looked into this question. The most important point is the dependence on the sun's distance of the two distances, to the shock-front and to the contact discontinuity. There happens to be some kind of maximum of these two distances near the orbit of the earth.- Dr. Schmidt thereupon showed model calculations of the locations of shock fronts. For comets which approach the orbit of Mercury, the shock front disappears. The maximum near the Earth is due to the ionization time scale being similar to the time which the molecules need to reach the bow shock. We have a drop-off beyond the Earth because the ionization there gets slower.

Dr. Biermann: I believe that differences in tail orientation in Comet Burnham may be explained by sector structures in the solar wind.

Mr. Dubin: Dr. Biermann discussed Type I comets and the tail, and the standoff distance. Normally, the comet also contains Type II components, like Bennett.

Dr. Brandt: Comet Bennett is indeed mixed - the two components are present. In some comets, notably Comet Mrkos, 1957, it is quite clear that the ionized and dust tails did interact.

References:

Brandt, J.C. and Hardorp,J. 1970, Astron. and Astrophys., 5, 322.

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NO. 13

COMET TAILS OF TYPE II

by R. F. Probstein
Massachusetts Institute of Technology

ABSTRACT

A summary is presented of a theory for the head and tail regions of Type II (dust) comets, wherein dust particles having a wide distribution of sizes are assumed to be released from the comet nucleus in an essentially continuous manner in time during the period of distinctive cometary phenomena. The dust particles are assumed to be accelerated radially outward from the nucleus as a result of a drag interaction with the expanding gas in the comet head. In the tail region the only significant forces assumed to act on the dust particles are solar gravity and the force of solar radiation pressure.

It is shown how results describing the surface density in the tail are obtained and how by matching calculated distributions with measured ones it is possible to determine the dust and head-gas emission rates as a function of time, the distribution of dust particle sizes, and the emission velocity from the inner head region as a function of particle size and time. The results of matching calculated density distributions with light intensity measurements from Comet Arend-Roland 1956h are summarized. Many properties of Comet Arend-Roland are shown to be derivable some of which are new and others of which are in agreement with results from independent measurements. It is also shown how the theory explains observed non-radial orientations of dust tails in the head region.

The subject of my talk may not be entirely relevant to this Conference since NASA plans do not at present include a mission to a dust comet. The work here described (Finson and Probstein 1968; Probstein 1969) was for the most part done jointly with Dr. Michael Finson, now of the Avco-Everett Research Laboratory. In my talk I shall not introduce any more basic cometary physics than what Bessel did in 1830. He suggested that dust tails could be described as made up of dust particles propelled outward by solar radiation pressure, the radiation force being comparable to that of solar gravity. The strength of the radiation pressure is usually measured by the quantity $1 - \mu$, the ratio of the radiation force to the gravitational force. The radiation force is proportional to the particle cross-sectional area and the gravitational force to the particle mass, both forces following an inverse square law with distance. Thus, $1 - \mu$ is inversely proportional to the product of the particle density ρ_d and diameter d. The coefficient of proportionality contains the scattering efficiency for radiation pressure. It will thus depend on the nature of the scattering medium, either dielectric or absorbing, but here I will assume it to be constant.

The most convenient description of comet tails is in cometocentric ξ,η coordinates, as shown in Fig. 13-1. The tail axis of a dust comet is usually characterized in one of two ways, either as a syndyname (syndyne) or synchrone, one being a locus for particles of a given size emitted over varying times, the other a locus for particles of varying sizes emitted at a fixed time. Fig. 13-1 shows a comet orbit and a syndyne which is the locus of particles emitted with zero relative velocity from the nucleus. Each particle emitted before the time of observation follows essentially a hyperbolic orbit, and the locus of the end points of these orbits at the

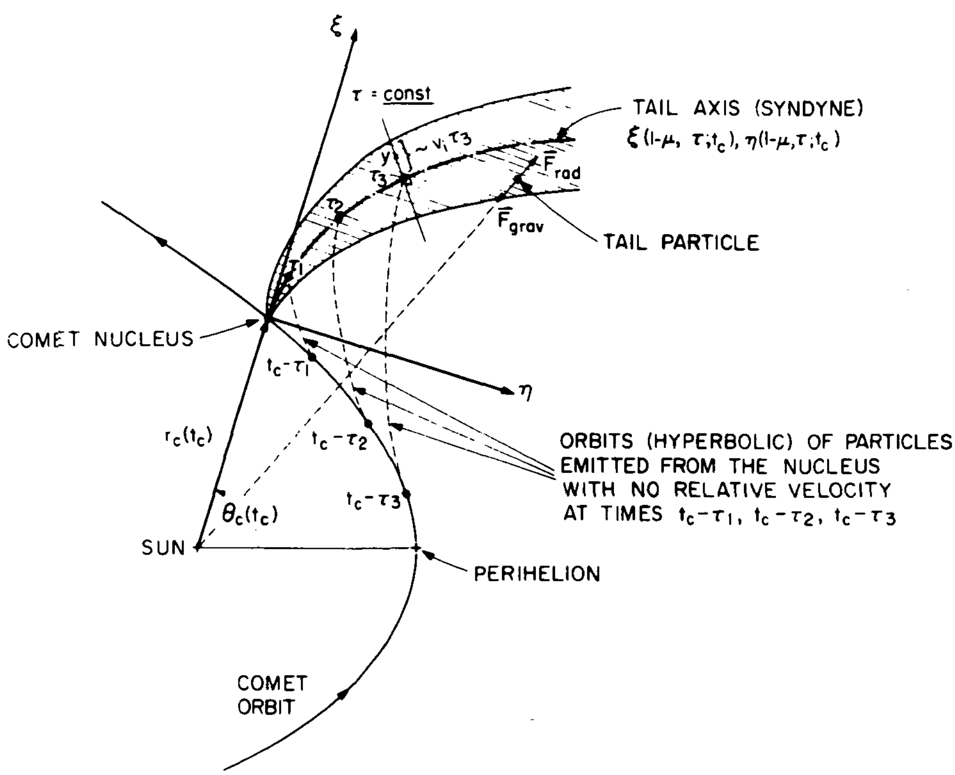

Fig. 13-1. Comet tail and particle orbits.

observation time is the tail-axis syndyne. The curvature in the $+\eta$ direction is essentially the result of Coriolis forces. By comparing observed curvatures with calculated syndyne curvatures, early investigators estimated values of $1 - \mu$. They were in the neighborhood of 0.1 to 1.0 and are appropriate for particle sizes of about a micron, assuming particle densities of the order of 1 gm cm^{-3}. Information on the particle emission velocities was easily obtained from the observed tail width, which at any cross-section is essentially the emission speed times the particle emission time τ.

Obviously there was other information which was obtained earlier and the dust-tail picture appeared to provide a satisfactory explanation until Osterbrock (1958) pointed out a difficulty with this description: namely, measurements had begun to indicate that the tails, contrary to expectations, were not directed radially outward from the sun at the origin. Rather, they showed a marked lagging angle with respect to the prolonged radius vector from the sun. It is clear from elementary mechanics that a syndyne for no relative emission velocity leaves the nucleus radially. One then began looking around for other forces to explain this phenomenon. But before I discuss that, let me show typical data on measurements of the initial tail angle in the comet orbit plane of Comet Arend-Roland. As can be seen in Fig. 13-2, the angles

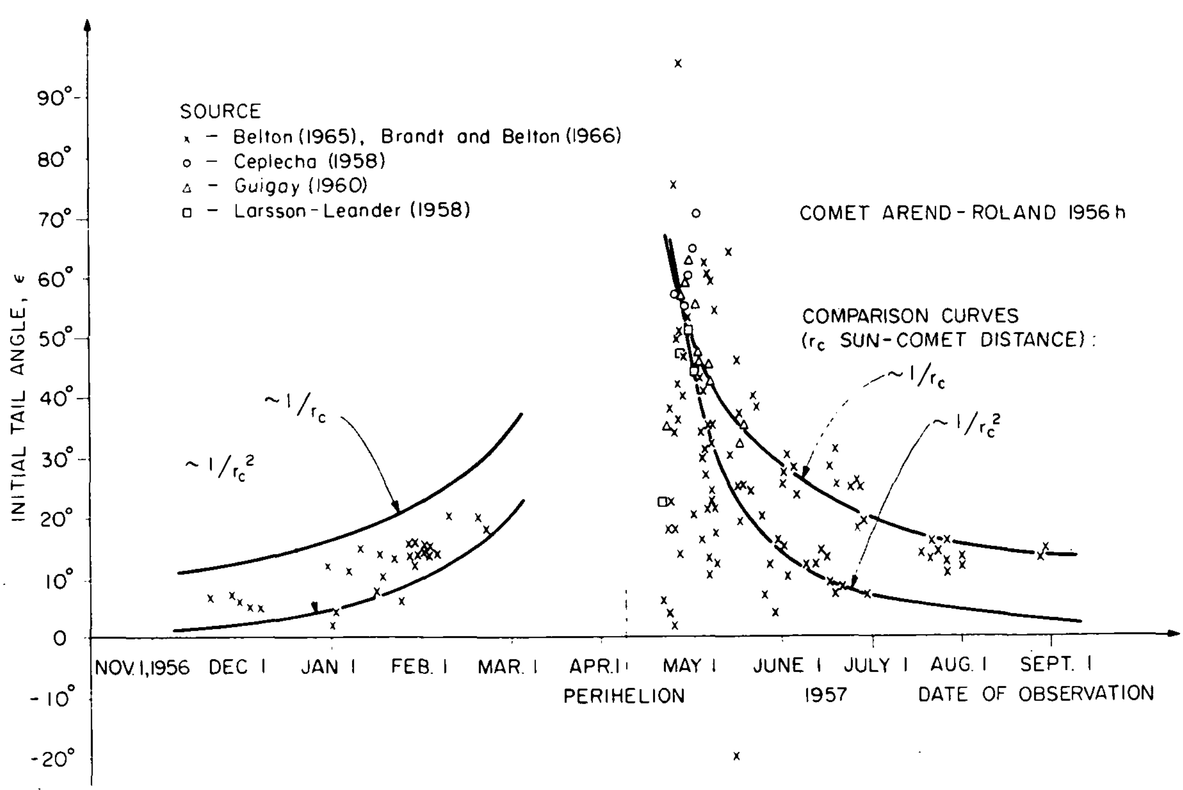

Fig. 13-2. Initial tail angle in comet orbit plane as measured from radial direction for Comet Arend-Roland (1957).

are quite different from normal. Here, the angle ε is the tail axis angle as defined by the locus of the apparent maximum surface density. Perihelion for Comet Arend-Roland occurred around April 8th, 1957, while the tail angle went up from around 5° for the first observations in November to as high as 70° to 75° near perihelion. At succeeding times, several months later, the angle again dropped down to around 10°. From these data it was clear that the tail could hardly be considered "normal". This may be seen again on Fig. 13-3 where data for Comet Van Gent are presented. It can be seen that there is a difference from Arend-Roland, in that after perihelion the tail angle stays reasonably constant which, as I shall show later, tells us a good deal about the nature of the dust emission that took place.

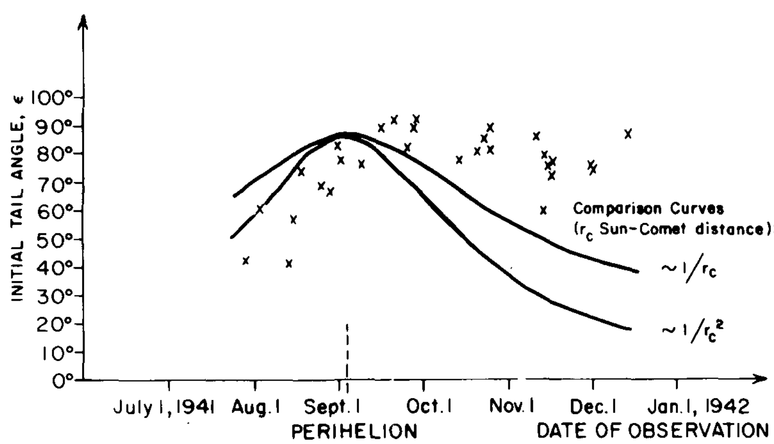

Fig. 13-3. Initial tail angle in comet orbit plane as measured from radial direction for Comet Van Gent 1941d.

Attempts were made to explain the non-radiality on various grounds. Among the suggestions were directed emissions which would give a non-radial orientation, electromagnetic forces, and magnetohydrodynamic forces. All of these explanations proved to be inconsistent in one way or another. Guigay, in a treatment of Arend-Roland, suggested that the tail was simply a synchronic emission, that is, the result of one brief burst of dust particles of, say, no more than a day in duration. This argument can be seen from Fig. 13-4, which shows at the same time the behavior of typical synchrone and syndyne tails, again, in ξ,η coordinates. Guigay argued that there was a sudden outburst around perihelion, that is, around April 8th, and the observed tail resulted from particle-size variations, the smaller dust particles for which radiation pressure effects are more important being repelled more strongly away from the sun. The important point, illustrated in Fig. 13-4, is that except for the degenerate case $\tau = 0$, synchrones are not tangent to the radial vector at the nucleus so that if the tail axis is taken to be a synchrone, a non-radial orientation is obtained. Comparison of the April 8 synchrone with Ceplecha's data on April 27.8 shows good agreement giving a tail angle of about 50°. Unfortunately, for Guigay's synchrone, this angle goes up continuously in time to around 56° two months later, whereas in Fig. 13-2 the actual measured tail angle drops rather sharply with time and around July 1 is about 10° - 20°. Obviously another explanation is required.

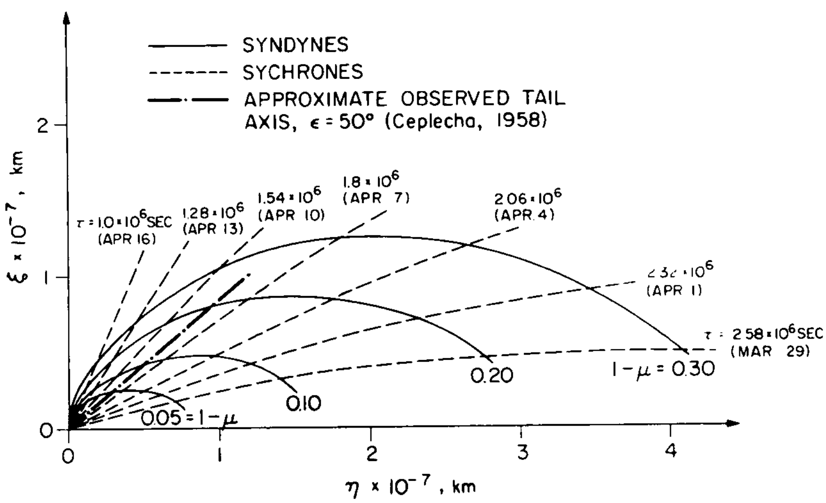

Fig. 13-4. Syndynes (full-line curves) and synchrones (dashed-line curves) for Comet Arend-Roland on April 27.8, 1957 (perihelion April 8.031).

After considering every force we could think of, without arriving at a successful explanation, we found it necessary to reconsider Bessel's concept of solar gravity and radiation-pressure force as the mechanism. What we did, however, was to say not that a particle of a single size was emitted at varying times, or a distribution of sizes at one time, which corresponds respectively to a single syndyne or a single synchrone, but rather that dust particles were emitted from the comet nucleus essentially in a continuous manner in time and essentially with a wide distribution of particle sizes.

In one picture the resultant tail structure we then envisaged at any given time of observation as coming from a superposition of a large number of tails of constant particle size, where constant particle size we recall is the same as constant $1 - \mu$. The axis of any one constant particle size tail is then the syndyne for one value of $1 - \mu$. Since all syndyne tails are tangent to the radial direction at the origin, it is not immediately evident how a non-radial tail results from superimposing a large number of syndyne tails. The answer to the question lies in the shapes seen in Fig. 13-4 of the individual syndyne curves. Each syndyne curve has a maximum value of ξ, and the values of ξ and η for which this maximum occurs increase for increasing $1 - \mu$. We recall here that the larger the value of $1 - \mu$, the smaller the particle. What this says is that the lighter particles go out farther before the Coriolis forces turn them, so that for the larger values of $1 - \mu$ the syndynes are nearly radial even at relatively large distances from the nucleus. However, the contributions to the net density from the lower values of $1 - \mu$, which may be close to or already past their maxima may be sufficiently large in comparison to the nearly radial syndynes so that for distances which can be small in comparison with any resolution lengths the tail, which is a composite of all the individual syndyne tails, will appear to be non-radial.

The question which immediately arises, however, is that since the approach of adding up synchrone tails is just an alternative but equivalent way of looking at the problem, how is it possible for a synchrone superposition to give rise to a radial tail at the origin, as does the syndyne superposition, since the synchrones are all non-radial at the origin except for the one $\tau = 0$? The answer to the apparent paradox lies in the fact that the limiting sychrone tail for $\tau = 0$ is infinitely narrow and tends to make an infinite contribution at the origin to the total density of the tail. This leads to the fact that the tail may be non-radial at any finite distance from the nucleus, but at the origin itself it must be radial. Therefore, the alternate syndyne and synchrone approaches are complementary and lead to the same result, as they should.

Fig. 13-5 shows the behavior with time of a typical syndyne ($1 - \mu = 0.15$) for Comet Arend-Roland. If we consider some constant value of ξ close to the nucleus and measure the non-radiality by the angle that the syndynes make with the ξ axis, we see at once that the appropriate variation of tail angle with time results. It is apparent that the non-radiality first increases up to the neighborhood of perihelion on April 8 and then decreases

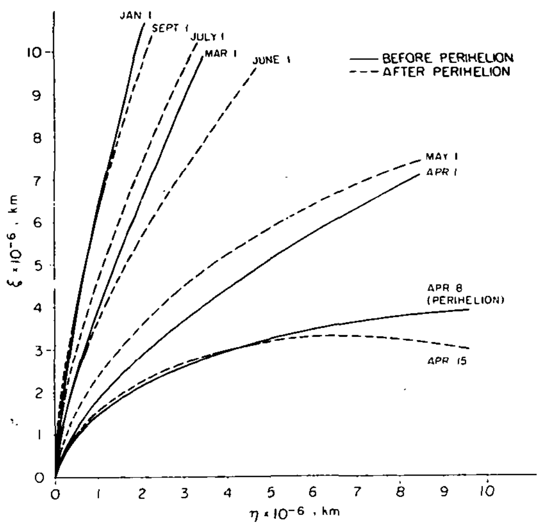

Fig. 13-5. Syndynes for $1 - \mu = 0.15$ for Comet Arend-Roland in 1957.

at later dates, which is what we had previously shown from observational data. Now the syndynes for other values of $1 - \mu$ show a similar behavior, so that the tail for composite values of $1 - \mu$ should also behave similarly.

In summary then, in our model we assume a distribution of particle sizes which is essentially constant along the orbit and denote this distribution by the distribution function $g(\rho_d d)$. Recall that at the beginning I had pointed out that $1 - \mu$ was proportional to $(\rho_d d)^{-1}$ (the particle density is ρ_d and its diameter is d). We also assume a rate at which the dust particles are emitted from the nucleus and we denote this function by $\dot{N}_d(t)$ which is measured in particles per second. Both $\dot{N}_d(t)$ and $g(\rho_d d)$ are then regarded as functional parameters to be determined by comparison of the calculations with observed tail density (isophote) data.

To complete the picture what was needed was a knowledge of the emission velocities of the dust particles from the nucleus. We assumed that the particles are emitted from the surface with no relative velocity and then accelerated outward as a result of a drag interaction with the expanding head gas. This is consistent with the Whipple model in that we consider an evaporating icy mass in which there are embedded dust particles and as the gas evaporates due to solar heating, it expands and drags the particles along. As Jackson and Donn pointed out, near the surface the flow is a continuum relative to the nucleus, though I would emphasize that relative to the particle the flow is free molecular. That is, the drag coefficient on the particles is free molecular, but the flow itself is actually a continuum. The calculation of this two-phase expanding source flow is interesting in itself. The important result is that the dust particles reach a terminal velocity, which is on the order of the gas sound speed, within 20-100 km of the nucleus. So far as the dust tail calculation is concerned we can therefore consider the gas particles to be emitted from the nucleus with this terminal velocity, since the distance of 20-100 km is negligibly small in comparison with the coma and tail dimensions. In terms of the other parameters previously introduced, the result for the emission velocity or terminal speed, denoted by v_i, can be expressed in the form

$$v_i = v_i(\rho_d d, \dot{N}_d, \dot{m}_g) \quad . \tag{1}$$

Here $\dot{m}_g(t)$ is the mass flow rate of gas, and it or v_i may be considered a third function along with $g(\rho_d d)$ and $\dot{N}_d$ to be determined by comparison of theoretically calculated tail shapes and density distributions with data from dust tail observations.

Based on the model I have discussed, it is possible to formulate the appropriate equations for calculating the density distribution of the dust in a comet tail, though the procedure itself is somewhat lengthy. As I have already implied, there are two alternative methods: (1) obtain the density for the tail composed of one particle size and then integrate tails such as this over all values of $1 - \mu$; or (2) obtain the density for that tail consisting of all the particles emitted at one time and then integrate tails of this type over all values of the emission time τ. For illustrative purposes I will present only the first approach.

In comparing the calculated densities with observed light intensities we are interested not in the actual particle fraction, but in this fraction weighted by its light scattering ability. Further, in the calculations it is more convenient to consider $1 - \mu$ rather than $\rho_d d$ as an independent variable. Since the amount of light scattered is proportional to a particle cross-sectional area, we have

$$(\rho_d d)^2 \, g(\rho_d d) \, d(\rho_d d) \propto f(1 - \mu) \, d(1 - \mu) \quad , \tag{2}$$

where here the d's outside the brackets refer to differentials.

It is relatively simple to show then that the surface density modified so as to be proportional to the light intensity is given for an indivisual differential syndyne tail by

$$\dot{N}_d \; f(1 - \mu) \; d(1 - \mu) \; [2v_i\tau \, \frac{dx}{d\tau}(\tau; \, 1 - \mu, \, t_c)]^{-1} \quad . \tag{3}$$

The product $\dot{N}_d$ $f(1 - \mu)$ is simply the number of particles at any point weighted by their light scattering ability. Referring to Fig. 13-1, it is easily seen that $2v_i\tau$ and $dx/d\tau$ are the reduction in density due to the dilation in the lateral and longitudinal directions respectively, x representing distance along the syndyne axis.

I would point out here that from Eq. (1) functionally $v_i = v_i(1 - \mu, \tau; t_c)$ where t_c is the time at which the comet is observed, the particles being emitted at the time $t = t_c - \tau$. Of course, each syndyne tail locus is itself determined by the orbit mechanics for the constant size particles which are acted upon by a reduced "effective" gravity as a result of the radiation pressure. The locus then is also a function of $1 - \mu$ and the emission time τ with t_c a parameter. For comparison purposes we are really not interested in the ξ,η plane, but rather in the plane defining the appearance of a tail to an observer on the earth. We denote the coordinates of this plane by M, N and merely note that the projection from the one plane to the other is just a matter of geometry.

The solution we discussed given by Eq. (3) will provide us with the total modified surface density simply by integrating the different syndyne tails over all values of $1 - \mu$. To do this, however, the three comet functional parameters $f(1 - \mu)$, $\dot{N}_d(t)$ and $v_i(1 - \mu, t)$ must either be known or assumed. The procedure we used was to assume the functions and adjust them until the best agreement was obtained with the observational data. Although not obvious, this procedure did provide us with unique functions and I will return to this briefly later on. Shown in Figs. 13-6, 7 and 8 are the functional forms which were found to provide the best comparisons with Ceplecha's data for Comet Arend-Roland.

I would point out that the dust particle emission rate which is plotted in Fig. 13-6 is a relative one, the determination of the absolute value requiring additional assumptions regarding the dust particle properties, such as mass, density and albedo. The discontinuous nature of the function simply results from calculational convenience. It is of interest to notice the spike

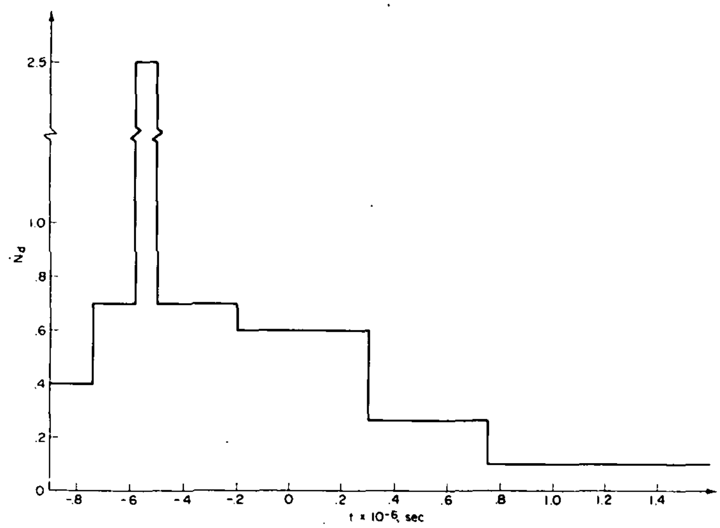

Fig. 13-6. Relative dust particle emission rate $\dot{N}_d(t)$ for Comet Arend-Roland.

in the distribution about 6 days before perihelion, indicating an outburst in dust emission. Although the outburst is drawn as being 1 day in length, in actuality it may have been less, though we are unable to determine this. Another important feature of the curve is the much higher dust emission rate prior to perihelion than after perihelion.

In connection with the particle size distribution function shown in Fig. 13-7, I should mention that the dashed curve represents the distribution used for the outburst. The time dependent part of the velocity function of Fig.

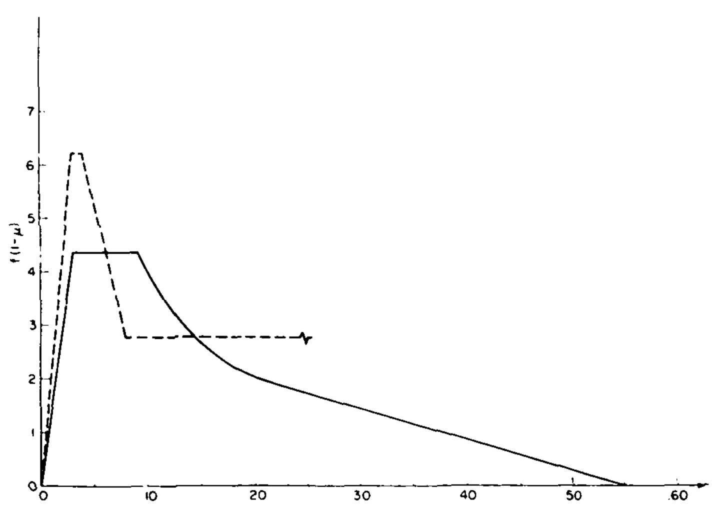

Fig. 13-7. Particle size distribution function $f(1 - \mu)$ for Comet Arend-Roland.

13-8b is practically a constant at around 0.3 km/sec. The total function itself is obtained as a product of the curves (a) and (b).

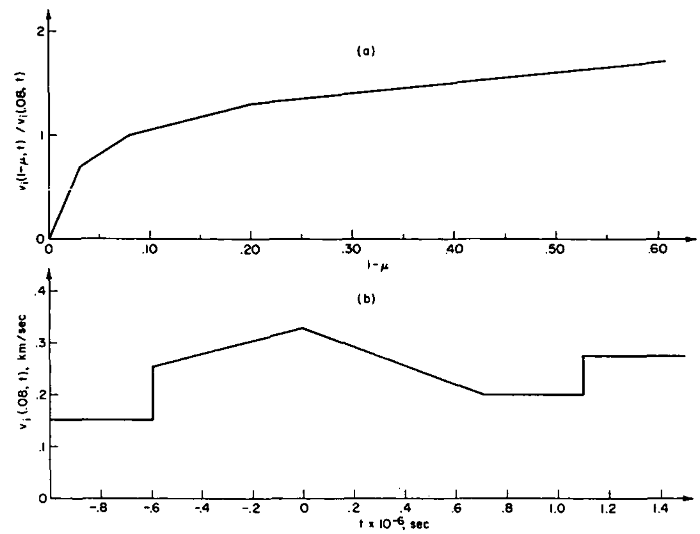

Fig. 13-8. Initial particle velocity function $v_i(1 - \mu, t)$ for Comet Arend-Roland.

Using the functions indicated provided the comparison between Ceplecha's observations and the theory shown in Figs. 13-9 and 13-10. The bulge shown in Fig. 13-9 is the outburst which I mentioned previously. In Fig. 13-9 the "forward spike" of Comet Arend-Roland can also be seen. Calculations

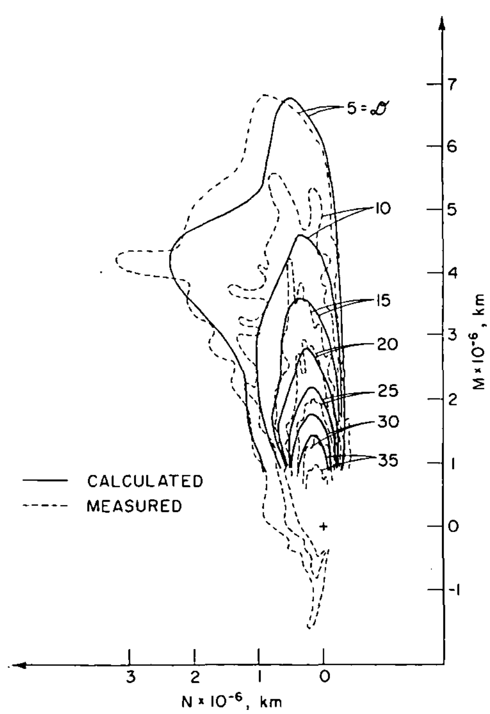

Fig. 13-9. Calculated and measured isophotes for Comet Arend-Roland on April 27.8, 1957.

for this spike which are not shown indicate that it was made up of particles emitted at exceedingly low velocities between February 6 and March 1, 1957, and not around April 1 as suggested by Öpik. It would appear that the observed non-radial dust tail orientations and the variations of the tail angle with time are indeed explained by the theory. It is remarkable that the differences between the theory and observations are nowhere greater than 10 to 20%.

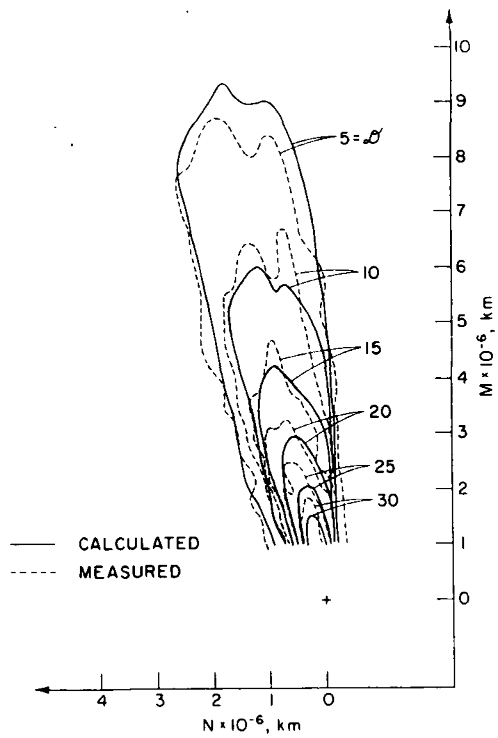

Fig. 13-10. Calculated and measured isophotes for Comet Arend-Roland on May 2.9, 1957.

At this point I would say that the uniqueness of the functional parameters used was justified, at least empirically, by showing that no substantial change of any one of the three functions could be made without altering at least one important feature of the calculated isophotes. The features considered in the uniqueness calculations were the apparent tail angle, half width of the tail, and relative density in the near and far tail regions.

The results so far shown depended only upon a relative dust emission rate. Using reasonable assumptions regarding the particle density and light scattering characteristics, a good deal more information was obtained. In particular it was found that the dust emission rate for Comet Arend-Roland in the neighborhood of perihelion was $\sim 7.5 \times 10^7$ g sec^{-1} and the gas flow rates were $\sim 1.5 \times 10^{30}$ molecules sec^{-1}, thus confirming the relatively high estimates of Biermann and Trefftz. Further, dust particle diameters of order 1μ were found and a particle size distribution shown in Fig. 13-11 was obtained by unfolding Fig. 13-7. This distribution is qualitatively similar to those found in studies of interplanetary dust particles and to one suggested by Remy-Battiau from completely different observations.

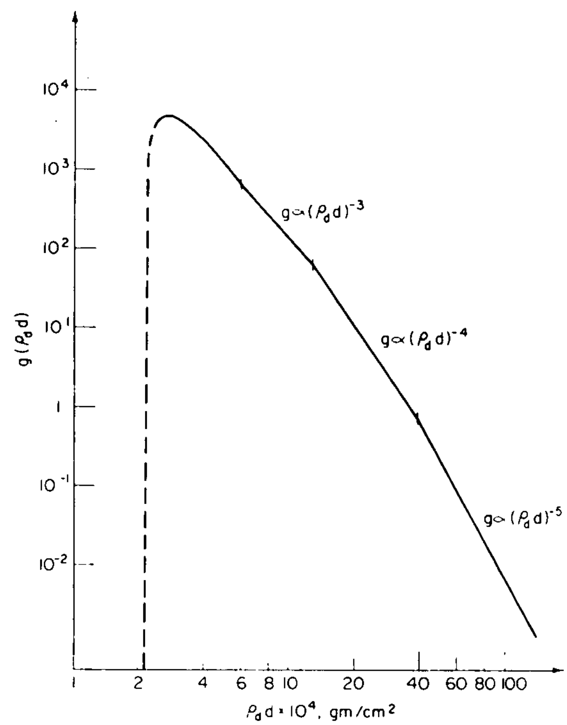

Fig. 13-11. Dust-particle size distribution for Comet Arend-Roland.

In conclusion, I feel that the present theory offers a unique opportunity to obtain relatively easily a great amount of information on the detailed structure and behavior with time of dust comets, once comet dust-tail isophotes are available.

Epilogue

In the Fall of 1971 Dr. Zdenek Sekanina of the Smithsonian Astrophysical Observatory undertook a program for NASA, the main purpose of which was to investigate the generality of the theory described above by applying it to other Type II comet tails. Through the courtesy of Dr. Freeman D. Miller, photometrically calibrated plates of Comet Bennett 1969i, Comet

Mrkos 1955e and Comet Mrkos 1957d were made available. In addition, Dr. Miller provided calibrated plates of Comet Arend-Roland which extend through June 18, 1957, the period for which the required type of observations are available.

Dr. Sekanina chose first to obtain isophotometric tracings of Comet Bennett, because the number of plates and their distribution in time (March 8-18, 1970) looked convenient for checking the theory. As of the writing of this epilogue (July 1972), he has completed the development of a computer program for the theory and calculated a number of syndynes and synchrones for comparison with isophotes of Comet Bennett on March 13, some 6.7 days before perihelion. Although a detailed fit has not as yet been obtained between the calculated and measured isophotes, Dr. Sekinina reports that the preliminary calculations do support the tentative conclusion that Comet Bennett, in contrast to Comet Arend-Roland, is much richer in very small particles, for which the radiation pressure force practically compensates the solar gravity force, or may even exceed it.

As Dr. Sekinina's study proceeds, it would appear that we may hope not only for a confirmation of the generality of the theory but also additional detailed information on Type II comet tails.

Discussion:

Dr. Probstein: (in reply to a question): If you take $\rho_d = 1$ gm cm^{-3}, then from Fig. 13-11 the peak particle diameter would be something like 3 microns. Actually, the optically most important diameter is the root-mean-square diameter, which can be easily computed as a moment of the distribution function shown in Fig. 13-11. That value turns out to be 5.6 x 10^{-4} g cm^{-2} so that for $\rho = 7$ gm cm^{-3} (iron) the optically important diameter turns out to be 0.8 microns. Unbelievably, Liller estimated 0.8 microns for iron from his light scattering measurements.

It was very exciting that we could actually compute the dust rates and the gas rates over the passage. Assuming a reasonable value for the albedo, we came out with the figure of 10^{30} to 10^{31} molecules per sec in the neighborhood of perihelion. The important point is that once the functions are fixed everything else comes out.

Dr. Whipple: I hope that NASA will encourage the study of Type II tails because the distribution of particle sizes, derived uniformly for several comets, should lead to important information on the variations.

Dr. Miller: Since you had to deal with particle-size distribution and consequently with trajectories, would you expect color differences across the tail axis? We are actually trying to determine this currently.

Dr. Westphal: As pointed out earlier, we find the thermal infrared intensities to fit a single black-body curve. The same curve appears to apply to densities 10 times lower than near the head. Instead of a large range of particle sizes, one could think of a smaller range of large fairy-castle particles.

Dr. Probstein: No, I think there is no question that there is a distribution of particle sizes. This result, however, does not contradict a near-constant color temperature.

Dr. Donn: If you put many particles in a clump, the total surface area decreases compared to the same number of particles spread out. So the total emissivity from the fairy-castle structure for a given mass is much less than from the distributed particles.

Dr. Probstein: Having a size distribution follows Dr. Whipple's suggestion made many years ago, that it can be linked to the distribution derived for the zodiacal light.

Dr. Kuiper: The surface of the moon has a spread of particle sizes but still has a single black-body curve. Each particle is optically thick and then it does not matter how big it is.

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NO. 14

COMET SPECTRA

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As is true in astrophysics generally, much of our knowledge about comets is based on their spectra. This report is divided into two parts: (A) a description of the spectra, and (B) a discussion of the excitation mechanisms responsible for their production.

A. Description

The structural subdivision of comets into three different parts, nucleus, coma, and tail, is reflected in their spectra, with three separate components: the continuum, emissions due to neutral molecules, and emissions due to molecular ions.

The continuum is a narrow strip produced by sunlight reflected by the nucleus, or more often, scattered by dust particles surrounding the nucleus. The spectral energy distribution in this continuum is often redder than sunlight, although sometimes undistinguishable from it in the optical region. This indicates that the solid particles may cover a wide range of sizes, from tiny grains of sub-micron diameter to larger particles or even pieces much greater than 0.5 μ. The width of the continuum is usually only a few seconds of arc, or the diameter of the "seeing" disk in the rare cases when the continuum is due to the nucleus itself.* Otherwise it represents the nuclear concentration of dust, having a linear diameter of around 10^3 to 10^4 km. The nature and chemical composition of the scattering particles is not known, except that for reasons of efficiency they cannot be molecules or electrons. Information bearing on this could be obtained from the spectral energy distribution and the polarization of the scattered radiation as

* The nuclei of the comets have dimensions of the order of 0.1 to 10 km, so that when they are bright enough to be seen, even the biggest ones always appear like stars. The continuum may also be widened by imperfect guiding during the exposure of the spectrogram.

well as its wavelength dependence, but observations are scanty. Table 14-I lists wavelength intervals in the photographic and visual regions where the continuum is accessible, free from the emissions reviewed below. In the infrared there will be additional pure continuum regions.

TABLE 14-I

CONTINUUM WINDOWS

3200 - 3300 A	4775 - 4825 A
3400 - 3440 *	5200 - 5300
3630 - 3670	5640 - 5680 *
4140 - 4180 *	5770 - 5860 **
4385 - 4425	6415 - 6455

* May include some weak emissions from CO^+ if an ion tail is present.

** May include a few very weak NH_2 emissions.

Superimposed upon the continuum are a number of emissions due to neutral di- and tri-atomic radicals, i.e., chemically unstable molecules, which form the roundish nebulosity called the coma of the comet. These radicals are made of the cosmically most abundant elements, hydrogen, carbon, nitrogen, and oxygen: CH, NH, OH, CN, C_2, C_3, NH_2. The transitions identified so far are listed in Table 14-II. It is remarkable that they all involve the ground or lowest electronic states of their molecules ("resonance" transitions). These various emissions are illustrated in Figs. 14-1 through 5. Other reproductions can be found in the Atlas of Representative Cometary Spectra (Swings and Haser 1956) or in recent reviews (Swings 1965; Arpigny 1965). Swings and Haser's Atlas was completed just before the first high-resolution spectra of comets were taken by Greenstein at the Palomar Observatory (Comet Mrkos, 1957V; see Greenstein 1958 and Greenstein and Arpigny 1962). A second volume of this Atlas is in preparation which will contain reproductions of all the medium- and high-dispersion spectra now available (40 to 0.2 A/mm). They will include in particular the largest series of spectra ever obtained on a single comet: the bright comet of 1970, Bennett (1969i), was given particular attention at the Haute-Provence Observatory and at the European Southern Observatory, which produced about 30 spectra with dispersions of 20, 12 and 7 Å/mm, taken

TABLE 14-II

MOLECULAR AND ATOMIC EMISSIONS OBSERVED IN COMETS

Emitter	Transition	Wavelength range λ (Å)
	COMA	
OH	$A^2\Sigma^+ - X^2\Pi_i$	3070 - 3160
		3450 - 3490
NH	$A^3\Pi_i - X^3\Sigma^-$	3350 - 3400
CN	$B^2\Sigma^+ - X^2\Sigma^+$	3555 - 3595
		3845 - 3885
		4175 - 4215
	$A^2\Pi - X^2\Sigma^+$	7800 - 11000
CH	$B^2\Sigma - X^2\Pi$	3885 - 3925
	$A^2\Delta - X^2\Pi$	4260 - 4350
C_3	Numerous vibronic transitions	3750 - 4100
C_2 *	$A^3\Pi_g - X^3\Pi_u$	4350 - 6200
NH_2	α - ammonia bands	4900 - 6900
K; Ca	Resonance lines	7665-99; 4227
Cr, Mn, Fe Co, Ni, Cu	Resonance and low-excitation lines	3200 - 5500
	TAIL	
CO_2^+	$A^2\Pi_u - X^2\Pi_g$	3370 - 3840
CO^+	$A^2\Pi_i - X^2\Sigma^+$	3400 - 6200
	$B^2\Sigma^+ - A^2\Pi_i$	3500 - 4240
OH^+	$A^3\Pi_i - X^3\Sigma^-$	3565 - 3620
N_2^+	$B^2\Sigma^+ - X^2\Sigma^+$	3540 - 4280
CH^+	$A^1\Pi - X^1\Sigma^+$	3950 - 4260
Na	$3^2S - 3^2P^o$	5890 - 5896
Ca^+	$4^2S - 4^2P^o$	3934 - 3968
[OI]	$^3P - ^1D$	6300 - 6364

* Including the $C^{12}C^{13}$ isotope (1,0) band at λ 4744.

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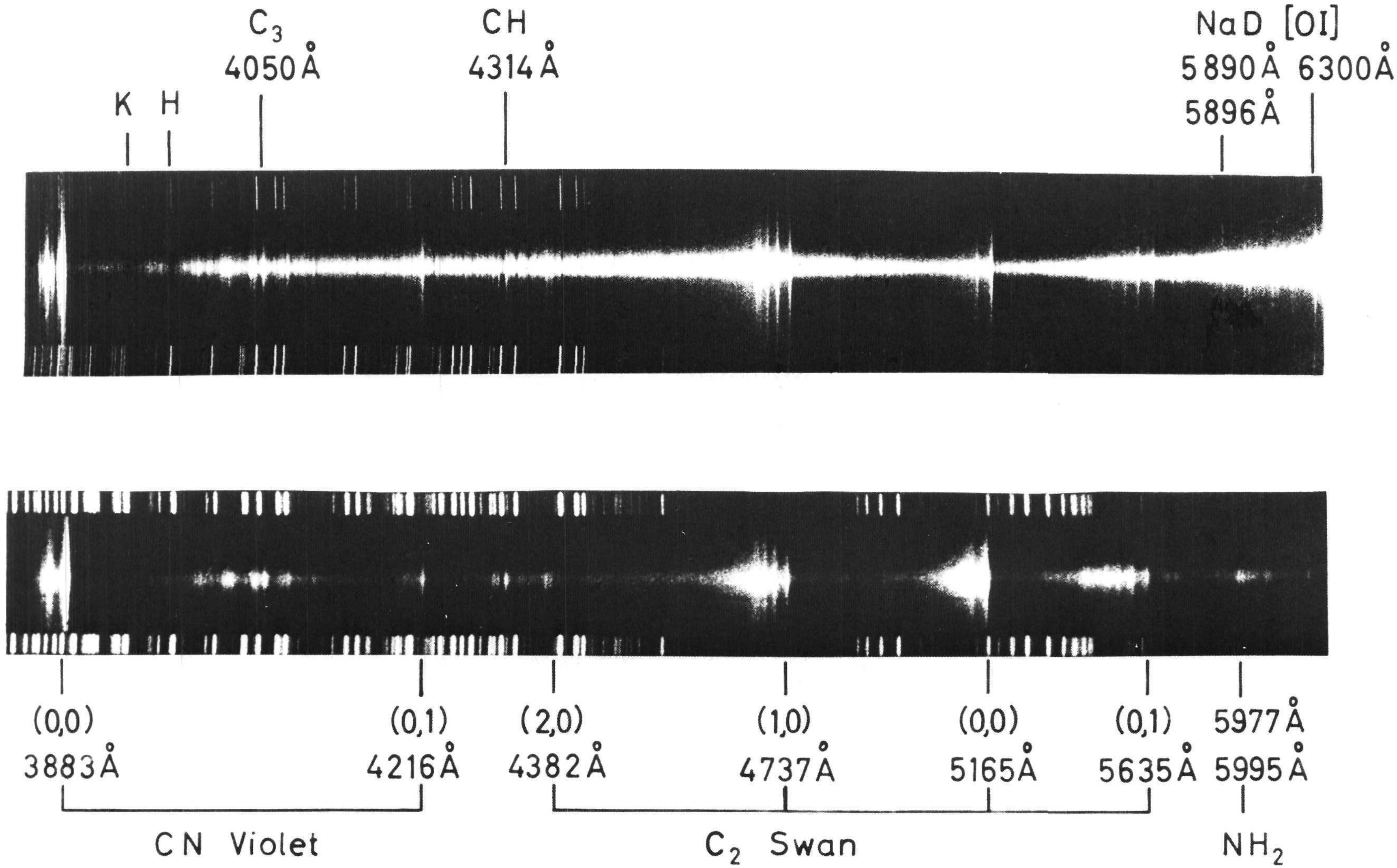

Fig. 14-1 - Low-dispersion spectra of comets in the region λλ 3800-6300 (prism spectrograph-original dispersion: 89 Å/mm at λ 3880). Note that the continuum is stronger in the Eclipse Comet (1948XI) (upper) than in Comet Cunningham (1941I) (lower) - McDonald Obs.

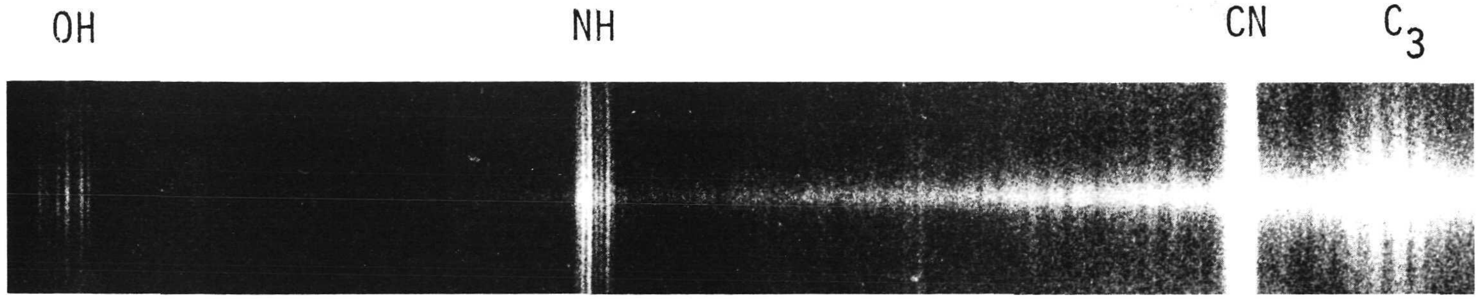

Fig. 14-2 - Ultraviolet spectrum of Comet Cunningham (1941I) (137 Å/mm at λ 3360) - McDonald Obs.

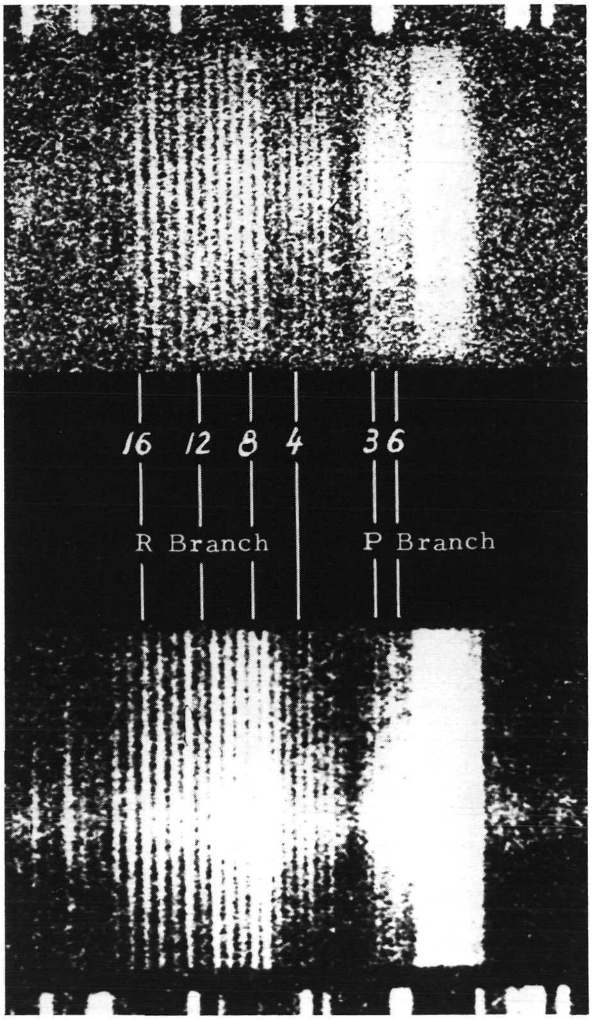

Fig. 14-3 - The CN violet (0,0) band at high dispersion (18 Å/mm). Lower: Mrkos (1957V) (r = 0.60 A.U., dr/dt = + 34.7 km/sec), upper: Seki-Lines (1962III) (r = 0.79 A.U., dr/dt = + 46.3 km/sec) - Palomar spectrogram.

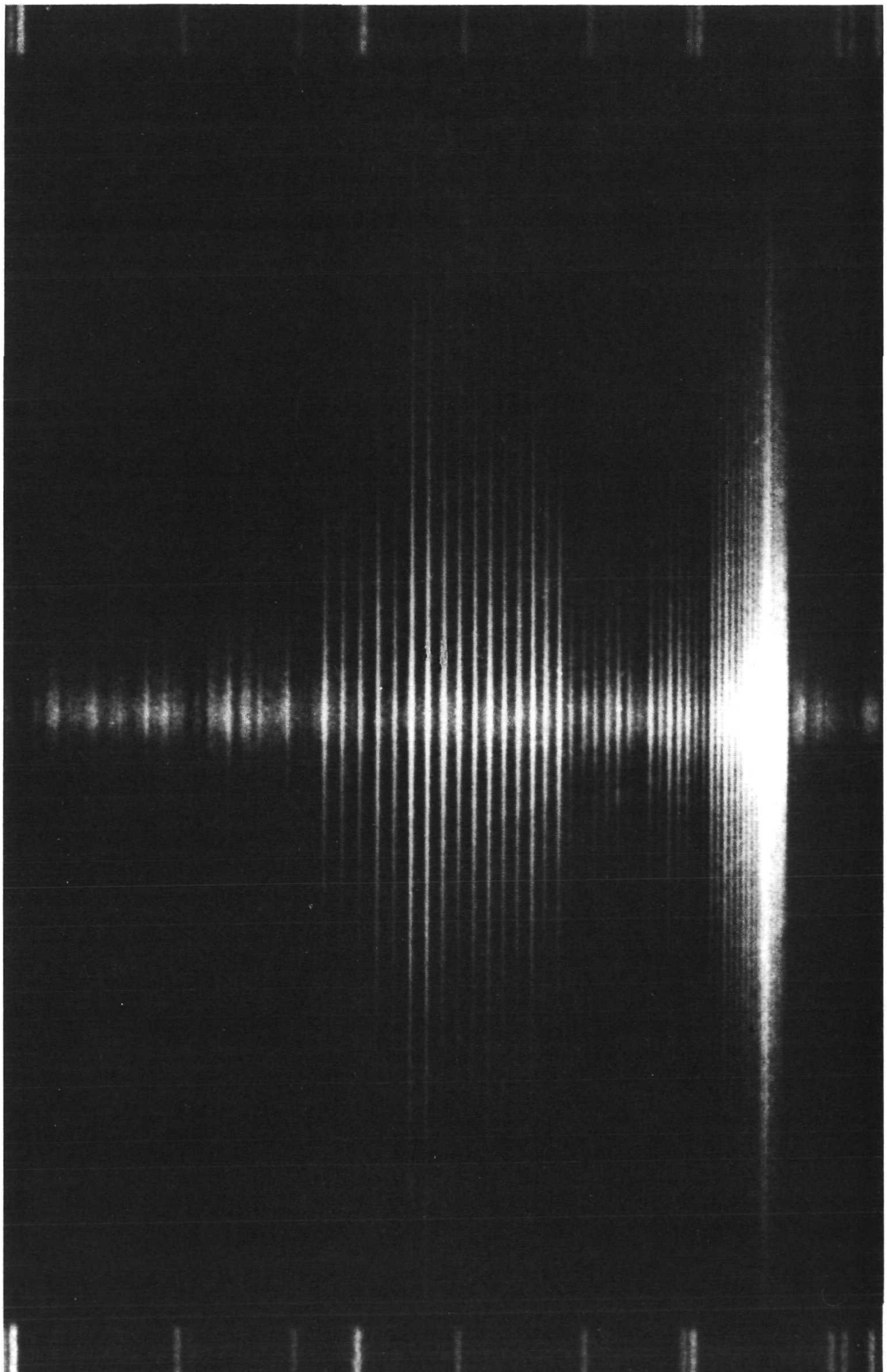

Fig. 14-4 - The CN violet (0,0) band in Comet Bennett (1969i) (r = 0.61 A.U., dr/dt = + 18.1 km/sec) (7 Å/mm)- Haute Provence Obs.

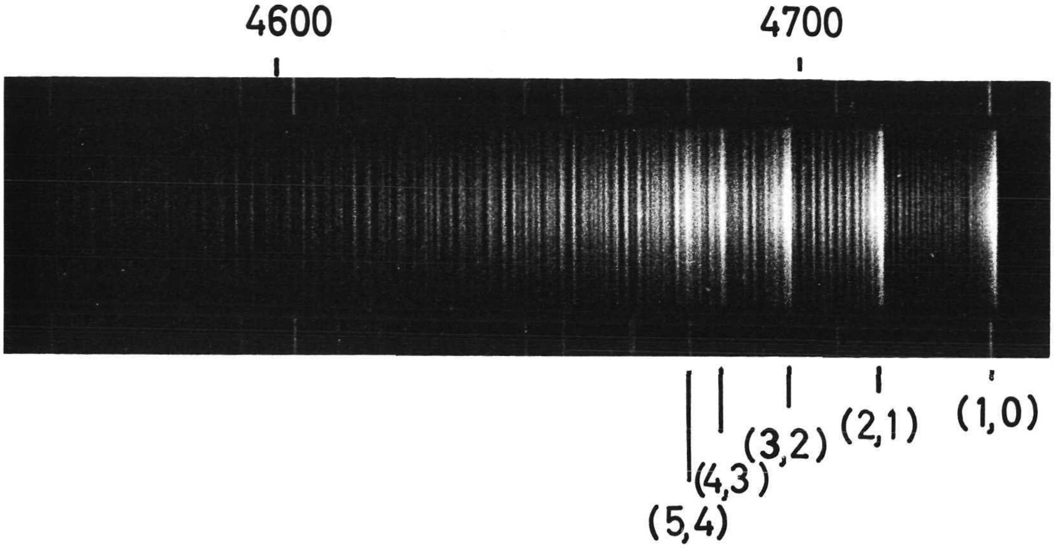

Fig. 14-5 - The C_2 Swan emissions (Δv = + 1 sequence) in Comet Ikeya (1963I) (r = 0.73 A.U., dr/dt = - 17.6 km/sec) (20 Å/mm) Haute Provence Obs.

at heliocentric distances r of 0.6 A.U. before perihelion, and 0.7 to 1.4 A.U. after perihelion. The highest dispersion ever used in observing the molecular emissions corresponds to 4.5 Å/mm, on a spectrum of the same Comet Bennett obtained by G. W. Preston at the Mt. Wilson Observatory and covering the region of the CN violet bands. The very high dispersions (1.2 and even 0.2 Å/mm) concern some exceptional spectrograms of an exceptional comet, the sun-grazing comet Ikeya-Seki (1965VIII) observed in bright daylight with the solar telescope of the Kitt Peak National Observatory. These spectra showed that, when a comet gets closer to the sun than about 0.2 A.U., atomic emissions appear in its spectrum due to neutral elements of the iron group (Cr, Mn, Fe, Co, Ni, Cu), to K and Ca, as well as to Ca^+. These are in addition to the Na-D lines which appear already at $\approx$ 1.0 A.U.

Some of these atomic emissions are illustrated in Figs. 14-6 and 14-7. (See also Dufay et al. 1965; Livingston et al. 1966; Curtis and Sacramento Peak Observatory staff 1966; Thackeray et al. 1966; Preston 1967; Spinrad and Miner 1968).

The spatial extensions of the molecular emissions (indicated by their lengths perpendicular to the dispersion) cover a rather wide range. CN has always the largest extension (typically, a radius a few times 10^5 km,

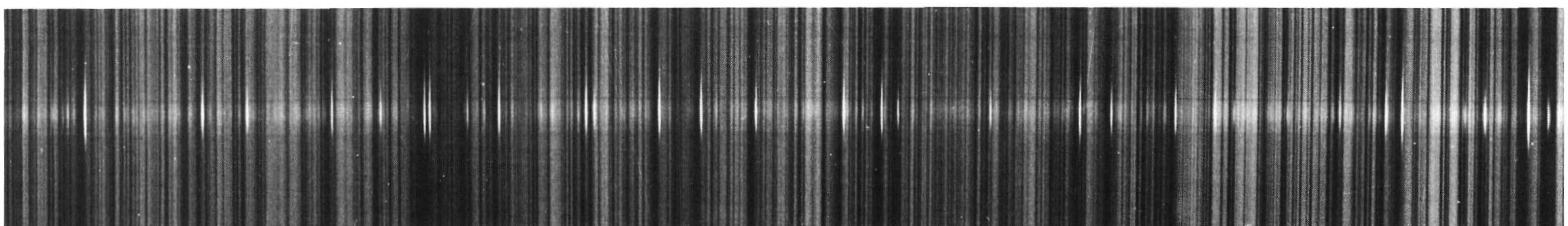

Fig. 14-6 - Atomic lines (Fe, Co, Ni) in the spectrum of the sun-grazing Comet Ikeya-Seki (1965VIII) (1.2 Å/mm). The cometary emissions are superposed upon the sky spectrum as the observation was made in broad daylight - Kitt Peak National Obs.

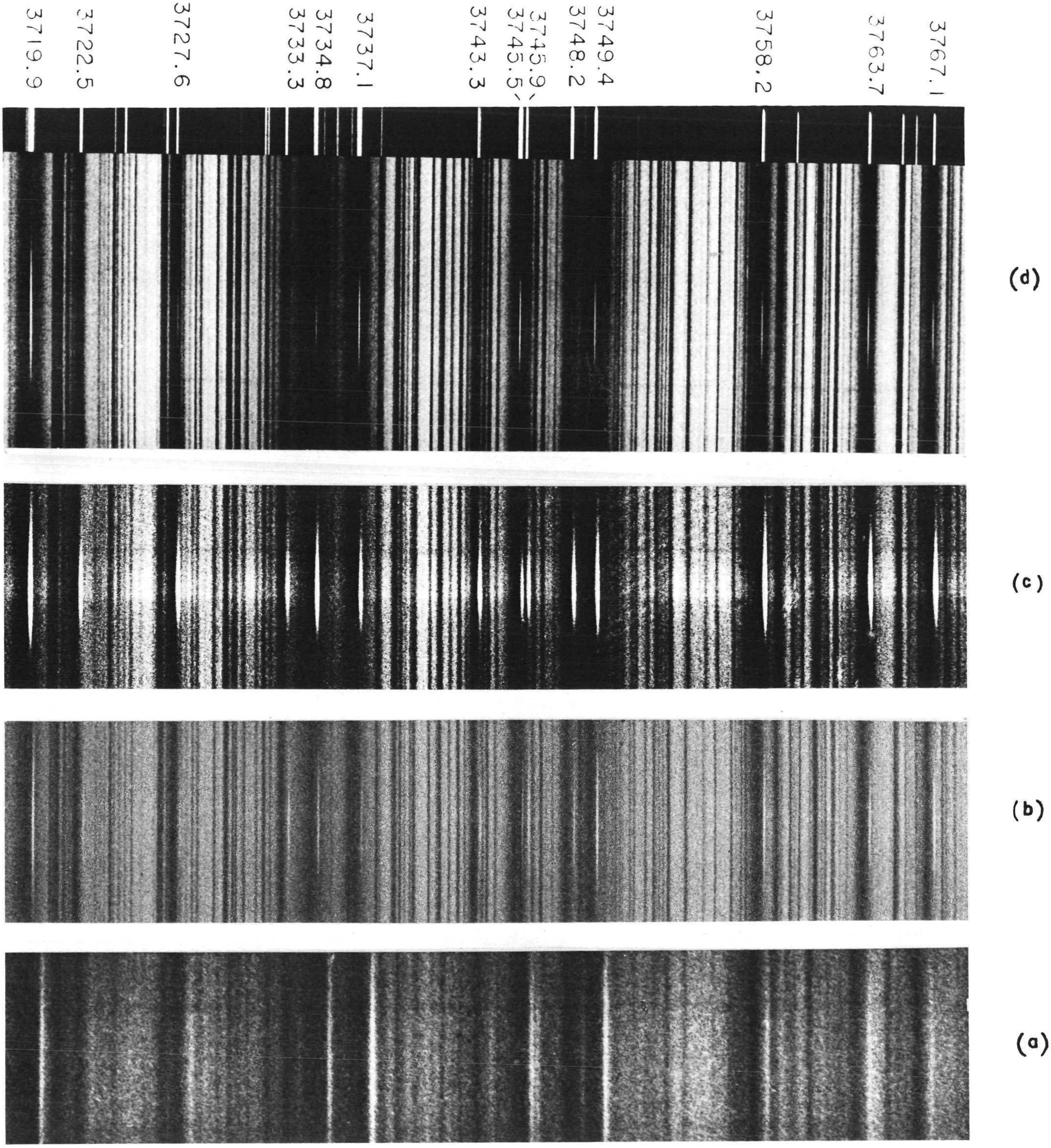

Fig. 14-7 - The region λλ 3720-3770 of the spectrum of Comet Ikeya-Seki (1965VIII) showing a few iron lines. The figure illustrates how the relative intensities of these lines varied as the comet moved along its orbit. Time increases upwards in the figure:

a) Oct. 20, 13:20 UT, 1965; r = 0.074 A.U., dr/dt = - 146 km/sec; (≈ 15 Å/mm) - Radcliffe Obs. (This prism spectrogram could not be perfectly alined with the others).
b) Oct. 21, 13:50 UT, 1965; r = 0.052 A.U., dr/dt = + 170.3 km/sec; (4 Å/mm) - Haute Provence Obs.
c) Oct. 21, 16:30 UT, 1965; r = 0.062 A.U., dr/dt = + 157.9 km/sec; (1.2 Å/mm) - Kitt Peak National Obs.
d) Oct. 22, 17:00 UT, 1965; r = 0.138 A.U., dr/dt = + 109.9 km/sec; (2 Å/mm) - Lick Obs.

up to 10^6 km in some cases). Then come C_2 (10^5km), NH and OH (several times 10^4 km to 10^5 km), while CH, C_3 and NH_2 are the shortest emissions (< 3.10^4 km). These radii are not sharply defined because the emissions decrease gradually with distance from the center. The radial profile, i.e., the surface brightness distribution along the diameter of the cometary disk seen by the slit of the spectrograph, can generally be divided into three sections, as indicated in Fig. 14-8, corresponding to three different regions of decreasing densities in the comet itself:

(1) the production region, of highest density, where the radicals are formed by mechanisms involving solar radiation, not yet identified: (photo) chemical reactions, evaporation of icy grains, photodissociation of parent molecules, desorption, . . .;

(2) the expansion region, where the radicals move essentially radially (velocity ~ 0.5 km/sec) and where the mean free path is large compared to the distance R from the nucleus (collisionless region); and

(3) the decay region, where the radicals are decomposed in some way (ionization or dissociation, e.g., $CH + H^+ \rightarrow CH^+ + H$, $NH_2 + h\nu \rightarrow NH + H$).

The surface brightness has a low gradient in the inner part, while it is inversely proportional to the projected distance in the expansion zone; and decreases exponentially in the destruction zone. The radial profiles

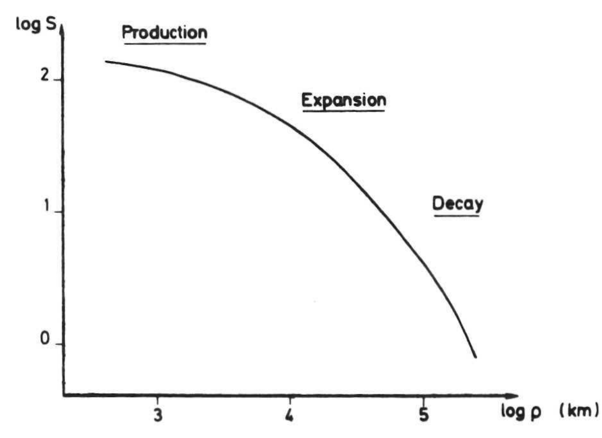

Fig. 14-8 - Typical radial profile of cometary emissions (coma). Note that the expansion zone, in which S varies as $1/\rho$, may be absent in some cases (CH, C_3, NH_2). It is present only when the characteristic time for destruction of the radical is much longer than the characteristic time for its production.

are often slightly asymmetric and not quite centered on the nuclear condensation. This is partly due to solar radiation pressure which does not have the same effect on molecules as on the dust particles; asymmetry is also introduced by probable departures from a monokinetic expansion. These profiles are not only different for the different emissions, but they also vary from comet to comet and, for a given comet, with the heliocentric distance, as a result of the changing strengths of the various competitive production and destruction processes.

These unknown processes govern the intensities of the emissions and their evolution as the comet approaches the sun and later recedes from it. Fig. 14-9 is based on the Atlas of Representative Cometary Spectra; it shows schematically and qualitatively the evolution observed. As a comet comes in, the radical is first seen at a heliocentric distance determined by the mechanism by which it is formed and by rate dependence on the available useful energy. This energy may be a function not only of the direct solar flux, but possibly also of secondary energy releases in the comet by electromagnetic or corpuscular solar radiation. In any case, it increases as r decreases and so does the radiation emitted by the radical. Thereupon, the emission goes through a maximum, because destruction mechanisms become increasingly important leading to ultimate extinction.

The relative intensities of the molecular emission shown in Fig. 14-9 actually vary from comet to comet. In particular, the relative amounts of

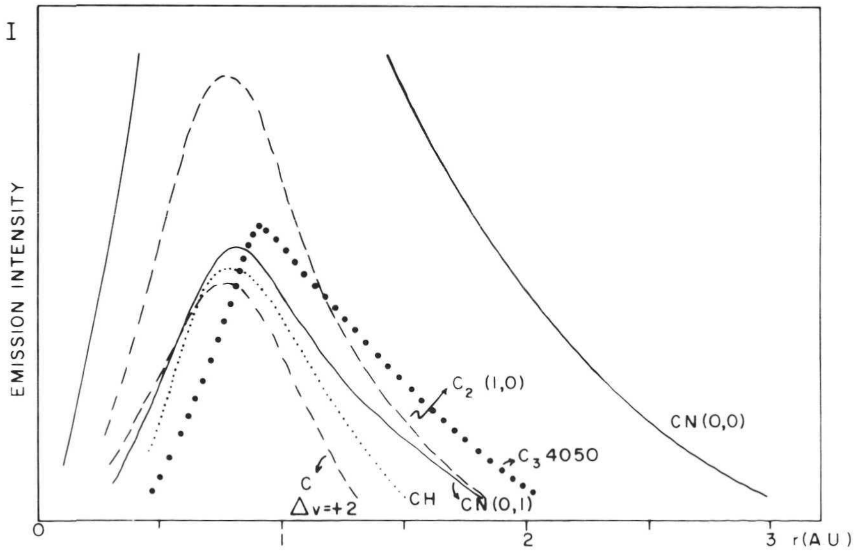

Fig. 14-9 - Evolution of cometary emissions as a function of heliocentric distance (schematic).

CH, C_3, and NH_2 released, as well as the OH/NH ratio, may vary appreciably. The case of OH is difficult because the λ 3100 Å emission is strongly absorbed by the earth's atmosphere and often by glass optics of the spectrograph, so that its observed intensity heavily depends on the zenith angle and on the equipment used.

Another variable is the intensity ratio of emissions to continuum. At the extremes, one has "gaseous" comets in which this ratio is large, the continuum being virtually absent (Burnham 1961I, Ikeya 1963I); and "dusty" comets in which the continuum is very strong (Mrkos 1957V, Bennett 1969i). P/Comet Halley is a "dusty" comet, whereas P/Comet Encke is a typical "gaseous" one. Recent spectra by E. Roemer and T. Owen indicate that P/Comet d'Arrest also has a weak continuum. In classifying comets according to the value of this ratio, one must specify the dispersion because higher dispersions reduce the continuum relative to the discrete emissions. Also, even the "gaseous" comets probably contain some dusty material in their central regions.

A similar classification can be made for comet tails, which belong to either one of two types: (1) gaseous, or Type I, and (2) dusty, or Type II. The spectra of the gaseous tails are due to molecular ions: CO^+, N_2^+, CH^+, OH^+, CO_2^+. The comet-tails band of CO^+ are always the strongest; the relative intensities of the other ions differ from comet to comet. The radial profiles of these emissions are asymmetrical, being very flat and considerably longer (well beyond 10^5 km) on the tailward side than on the sunward side of the nucleus. They tend to become symmetrical when the angle between the line of sight and the direction of the tail is small. An example of this is seen in Fig. 14-10, reproducing the spectrum of Comet Humason (1962 VIII), an extraordinarily active object which showed the CO^+ emissions out to over 5 A.U. from the sun, whereas ion tails are usually observed in comets at $r \lesssim 2.0$ A.U. The repulsive force and the formation of the ions are associated with the solar wind; the orientation of the ionic tail is given by the direction of the solar wind as seen by the moving comet. Since the velocity of the solar particles is much greater than that of the comet, this orientation does not depart much from the radius vector from the sun. Most of the resonance bands or band systems of the tail ions are concentrated in the blue-violet, so that the gaseous tails are quite weak visually.

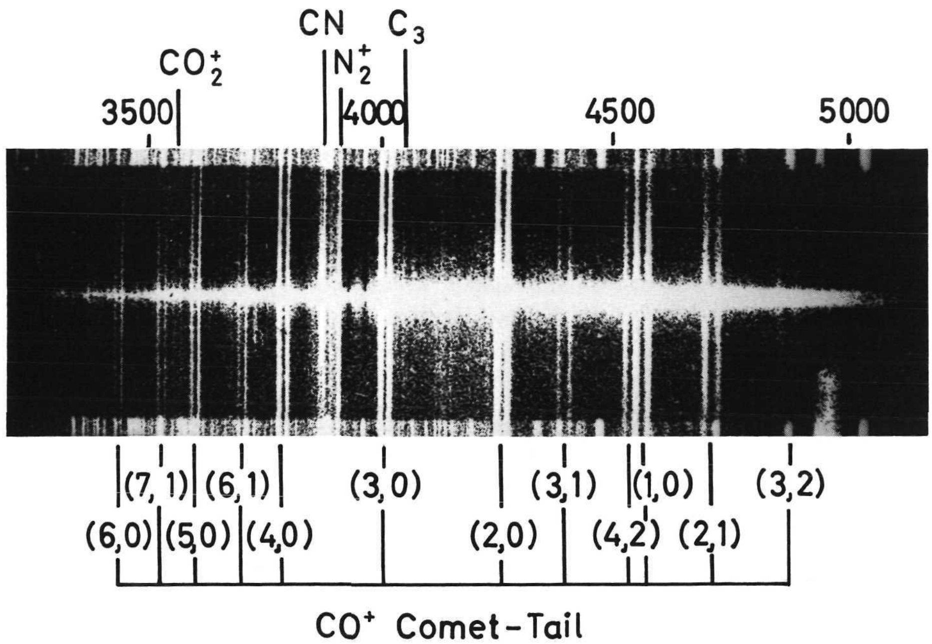

Fig. 14-10 - The spectrum of Comet Humason (1962VIII) (r = 2.6 A.U., dr/dt = - 11.0 km/sec) (180 Å/mm) - Palomar spectrogram.

By contrast, the Type II tails, whose spectra are due to the scattering of the solar radiation by solid particles (0.1 to a few microns in diameter), contribute most of the light received in visual observations of comets seen with bright tails. The solar radiation pressure is the main driving force, although probably not the only one, responsible for the formation of the dust tails which always show some degree of curvature (and little or no structure), contrary to the Type I tails, because the repulsive accelerations imparted to even the smallest dust grains are considerably lower than those produced by the solar wind acting on the gas.

The two kinds of tails may occur simultaneously in a given comet, as was the case for Comet Bennett (1969i). Part of the spectrum of this comet is shown in Fig. 14-11. All three components are present: the continuum from the nuclear region, the "neutral" emissions from the coma, and the "ionic" emissions from the gaseous tail. In addition, one also notes a continuous spectrum due to the dust tail. This continuum is weaker than the nuclear continuum because the dust in the tail is more dispersed.

Also extending into the tail are the emissions due to three atomic species: neutral Na (D lines, present at $r < 0.8 - 1.0$ A.U. and sometimes so strong as to give the comet a yellowish color), neutral O (forbidden red doublet, observed so far only in a few comets with $r \simeq 0.6 - 0.8$ A.U.),

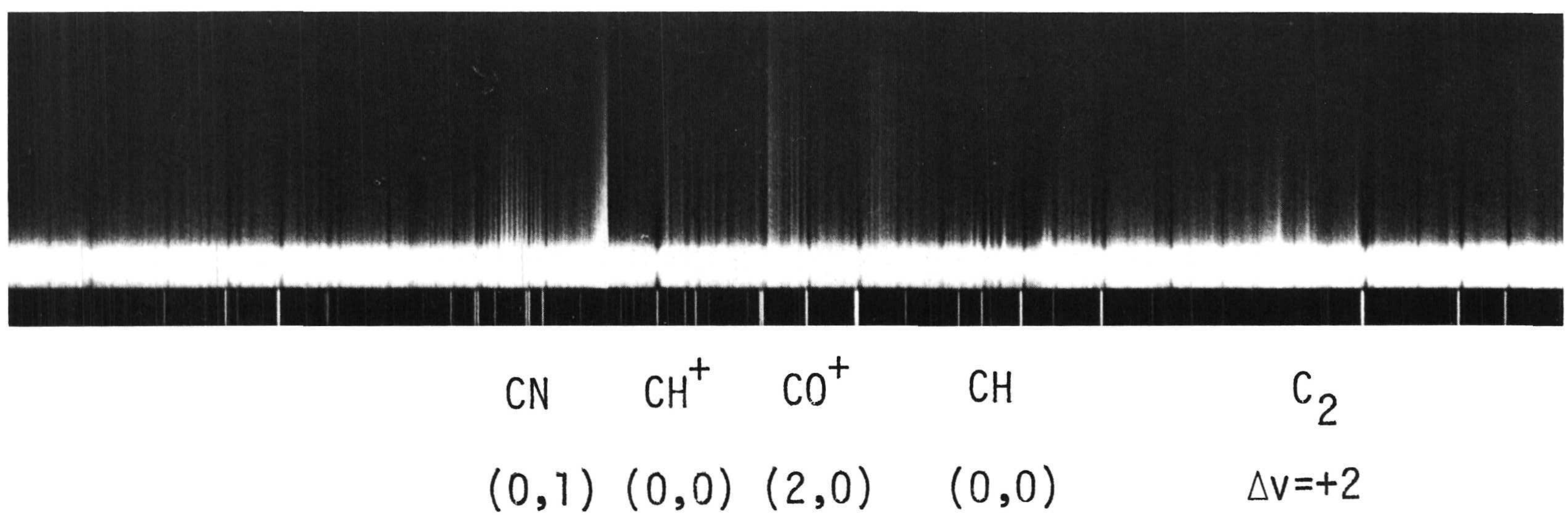

Fig. 14-11 - The region $\lambda\lambda$ 4150-4400 of the spectrum of Comet Bennett (1969i) (r = 0.67 A.U., dr/dt = + 22.5 km/sec) (20 Å/mm) - Haute Provence Obs.

and ionized Ca (H and K lines, detected in the sun-grazing comet Ikeya-Seki at $r < 0.2$ A.U.). These emissions are all quite asymmetric, typically two or three times longer on the tailward side of the nucleus than on the sunward side. This asymmetry is due to the radiation pressure exerted by sunlight in the case of the D lines, which are much more sensitive to this effect than the molecular emissions because of their larger f-values. This may also work for Ca II, H and K; but for this ion the radial intensity distribution is probably also influenced by the solar corpuscular radiation. The situation is not clear for the [O] lines, although their radial profiles suggest that their excitation also involves an ion (e.g., dissociative recombination of a molecular ion containing oxygen). They are thus indirectly affected by the solar wind.

B. Excitation Mechanisms

In the preceding section we have considered the spectral intensity variations along the spectrograph slit and offered some explanations for these spatial variations. We now examine the spectral intensity distributions of the molecular and atomic species, which should illuminate the physical processes.

The spectral profiles of the emission bands like CN and the hydrides are strikingly irregular, in contrast with the smooth distributions usually observed in the laboratory. If we now try to approximate the resulting envelopes by thermal profiles, we find that the rotational temperatures so derived differ from molecule to molecule, being smallest for the hydrides and CN (200 - 400°K) and largest for C_2 (4000-5000 °K). Similar values are obtained for the vibrational temperatures, estimated by comparing the relative intensities of different bands of a given system. These facts and the mere presence of chemically unstable substances suggest that the particle density in the cometary gas must be very low for thermodynamic equilibrium to set in. This agrees with the densities of observed radicals determined for a few comets 10^2 - 10^4 cm^{-3} at 10^4 km from the center, for comets with "reduced" visual magnitudes* 6 to 11; and with upper limits for total densities, n_T, of molecules and atoms, visible plus

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* At heliocentric dist. = geocentric dist. = 1 A.U.

invisible, based on reasonable estimates for the total gaseous mass loss (n_T at 10^4 km < 10^5 - 10^{11} cm^{-3}).*

Considering these small densities and the low average energies available (0.02 - 0.2 ev), we conclude that collisions involving heavy particles are totally inadequate for producing the observed electronic transitions. While there will be electrons having the required energies (a few ev) in the outer parts of the coma, their densities will again be several orders of magnitude too low. The characteristic times, τ_c, for these collisional processes are days or months, i.e., comparable to or even longer than, the total period during which the gaseous part of a comet is observed to shine. Similar minimum time scales are found for processes involving the solar wind. Radiative processes may be considered, e.g., dissociations leaving the radicals in excited states. However, these photodissociations are very slow also (10^5 - 10^6 sec at 1 A.U. from the sun) owing to the low level of solar UV radiation.

We conclude that the excitation mechanism is essentially a resonance-fluorescence mechanism: absorptions of sunlight through transitions in the observed electronic systems or multiplets themselves raise the radical (or atom) from levels in the lower term to levels in an excited term, from which the observed features are then emitted immediately. This explains why all the cometary transitions have a lower term that is either the ground state of the molecule or atom, or one of its metastable terms (C_2, Fe I, Ni I). Indeed, the mean time, τ_a, between two successive absorptions of sunlight at r = 1.0 A.U. is typically 10-100 sec, short compared to the lifetimes of the ground or metastable levels involved, but much longer than the lifetimes of the excited non-metastable levels. Thus, only those atoms or molecules which have resonance transitions in the optical region (where the sun emits most of its energy) will be conspicuous in cometary spectra. This will exclude atoms and molecules like

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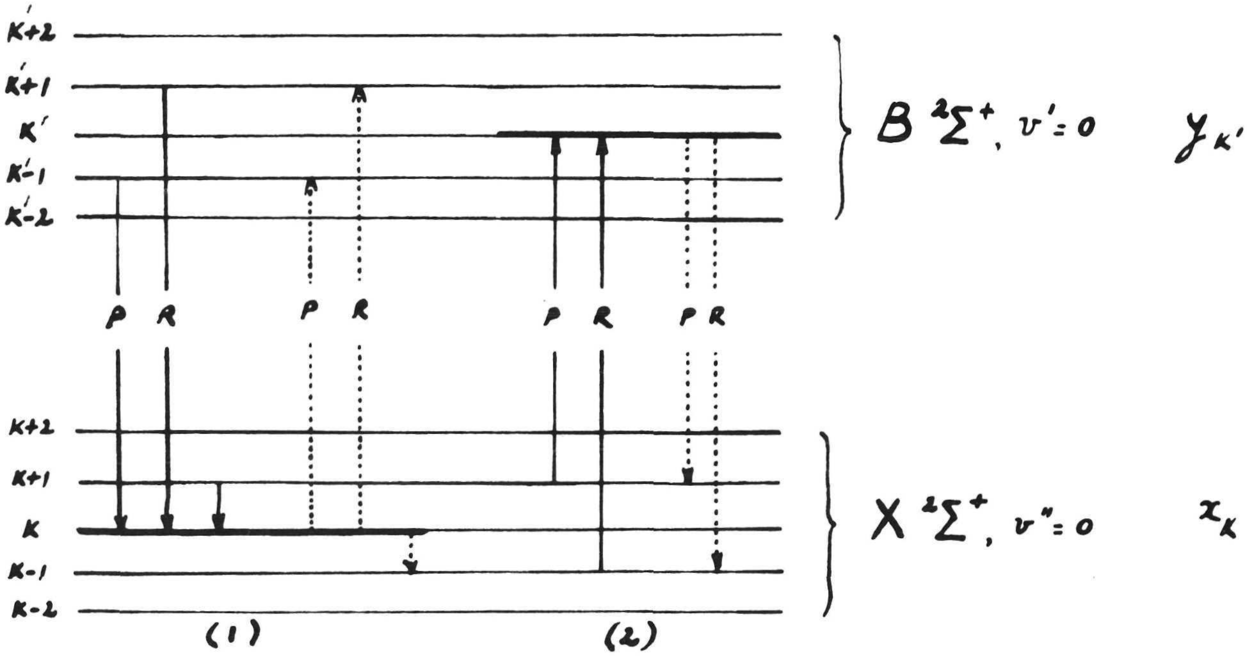
* The lower value would represent a rather faint comet like P/Encke, while the higher density would correspond to a very large object with a total mass of some 10^{21} gm (radius 60 km, mean density 1 gm cm^{-3}) losing 1% of this mass in gaseous form per revolution, the release being assumed to take place at constant rate for an effective period of about 3 weeks (hence the figures quoted give maximal values). An isotropic expansion model is adopted to derive n (10^4 km) in both cases.

C, C^+, N, N^+, O, O^+, H_2, H_2^+, CO, N_2, O_2, O_2^+. Atomic hydrogen is an exception because the solar Lα emission is sufficient to produce appreciable resonance in comets so that Lα is expected (Biermann 1968) and in fact observed to be prominent (cf. Chapt. 11). Forbidden lines of oxygen (red doublet) are also observed in comets, but these are produced by another mechanism.

The characteristic time, τ_a, is much shorter than τ_c and since it is proportional to r^2 (inversely proportional to the intensity of sunlight), there will be virtually no change in τ_a for periods long ($\sim 10^5 - 10^6$ sec) compared to τ_a itself. Thus, it is a good approximation to assume that stationary conditions are achieved (the time, τ_f, for establishing such a statistical equilibrium by fluorescence excitation is $\simeq 10\ \tau_a$ for CN, i.e., $\simeq 100$ sec at r = 1 A.U.); further that the populations of the various energy levels, hence the intensities, depend on the solution of appropriate "rate equations" - which express the equality, for each level, of the total rate at which that level is populated to the rate at which it is depopulated.

The CN emissions have been studied most (Fig. 14-12a, b). We assume that only transitions in the (0,0) band of the violet system need be considered, and neglect the small spin splitting of the 2Σ term. Thus, only the P- and R-lines exist. Fig. 14-12a shows a set of rotational levels in the lower and upper electronic and vibrational states ($X^2\Sigma$, v" = 0 and $B^2\Sigma$, v' = 0) and the steady-state equations for a lower rotational level, with quantum number K, and with relative population x_K; and for an upper rotational level, with quantum number K' and with relative population $y_{K'}$. The C's and A's are the absorption and emission rates per molecule in the initial level ($C = B \cdot U_\nu = \tau_a^{-1}$; B = Einstein's coefficient; U_ν = energy density per unit frequency interval). The S's are the rotational line strengths ($S_K^P = K$, $S_K^R = K + 1$), $g_K = 2K + 1$ is the statistical weight of level K, and W is the dilution factor. The solar-disk intensity F is the local continuum-intensity $\times\ i_\lambda$, the residual line intensity.

In addition to the electronic-rotational transitions, we have to include in the lower electronic term pure rotational transitions, like $K \rightarrow K-1$, the rate of which is denoted by A_K^{rot}, proportional to the square



$$y_{K'=K-1}\, A_{00}^{P(K)} + y_{K'=K+1}\, A_{00}^{R(K)} + x_{K+1}\, A_{K+1}^{rot} = x_K \left(C_{00}^{P(K)} + C_{00}^{R(K)} + A_K^{rot} \right) \qquad (1)$$

$$x_{K=K'+1}\, C_{00}^{P(K)} + x_{K=K'-1}\, C_{00}^{R(K)} = y_{K'}\, A_{00} \quad , \qquad (2)$$

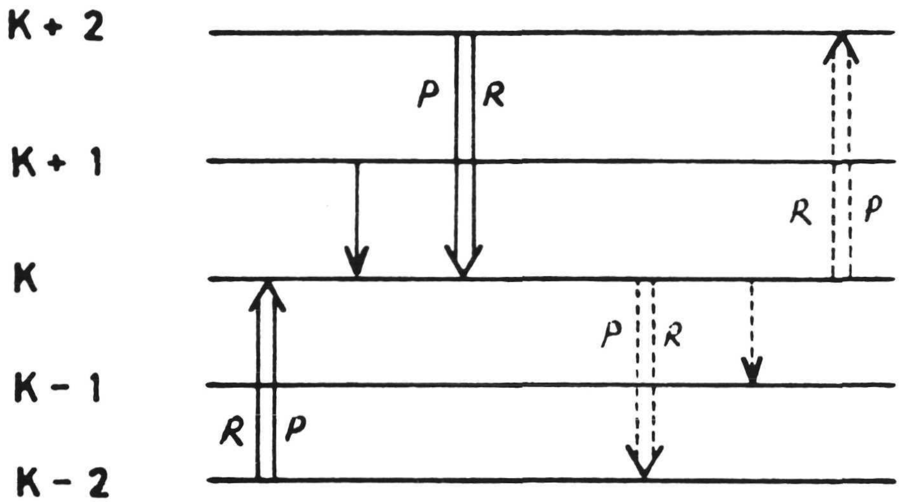
where:

$$A_{00} = \frac{8\pi^2 e^2}{mc} \cdot \frac{g_\ell}{g_u} \cdot \frac{f_{00}}{\lambda_{00}^2} \qquad C_{00} = \frac{4\pi^2 e^2}{mhc^3}\, \lambda_{00}^3\, f_{00}\, W\, F_{sun,\lambda_{00}}$$

$$A_{00}^{P(K)} = A_{00} \cdot \frac{S_K^P}{g_{K-1}} \qquad C_{00}^{P(K)} = C_{00} \cdot i_\lambda^{P(K)} \cdot \frac{S_K^P}{g_K}$$

$$W \simeq \frac{R_{sun}^2}{4r^2}$$

Fig.14-12a - Illustrating the fluorescence of the (0,0) violet band of CN.



Rotational levels in the ground state of CN.

$$x_{K-2}(\bar{S}_R S_P)_{K-2,K} \cdot C_{00} + x_{K+1} A^{rot}_{K+1} + x_{K+2}(\bar{S}_P S_R)_{K+2,K} \cdot C_{00}$$

$$= x_K \left[(\bar{S}_R S_P)_{K,K+2} \cdot C_{00} + (\bar{S}_P S_R)_{K,K-2} \cdot C_{00} + A^{rot}_K \right] \quad (3)$$

where:

$$A^{rot}_K = \frac{64\pi^4}{3hc^3} \nu_K^3 \mu^2 \frac{K}{2K+1}$$

$$\doteq \mu^2 K^3$$

and:

$$\frac{A^{rot}_K}{C_{00}} \doteq \overbrace{\frac{\mu^2 r^2}{f_{00}}}^{R} K^3$$

Fig. 14-12b - The fluorescence of the CN (0,0) violet band (cont'd).

of the electric dipole moment (μ) of the molecule in this lower term, and to K^3, as indicated in Fig. 14-12b. Thus, while A_K^{rot} is only $\simeq 10^{-5}$ sec^{-1} for K = 1, it becomes comparable to C ($\simeq 10^{-1}$ sec^{-1}) for K $\simeq$ 20. These transitions are represented by short arrows in Fig. 14-12a and by single arrows in Fig. 14-12b.*

Combining Eq. (1) and (2) we obtain Eq. (3), which involves now only x_K's. The solution of this system of equations (K = 0, 1, ... K_M, if K_M + 1 is the number of rotational levels) will be combined with Eq. (2) to get the y_K's, which in turn will give the relative intensities of the lines after multiplication by the appropriate relative line strengths.

Eq. (3) can be written at once by considering absorption-emission sequences rather than separate absorption and emission steps. These sequences are represented by double arrows in Fig. 14-12b. For instance, the first double arrow on the left stands for a sequence leading from K-2 to K via an absorption in the R-branch (K-2 → K' = K-1) followed by an emission in the P-branch (K' = K-1 → K). The corresponding rate is:

$$(C_{00} \cdot i_\lambda^{R(K-2)} \frac{S_{K-2}^R}{g_{K-2}}) \cdot \frac{S_K^P}{g_{K'=K-1}} = (\bar{s}_R \cdot s_P)_{K-2,K}\, C_{00} \;,$$

provided we set $(\bar{s}_R)_{K-2} = i_\lambda^{R(K-2)} \cdot (S^R/g)_{K-2}$ and $(s_P)_K = S_K^P/g_{K-1}$. Remember that $\bar{s}$ is an absorption factor and includes a residual intensity factor $i\lambda$, while s, the emission factor, involves the statistical weight of the upper level of the transition; s represents the fractional probability that, once level K' = K-1 has been reached (at the rate $x_{K-2} \cdot (\bar{s}_R)_{K-2} \cdot C_{00}$), emission will occur in the P-branch rather than re-emission in the R-branch (to the latter would correspond an $(s_R)_{K-2} = S_{K-2}^R/g_{K-1}$ such that $(s_P)_K + (s_R)_{K-2} = 1$). This more condensed and elegant scheme of Fig. 14-12b has practical importance because it reduces the number of equations needed under the more complicated condition often encountered.

Clearly, the occupation numbers, x_K and $y_{K'}$, as well as the relative intensities of the rotational lines, will be governed by two effects: (1) the competition between two opposing trends, (a) a tendency for higher

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* Absorptions in the microwave region (K-1 → K), as well as pure rotational transition in the upper electronic term (K' → K' - 1), are negligible.

and higher rotational levels to be populated through fluorescence processes,* and (b) a tendency for molecules to be brought back to lower rotational levels by pure rotation transitions;** (2) the influence of the spectral energy distribution of the exciting solar radiation.

Ignoring the latter, we find that the determining quantity is the ratio A_K^{rot}/C_{00} or more specifically, R, which is the same except for the K^3 factor (see Fig. 14-12b). The distribution law will go through a maximum for a value of K that is the higher, the lower the ratio R, or the smaller the heliocentric distance r for a given molecule (fixed μ and f_{00}). This is illustrated in Fig. 14-13. If, on the other hand, r is fixed, we expect that, as observed, the apparent rotational "temperatures" will be different for different molecules, according to the values of μ and f_{00}. In particular, if R is zero or small, as is the case for C_2 (homonuclear, $\mu = 0$) or Fe (metastable levels), the various distributions will depend entirely upon the radiation temperatures of the exciting light in the relevant wavelength interval, and it can be shown that they

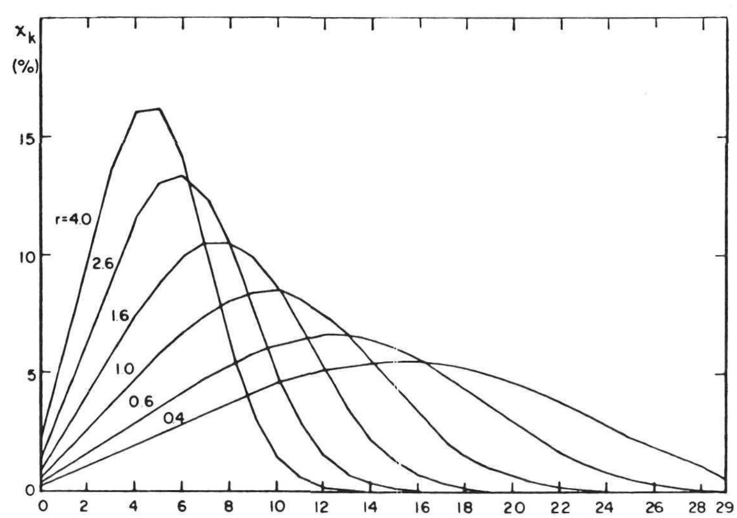

Fig. 14-13 - Relative populations of rotational levels of the ground state of CN in comets for various heliocentric distances (r in A.U.).

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* Consider the time-dependent situation that precedes the establishment of the steady state; even if we assume that initially all molecules are in the lowest rotational level, it is obvious that some of them will be shifted upwards gradually after successive absorptions and emissions (RP sequence).

** Note that these transitions also ensure the connection between even and odd levels.

will indeed resemble very closely the thermal distributions corresponding to that radiation temperature, although the populations of the upper levels will of course be reduced, as compared with actual Boltzmann values, in proportion to the dilution factor.

Returning to the CN problem and taking account of the second effect mentioned above (the solar spectrum), we understand the mutilated character of the observed intensity profiles to be due to the presence of Fraunhofer lines in the solar radiation. This correct interpretation was first given by Swings (1941), who also pointed out that the intensity distribution would furthermore be a function of the radial velocity of the comet relative to the sun. Those upper levels that are excited by transitions (P and R lines here) which, after correction for the Doppler effect due to the heliocentric velocity, fall near the bottom of Fraunhofer lines, will be underpopulated and the corresponding lines will be weak. On the contrary, levels and lines that are excited near peaks in the solar spectrum will be favored. Fig. 14-14 shows examples of x_K-distributions for Comet Mrkos (1957V). Thus, the irregularities we see in this (curve C) and Figs. 14-3, -4, and -7 are merely due to the intensities of the exciting light upon the fluorescing molecules or atoms.

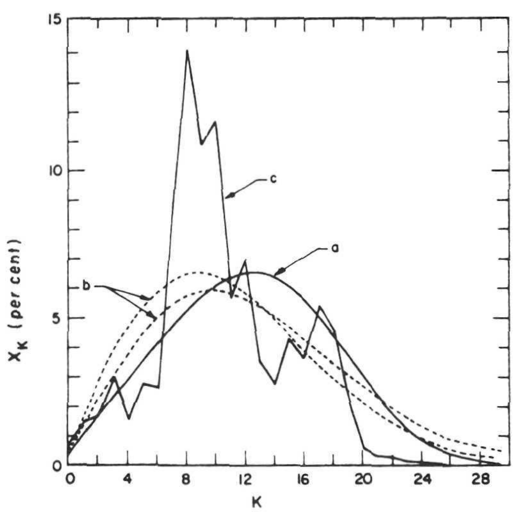

Fig. 14-14 - Comparison of distribution of relative populations of rotational levels of CN at r = 0.6 A.U.:

a. from steady-state equations neglecting Fraunhofer lines
b. Boltzmann distributions (450 and 550°K)
c. from steady-state equations taking account of Fraunhofer lines (dr/dt = + 34.7 km/sec).

It has been possible to show that the various kinds of cometary emissions - due to neutral radicals, molecular ions, or atoms - are excited by the resonance-fluorescence mechanism, with the exception of the forbidden oxygen lines, as mentioned before.

The fluorescence is now treated in great detail. For instance, in the case of CN, the calculations include transitions not only in the violet (0,0) band, but also in the(0,1), (1,0), and (1,1) bands of this system,as well as in several bands of the red system, which implies that the spin splitting be taken into consideration. An example of a comparison between observed and theoretical profiles appears in Fig. 14-15. The agreement found in this figure and in similar comparisons on several other comets could be deemed entirely satisfactory, but for two important secondary effects. The latter usually produce differences in relative intensities of the order of 10-25% (50% in rare cases).

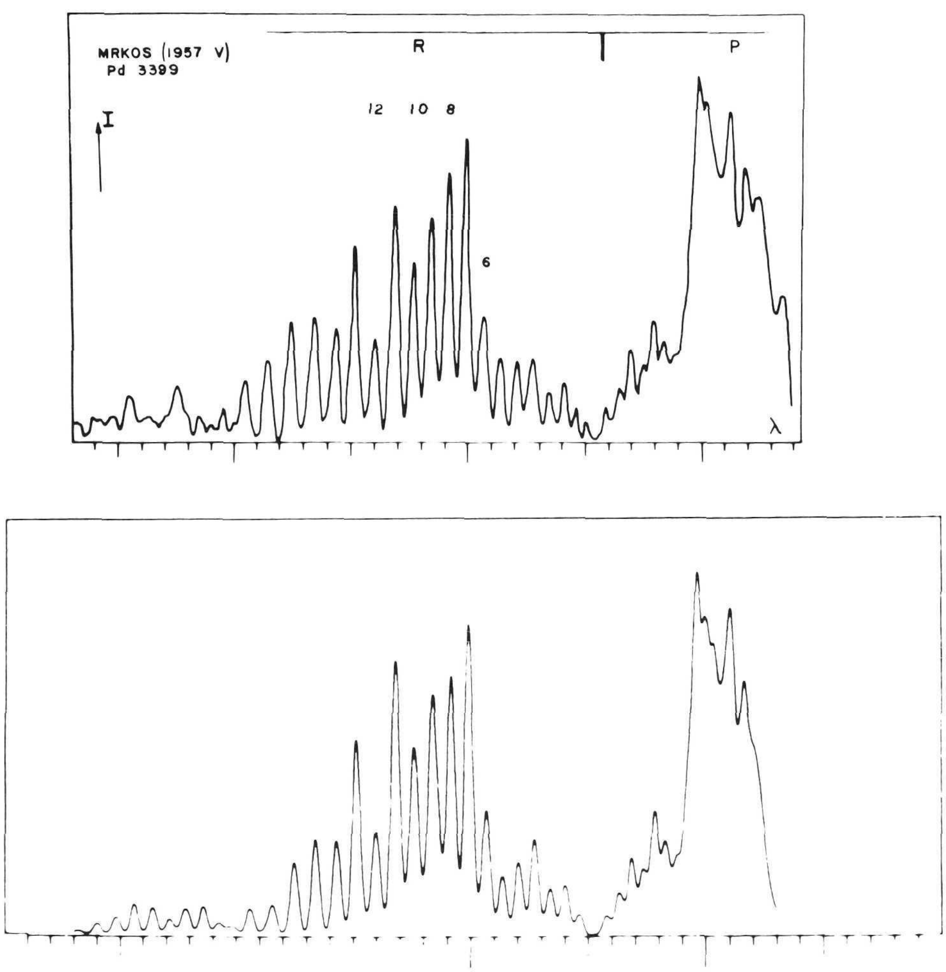

Fig. 14-15 - Comparison between observed (upper) and theoretical (lower) profiles of the CN violet (0,0) band in Comet Mrkos (1957V).

The first of these, called the Greenstein effect, is due to internal motions in the coma, which cause some additional heliocentric velocity shifts. These shifts will vary within the comet and, although rather small ($\approx$ 1 km/sec), may give rise to noticeable variations in the relative intensities of some rotational lines perpendicular to the dispersion. These are lines whose excitation wavelengths fall in the wings of strong solar absorptions. The best example is that first noticed by Greenstein in the spectrum of Comet Mrkos (1957V) and shown in Fig. 14-3: the intensity ratio $R(9)/R(10)$ is reversed when one goes from one edge of the spectrum to the other.

The second effect involves some collisional processes, so far not considered here. Although collisions are inadequate to excite the electronic transitions themselves, it is not excluded, as Jackson and Donn (1966) first pointed out, that they might play a role in populating the rotational levels in the lower electronic term, both energetically and because the cross sections are larger.

Considerable effort is now devoted to the study of these secondary effects. A detailed interpretation of the Greenstein effect would provide data on the velocity fields in cometary atmospheres. For example, will a simple isotropic expansion model with constant velocity explain the observations or are other motions required (puffs, shocks, ...)? On the other hand, collisional excitations of the lower rotational levels might provide a means of estimating the densities of "invisible" molecules (H_2O?).

However, this will require great precision. The character of the observed intensity profile, say of the CN violet (0,0) band, is determined essentially by the resonance-fluorescence mechanism as influenced by the Fraunhofer lines. The details we wish to analyze are only the fluctuations over some average profile.

For instance, in the case of CN, both the ratio R and the ratio V, related to vibration-rotation transitions in the lower term, must be known accurately, as well as the ratio of the transition probabilities in the red to those in the violet system. It is also important to have precise wavelength scales, both for the rotational lines of CN and for the solar spectrum itself. For the latter, one must use the light from the entire disk, not from merely the center of the disk as has been done so far. That the wavelengths must be accurate is illustrated in Fig. 14-16, where it is

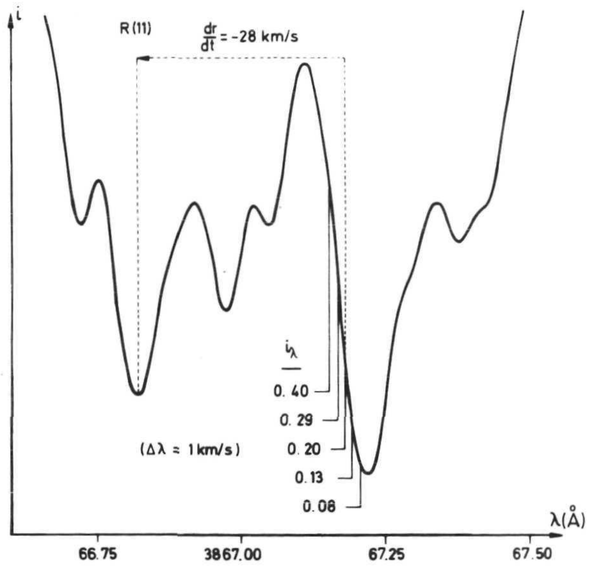

Fig. 14-16 - A small section of the solar spectrum in the neighborhood of the R(11) line of the violet (0,0) band of CN. In the example chosen of a comet approaching the sun with a velocity whose radial component is - 28 km/sec, the R(11) line is excited at λ3867.180 in the solar spectrum (so that this λ is seen at the rest λ of the line, λ3866.819, by the cometary CN). The residual i_λ is then 0.20. Obviously, errors by ± 10 to 15 mÅ (1 km/sec = 13 mÅ) in the λ's involved, as encountered sometimes until very recently, would lead to erroneous i_λ's in cases like the one we have here with i_λ very sensitive to λ.

seen that shifts corresponding to 1 km/sec, i.e., to ≃13 mÅ at the wavelength of the violet (0,0)band, may produce changes of 50% or more in iλ. Up until recently, the available wavelength scales contained errors of up to ± 10 to 15 mÅ and were thus inadequate for interpreting the secondary effects. Malaise (1970) apparently has proved for three comets the existence of collisional processes of the kind considered here. While this existence may be granted, we nevertheless question his numerical values for the densities because his computations are affected by significant uncertainties in all the quantities or parameters used. In fact, the densities derived by Malaise would lead to unacceptably high mass losses for two of the three comets (Seki-Lines (1962III) and P/Encke: 20% or more of the mass of the comet per perihelion passage). Presumably, collisional effects are important in the dense inner regions of the bigger comets releasing volatiles with sufficient efficiency. We hope that the recent data concerning both CN and the solar spectrum will allow a determination of how big the comet has to be and how dense it can be, and thus to obtain quantitative estimates for the total gaseous mass losses. The hydrides should also be studied in great detail.

Summarizing, the principal process producing the cometary emissions is well understood; while additional effects can in principle yield data about the velocities of the molecules and the gas densities in the coma. Besides these physical properties of comets, their chemical composition is of interest. The relative abundances of H, C, N, O, etc., will require a clarification of the production of the observed radicals from the ices and of the ices from the elements. Only for isotope ratios, such as C^{12}/C^{13}, the problems are simplified. The C^{12}/C^{13} isotope ratio in Comet Ikeya (1963I) did not differ significantly from the terrestrial value (Stawikowski and Greenstein 1964). In Liège work is in progress on the relative abundances for the iron group elements (Cr, Mn, Fe, Co, Ni, Cu) using spectra of the sun-grazing comet Ikeya-Seki (1965VIII).

Comet Humason (1962VIII), like Comet Morehouse (1908III), was characterized by a high abundance of CO^+ and a low content of neutral molecules, contrary to many other comets in which the neutral molecules are much more abundant than CO^+. Does this suggest that there exist oxygen-rich comets and carbon-rich comets? Although this would be an exciting possibility in connection with the origin of comets, we still know too little to consider this problem fully. Moreover, 3 of the 4 comets in which the red [O] doublet has been identified with certainty (Mrkos 1957V, Wilson-Hubbard 1961V, Seki-Lines 1962III) were rather poor in CO^+; only in the fourth comet (Bennett 1969i) was CO^+ present in appreciable amount.

While the UV and IR spectra of comets may throw some light upon this crucial problem, it is likely that we shall not learn the chemical nature of comets until space probes have been sent to some of them.

Discussion:

Dr. Kuiper: What is the variation of the strengths of the various emissions with heliocentric distance to the comet? Does this variation provide clues on the identification of still unidentified features?

Dr. Arpigny: The diagrams I have shown are based on the old low-dispersion spectra, whereas the unidentified features have been measured in more recent high-dispersion spectra. We don't have the data to establish the distance dependence needed. Near-continuous observation at high dispersion is needed. Maybe some association must be set up among interested scientists who have access to large telescopes to make such observations for several comets, in each case beginning as early as possible, and continuing through perihelion passage and as far out as possible.

Dr. Kuiper: My question then is rephrased: have you interpreted the progression of emission strengths that you showed?

Dr. Arpigny: No. Clues as to the physical processes responsible for the radicals might result, but I am not sure that one would have a unique solution. One sees only a few radicals and special results of complex phenomena. Not until we have a comet probe will we know for sure of what comets are made.

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NO. 15

SPECTROSCOPIC OBSERVATIONS OF COMETS

by T. C. Owen
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I second Dr. Arpigny's plea for more high-dispersion observations. However, it is often difficult to get the telescope time. I was fortunate to be able to investigate both Comets Tago-Sato-Kosaka and Bennett with the 200-inch reflector at twilight, and I will report on some preliminary results.

I was particularly interested in the value of C^{12}/C^{13} for these comets. As Arpigny mentioned, this ratio has been evaluated by Stawikowski and Greenstein in Comet Mrkos who found 75 ± 15. This isotope ratio varies from about 4 for carbon stars, to intermediate values for the interstellar formaldehyde, to about 90 for the earth. Stawikowski and Greenstein thought their determination was reasonably consistent with the telluric value. There are models for the early history of the solar system which suggest that there might be a presently detectable gradient in this ratio; the C^{13} abundance decreasing with distance from the sun. But so far the atmospheres of both Mars and Venus show values which are compatible with the terrestrial number. No determinations have been reported in the atmospheres of the outer planets.

There is a problem in analyzing the cometary observations made for this purpose. There is an isotopic band of C_2 that is relatively strong, but it is blended with a band of NH_2. Stawikowski and Greenstein assumed for good reasons that they could ignore the NH_2, and that led to the value I have quoted. If I do the same thing with my observations, I find that I can only establish a lower limit on the ratio. The result is $C^{12}/C^{13} > 50$, which may well turn out to be consistent with the earlier work (cf. Supplementary Comments).

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* Now at State University of New York, Stony Brook, N.Y.

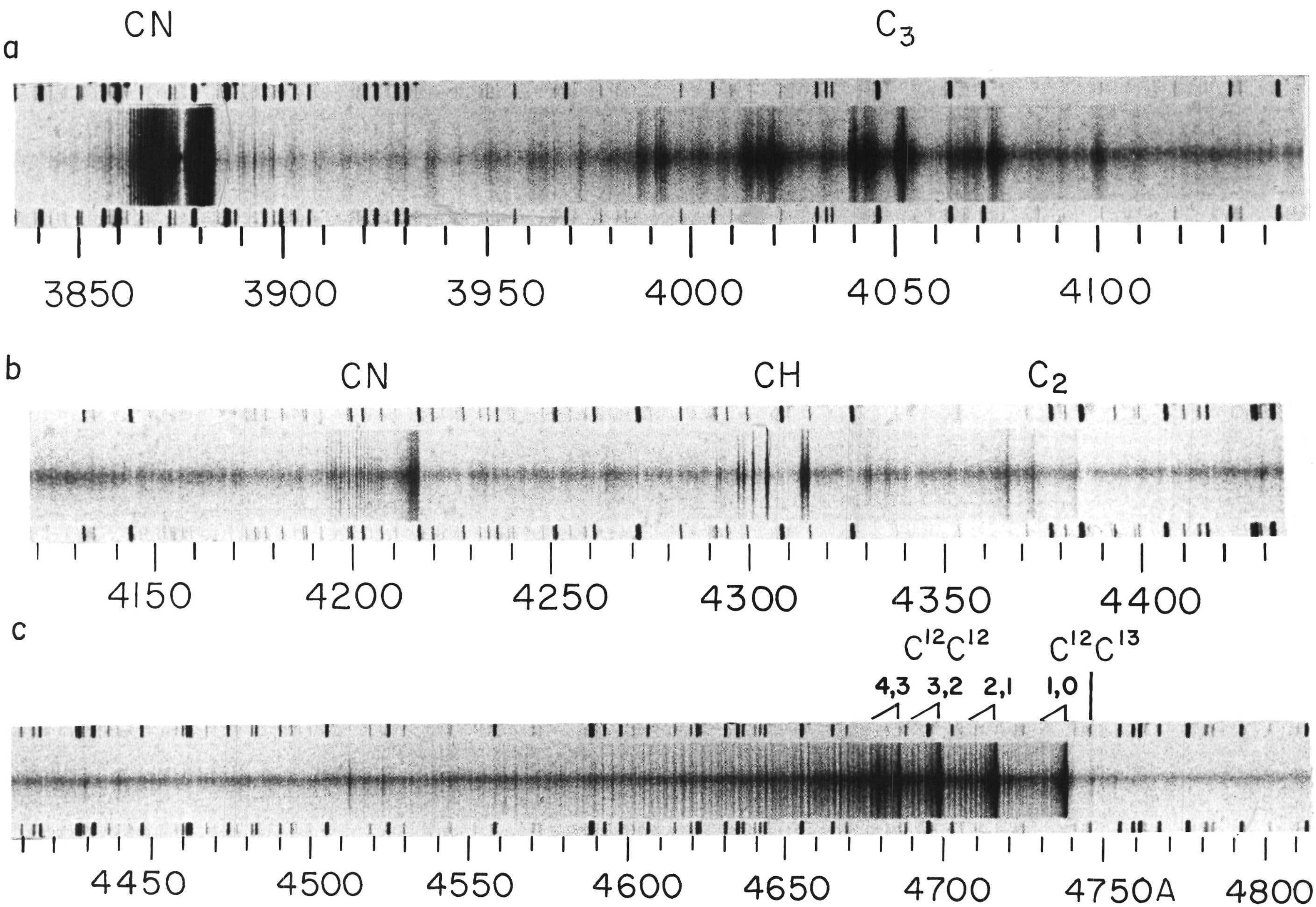

Fig. 15-1 - Comet Tago-Sato-Kosaka: 200-inch coudé spectrogram.

Some illustrations of these spectrograms are appended. Fig. 15-1a illustrates the short wavelength region of spectrogram of Comet Tago-Sato-Kosaka. The CN and C_3 bands are the most prominent features.

Fig. 15-1b shows the same spectrogram at slightly longer wavelengths. It should be possible from this spectrogram to do some work on the (0-1) CN. The CH and the (2-0) C_2 are also shown. The latter is used as a standard to get the isotopic C^{12}/C^{13} ratio. It should be noted that one has the opportunity of measuring the spectrogram on both sides of the continuum, and thereby avoiding or at least strongly suppressing the contribution of continuum to the comet's spectrum.

Fig. 15-1c shows the (1-0) C_2 and the isotopic band of $C^{12}C^{13}$. On the original plate it is very easy to trace this feature on both sides of the continuum. The other little features that show up here are NH_2, so it should be possible to work out and compensate for the relative intensity of the NH_2 band that is blended with the isotopic band.

Fig. 15-2 shows one of the long-wavelength scans from the OAO observations of the same comet. The remarkably strong OH at 3090 Å is clearly evident. I think we had come to assume this feature is weaker than it really is on the basis of observations from the ground, which are hindered by the ozone absorption and the transmission of our optics, both of which are problems at these short wavelengths. Some new OH features are evident below 3000 Å.

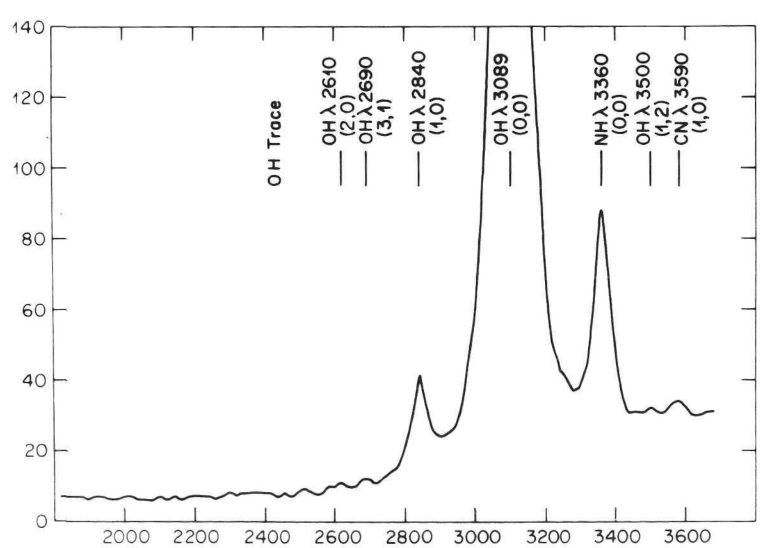

Fig. 15-2 - Comet Tago-Sato-Kosaka: OAO observations.

Fig. 15-3 shows the Ly α in that comet. There are some other features that may or may not be real. Dr. Lillie has suggested that a bump at 1360 Å might be OI. Another possibility would be molecular hydrogen, which is excited by Ly β. But then there should also be an emission feature at 1026 Å, which is not very evident from this tracing.

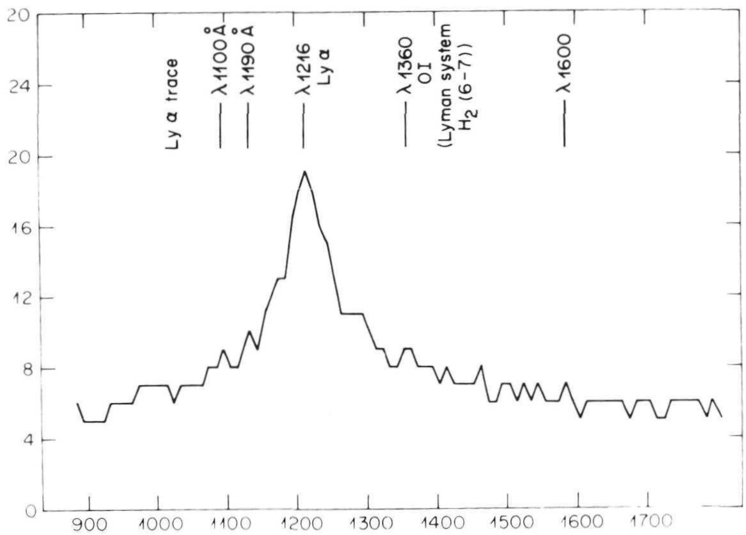

Fig. 15-3 - Comet Tago-Sato-Kosaka: OAO observations.

The point to remember about looking at comets in the far ultraviolet is that although the excitation is still by resonance-fluorescence, the solar continuum disappears at about 1500-1700 Å and one must then worry about discrete line emissions as energy sources. So the problem of excitation becomes somewhat more complex, and in particular, one would expect differences as the comet is approaching and receding from the sun, depending upon the effective wavelength of the Doppler-shifted line as seen by the comet.

Fig. 15-4 shows the response of the OAO folded in with the solar spectrum and indicates why, for example, we don't see a lot of emissions in cometary spectra around 2000 Å which one might have expected from models for the composition of comet nuclei. The dramatic fall-off in intensity with decreasing wavelength is clearly evident from the illustration.

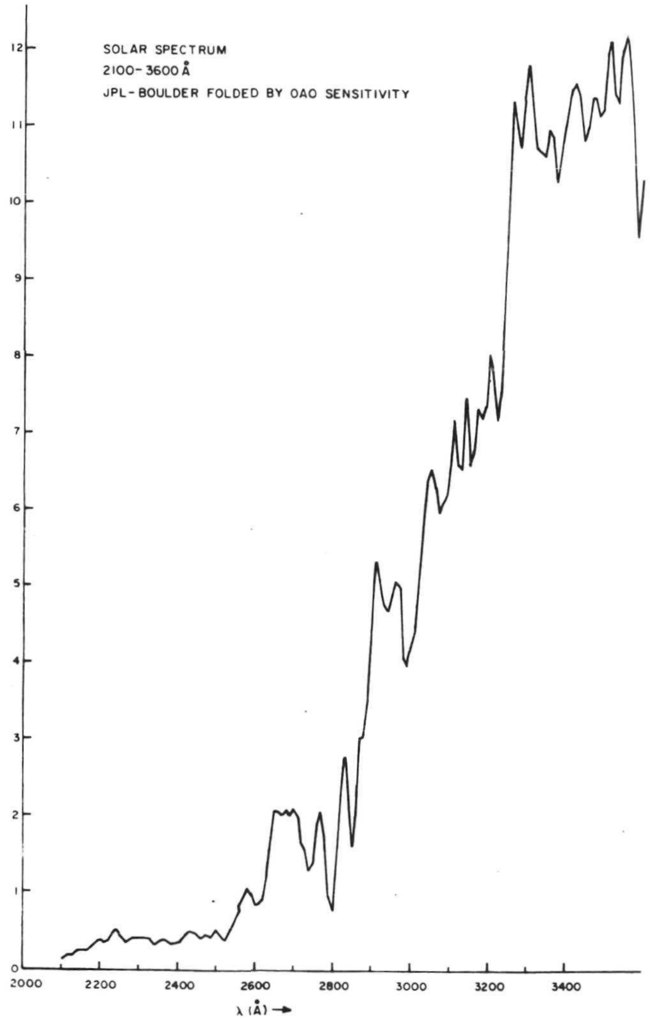

Fig. 15-4 - OAO instrumental response.

Fig. 15-5a is from a spectrogram of Comet Bennett taken by Helmut Abt at Kitt Peak showing the CN and a very strong continuum. Bennett was, of course, a much dustier comet than Tago-Sato-Kosaka. Solar H and K are clearly visible. Fig. 15-5b shows the region of the sodium lines. In this case one was aware of the fact that the coma was not completely symmetric and in fact, at the Palomar coudé, the image appeared something like the sketch in Fig. 15-6. The slit of the spectrograph crossed the coma as shown, so the direction toward the sun is downward in Fig. 15-5b.

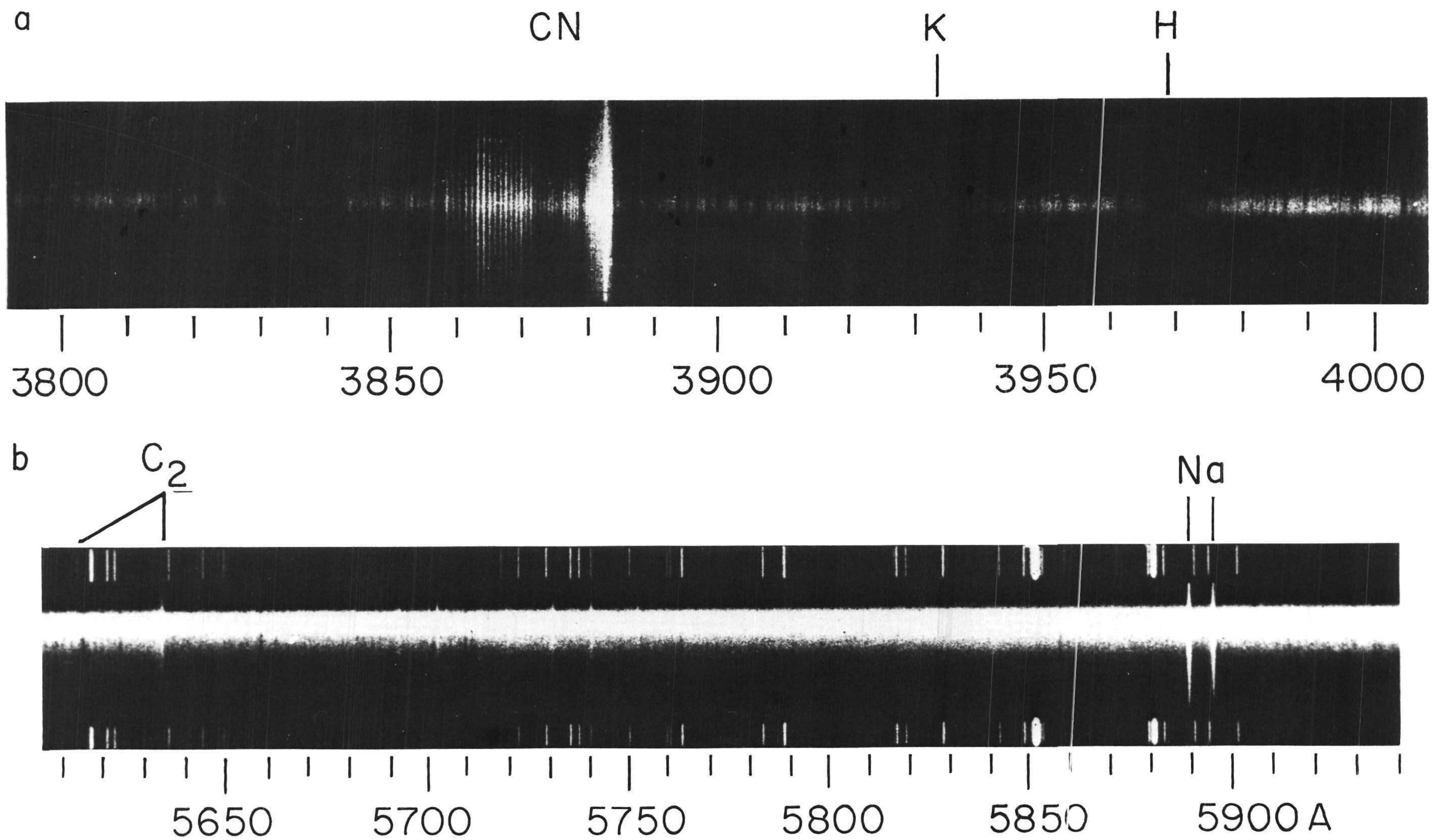

Fig. 15-5 - a. Comet Bennett: KPNO 84-inch coudé spectrogram.

b. Comet Bennett: 200-inch coudé spectrogram.

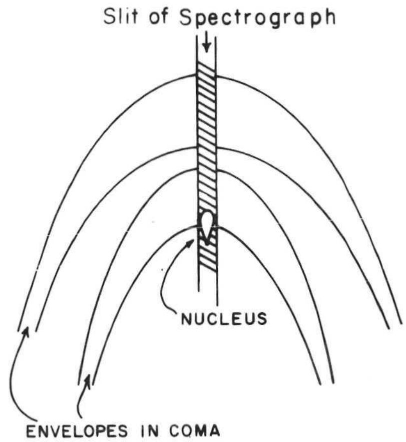

Fig. 15-6 - Comet Bennett: sketch of image on slit at 200-inch.

Supplementary Comments

August 1972

1. Comet Tago-Sato-Kosaka:

The analysis described in a preliminary way in the preceding discussion has been completed. After correcting the intensity of the (1-0) $C^{13}C^{12}$ band head for blending by NH_2, a comparison of the intensity of this feature with the (2-0) head of $C^{12}C^{12}$ gives an abundance ratio $C^{12}/C^{13} = 100 \pm 20$. An enlargement of the relevant region of the spectrum is given as Fig. 15-7.

The large uncertainty is a necessary consequence of the rather substantial blending correction. Observations of $C^{13}C^{12}$ in brighter comets at higher spectral resolution would help to improve the precision of such determinations. At present, we are forced to conclude that the earlier determination of 70 ± 15 by Stawikowski and Greenstein (1964) (see text) is indeed a lower limit (as these authors themselves suggested might be true). Within experimental error, cometary carbon seems to exhibit the same isotopic ratios as terrestrial carbon.

A complete discussion of this work will be published elsewhere.

2. Comet d'Arrest:

Largely as a result of the interest stimulated by this Conference, (cf. Part II of these Proceedings), a concentrated effort was made subsequently to obtain spectra of Comet d'Arrest during its 1970 apparition. The only successful attempt was that carried out by Dr. R. E. White of

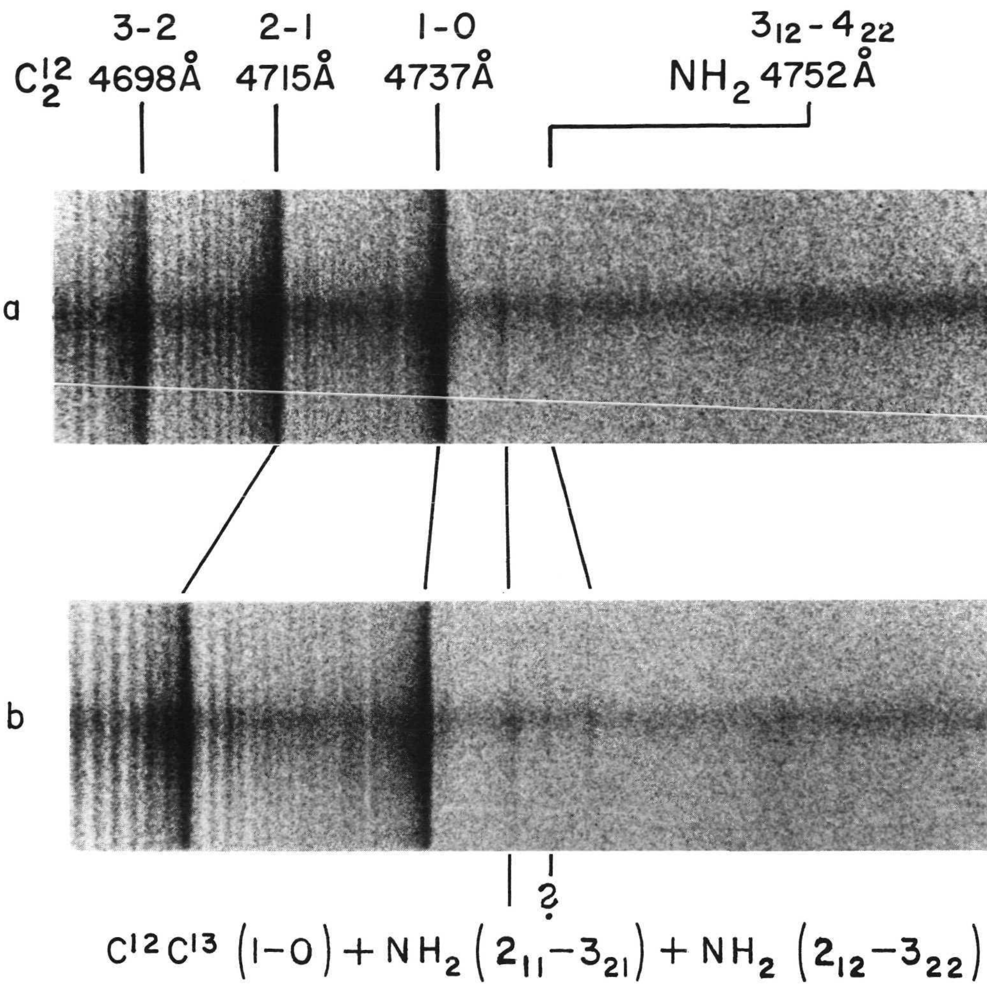

Fig. 15-7 - Spectrograms of Comet Tago-Sato-Kosaka obtained with 200-inch coudé January 27, 1970, 02:00 - 05:00 UT. a: Second Order, 27 Å/mm; b: Third Order, 18 Å/mm. Wavelengths and identifications of principal features are indicated. The unidentified feature is at λ4748 Å.

the Steward Observatory in response to a request by Dr. Elizabeth Roemer. The comet had been observed by Dr. Roemer through the spring of 1970 and showed signs of becoming brighter than expected. On May 7, she estimated the photographic magnitude to be approximately 16. The comet was distinctly diffuse compared with stars (Fig. 15-8).

The spectrogram obtained by Dr. White was recorded with an image tube camera at the Cassegrain spectrograph of the Steward Observatory 229-cm telescope from 9^h56^m - 11^h05^m on July 10, 1970 (UT). The observation was made through clouds with an effective exposure of 20 minutes at a dispersion of 95 Å/mm. The projected slit length was 40 arcsec; the slit was centered on the image of the comet.

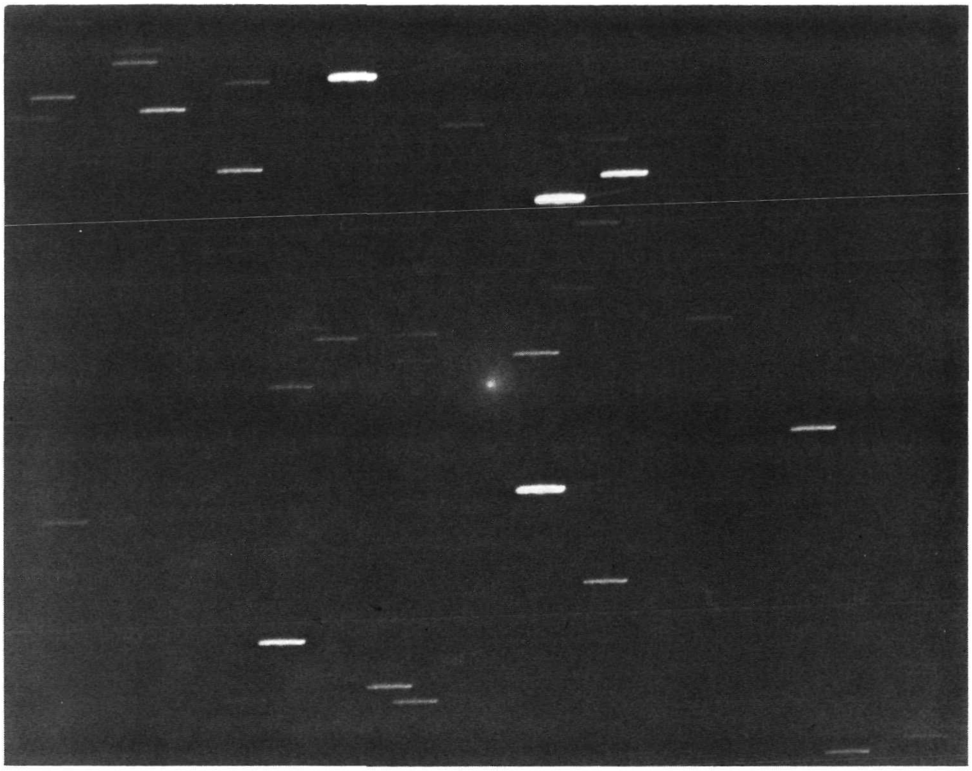

Fig. 15-8 - Comet d'Arrest. Exposure 23^m, 103a-O, Steward Observatory 229-cm telescope at f/9, 1970 May 7 UT by Dr. Elizabeth Roemer. Scale of the original (8x10) print: 10 arcsec/mm. Coordinates $23^h30^m.6$ - $0^\circ 09'$; H.A. 5^hE, m_{pg} = 16.

A density tracing of the resulting spectrogram is reproduced here as Fig. 15-9. The comet's position low in the eastern sky led to significant contamination of the spectrum by lines from mercury vapor street lights in Tucson, in addition to the usual night sky contribution. The principal features in the spectrum of the comet itself are marked. It is apparent that the usual fluorescence spectrum is present, superimposed on a relatively weak continuous spectrum from scattered solar radiation.

The results of this effort thus indicate that Comet d'Arrest would provide both the dust and gas emission that one would like to study in situ with a suitably instrumented probe. In that sense, it would indeed be a good target for a space mission. We have also been able to demonstrate that it is possible to obtain good basic information on comets while they are still quite faint ($m_v \lesssim 15$ mag) within a relatively short period of time. With suitable advanced planning, it should be possible

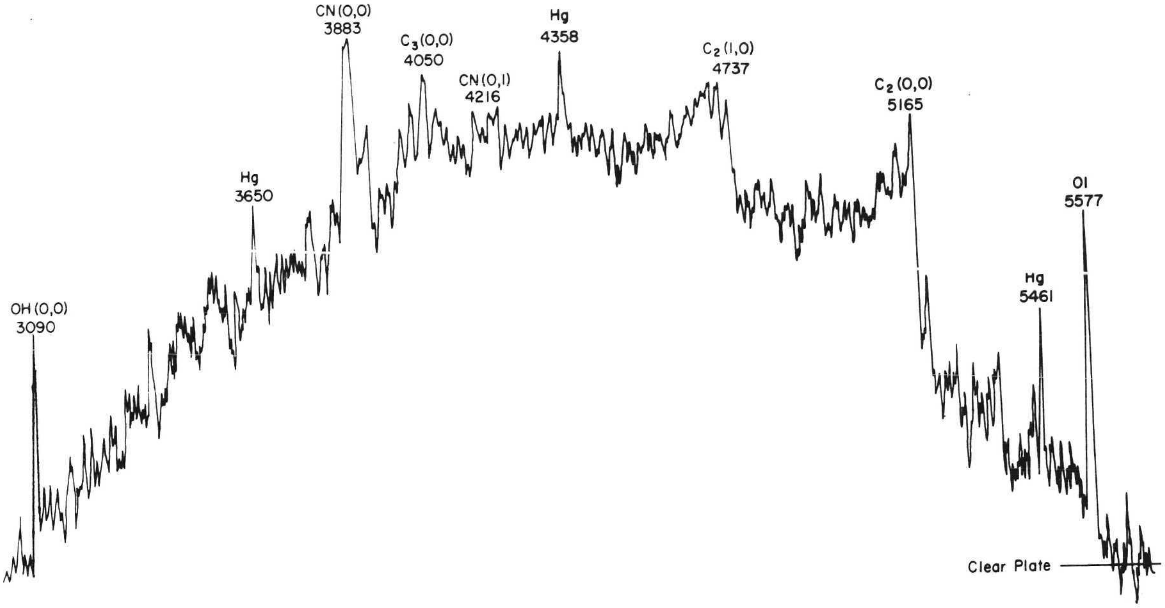

Fig. 15-9 - Spectrogram of Comet d'Arrest obtained with 229-cm Steward Reflector July 9/10, 1970 by Dr. R. E. White. Original dispersion 125 Å/mm. This is a density tracing of the spectrogram, with an arbitrary vertical scale. Wavelengths and identifications of principal features are indicated. The OI line at 5577 Å is from the terrestrial night airglow and the Hg lines at 5461, 4358, and 3670 Å are due to distant streetlights.

to do even better. This capability should be kept in mind by mission planners concerned with the updating of information on periodic comets just after recovery, while there is still time to influence the design of a mission prior to the launch date.

NO. 16

SPECTROPHOTOMETRY OF COMET 1969g (TAGO-SATO-KOSAKA)

by C. R. O'Dell
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ABSTRACT

The spectrum of Comet 1969g (Tago-Sato-Kosaka) was studied over the wavelength interval λ3800Å - λ8500Å. Composite spectra were formed and the results are shown as relative absolute energy distribution plots. Earlier (photoelectric data) conclusions of a disagreement of theory and observation of Swan band intensities are confirmed and it is suggested to be due to non-inclusion of the Ballik-Ramsay bands in the calculations. The Phillips bands are seen in emission and enable a C_2 singlet/triplet population ratio to be derived. Both the red and violet CN band sequences are observed and quantitatively compared with theory. NH_2 is quite strong and dominates the red spectral region. An upper limit to the Hα surfacebrightness is consistent with the OAO observations and Bierman's chromospheric resonance fluorescence model, but does not allow discrimination between detailed models. A tentative identification of the λ5015 line of HeI is made, possibly produced by the Biermann mechanism.

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O'Dell, C.R. 1971, Ap. J., 164, 511-519.

NO. 17

COMET ORBITS: PREDICTION, NONGRAVITATIONAL EFFECTS

by B. G. Marsden
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ABSTRACT

The problems of calculating cometary orbits are discussed, with particular attention to that of predicting the returns of periodic comets. It is shown that the only inherent difficulty arises from the action of nongravitational forces. Recent progress toward an understanding of these forces is described in detail, both from the point of view of fitting the observations and of interpreting the forces in terms of the Whipple icy-conglomerate model.

There are four computational stages in the process of determining the orbit of a comet: (i) the initial calculation from three positional observations obtained shortly after the comet's discovery; (ii) the progressive improvement by means of differential corrections as more observations become available; (iii) the incorporation of the perturbations due to the gravitational attractions of the planets; and (iv) allowance for nongravitational effects.

In principle, the first three stages are straightforward, and only the fourth may cause difficulty. Of course, problems can arise from the inherent indeterminacy of the solution, which is limited mainly by observational uncertainty; in the past, however, problems have also arisen because of approximations introduced into the computation. Such approximations may be convenient if the computation has to be made using logarithms or a desk-calculator, but they are unacceptable when it is performed on a modern high-speed machine. There is no excuse nowadays for employing approximations that produce unnecessary errors in the future predicted positions of a comet. Such errors can be costly: this is true whether the computation is to be used for recovering a returning periodic comet when it is near the limit of detection with a large telescope, for bouncing a radar pulse off a comet, or for intercepting a comet with a space probe.

I do not intend to discuss all the traditional approximations here. The more prevalent ones, however, arise from the assumption that the afore-mentioned stages (ii) and (iii) are independent. It may be satisfactory to regard the differential correction process as distinct from the perturbation calculation when one is determining a nearly parabolic orbit - or indeed the orbit of any comet observed at a single perihelion passage; but if one is working on the orbit of a periodic comet observed at several returns - a comet that is of relevance from the point of view of the space program - it is necessary to iterate the computation of the two stages together. The differential correction process involves equations of the form

$$\Delta\delta = \sum_{1}^{6} \frac{\partial\delta}{\partial c_i} \Delta c_i; \qquad (1)$$

$\Delta\delta$ denotes the difference between the comet's observed declination at some time and the declination calculated from the assumed orbital elements c_i ($i = 1, \ldots, 6$), the planetary perturbations of course being included. The solution of several such equations, together with the corresponding equations in right ascension, yields corrections Δc_i to be applied to the assumed elements. The perturbations should then be recalculated and the orbit recorrected, the procedure being repeated until the squares of the corrections become negligible.

The most widespread approximation involves the computation of the partial derivatives in Eq. (1). Many textbooks provide expressions for them, but without exception they have been derived from the equations of Keplerian motion. The partial derivatives mean precisely what one would expect: the derivatives of the instantaneous perturbed declination (or right ascention) with respect to constants of the orbit, the latter being most conveniently the elements of the osculating orbit at some specified epoch. It is an unnecessary approximation to replace these partial derivatives by expressions based on the assumption that the motion is a fixed conic. Indeed, if one is attempting to calculate the orbit of a typical short-period comet, one having a revolution period of six or seven years and its aphelion near Jupiter's orbit, it will often be desirable to include in the same solution observations made both before and after a close approach to Jupiter, and in such a case use of the conventional expressions for the partial derivatives can be most misleading. The iterative process I have mentioned might converge in the sense that the residuals resulting from substitution into the differential correction equations become identical after successive iterations, but one will not obtain the correct solution, and these residuals will not be the same as those that actually follow from the final elements. It is necessary to include the perturbations in the partial derivatives, and the easiest and surest way to do this is to calculate the planetary perturbations, not only on the preliminary orbit, but also on the six orbits obtained by varying each element one by one by a small amount; the various partial derivatives are then formed as the differences between the residuals from the preliminary orbit and from the orbit with the appropriate element varied.

The necessity for stage (iv) of the orbit determination, allowance for nongravitational effects, arises only if systematic trends remain in the residuals after stages (ii) and (iii) have been conducted. The existence of nongravitational effects has been a controversial topic ever since Encke first brought up the matter a century and a half ago. It is obvious that one cannot have much confidence in the results if invalid approximations are introduced in the earlier stages, and it is only since about 1967 that any computations have been made in which perturbations were included in the differential correction partial derivatives.

But when stages (ii) and (iii) are performed rigorously it becomes quite clear that, for several of the periodic comets at any rate, unacceptable systematic residuals remain. These systematic trends become larger the longer the interval of time covered by the observations used, and in some cases they amount to several minutes of arc over only three apparitions. This shows rather definitely that additional forces are involved, not merely an effect such as the possibility that the center of mass of a comet may depart significantly from the center of light.

An important question to be answered is whether the nongravitational forces take the form of random impulses or whether they act more or less continuously. Certainly, there is a great deal of evidence that impulsive forces do act on comets: one need only consider the numerous instances where comets have been observed to split or to flare up suddenly in brightness. On the other hand, the earlier studies - affected though they might have been by approximations - did suggest that the nongravitational forces were surprisingly regular in their action. Since the most readily detectable nongravitational effect is a progressive advance or delay of successive returns of a comet to perihelion, the standard way to allow for the forces has been to postulate a secular variation in the mean motion. Studies made in this manner indicated that for a particular comet this variation remained about the same for several revolutions. Some investigators claimed the existence of small and regular nongravitational secular variations in other orbital elements as well.

Tentatively at least, it is therefore reasonable to assume that the nongravitational forces are continuous. As far as the planetary perturbations are concerned, it is definitely more convenient, particularly if great accuracy is required, to integrate the equations of motion in rectangular coordinates, by Cowell's method, for example. When a comet makes a close approach to Jupiter, any advantage a variation-of-elements method may have, even for approximate work, is completely lost. If one is using a rectangular-coordinate method for calculating the planetary perturbations, it is certainly appropriate to express the nongravitational parameters in rectangular coordinates also. Encke in fact did this, supposing that the nongravitational force acted along the comet's velocity vector and varied in some way with heliocentric distance. We cannot seriously consider any more his reasoning that the force arose on account of a resisting medium, but his equations in rectangular coordinates are suitable for attempting to analyze the situation.

We have found it appropriate to generalize his equations, however, and admit the possibility that the nongravitational force has components, not only along the velocity vector, but also along the radius vector and even out of the orbit plane as well. In practice, we add to the equations of motion in rectangular coordinates extra acceleration components F_1, F_2 and F_3, where F_1 is directed outward along the radius vector, F_2 is directed parallel to the line from the sun to the point in the orbit with true anomaly 90° greater than the comet (i.e. approximately along the velocity vector for orbits of low eccentricity), while F_3 is directed perpendicular to the orbit plane and such that one has a right-handed system (i.e., it is toward the north pole of the orbit). The F_i are supposed to take the form

$$F_i = G_i \exp(-r^2/C)\, r^{-\alpha}, \tag{2}$$

where

$$G_i = A_i \exp(-B_i \tau), \tag{3}$$

the A_i and B_i being constants, C and α non-negative constants, r the comet's heliocentric distance, and τ the time from some initial epoch.

The choice $C = \infty$, $\alpha = 2$, $B_i = 0$ corresponds of course to an inverse square law, but we have found that this in general does not give a very good representation of the observations. If one wants to use an inverse power law, the power has to be rather large. On the other hand, very satisfactory fits may be obtained if both C and α are small. We have established that the precise values of C and α are of little consequence and in general have arbitrarily adopted $C = 2$ (with r measured in astronomical units) and $\alpha = 3$. The suggestion to include the $\exp(-r^2/2)$ factor was originally due to Dr. Whipple. We have also established that, within the error of its determination, $A_3 = 0$, showing that there is no significant nongravitational force component perpendicular to the orbit plane. For most comets, therefore, it is necessary to solve only for A_1 and A_2, the basic parameters for the radial and transverse components of the nongravitational force. This can be accomplished in precisely the manner discussed earlier; two additional orbit integrations are made in which the assumed values of A_1 and A_2 (initially zero) are incremented by small amounts. These yield the partial derivatives with respect to A_1 and A_2, and the solution involves the correction of eight orbital constants instead of the usual six.

As might be expected, for periodic comets the transverse component A_2 is much better determined than the radial component A_1, simply because the transverse component is more directly related to the variation in the mean motion. In some cases the magnitude of A_2 is several hundred times the mean error of its determination. However, A_1 can often be determined surprisingly accurately too, occasionally to several tens of times its mean error.

The magnitude of the nongravitational force acting on a comet (or at least the transverse component) seems to bear some relation to the comet's physical appearance, in that the force is largest for the very diffuse comets with little or no observable condensation, such as P/d'Arrest and P/Honda-Mrkos-Pajdušáková. Comets that are almost asteroidal in appearance and show only the most tenuous of comas, such as P/Arend-Rigaux and P/Neujmin 1, are not affected by any detectable nongravitational forces at all (with the observations of P/Neujmin 1 spanning an interval of 53 years). In the reliable determinations A_1 is invariably positive, which means that the radial component of the force acts away from the sun, and when normalized to an inverse square law it is typically 10^{-5} that of the solar gravitational attraction on the comet; the transverse component can act in either direction and is typically an order of magnitude smaller than the radial component.

This is more or less what one would expect from Whipple's icy-conglomerate model for a cometary nucleus: if the comet's axis of rotation is perpendicular to the orbit, a positive A_2 corresponds to direct rotation of the nucleus and a negative A_2 to retrograde rotation; and the angle by which the direction of maximum mass ejection lags behind the subsolar point is numerically the arctangent of A_2/A_1, some 5 to 10 degrees. The fact that the lag-angle is so small is rather encouraging, for it suggests that the angle may be approximately constant, whereas from a theoretical point of view it is very difficult to calculate the lag-angle and its variation with heliocentric distance. Theoretical work indicated that there was no reason why the lag-angle should not be greater than 90°, or indeed why it should not sometimes amount to more than 360°. Of course, if we had an isolated practical example, we could not exclude the possibility that the lag-angle might amount to more than one complete rotation of the nucleus, but we have at least half a dozen excellent examples where A_2/A_1 gives a very small quantity. So I think this suggests a small value of the lag-angle in the first quadrant.

The most notable exception is P/Encke, where it is evident that A_1 is definitely not an order of magnitude larger than A_2 and directed away from the sun. Indeed, there is an indication that in this case A_1 might be slightly negative. But we know that the orbit of P/Encke has remained relatively unchanged for some millennia, and with a perihelion distance of only 0.3 A.U. and a revolution period of only 3.3 years, the nucleus of this comet has been subjected to frequent and tremendous variations in conditions, with the result that its surface features and rate of mass ejection are likely to be most irregular. On the other hand, a comet that is a "clean snowball", only recently perturbed by Jupiter into an orbit of relatively small perihelion distance, represents a much more straightforward and regular situation.

At this stage it is worth mentioning that there is evidence that the motions of comets are scarcely affected by nongravitational forces at relatively large distances from the sun. Our selection of values $C = 2$ and $\alpha = 3$ implies a rather strong dependence on heliocentric distance, but it is not impossible that beyond about 3 A.U. the nongravitational forces cease acting entirely. Of the nine comets observed at three or more passages through perihelion and having perihelion distances q greater than 2 A.U., only in the case of P/Schwassmann-Wachmann 2 ($q = 2.2$ A.U.) is the effect of nongravitational forces noticeable from the observations at three apparitions. Nongravitational forces do affect the motion of P/Whipple at $q = 2.5$ A.U. (and probably P/Wolf at 2.5 A.U. and P/Holmes at 2.3 A.U.), but they are very small. The only such comets with larger perihelion distances are P/Oterma and P/Schwassmann-Wachmann 1. The former comet was under observation more or less continuously for 20 years when it had a low eccentricity orbit at $q = 3.4$ A.U., and one could not have wished for a better purely gravitational fit to the observations. (Unfortunately, there is a gap, no comets with perihelia between 2.5 and 3.4 A.U. being available for studies of nongravitational effects. It may be that 3.0 A.U. is as good a guess as we can make of the distance at which such effects become negligible.) According to the results by Herget and by Cunningham, the motion of P/Schwassmann-Wachmann 1 ($q = 5.5$ A.U.) has not shown any effects of nongravitational forces over more than 60 years. However, we know that the last-mentioned comet is affected by nongravitational forces, for every few months it bursts up in brightness by some five magnitudes, and this accompanies the sudden release of a shell of matter, which expands from the comet at a speed of some 100 to 200 m/s. This is a particularly good illustration that the sudden, directly observable non-gravitational events that take place in some comets do not always lead to observable effects on the motions.

The result that for short-period comets the radial component of the nongravitational force is outward and some 10^{-5} that of solar gravitational attraction agrees precisely with the average value determined in 1953 by

Hamid and Whipple through modification of the original definitive orbit solutions for 64 comets with nearly parabolic orbits. The individual values showed considerable spread, however, and most of them should be regarded with extreme caution. There are two recent single-apparition comets where I think one can definitely establish that nongravitational forces were influencing their motions. These are Comets 1957III (Arend-Roland) and 1960II (Burnham), the purely gravitational solution being particularly unsatisfactory in the latter case, even though the comet was under observation for only six months. Here it is the radial component that is the better determined, and it also seems clear that it varies more according to an inverse square law. It is not excluded that the radial components of the nongravitational forces on the short-period comets also vary according to an inverse square law; it just happens that the determinacy of the solution for the transverse component is overwhelming, and this component does not go according to an inverse square law. The forces on Comets 1957III and 1960II are relatively large: $(7 \pm 1) \times 10^{-5}$ and $(20 \pm 1) \times 10^{-5}$ that of solar attraction, respectively. For both comets the purely gravitational solutions had suggested that their "original orbits" (evaluated for when the comets were some 40 or 50 A.U. from the sun on the way in, and referred to the barycenter of the solar system) had been noticeably hyperbolic; the solutions that include nongravitational terms not only significantly improve the representation of the observations, but they show that the original orbits were elliptical.

I have not yet discussed the quantities B_i in Eq. (3), having assumed that they were zero. Actually, only B_2 seems to be of any consequence. Nearly a century ago Backlund claimed that the secular acceleration of P/Encke suddenly decreased, possibly by as much as a factor of two, and the more recent results, mainly by Makover and his colleagues, suggest that there have been further decreases. It is certainly not evident from their work that the secular acceleration decreased in discontinuous steps, and we have found it more convenient to assume a continuous variation. We adopted the exponential variation shown in Eq. (3), rather than a linear variation, because initial experimentation using the latter form indicated that the force would change sign after only a few decades (but outside the range covered by the observations), and we had no direct evidence that this in fact happened. Considerable caution is necessary when one solves for B_2

because it is highly correlated with A_2, and one should not attempt to solve for it unless it is absolutely certain that use of A_1 and A_2 alone is inadequate. Useful independent confirmation can be obtained merely by comparing the values of A_2 determined at different times from shorter arcs.

There are three comets where the determinations for B_2 are particularly reliable and different from zero. In each case B_2 turned out to be positive, showing that the nongravitational forces (the transverse components, at any rate) become smaller with time as earlier investigators had found for P/Encke. This is to be expected if the inner regions of a comet contain less volatile material than the outer, and it is consistent with evolution from a diffuse comet such as P/Honda-Mrkos-Pajdušáková, where the nongravitational forces are large, to an almost asteroidal comet such as P/Arend-Rigaux, where the nongravitational forces are below the limit of detection. For the three comets the "half-lives" associated with B_2 (i.e., the time required for the transverse force component to decrease by a factor of e) are:

	Half-life
P/Encke	36 years
P/Tempel 2	68
P/Schwassmann-Wachmann 2	91

These half-lives should not be taken too literally, of course, but they suggest that a short-period comet can suffer significant deterioration after an interval of only a few centuries. Another indication of this is that the comets that seem to have evolved the most have the most stable orbits, in that the perturbations by Jupiter have not caused much change in their orbits for the better part of a millennium. The "asteroidal" comets P/Arend-Rigaux and P/Neujmin 1 have not passed within 0.9 A.U. of Jupiter - which seems to be about the border of the danger zone - for nine centuries and more. On the other hand, all the other 52 periodic comets of more than one appearance and period less than 24 years have been within that distance at some time during the last two centuries; many of them have on several occasions been considerably closer, and while it is practically impossible to trace them through several encounters with Jupiter, it is statistically probable that not too many centuries ago most of them had orbits of larger perihelion distance, and the onset of significant aging would date from the time of transition of their perihelion distances below about 3.0 A.U.

The half-life for P/Encke was determined from observations made since 1927. Extrapolated back to the late eighteenth century, when the comet was first observed, it gives a nongravitational force that is quite a lot larger than was observed. The half-life was then evidently rather longer, more like the value quoted above for P/Schwassmann-Wachmann 2. Does this suggest that "new" comets have longer half-lives and dying comets shorter ones? We know that P/Schwassmann-Wachmann 2 is a "new" comet, for prior to an approach to Jupiter in 1926, shortly before discovery, its q was 3.6 A.U.

We must turn now to the question of the reliability of the determination of the nongravitational effects and thus to the related problem of how accurately the positions of comets can be predicted into the future. As recently as 1965 one was pleased if the perihelion time of a returning comet could be predicted within half a day. Nowadays it is sometimes possible to predict the perihelion time within 0.01 day, although for the comets on which the nongravitational forces are rather large one usually cannot do much better than 0.02 or 0.03 day. Because of the difficulty of determining B_2 (and its rate of change), I doubt that it will ever be possible to guarantee that a prediction for a typical short-period comet (however well observed it may have been at past returns) will be within 0.02 day. In 0.02 day a comet of perihelion distance 1.5 A.U. and mean distance 3.5 A.U. will travel, when it is at perihelion, 50,000 km. This is the uncertainty along the orbit: that in the radial distance could be ten times greater.

But there is a more serious difficulty. Occasionally the error in the predicted perihelion time of a comet is considerably larger than 0.02 day, even when every effort is made to produce a rigorous prediction. The most noteworthy example of this is P/Perrine-Mrkos at its return in 1968. At Warsaw Dr. Sitarski computed an orbit from the observations made at the 1955 and 1962 returns. We confirmed his result very closely and then modified his 1968 prediction with allowance for nongravitational effects, which we estimated from extrapolation of the orbit to the earlier apparitions, in 1909 and 1896-97. Inclusion of the nongravitational terms suggested that the 1968 perihelion time would be advanced by 0.10 day. Such a change is fairly typical for a short-period comet; it is a little on the large side, but P/Perrine-Mrkos is a particularly diffuse and uncondensed comet. When the comet was actually picked up in 1968, its perihelion time was found to be 0.7 day earlierstill than the best of the predictions,which meant that the error along the orbit was almost 2 million km. It was originally our feeling that the discrepancy was due in some way to the moderately close approach to Jupiter made by the comet in 1959. The minimum separation was 0.4 A.U., but I hasten to add that if there had been no nongravitational forces acting on the comet, the perturbations by Jupiter would have caused no problem. It seemed that some interaction took place between the gravitational and the nongravitational forces; perhaps it was merely a mathematical effect that was somehow accentuated, for after all, the nongravitational portion of our equations of motion is empirical. If you like, the anomaly can be considered as a sudden decrease in the comet's velocity when it was near Jupiter; the comet's heliocentric velocity was then 7.4 km/s, and the decrease would have amount to 3.5 m/s.

There is also evidence that the same phenomenon took place in the case of P/Schaumasse, another comet on which the nongravitational forces are normally rather large, around the time of its approach to Jupiter (again to 0.4 A.U.) in 1937. On the other hand, other comets, notably P/Grigg-Skjellerup and P/Kopff, have recently passed even closer to Jupiter, yet they have been perfectly predictable afterwards; but the nongravitational effects on these comets are normally small. We became rather worried about the situation with regard to P/d'Arrest (on which, as I have already remarked, the nongravitational effects are normally large), for this comet has been widely discussed as the possible objective of a space probe. Calculations made originally at the IIT Research Institute indicated that this comet would be exceptionally well situated for a flyby mission in 1976, this the result of perturbations by Jupiter in 1968. The situation with P/d'Arrest in 1976 would thus be similar to that with P/Perrine-Mrkos in 1968, and one could anticipate the possibility of a large error in the predicted position. The IITRI scientists estimated that the comet could be recovered 100 days before the proposed launch date for the probe - which would be sufficient for making last-minute corrections. But I think they have been over-optimistic about this. As a result of Dr. Roemer's remarks this morning, I just did some figuring based on the recovery in March of P/d'Arrest at its 1970 return. I think we can expect it to be of 19th magnitude at launch date and fairly well placed for observation, but I think the important thing is that one has to get the 200-inch telescope on to this comet as early as possible in 1976.

[See Marsden's Addendum to this Report, discussion of the orbit correction on the basis of astrometric observations of P/d'Arrest in March, April, and May 1970].

We don't know for certain that the trouble with P/Perrine-Mrkos arose during the 1955-62 revolution; it could have occurred between 1962 and 1968, during which time the comet was far from Jupiter. Dr. Yeomans, at the University of Maryland, has been working on the orbit of P/Giacobini-Zinner and has produced rather convincing evidence that there was a change in the nongravitational parameters of this comet during the 1959-66 revolution, an interval that did not involve a close approach to Jupiter. The motion of this comet (including nongravitational effects, which are again quite large) was very regular from 1900 to 1959, but the observations at the 1966 return suggest that a sudden change had occurred. If this change had taken the form of an impulse in 1960, it would have amounted to about 0.5 m/s. Yeomans also found that B_2 seemed to be slightly negative for P/Giacobini-Zinner. More recent calculations have revealed other cases of negative B_2, most notably P/Biela. As is well known, P/Biela was observed in two fragments at its returns in 1846 and 1852, and it has not been seen since. We have also evidence for a sudden change in the nongravitational parameters of P/Biela toward the end of the eighteenth century. P/Brorsen, another lost comet, seems to have experienced at least two of these sudden changes.

So there seems to be some circumstantial evidence for a connection between these sudden changes, negative values of B_2, and cases where comets have disappeared. (I point out that several of the comets long regarded as lost have been found in recent years, now that the necessary calculations can be done with full rigor; but in some cases these attempts have failed, and I am prepared to concede that P/Biela and P/Brorsen, as well as perhaps P/Tempel-Swift and P/Neujmin 2, will not be recovered.) A comet exhibiting a negative B_2 can be interpreted as having a nucleus that shrinks, due to sublimation, by about the same radial amount during each revolution about the sun. Since the nongravitational force represents the ratio of the amount of mass lost per revolution to the total mass, this interpretation will cause the force to increase as the comet ages; i.e. B_2 is negative.

In fact, B_2 will become increasingly negative with time. There are no clear-cut observed cases of strongly negative B_2, but any comet in such a situation would presumably be extremely small and thus probably unobservable; the question as to whether there exists a tiny asteroidal core then becomes academic.

Comets with negative B_2, such as P/Giacobini-Zinner, P/Biela, and by inference P/Brorsen, P/Perrine-Mrkos and P/Schaumasse (there is direct evidence for negative B_2 in the case of the last-named comet), must be physically rather different from the comets, mentioned earlier, as having significantly positive B_2. The latter comets, presumably evolving into quite large asteroidal objects, are probably much more massive than the comets of negative B_2, which even while readily observable may consist almost entirely of low-density snow and dust impurities. The cause of the sudden changes in the nongravitational parameters is not completely clear, but Dr. Sekanina has made a case for considering them as due to impacts from interplanetary boulders (which could also therefore be the cause of the splitting of P/Biela), a given impact by one of these 5- to 10-meter-sized objects producing a far greater impulse in the motion of a snowball comet than in that of one with a substantial core.

These experiences suggest that if one wants to send a space probe to a comet that can be more or less relied upon to be at a certain time in the position predicted some years in advance, he should select one of the comets on which the nongravitational forces are either small already, or at least, substantially decreasing in time. If one is thinking in terms of flybys, good opportunities would arise for the two comets that seem to be least affected by these forces, P/Arend-Rigaux and P/Neujmin 1, in 1984. The former comet will pass about 0.56 A.U. from the earth about a month after perihelion and the latter 0.87 A.U. from the earth two months before perihelion; the nuclei of both comets should rise to about fifteenth magnitude. From a scientific point of view, an attempt to rendezvous with a comet is preferable to a flyby; it would be a more expensive proposition, but one has greater freedom in selecting a suitable comet. In this case I should like to suggest that one of these rather inactive comets be selected (preferably P/Arend-Rigaux, because the orbit computation can be further refined using observations at the 1971 and 1978 returns), not only because its position can be predicted with greater certainty, but because the sparse activity should make it easier for the probe to locate and rendezvous with the comet's nucleus and to observe the development of the coma from the nucleus. P/Encke, well placed at its returns in 1980 and 1984, is also eminently worthy of consideration; for its nongravitational effects are nowadays rather small, and the very short revolution period is certainly to our advantage in attempting to predict them.

Finally, I want to return to the fundamental question of the choice of the equations of motion to handle the nongravitational terms, in particular, the assumption of an exponential variation with the time. Calculations on the orbit of P/Pons-Winnecke have indicated that the secular variation in the mean motion changed from a moderate acceleration during the nineteenth century to a slight deceleration now. A_2, or more correctly, G_2, has changed sign, and this is clearly incompatible with an exponential variation. But this comet is unique (among observable comets) in that it has suffered repeated perturbations by Jupiter every alternate revolution for the better part of a century and since its perihelion distance is now 50 percent larger than it was a century ago, changes in the nongravitational parameters are perhaps not surprising. Calculations that Dr. Sekanina and I made on the orbit of P/Faye illustrate the same phenomenon however, and in this case planetary perturbations have produced very small changes in the orbit. Separate solutions over different sections of the interval 1888-1970 show that A_1 has remained positive and approximately constant, but A_2 seems to have changed sign. The ratio A_2/A_1 is particularly small for this comet, much smaller numerically than the usual 0.1, which accounts for the fact that no previous investigator has reported that nongravitational forces were affecting this comet. Three solutions are:

	A_2/A_1
1888-1926	+0.036
1910-1948	+0.018
1932-1970	-0.002

These figures can be taken as instantaneous values at the middle of the indicated ranges. We have yet to do a solution for the range 1843-1881, but since 1888 it seems as though A_2/A_1 has changed almost linearly. I doubt that A_2/A_1 will become appreciably more negative in the future, but it does seem that B_2 is now effectively slightly negative. I might also mention that Yeomans found a slightly negative value of B_2 for P/Giacobini-Zinner, although in the case of that comet A_2 did not change sign.

If A_2 (or G_2) can change sign, there is no need for the exponential term, and we should investigate other ways of allowing for the variation with time. We might consider more directly the Whipple model and assume that the comet nucleus is a rotating sphere subject to the effects of solar radiation. The expressions for G_i are then:

The transverse component:

$$G_1 = \xi \; [\cos \lambda (1 - \frac{1}{2} \sin^2 I) + \frac{1}{2} \sin^2 I - \frac{1}{2} (1 - \cos \lambda) \sin^2 I \cos (2\phi + 2f)]$$

The radial component:

$$G_2 = \xi \; [\sin \lambda \cos I + \frac{1}{2} (1 - \cos \lambda) \sin^2 I \sin (2\phi + 2f)] \qquad (4)$$

The component perpendicular to the orbit:

$$G_3 = \xi \sin I \; [\sin \lambda \cos (\phi + f) - (1 - \cos \lambda) \cos I \sin (\phi + f)].$$

Here f is the comet's true anomaly, ϕ is the longitude of the meridian of the comet facing the sun at perihelion, I is the inclination of the comet's equator to its orbit, λ is the lag-angle - the longitude by which the direction of maximum mass ejection lags behind the subsolar meridian, and ξ ($\gtrsim 0$) gives the magnitude of the force.

One often assumes that sin I = 0. This gives, simply,

$$\begin{aligned} G_1 &= \xi \cos \lambda \\ G_2 &= \pm \xi \sin \lambda \qquad (5) \\ G_3 &= 0. \end{aligned}$$

The choice of sign depends on whether I is 0 or 180°. G_3 is indeed observed to be zero, and since G_2/G_1 is observed to be small (numerically) in most instances, it follows that λ is generally small, as noted before.

But maybe one should not make any assumption about I. Let us just assume that λ is small. We can replace cos λ by unity. For sin λ, we can perhaps replace it by zero in the expression for G_3; but G_2 is more directly observable, so in the expression for G_2 we should replace sin λ by λ. In order to obtain the actual acceleration components F_i, we must multiply the G_i by some function of the radius vector. If we suppose, for the moment, that the function is an inverse square, we obtain:

$$F_1 = \frac{\xi}{r^2}$$

$$F_2 = \frac{\xi}{r^2} \cos I \qquad (6)$$

$$F_3 = 0.$$

It has not been absolutely proven that λ is a small angle, but Eqs. (6) are less restrictive with regard to I than are Eqs. (5), and they can perhaps serve as a suitable basis for further considerations.

We found from observations that the transverse component of the force does not vary according to an inverse square law. The additional variation with r can logically be put into λ. More theoretical, or even experimental, work is definitely required on this problem. We can presume that ξ decreases with time, although it might depend onthe comet's perihelion distance as well. We should not exclude the possibility that λ has a secular change with time, and particularly that I changes with time: the change of sign observed in A_2 for P/Faye and P/Pons-Winnecke can be explained most simply by passage of I through 90°. Eqs. (6) would seem to be incompatible with the rare cases where negative values have been found for A_1, but none of these determinations is particularly certain.

It is unfortunate that we have only two observational quantities, one of which is quite a bit more reliable than the other, from which we have to determine three quantities, ξ, λ and I. It would perhaps be useful to concentrate mainly upon ξ and I, supposing that, for given heliocentric distance r, λ is the same specified value for all comets. It is often alleged that there is a tendency for sin I to be near zero. Dr. Gehrels has produced observational and theoretical evidence, however, that while I may be near 0 or 180° for a new comet, as a comet ages I tends towards 90°. If this is so, some of the observed decrease in the transverse components of the nongravitational forces on comets could be attributable to the cos I factor. Furthermore, the cases where G_2 changed sign, or where B_2 was found to be slightly negative, could be explained by an initial pass of I slightly beyond 90° (by some 10° or 20°, say), followed then by strongly damped oscillations to the stable value of 90°. Clearly, this is another problem requiring more theoretical study. As for the sudden changes in nongravitational parameters observed for a few comets, it may be reasonable to associate these with I rather than with ξ.

Addendum concerning attempts to observe the spectrum of P/d'Arrest in 1970

Following the suggestion made at the Conference that information concerning the spectrum of P/d'Arrest would be of value, T. Owen attempted to arrange that this comet would be observed with the 508-cm (200-inch) reflector at Palomar in late May 1970. Since the comet was not expected to be brighter than eighteenth magnitude, and since a large moon would be present in the sky, it was necessary for the observer to be able to identify the comet by direct visual inspection. This required a prediction of the comet's position accurate to a few seconds of arc.

The pair of recovery observations by E. Roemer on March 14, 1970 gave residuals of some 15" from the predicted orbit by the writer. They would be used to determine a correction ΔT to the predicted perihelion time. The least-square solution gave $\Delta T = -0.0070 \pm 0.0011$ day; this fitted the right ascensions very well, but (O-C) declination residuals of some -3" to -4" seemed rather unacceptable. The next observation was made, also by E. Roemer, on April 7, 1970. The orbit corrected for ΔT from the March 14 pair gave a residual of 14". Solutions for ΔT alone and also for ΔT and $\Delta\omega$ using the March and April observations were unsatisfactory, while one for the four corrections ΔT, $\Delta\omega$, $\Delta\Omega$ and Δi was not well determined. A solution for ΔT from the April 7 observation alone gave $\Delta T = -0.0132 \pm 0.0004$ day and satisfied this observation very well, but it was (not unexpectedly) inconsistent with the March 14 observations. Finally, there was another observation on May 7, 1970 (also by E. Roemer, and apparently the only other one made anywhere before June), and attempts to combine this with either or both the March 14 and April 7 observations and to solve for ΔT alone, ΔT and $\Delta\omega$, and all four corrections ΔT, $\Delta\omega$, $\Delta\Omega$ and Δi were not satisfactory. A direct solution for ΔT from this observation alone gave $\Delta T = -0.0209 \pm 0.0018$ day, an (O-C) declination residual of +4" and residuals of 18" on April 7 and 30" on March 14, 1970.

How could a reliable prediction be made of the comet's position for the end of May 1970? It was evident from the three values quoted above that ΔT was effectively changing with time very nearly linearly. One could therefore extrapolate a value of $T = -0.026$ day. An accurate astrometric ephemeris, including a parallax correction to reduce it to Palomar, was therefore calculated. Extrapolation also of the (O-C) declination residuals from the three solutions suggested that by then the residual would amount to some +7".

This is clearly a very curious way to predict the position of a comet! What was the alternative? One could perhaps have tried linking the observations accurately with those made at the comet's 1963 return, but in view of the intervening close approach to Jupiter (0.41 A.U. in 1968) and its unknown effect on the comet's nongravitational parameters, this did not seem to be a very promising solution to the problem. Another possibility was to make a general determination of the six orbital elements from the 1970 observations. Since the observations had been made on only three nights, however, this led to a rather indeterminate result, and the comet's predicted position in late May was very uncertain. Furthermore, there was no check on errors that might exist in any of the 1970 observations. But a satisfactory solution could be made for five of the orbital elements. This was done, with the value of the eccentricity assumed from the prediction, and the ephemeris calculated thus for late May agreed within 2" or so of that calculated by the method of the previous paragraph. This ephemeris was adopted, and the linearity with time of the individual ΔT corrections was looked upon as a good check that nothing was seriously wrong with any of the 1970 observations.

What is to happen in 1976? Are we also to launch a $100,000,000 space probe on a bare minimum of information? We draw attention to the problem in the hope that other astronomers will be induced to secure astrometric observations of the comet between recovery and launch date. The situation may not be quite so bad as in 1970, however, for the absence of large perturbations by Jupiter will make it easier to link the first of the observations in 1976 with all those of 1970/71.

The table below summarizes the residuals from the various solutions mentioned:

1970 UT	Mar. 14 ΔT		Apr. 7 ΔT		May 7 ΔT		e assumed	
	$\Delta\alpha\cos\delta$	$\Delta\delta$	$\Delta\alpha\cos\delta$	$\Delta\delta$	$\Delta\alpha\cos\delta$	$\Delta\delta$	$\Delta\alpha\cos\delta$	$\Delta\delta$
Mar. 14.50	+ 0".4	- 4".5	-12".4	- 3".4	-28".4	- 1".9	+ 0".7	- 0".6
14.52	- 1.1	- 3.3	-13.8	- 2.1	-29.8	- 0.7	- 0.7	+ 0.6
Apr. 7.48	+14.4	- 1.5	0.0	- 1.0	-18.1	- 0.4	0.0	0.0
May. 7.46	+31.9	+ 4.2	+17.7	+.4.2	0.0	+ 4.1	0.0	0.0

As it turned out, no observations were in fact attempted with the 200-inch telescope. With the cooperation of R. E. White an image-tube spectrogram of P/d'Arrest was obtained with the 229-cm (90-inch) Steward Observatory reflector, Kitt Peak, in July. This showed CN $\lambda3883$ to be the most prominent spectral feature, but several of the other typical emissions were present, and there was a weak continuum.

NO. 18

SHAPE AND ORIENTATION OF NUCLEUS

by Tom Gehrels
Lunar and Planetary Laboratory

If a solid nucleus within the head of a comet could be isolated, its shape and its rate of rotation could be derived from brightness-time variations of the reflected sunlight. Such measurements are made on asteroids, and could, in principle, be made on a cometary nucleus as well. For Geographos, for example, we know that the length is about 2.4 km and the width is 0.7 km, a strongly elongated body. The lightcurve of Geographos was observed by Mr. J. L. Dunlap with the 60-inch reflector at Cerro Tololo in August 1969. The amplitude is nearly 2 magnitudes and the period of the light variation for two maxima and two minima is 5^h12^m. Apparently, the rotating object was observed nearly equatorially, and it is elongated so that at the maxima the long axis was seen projected against the sky, and during the minima, the short axis.

A lightcurve could, instead, be due to variations of the reflectivity over the surface. In the case of Geographos, the two maxima are at slightly different levels, and so are the minima; these minor effects are apparently due to reflectivity variations over the surface.

The observations are usually made with three filters, UBV, and a check is made for color changes over the surface. Vesta is one of the few asteroids for which measurable variation of color over the surface has been found. In the future, these effects could be looked into in more detail, especially by using a multi-channel photometer.

The orientation of the rotation axis can be observed from a set of lightcurves seen at various times and aspects. Geographos showed nearly the same amplitude of the lightcurve at various times (observations were made in January, August, September and October of 1969). The conclusion is that the rotation axis is nearly perpendicular to the plane of the ecliptic. The Trojan asteroid, Hektor, on the contrary, showed lightcurve amplitudes of

0.8, 0.1, 0.4, and 1.1 mag in 1957, 1965, 1967, and 1968, respectively. Especially the low amplitude in 1965 indicates that the object was observed nearly pole-on, and that the obliquity is large. A numerical analysis of the amplitudes at various aspects can give the position of the rotational pole with fair precision (Dunlap and Gehrels 1969).

Icarus was observed and analyzed in 1970 (Gehrels, Roemer, Taylor, Zellner 1970). The period of rotation is 2^h16^m which is the shortest period found for any of the asteroids (the periods of rotation typically lie between 5 hours and 16 hours). In combination with radar observations by Goldstein (1969) the roughness on a 21-cm scale is found to be greater than encountered anywhere on the moon. Goldstein also concluded that the roughness of Icarus is appreciably greater at the South Pole than it is at equatorial regions.

Even though Icarus was observed at various aspects, the lightcurve amplitude never was greater than 0.3 mag. This object therefore is much more nearly spherical than Geographos and Hektor. The roundness of the object as well as the peculiar orbit are considered indications that Icarus is an extinct cometary nucleus. A further indication may be derived from the orientation of the rotational axis which is perpendicular, to within about 20°, to the direction of perihelion, while the obliquity is nearly 90°.

In conclusion, I would like to make the suggestion that an asteroid mission be considered as a possible precursor to a comet mission.

Discussion:

Dr. Whipple: These are beautiful observations. Dr. Colombo once made a study of nongravitational forces and their effect on the rotational axis, with the conclusion that the axis of rotation would probably stabilize normally (i.e., around 90° to the orbit).

Dr. Gehrels: Further study will be made of these effects on the rotation axis of Icarus.

Dr. Delsemme: In comets, the lightcurve of the nucleus could conceivably be hidden by the existence of the halo of dusty and icy particles which is partially responsible for Öpik's "false" nucleus.

Editorial Comment:

Paper No. 25 presents some direct data on the rotation and orientation of a comet nucleus.

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Also: "Physical Studies of Minor Planets", NASA SP-267, 1971, esp. C. D. Vesely, 133-139; J. L. Dunlap, 147-154.

NO. 19

EVIDENCE FROM STREAM METEOROIDS

by Richard McCrosky
Harvard College Observatory

The association between comets and meteors is irrefutable - most of the prominent meteor showers can be attributed to specific comets and most comets with orbits within 0.1 A.U. of the earth's orbit produce some meteor stream activity. The question is, what can be determined about cometary structure from ground-based observations of meteors? Most of the information has resulted from photographic meteor data. Of the other forms of data, the visual and telescopic observations are too inaccurate for almost any problem and radar observations are encumbered by physical biases that are just becoming understood. Spectrographic observations put some limits on the physical processes involved in the entry phenomena but do not, now at least, give quantitative information on the composition.

An adequate observation of the meteor from two stations gives complete trajectory information (i.e., velocity and position as a function of time) and intensity as a function of time. Historically the first meteors observed were those bright enough to photograph with simple cameras and frequent enough to occur in their fields. By chance it is this kind of object which could be analyzed in terms of a rather simple theory, as follows: Both the meteoroid luminosity and its kinematics are in some way related to its mass. Photometric mass depends - among other things - on the efficiency, τ, with which the kinetic energy is transformed to luminous energy

$$m_p = \tau f(V, I, \ldots.)$$

where

V = Velocity

I = Intensity.

The dynamic mass is that found by the drag equation; the observable quantity is

$$\frac{m_d}{C_o A} = -\frac{\rho V^2}{2\dot{V}}$$

where

A = frontal area

C_o = drag coef.

ρ = atmospheric density.

If the meteoroid maintains its structural integrity during flight, then these two quite independent determinations of mass can be equated and the observations then yield the quantity:

$$K = \frac{(C_o S)^3 \tau}{\delta^2} = F\ (\rho,\ V,\ \dot{V},\ I,\ \ldots)$$

where A has been rewritten as

$$A = Sm^{2/3}\delta^{-2/3},$$

where

δ = meteoroid bulk density and

S = a dimensionless shape factor.

At one time there was a general consensus that the theory was adequate and that the major unknowns in the observables were the luminous efficiency and the bulk density. Some investigators assumed that all meteoroids have the density of stony meteorites. This is an over-simplification of the problem and precludes learning something new. We and others have spent much effort in determining the luminous efficiency, and at this time we have a good first approximation. If this value be accepted, a characteristic density of much meteoric material derived from comets is of the order of 0.5 g/cm^3. Together with an additional constant defining the rate of ablation of the meteoroid, these constants adequately describe the history of many meteors within the simple theory. The major assumptions in the theory are that 1) the luminosity is produced entirely by emission-line radiation of meteoric species - as is suggested by the spectra, 2) the luminous efficiency does not vary along the trajectory in any marked manner, and 3) the meteoroid remains as a single body throughout flight. Had the history of meteor physics proceeded along the lines I have described, a single-body theory and low-density meteoroids would probably have become generally accepted. Actually, the analysis of faint meteors observed with the Baker-Super-Schmidt in the 1950's, and before the question of luminous efficiency was fully resolved, showed that great departures from the single-body theory were common. These observations could be understood only if some new characteristic were attributed to the meteoroid. Jacchia (1955) suggested that they were fragile objects that continually fragmented as they progressed deeper into the atmosphere. For the most part we have accepted Jacchia's view as the most likely description of the faint meteor phenomena. It is reasonable that fragility should accompany low-density. Others have viewed the Super-Schmidt result as a symptom of a fatal error in the theory and have undertaken the more difficult task of re-writing the meteor theory in terms of new physical concepts. Again, it has been a general practice in these attempts to introduce the simplifying assumption that meteoroids are similar in structure to meteorites. Some such assumption is required since these new models depend on the bulk behavior of the material. The most ingenious and in many ways the most satisfactory new model is the one of Allen and Baldwin (1967) in which they propose that a high-density meteoroid entering the atmosphere becomes a low-density object by the production of froth during the ablation process. A second model, by Jones and Kaiser (1966), uses thermal shock to break up a high-density object into a multitude of pieces; thus negating the validity of a single-body theory.

In recent years we have acquired and analyzed substantial data from the Prairie Network at the other extreme of the meteor phenomenon, the fireballs (McCrosky and Ceplecha 1970). Photometric masses of these objects are of the order of 10^6 times the Super-Schmidt meteors. Surface froth cannot affect their apparent density appreciably, and in any case they penetrate deep into the atmosphere where the forces are certainly too large to permit froth to accumulate. If the frothing model is correct and if we can extrapolate results over this larger range in mass for other aspects of the theory, then these bodies should appear to be of high density. Similarly, it can be shown by a simplified theory that thermal shock will not be important for bodies above a given size - roughly a radius of 10 cm. Whether that theory is entirely correct is unimportant since the existence of meteorites in that size range demonstrates adequately that thermal shock is not efficient. The apparent bulk density of these large bodies is found to be quite similar to that derived from faint meteors.

There are a few faint and intermediate meteors that stand out, among others, because of their high apparent bulk densities. We have attributed these to asteroidal, i.e., stone meteorite, origins. If we assume a density of stone for these objects, we can calibrate the rest of the data. When this is done, we find a very good agreement between the luminous efficiency derived from these objects and that determined by various laboratory and free-flight experiments. The same kind of calibration is now possible for the fireballs since we have recovered a meteorite resulting from a -12th magnitude object (McCrosky et al. 1971). The photographic observations were excellent and comparison of the photometric and dynamic masses can be made in the latter part of the trail where deceleration measures are possible. The agreement is good if we use the normal luminous efficiency for the photometric mass, a shape factor determined from the meteorite, and a drag coefficient deduced from the final portion of the trail for the dynamic mass. While these results are preliminary (wind tunnel measures of the drag coefficient may revise the values we would suggest), we believe that the densities of the large bodies - if they have aerodynamic characteristics similar to those of the Lost City meteorite - have been underestimated by no more than 4X. Then the average fireball has a density between 1 and 2 and should still be distinguishable from meteorites.

We also note large differences in the general characteristics of most fireballs as compared to the Lost City meteorite. A single example will demonstrate that there is more than one kind of material among the small bodies of the solar system. Another Prairie Net object, very much brighter than Lost City, reached an altitude of 25 km where it still had a velocity of 10 km/sec, both the same as Lost City. The pressure and thermal loading on the two meteoroids must therefore have been similar. Yet the brighter object disintegrated completely at this point and its brightness decreased by at least 15 magnitudes in 0.1 seconds.

Returning to the faint Super-Schmidt meteors, Ceplecha (1968) has found it possible to subdivide the low-density material on the basis of the very simple and direct criterion of the beginning height of the optical phenomena. He plotted all sporadic Super-Schmidt meteors on a diagram with the beginning height as abscissa and velocity outside the atmosphere as ordinate. He found three ridges of population; the lowest of these, called Class A;

the highest, Class C; and an intermediate one, B, apparent only from 27.5 to 43.7 km/sec. His Class C shows two peaks, one below and one above 41.8 km/sec. He named these regions Classes C_1 and C_2. Not all Super-Schmidt meteors show fragmentation, and Jacchia's analysis of the best Super-Schmidt data distinguishes between those that follow the single-body theory and those that do not. Ceplecha and I have chosen the well-behaved Super-Schmidt meteors and investigated their K-characteristic as a function of his meteor class. The results are shown in Fig. 19-1. The data are sparse but there is a clear separation between his Class C and Class A and an even greater separation, as expected, from the Super-Schmidt meteor No. 7946 attributed to asteroidal origin.

Ceplecha's original work suggested that no shower meteors were of Class A. In reaching this conclusion, he used my very conservative specification of shower members. Since that time Southworth has developed an analytical method to determine shower membership and the technique has been employed by Lindblad (1970a, 1970b) to derive a more realistic description of shower meteors in that particular set of photographic data. Recently, Cook (1970) has found that most well-observed showers can be clearly attributed to a specific Ceplecha class.

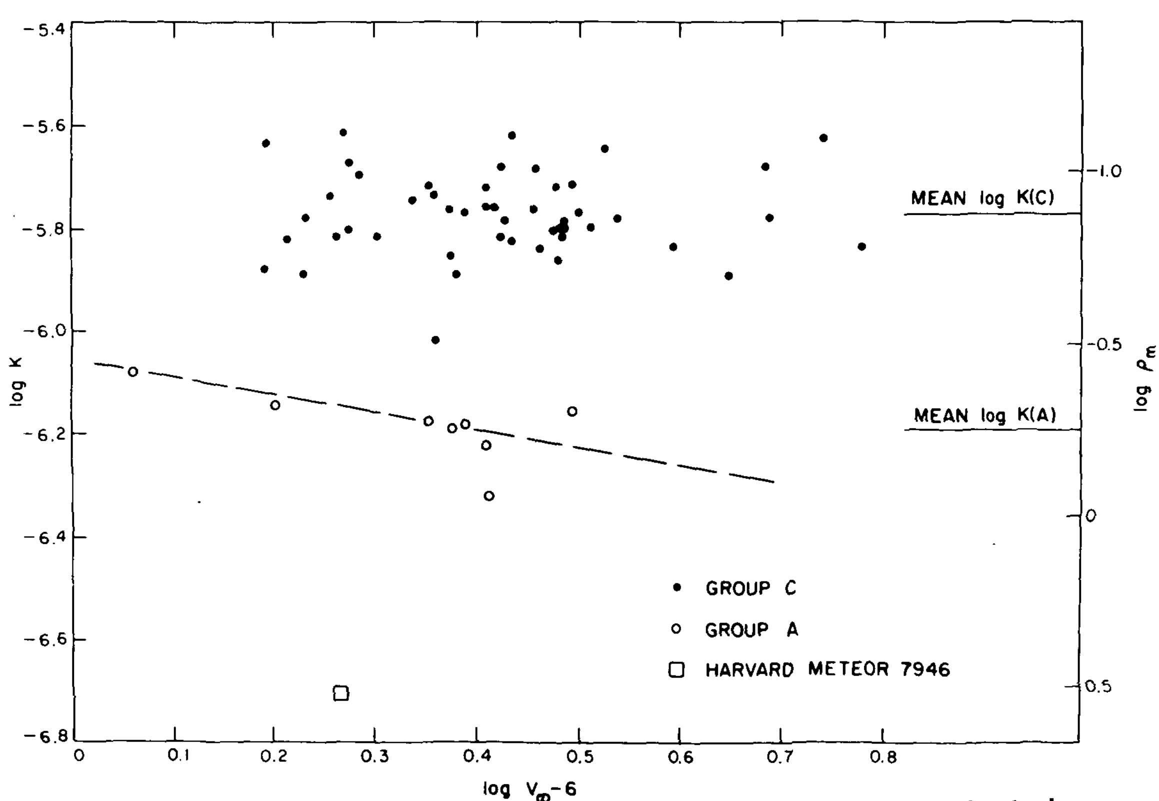

Fig. 19-1 - K-Characteristics as a function of Ceplecha's meteor class.

Cook notes that for the comets currently accessible to observation there are two streams above C_1, one above C_2, two C_1, two C_2, one not A and one A. The only comet known to have disappeared (P/Comet Biela) has a stream exhibiting Classes A and C_2 together.

Cook's interpretation of these results that bear on cometary structure are 1) meteoroids of Ceplecha's Class A have a density of about 1.2 g/cm^3, a value nearly comparable to that of Type I carbonaceous chondrite meteorites (about 2 g/cm^3). 2) Whipple and Stefanik's (1966) model for the redistribution of ices within the nuclei of comets by radioactive heating might lead to gravitational compaction of the less volatile material in the interior, a natural explanation of Ceplecha's Class A and of carbonaceous chondrites of Type I (although rather large nuclei would be required in this last case). Meteorites of Classes C_1 and C_2 would then be the low-density residual framework left after evaporation of the volatile ices from the outer shell. 3) Comet Biela, which presumably split through the core into two pieces, has exposed both kinds of material thus giving the bimodal A and C_1 distribution.

Other differences in the physical behavior of shower meteors have been noted previously. In particular, Jacchia, Verniani, and Briggs (1967) have given a thorough statistical treatment of Super-Schmidt shower meteors. They have noted the great diversity among the showers in such characteristics as the degree of fragmentation of the meteors and the apparent density. While it is generally difficult to associate these parameters with the physical characteristics of the parent comet, the result substantiates the conclusion of the other work cited here that there is a multiplicity of materials in the very small bodies of the solar system that are derived from comets.

Discussion:

Dr. Owen: In reference to one of your slides, is it possible that you are showing all three classes, not just two?

Dr. McCrosky: There are no B showers for which the comet is known.

Dr. Brandt: How many real calibration points do you have where you analyzed some observations, and had a subsequent field check on a recovered body?

Dr. McCrosky: Exactly one. We did have ten other cases where we didn't find the body afterwards, but we knew what it was.

Dr. Marsden: I wanted to mention the work on two comets. There are three comets in the A group, parts of P/Biela,Lexell, and Schwassmann-Wachmann 3.

These three are rather troublesome cases. For Comet Lexell you were trying to relate meteors to the inner part of the comet; it was observed only in 1770 and had just been thrown in from an orbit of much larger perihelion distance; it went out again 12 years later, so it seems to have been a very new comet. There was no evidence that it had been close to the sun earlier and probably the meteors would be the outer stuff of the comet if indeed the shower is to be identified with the comet. For Schwassmann-Wachmann 3 the evidence is from the comet observed in 1930. In 1882 there was a very close approach to Jupiter but we don't know what happened before that. But the C comets seem much more long-lived. Is there a contradiction here?

Dr. McCrosky: The A comets no longer exist.

Dr. Marsden: But not for the reason that you are implying.

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Editorial note: Dr. McCrosky added some current references but was unable to provide a complete up-dated version.

NO. 20

EVIDENCE FROM POLARIZATION

by Tom Gehrels
Lunar and Planetary Laboratory

We have made polarization observations on the coma of Comets Ikeya-Seki, Tago-Sato-Kosaka, and Bennett, the last jointly with Mr. L. R. Doose and Drs. D. L. Coffeen, and B. H. Zellner. Special filters were used in order to minimize the effects of emission, which were the least disturbing for Comet Bennett.

On Comet Bennett at 90° phase angle, the linear polarization is strongly wavelength-dependent: as much as 41% is observed at 9600 Å while with a filter at 5200 Å the polarization is 25%. Elliptical polarization has been looked for, but was not found, at most 0.2%.

Preliminary attempts to fit calculations on the Mie theory of light scattered by small spherical particles have not been successful. It might, however, be possible to fit a mixture with two size distributions.

Discussion:

Mr. Dubin: What size ranges were you referring to for the Mie theory polarization?

Dr. Gehrels: About 1 μ for the first, and possibly 100 μ for the second.

Dr. Donn: With regard to the applicability of the Mie theory for particles other than spheres, laboratory measurements of an arbitrary nature indicate that the brightness is not very dependent on shape, but I do not know of any measurements of polarization.

Dr. Gehrels: There is no laboratory work, and this should be done.

NO. 21

1976 D'ARREST COMET MISSION STUDY

by J. A. Gardner,
Jet Propulsion Laboratory

SUMMARY

The objective of the d'Arrest Comet Mission Study is to determine the feasibility of the mission using a standard launch vehicle in the medium size class, and a spacecraft configured from suitable subsystems inherited from Mariner class spacecraft. Detailed objectives are discussed in Section II. d'Arrest is a faint short-period comet whose 1976 apparition will provide a favorable opportunity for a mission to fly through the coma with an imaging system and instruments to determine the extent and composition of the comet's gas and dust, as well as its interaction with the interplanetary medium. The mission is not difficult from a dynamical or communications viewpoint, because injection energy is low, transit time short, and communications distance small relative to other Mariner missions. However the relative velocity at intercept is high, as is typical for comet missions. Since a major objective is imaging to determine the nature of the comet's small, faint nucleus, a close flyby is needed and this in turn requires optical approach guidance and a spacecraft maneuver shortly before encounter.

The baseline spacecraft, utilizing the selected hardware and hardware designs, will satisfy science and mission requirements. The sensitivity threshold and resolution of the approach guidance and science television cameras will permit sufficiently early acquisition of the comet nucleus for the pre-encounter corrective maneuver, and for imaging the nucleus during closest approach to the nucleus. However because the luminous flux from d'Arrest is based on an inexact photometric model, the TV vidicon performance should be increased beyond the model requirements to assure an acceptable mission risk or increased confidence. The performance capabilities are discussed quantitatively in Sections III and V.

Additional development activities which might be considered to improve the imaging of the nucleus at the required distance are discussed in Section X. They were not considered for baseline spacecraft because a low cost mission was selected as a basic guideline for the study.

Atlas/Centaur was found to be an adequate launch vehicle, and Mariner spacecraft subsystems were selected from Mariner Mars '69, Mariner Mars '71, and Mariner Venus-Mercury '73, except for the boost regulator and inverter, which required Viking '75 ratings. All of the selected subsystems were integrated to configure the baseline spacecraft. The injected spacecraft weight is 623.7 kg, and the injection energy (C_3) required is 9.67 km^2/sec^2 for a June 3, 1976 launch and August 17, 1976 arrival.

Editorial Note:

The above Summary was taken from the completed JPL study published as a 277-page document 760-66, May 10, 1971, not from the preliminary paper presented by Dr. Gardner at the Conference.

Dr. Gardner calls attention to two related publicatons:

"Study of a Comet Rendezvous Mission, TRW 20513-6006-RO-00
Prepared for JPL under Contract No. 953247, April 12, 1972,

and

"A Mission Analysis Study of Comet Rendezvous and Asteroid Docking",
JPL Document 760-71, June 15, 1972.

NO. 22

TRAJECTORY REQUIREMENTS FOR COMET RENDEZVOUS

by Alan L. Friedlander, John C. Niehoff, and John I. Waters
IIT Research Institute, Chicago, Illinois

ABSTRACT

This paper presents a new look at spacecraft mission opportunities to the short-period comets in the time period 1975-1995. The objective is to identify the most promising rendezvous opportunities and flight modes from the standpoint of trajectory requirements and launch vehicle/payload capabilities. A "broad-brush" treatment of wide scope underlies the analysis. Selection criteria leading to 16 comet apparitions for study are described. The candidate flight modes include: 3-impulse ballistic transfers, Jupiter-gravity-assist transfers, solar-electric and nuclear-electric low-thrust transfers. Results show that the best early opportunities are Comets Encke/80, d'Arrest/82, and Kopff/83. Although these missions can be performed ballistically, solar-electric propulsion offers greatly improved performance. Practical accomplishment of the very difficult Halley rendezvous depends upon the development and availability of nuclear-electric propulsion by 1983.

Editorial Note:

The above abstract was taken from the completed IITRI study published in the Journal of Spacecraft and Rockets, Vol. 8, No. 8, August 1971, 858-866, not from the preliminary paper presented by Dr. Friedlander at the Conference. The substitution was made in consultation with Dr. Friedlander who wishes to consider the 1971 paper the final reference.

NO. 23

SOME SCIENTIFIC CRITERIA FOR A COMETARY MISSION

by A. H. Delsemme
University of Toledo

1. Spatial resolution for photometric profiles in the visible and U.V.

In cometary heads, the present observational evidence points to decay lengths of "precursors" - whatever they are - of the order of or less than 10,000 km. No precursor molecule has been positively identified so far. The decay lengths are poorly known, because of poor spatial resolution. Their variations with heliocentric distance is practically not known, also because spatial resolution is quickly lost for ground-based observations, when the comet is not in the Earth vicinity.

Decay lengths for ion "precursors" could be as short as 100 km, but they are not really known either and conflicting views are expressed in the literature.

The present knowledge comes from an average spatial resolution of 1000 to 3000 km when the comet is near the Earth. Rare observations in the vicinity of the Earth are known with spatial resolution of 300 km (for instance, Malaise in "Nature and Origins of Comets", Coll. Internat. d'Astrophysique, 1966).

Photometric profiles with a spatial resolution of 100 km could bring a breakthrough in the understanding of the precursor problems, in particular:

a) if they could be extended to distances at least from 2 to 0.5 A.U.

b) if they could be extended to the major molecular and atomic emissions plus the continuum in the visible and the ultraviolet.

c) if the brightness range studied could cover at least five orders of magnitude from the nuclear region to the outer coma.

d) if the photometric profiles could be scanned, radially from the nucleus, along several diameters.

From a 50,000 km distance from the nucleus, this implies a spatial resolution of 7 arc min, which makes it accessible (but not easy) for a small photometer with diaphragm. The light collection would be so much easier and the instrument weight accordingly reduced if the distance to the nucleus were only 5,000 km.

2. Spatial resolution for infrared observations

As no infrared band has ever been observed in a comet, the search for molecules like H_2O, CH_4, NH_3, CH_2O, HCN or CO is based on circumstantial evidence, like their observation in interstellar space, Whipple's icy conglomerate model, and the hypothesis, not yet substantiated, that the observed radicals come from "precursor" molecules. I have discussed today an alternate possibility, namely the presence of icy grains as precursors. However, it is likely that at least some molecules do exist, water being so far the best candidate.

A resolution of the order of the diameter of the nucleus, as suggested by Owen, may certainly help in our search for infrared bands, in particular for low abundance constituents whose concentration is likely to be enhanced near the nucleus. However, I would be surprised if a space resolution of say 100 km coupled with the fact that the observations will be done from outside our atmosphere, would not give the infrared bands of the major constituents. This assessment could be easily checked numerically from cometary models. Of course, the next step after the discovery of any molecular band in the infrared, would be the study of its photometric profile, and in the absence of any other information, the same arguments for a space resolution of the order of 100 km could also be used.

A high space resolution as proposed by Owen may be very useful for some purposes. However, for the study of the precursor problem, it could confuse the issues by making it impossible to study the brightness variations from the nuclear region to the outer coma, where not enough light is available for a high space resolution.

3. Visual imaging with filters

The major drawback of visual imaging is the problem of reliable photometry if one wants to cover brightnesses several orders of magnitude apart; its second drawback is the stray light admitted by the width of the filter. Its advantage may be its good resolving power. It could therefore be used as a complement to study the inner coma. A 1 km nucleus could be seen from 50,000 km as a 4" disk. The optics needed to resolve better than that do not seem to be too sophisticated. From my recent work, the nucleus might be embedded, at least sometimes, in a halo of icy grains, whose extreme size could be as large as 10,000 km but whose brightness would be concentrated in a halo of 100 to 1,000 km around the true nucleus. It would easily be noticeable on any type of picture showing the inner coma.

4. Study of the nucleus proper and sampling of inner coma

From ground-based observations, all that we can say about the nucleus is a wild guess about its size because of its photometric properties (as we do not even know its albedo). However, it is obvious that the nucleus is the most important part of the comet to study, because it is the seat and the origin of all the cometary phenomena.

The very first thing to do is of course to measure the size of the nucleus. The next thing is to measure its shape. The third one is to try to see features and details on the nucleus. The fourth is to try to correlate the inner coma with the nucleus, to describe the mechanism of the cometary "activity". As the nuclei are in the range of 0.1 km to 100 km, with probably an accumulation near 1 km, it is too bad to learn that if we send a probe to a comet, we will miss the nucleus by some 50,000 km. For the sake of the study of the nucleus proper, try to go closer than that, say at 1,000 km from the nucleus. The study of the nucleus would be so much easier (1 km = 3 arc min). If, instead of a true nucleus, we had a chaotic nuclear region with many separated chunks of snow, it is unlikely that it would occupy a size more than one order of magnitude larger; we still want to be as close as possible. Besides, 1,000 km is already the inner coma, where actual sampling could be crucial to discuss the problem of the parent molecules.

If 1,000 km is unrealistic, then 5,000 km would make already a big difference: we are playing here just within the range where the most important phenomena take place; decay lengths of hypothetical precursors are of the order of or less than 10,000 km. At 50,000 km, we will not be in a position to sample anything significant to understand the precursor problem.

5. Selection of Comet d'Arrest for first fly through mission

If we had all freedom to pick up the "best" first comet to be studied from space within the next ten years, it is likely that most astronomers would pick up a very bright comet (luminosity always helps to get started); the trouble is that bright comets are almost always new comets, and new comets have to be ruled out because we have their ephemeris at too late a date for the logistics of spacecraft launching.

On the other hand, too much dust may be a nuisance, at least for a first mission; the continuum reflected by the dust may bring trouble for the study of the molecular emission bands for instance.

Also, much of the light of a bright comet may come from the dusty component, and the comet may be deceivingly bright, with almost no molecular emissions. Finally, it would be useful to know as much as possible beforehand about the physical properties of the comet, to plan the experiments as carefully as possible.

These considerations would lead to the brightest possible well-studied periodic comet, whose orbit is well known, and whose dust content is not too large. There is only one known comet corresponding to this description within the next ten years; this is Encke.

If we extend the period under consideration to the next twenty years, there is an obvious consensus on Comet Halley, in spite of its retrograde orbit. The real problem is therefore: to get ready for Halley, what should we do during the next ten years? If I understand correctly, logistics arguments are not in favor of Encke but point to d'Arrest as the next best choice. From the astronomer's point of view, d'Arrest is not a bright comet, it has a rather small nucleus, and not much is known on its physical parameters. However, a ground-based program could bring early enough some information on its spectrum with the help of the large observatories.

As we have only one Comet Halley during this century, to make sure that we will not miss the opportunity it offers, at least one preliminary fly through mission on another comet seems a minimum requirement. Comet d'Arrest would not be picked up as the most representative comet for a unique cometary mission; but it can be entirely satisfactory as a first mission to get a larger cometary program started. Such a mission will allow experimental techniques and gain some experience before Comet Halley, and it may even bring already some exciting new results to understand better the cometary phenomena.

6. What is the best place to perform a rendezvous?

The distance at which some activity begins to be noticeable in a comet is often around 3 A.U. As the probe is supposed to remain near the comet and send back some information hopefully for one or two years, the best place to start the observations would of course be near 3 A.U. The activity onset and its disappearance are roughly symmetrical on both sides of the perihelion, but with wide fluctuations that we would like to be able to study. If we join the comet near perihelion only, we lose half of the observations, as well as the whole comparison between activities before and after perihelion.

Of course, an extended rendezvous would allow us to wait for the next return of any periodic comet. For Halley, most of us might become impatient, but Encke would be a very good case, not only because it comes back every three years, but because it covers an interesting range of heliocentric distances: just enough, not too much, as far as activity is concerned, and it could be joined for a rendezvous at any place of its trajectory, to optimize fuel consumption, etc., without damaging the scientific program. Finally, it does not have too much dust, which may help at least in the first programs, to study an activity of the purely molecular type. Of course we'd better hurry and do it this century, because its activity is likely to diminish steadily at each passage.

7. Preparing for a mission by ground-based observations

Before sending a space probe to a specific comet, it would be important, not only to know its spectrum, but to be sure that we will be in a position to study some photometric profiles of the different molecular bands with a moderately good space resolution. The space probe results will be complemented and better understood if we can do so, in particular for the outer parts of the coma that can be either too faint or oddly placed to be conveniently studied from the space probe. This would imply a comet becoming as bright as perhaps the sixth (total) magnitude, as seen from the Earth; if it is fainter, then we need many hours of observing time even at the 200-inch to reach the outer coma in the spectra.

8. Tracking on nucleus for position reference information

Even if the presence of a true nucleus were to be contested, in most comets there is a "photometric" nucleus where light is concentrated near the center of the head. This nucleus is characteristic of near-stellar appearance, even when high angular resolution is possible. For example, at the passage of P/Pons-Winnecke, intrinsically a small comet, within less than 0.05 A.U. of the earth in June 1927, the nucleus was still described as quite stellar in appearance and of magnitude about 9. By analogy, it would seem reasonable to expect a much brighter comet, like Halley's, at 1 A.U. from the sun, and 50,000 km from a spacecraft, still to have a star-like nucleus. The brightness might be as great as magnitidue -4, or even higher, depending on the precise character of the nucleus, especially its dimensions and surface reflecting properties, as well as the geometry of its illumination and observation.

Editorial notes:

An interesting discussion of various aspects of scientific interest in probes to comets has been given by Rh. Lüst in "Cometary Probes", 1969, Space Sci. Rev., 10, 217-229.

Observation of P/Encke at magnitude 20.5 by Dr. Roemer in August 1972, close to aphelion at 4 A.U., has demonstrated the applicability of the inverse square law, including an asteroidal phase-angle dependence, for the observed nuclear brightness. The derivation in the text is based on an extrapolation of this nuclear brightness to small geocentric distances.

NO. 24

GENERAL DISCUSSION

Dr. Marsden: I take it that the idea is to make a final correction to the orbit before perihelion, after optical recovery has been accomplished?

Dr. Friedlander: Yes.

Dr. Marsden: What happens if the comet is 2 million km away from the predicted position? Is that a feasible correction?

Dr. Friedlander: For a rendezvous, the problem is different: while 5,000 km from the nucleus may be good enough for a fly-by, it is not for a rendezvous. You must maneuver around, i.e. you have to have a fairly good reference. You must know where you are in the comet vicinity. This almost implies that you must have an on-board comet seeker.

Dr. Marsden: At what distance would the probe begin looking for the comet?

Dr. Friedlander: It would depend upon what the comet seeker is going to see; perhaps 2 million km. The farther away the better, of course. It is going to cost more to adjust the trajectory the closer one gets.

Dr. Marsden: I feel that it would be better to choose a comet that we can rely on. Comet d'Arrest is an unreliable comet; this is also true of the 1976 apparition. Some others are unreliable as well, e.g. Honda-Mrkos-Pajdušáková. Just as you are using Jupiter to maneuver the probe, Jupiter will be doing strange things to the comet at that time. I think you would be much better off choosing a comet where the nongravitational forces are very small. These happen also to be comets where you are seeing the nucleus. You are not getting confused by coma. A comet like Arend-Rigaux would, I think, offer a suitable opportunity for 1984; it is very predictable. There has not been a close approach to Jupiter for 900 years and there do not appear to be any nongravitational effects on it. Why take chances?

Dr. Friedlander: You are quite right. We are not saying that these are the missions one must fly. At the beginning we selected some 60 missions for study. Your comments are appreciated.

Dr. Roemer: The first question, whether you are planning fly-by or rendezvous missions, is the matter of the orbit and optical recovery. Recovery is most appropriately done with long-focus reflecting telescopes. You have no business considering a comet for this type of mission if its position is not already well known, so there is no need in using an instrument such as the 48-inch Schmidt. The observations are made photographically by carefully setting off the predicted comet motion. It should be recognized that telescope schedules are made out some time in advance - one to three months - and some thought has to be given to appropriate requests about telescope time. You cannot commandeer it many times on short notice.

Prolonged astrometric observations at a comet's return will help, but the main thing is to derive the correction ΔT, which three plates will define fairly well. The full moon will of course interrupt observations of faint objects, not just twilight.

Information of the kind I present now is available on every periodic comet on the list under consideration. The descriptive notes and positions were published (1966, Astron. J., Vol. 71, No. 6, 443-457). Comet d'Arrest is not typical in appearance, and recovery often does not come until the comet is within a month or two from perihelion. It is unusually diffuse in appearance and the nucleus is probably not observed directly at all. Therefore it is not a matter of reaching a faint stellar magnitude but one of reaching a low surface brightness. For this reason even the 200-inch telescope would not help much. The nucleus is probably less than 1 km radius, and may be less than 1/2 km, because the estimates are based on photometry that does not completely resolve the nuclear contribution in this case.

For Comet d'Arrest, there is also considerable asymmetry in the activity with respect to perihelion passage. The last apparition with complete observational information is 1963. The comet was brightest, 17th mag., in December, well after perihelion. The coma diameter (magnitude around 18.3) based on the photographic plate was 40,000 km in October and 75,000 km in December. So, on Comet d'Arrest, one could consider a fly-by after perihelion by a couple of months. Our recovery in March 1970 was based first on an all-out effort at the 61-inch the first week of March, with single 1-hour exposures - all the observing time per night that the position of the comet permitted - which failed to reach the comet. The following week, with the 90-inch reflector of the Steward Observatory, the comet was observed. (This telescope has nearly the same focal length but 2.2 times the light-gathering power.)

On the basis of present experience, and with Dr. Marsden's collaboration, I predict recovery of Comet d'Arrest at the end of April 1976. The comet could be reached late March, but the chances are very slim. If we get a couple of months of observations, and use a two-step reduction process to have better reference star positions, it might be possible to get a position along the orbit within about 5,000 km - this conclusion also represents Dr. Marsden's thinking. As he has pointed out the effects of the nongravitational forces mean that Kepler's laws cannot be relied upon in getting the distance. The range could be uncertain by 50,000 km, even though you know the position along the orbit more accurately than that. Therefore, there is perhaps some need for a comet seeker in order to gain adequate guidance in the fly-by stages, if we are talking about nuclear miss-distances on the order of 10,000 km. Those are the essential points. I would like to reemphasize that this kind of information is available from published data with respect to all the periodic comets on your lists.

Dr. Whipple: I think that Dr. Roemer's statement points up a very important issue. If we are going to the effort and expenditure of this fly-by we should spend some money to improve the methods of finding and observing comets.

Dr. Roemer: And the manpower that's involved in doing it.

Dr. Whipple: That means designing a telescope for this purpose. It still has plenty of other uses. We would want the design to be optimum for comets and to use the best modern techniques as they develop for sensing comets. I presume that probably means an image-tube type operation to increase speed. You must get contrast.

Dr. Roemer: There is a difficulty there because you do not have the field; therefore you do not have the astrometric reference star field.

Dr. Whipple: You can solve this problem if you spend some money on it. Furthermore, you can take more exposures. The exposure times are short, so in the same length of time you can get a number of exposures to cover the field. This is a solvable problem; all you have to do is decide to spend enough money to solve it. I think it should be done. I think the conclusion is very obvious that we are faced with the fact that one must improve the techniques because, except for a little improvement in photography, there has not been much change since I have been in astronomy - maybe a couple of magnitudes?

Dr. Roemer: I think a little more than that. Part of it is persistence in making the effort.

Dr. Whipple: That's the other point. I think these conclusions should be put on top of the list.

Dr. Brandt: I think workers in the field would agree that whenever one plans a mission like this, some fraction of the money should be set aside not only for ground-based observations but for laboratory support.

Dr. Whipple: One should choose one's comet on the basis of scientific interest and engineering feasibility, and spend the necessary funds to solve it.

Dr. Brandt: The other comment that I would make, listening to Drs. Roemer and Whipple, is that probably Comet d'Arrest is not a particularly good choice. (This statement was challenged by Dr. Jackson only).

Comment: The data presented by Jack Gardner leave a mission compatible with recovery as late as May 1st. The launch can be as late as July 1st. Based on Dr. Roemer's predictions one can recover the comet and not yet have to launch the spacecraft.

Comment: Are Dr. Roemer's predictions based on a 3σ confidence level?

Dr. Roemer: With decent seeing and weather conditions and telescope time, the comet would be observable before launch date.

Mr. Dubin: The solar-electric system gives the best propulsion and Dr. Friedlander said that this is already developed. As I see it, the solar-electric system allows continuing mid-course correction upon position acquisition, whether on the vehicle or from the ground. It also allows additional weight for an additional large Δv change.

Dr. Friedlander: If it is in a fly-by.

Mr. Dubin: The 1976 d'Arrest was not covered in your study.

Dr. Friedlander: There is one graph in the hand-out. The question arose when we were looking at 1982 of a fast rendezvous with d'Arrest. It turned out that we found one which was only 300 days. However, in order to get a fast rendezvous you have to arrive after perihelion. So since we found the possibility in 1982 - we looked for, and found, a similar opportunity in

1976. The trajectory is a 280 day rendezvous with d'Arrest, using the solar-electric system; the arrival is 100 days after perihelion. We had thought, of course, that to arrive that late after perihelion was a disadvantage. Also in the case of this type of mission you would not be able to recover the comet before launch. You realize from the flight time, for a rendezvous in general, that one must launch before one has made the recovery. The flight times may be 2-5 years, so the spacecraft is gone and one has to rely on prediction; and one must rely on recovery in the year of passage in order to improve the trajectory and make final corrections.

Mr. Dubin: This is a launch on February 15, 1976 with a rendezvous condition at $\Delta v = 0$; it's feasible?

Dr. Friedlander: The technology is here but a planetary solar-electric system has never been built.

Mr. Dubin: There would be more than one set of flights; the back-up position would be to go to Comet Encke and the other targets that you suggested in this study.

Dr. Friedlander: The only thing that will allow the solar-electric system to be built is a multiple-mission capability, not necessarily a multiple-comet mission capability. If you can show that with a fixed design a solar-electric system can do many missions (which you would not be able to do ballistically), then it would be cost-effective. It would apply to comets, planets, and asteroids.

Comment: This has to do with predictions by Drs. Marsden and Roemer. You indicated that an error in the observed position of d'Arrest resulted in a position error of 5,000 and 50,000 km in the range?

Dr. Marsden: Yes.

Comment: Was that before you recovered or after?

Dr. Marsden: It is after recovery. Before recovery I would say if we are lucky the prediction would be good to 50,000 to 100,000 km along the orbit. If we are unlucky before recovery it may be 2 million km. But after recovery I am sure we can bring it down along the orbit to 5,000 km. The distance is more difficult. You cannot use Kepler's third law, and the nongravitational force situation with P/d'Arrest is hopeless because you need to use observations before 1968 and this close approach to Jupiter in 1968 confuses the thing. The same would be true in 1982, because you have another approach to Jupiter. That is why you should choose a comet that does not come close to Jupiter, preferably one that does not have nongravitational effects, so that it will be where you expect it to be.

It is a fairly normal situation to multiply the uncertainty along the orbit by close to an order of magnitude to get the uncertainty in the distance. Maybe it could come down to about 30,000 km but it is still a rather largerfigure, I think, than has been quoted earlier.

Dr. Sirri: Is there any reason besides the nongravitational effects why d'Arrest is a bad comet?

Dr. Brandt: Let us proceed with the basis of selection of a comet.

Dr. Jackson: We are interested, among others, in the derivation of the density and velocity of the gas emitted by a comet. The broad problems of a cometary study are (1) to learn about the cosmology of the solar system, and (2) to understand the cometary processes. If we understand the processes occurring in the plasma, then comets can probe inaccessible parts of interplanetary space. There is a bit of a paradox here: Drs. Roemer and Marsden contend that the best kind of comet for recovery purposes, as far as the orbits are concerned, are the small stellar-like objects. These tend also to be the comets that have the smallest gas clouds around them. When the gas cloud gets small the problem of doing an experiment on it gets more difficult. Even though you may get closer, you may not have anything to measure when you get there, using the present instruments. It therefore seems to me that one of the major things we want to do is to go to a comet that is very bright, even if you have to make mid-course corrections. That is more expensive but the probability of making the kinds of measurements that you want to make is much greater. For practical reasons there will be some optimum size of a comet.

Dr. Biermann: If we take the long-term view there will be no contradiction between astrometric and physical criteria, because by the time Comet Halley is going to reappear the techniques will be available to do what is needed concerning Halley. In the long list of comets discussed, Comet Halley is, I think, the only one which is really outstanding in the sense in which Dr. Delsemme and our group would see it. Only a naked-eye object with a reduced magnitude of 4th or 5th magnitude is likely to give valid information on the gas output and related questions. Comet Halley has shown many of the characteristics of a really large object. It has reappeared two dozen times and an effort should be made to recover Halley as early as possible before perihelion.

Dr. Roemer: It was followed for 400 days after perihelion the last time and I would expect the next time the recovery might come something like that before perihelion.

Dr. Biermann: With regard to scientific objectives, I would place Halley on top of the list, with the others a long way down, for reasons already discussed, e.g. by Dr. Jackson. But Comet Halley could obviously not be the first cometary probe. So we should have at least one before, and for this a good compromise must be made.

Dr. Brandt: I concur with this positon.

Dr. Suess: As a chemist I would like to see that we learn from a comet mission about the chemical composition of the comet parent body itself. Then, the first thing we should try to observe is its mass. Now I am somewhat confused about the possibilities: would a fly-by give enough information to determine the mass accurately? I am sure that there is no problem about mass in a rendezvous. Maybe the first thing to investigate is what we can do to improve the accuracy of determining the mass of the comet in a fly-by.

The next question is to determine the volume so you get the density. When you have the density you know pretty well what it can consist of. This is probably a better source of information than the spectra. If it is the real density, with no peculiarities, it will give you the best information on the chemistry. Then of course when you do your mass-spectrometric determination or spectroscopic determination, you know what is coming off from the parent body, and this is an indirect information on its composition. There again I think the spectroscopist would need his information on electron flux and solar wind intensities to calculate the density. But the problem of obtaining an accurate mass, I think, is what we want most.

A brief discussion indicated that a fly-by would not suffice to yield a good mass for the comet.

Dr. Whipple: There is one point that is important and it backs up Dr. Jackson's from a slightly different point of view. I believe now we can see that a comet nucleus of a big comet has a central part that is somewhat different from the outside. The outside has finer material and material that may be more primitive than the stuff inside. I think Comet Encke was once a very large comet and now we are looking at something near the nucleus - maybe this was the original core on which the outer parts grew. When you go down to the deeper nucleus, you may have material that was metamorphosed chemically, or by pressure or heat. On the outside you have something that is the original stuff that accumulated in the last phase of the accumulation process. So this may be more primitive but it may be altered also from what it was originally. It is primitive only in terms of accumulation. I think that in Comet Encke we are down near the deeper nucleus. So Comet Halley is an intermediate case in terms of comet composition and history, and Comet Encke is nearly towards the dead-end. A new parabolic comet would give the very outside accumulation.

Comment: With due respect to the scientific problems I think we should eliminate here one class of comets, the heavy dust comets, because of the hazards to the mission. I suggest that one adds gas-to-dust ratio to the selection criteria.

Dr. Whipple: I should warn that the idea that Comet Encke, because it does show gas, does not have solid material, is nonsense. Comet Encke has contributed the largest mass of meteoritic material known among comets, and it has distributed this all through the solar system. It is in a huge torroidal volume, with a very large amount of solid material coming out. In the so-called dust comets the dust is very fine; I do not think there is much heavy stuff. But the concept that old comets are gas and new comets are dust is erroneous. The ratio may be the same for both.

Dr. Probstein: Are plates available of objects like Comet Encke where we might deduce the dust size-distribution?

Dr. Whipple: It would require special observations to get the dust and gas in Comet Halley.

Dr. Probstein: Are plates available with sufficient calibration?

Dr. Brandt: You would have to organize a new program.

Dr. Donn: I would like to propose that this group resolve that NASA Headquarters should set up some sort of a working group - a panel of cometary experts - to plan comet missions. Something like a half a dozen comet mission studies have been made. There are outlines of problems - types of mission constraints, payloads involved - but none of these have been made by persons in a position to chose what is a good comet, the most valuable experiments, the questions we are discussing now. This involves knowing these problems, knowing the observational problems, the orbital problems that Drs. Marsden and Roemer discussed, and the physical problems. I think what NASA ought to be encouraged to do is to continue a small working group of people who will look into what are the scientific problems, what observational programs ought to be carried out, what thought ought to be given to the areas here discussed.

Mr. Dubin: We have attempted in the past to set up such a group. NASA has a Lunar and Planetary Mission Board, and the Astronomy Missions Board. The National Academy has studied the problem of priorities and they concluded that meteoroids, asteroids, comets are important but not as important as planetary or lunar investigations. These smaller bodies have usually been relegated to a less important level. On account of this there haven't been any specific missions. We have attempted astronomical observations, and this activity with d'Arrest is probably the most recent step in favor of observations and investigations of comets - and for that matter asteroids, because the d'Arrest mission is probably the same type technically that would be used for an asteroid msssion.

Dr. Sirri: The NASA Lunar and Planetary Mission Board is setting up a comet panel with Drs. Marsden and Roemer on it. The Lunar and Planetary Office would like to implement a comet mission; if you pass a resolution, that would assist us.

A vote was taken, 23 to 0, in favor of a resolution that NASA form a smaller group of experts in a suitable position to push for a comet mission.*

Dr. Kuiper: As an interested outsider in cometary matters, I note that the observational work on comets as now practiced is done by very few people, who carry a heavy workload and an unduly heavy responsibility to science. As Dr. Marsden has stated in a recent Annual Report on Comets (Quarterly Journal, Royal Astronomical Society, 1972), "An analysis of world-wide observations of comets during calendar year 1971 shows that of 20 comets under observation 'twelve seem to have been observed only by Elizabeth Roemer . . . .'.".

Dr. Brandt: This situation was stressed also by Dr. Whipple. I think everybody present concurs.

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* NASA has since implemented this recommendation and appointed a Cometary Science Working Group which had its first meeting at the Yerkes Observatory, June 1971. A 113-page report on this meeting was issued by the IIT Research Institute, December 1971 (NASA Contract NASW-2144).

Dr. Roberts: Could I try to add some perspective to the d'Arrest mission. It has been said that among comet missions there is a choice between several aspects of science and of engineering. While this is generally true we do not have a choice for the d'Arrest mission. It is presented as a mission opportunity because it is a one-time chance to go to a comet, cheaply, using a basic type of spacecraft that already exists. I suggest that we should consider this as the preliminary mission - the mission that answers the question that Dr. Roemer raises about secular variations, the mission that answers the question that Dr. Jackson raises about what experiments to fly. The d'Arrest decision is whether or not the mission is wanted; if not, then there is no other mission in the same class from a cost or timing standpoint. For all other comet missions, a panel can be set up to make a selection, pick the best comet on scientific and engineering grounds, decide between rendezvous or fly-by; but for d'Arrest in 1976 that is not the choice. I recommend that the 1976 d'Arrest fly-by be taken and used as an experimental mission to find out how we should really do comet missions.

Dr. Brandt: This was in a sense the thrust of earlier remarks by Prof. Biermann, that indeed it is the larger, more active comets that we would like to observe, but that they should not be the first comets to which a mission is sent.

Dr. Biermann: In this connection the question arises whether or not Comet Halley is of comparable interest with the planets being investigated. I believe that Halley offers such rare, if not unique opportunities, that this mission has an interest justifying a major effort.

Dr. Brandt: NASA already has advisory boards which have advised that a comet mission does not have an interest as great as planets; but this conclusion can be challenged.

Dr. Whipple: The Panel did not have anybody on it who knew about comets, or about asteroids; and only one member who knew about meteorites.

Dr. Jackson: And probably no one about chemical compositions of planets and the cosmology of these planets.

Dr. Miller: The composition- or age-classification used by Dr. Whipple should be considered in the comet selection. I do not know where Comet d'Arrest would fit.

Comment: The nearer you can get to the Halley type the more ground-based observations you can get to use with the data from the mission and, other things being equal, it is certainly desirable to be able to make significant ground-based observations parallel with the space-based observations.

Dr. Schmidt: A question about cost: Is the d'Arrest mission really a family of its own? Are Encke and Kopff incomparable in matters of cost?

Dr. Roberts: Yes. The rendezvous is a much more expensive mission. In terms of fly-by, d'Arrest is unique - you can use an existing spacecraft. It is a much cheaper mission and it is fairly soon.

Dr. Niehoff: I have some data regarding Dr. Schmidt's question. For example, there is a moderately good fly-by opportunity to Encke in 1980. The flight time is around 60 to 80 days but the arrival velocity is 20 to 23 km/sec. The Kopff mission does not occur until 1983, probably not soon enough before Halley to incorporate the mission results into the Halley spacecraft. Its flight time is 175 to 190 days, not bad; and it has the lowest fly-by approach velocity of 8 to 9 km/sec. The Kopff fly-by opportunity is really very attractive except that it occurs almost on the doorstep of Halley so the timing is not good.

Dr. Newburn: If the mission to d'Arrest is worthwhile scientifically but looks unattractive because you might not be able to choose the appropriate miss-distance, you are really arguing for terminal guidance.

Dr. Gardner: In the mission that I presented, the spacecraft is using developed technologies. The substance of the spacecraft hardware would be built in the time-frame immediately following a prior Mariner mission. You would be using a Mariner Venus-Mercury solar panel and a Venus-Mercury propulsion system. And it also assumes that you could use a lot of ground-based check-out equipment. It all affects cost. That is for a 1976 mission, because we have a 1973 opportunity for a Venus-Mercury and a 1975 opportunity for a Viking, both of which are Mariner-class missions. If you wait until 1980 or 1982, and there is no mission just prior to that time, the assumption of usable hardware may not be true. There may not be any Mariners after that time frame. You may be concerned only with the Grand-Tour missions which are a new and different type of spacecraft.

Dr. Whipple: I do not know which type of comet would be the most important! I do not think that the orbital considerations, the predictions, should be a major factor in the selection because I think they are solvable. I think the selection should be on the basis of the engineering and some consensus of scientific opinion; and that will depend upon your committee, whether the members like particles-and-fields better than meteoritic analysis!

Dr. Sirri: One important thing has come out of this discussion. If it is concluded that d'Arrest is a bad mission, this could negatively influence the outcome. I wonder if the group wants to consider once more whether d'Arrest is a bad mission.

Dr. Jackson: I was one of the main people who criticized it and I do not want to be misunderstood. Comet d'Arrest, as a mission before Comet Halley, is a good mission - that is clear. But this is a political question too. If you do d'Arrest and it is then said: "Don't do Halley" or "you went to d'Arrest and it didn't come off", you may not get Halley. Halley is probably more informative than d'Arrest and is something the public is really interested in.

Dr. Brandt: This kind of discussion points to the need of a small group of people knowing something about comets being consulted before decisions are made.

NO. 25

PRESENT UNDERSTANDING OF COMETS

by A. H. Delsemme
University of Toledo
1 July 1972

Since the Tucson Comet Meeting, much has been learned about comets. Two years ago not many people were yet aware of the significance of the discovery of the Lyman α halo of Comet Tago-Sato-Kosaka, and Comet Bennett was still being observed. Therefore, it seems now proper to make a short assessment of cometary research from 1970 to 1972, even if it may somewhat lack proper perspective. The writer is also aware that his range of interests concentrates on the comet itself and not on its interaction with the solar wind. On the latter subject it may suffice to say that the bow wave ahead of the comet in the solar wind is much less prominent than was suggested two years ago.

The Nucleus

At the Tucson meeting, Professor Lyttleton had expressed his doubts whether the cometary nucleus had a tangible material existence, or whether it was an optical illusion created by a vast swarm of tiny particles separated by large distances. Recently, he has reviewed all his arguments (Lyttleton 1972). He quotes, after 1945, only two references which are not his own from among the other 800-odd references on comets. It is difficult to accept that this vast literature has no relevance to his argumentation.

Following a different approach, O'Dell (submitted to Icarus 1972) has recently tried to give a fair treatment to the sand-bank model, as he had been struck by the similarity of comet particles and interstellar grains. Discussing the possible origin of comets, he considered a formation model that could be loosely described as a sand bank whose grains are covered with frost. Because of inelastic collisions, he ends up with a lump nucleus which looks very much like the icy conglomerate.

At the meeting of the IAU and CERN Colloquium at Nice, France, I tried to review very sketchily (Delsemme April 1972) the bearing of the present literature on the validity of the sand-bank model. Many arguments against it have been proposed during the last three decades; unfortunately, they are often forgotten. For instance, Schatzmann's (1952) argument on the rapid collapse of all those grain clusters that are dense enough not to be scattered away, seems still very strong to me. Whipple's (1963) exhaustive discussion cannot be taken lightly either. However, large gas productions were required to accept Whipple's icy conglomerate. The same gas productions would drag away any sand-bank whose cohesive forces would always be several orders of magnitude smaller than the gas drag.

Whether we are actually observing large gas productions therefore became the touchstone of the comparison between icy-conglomerate and sand-bank models. This crucial question was not easy to answer. However, it had become increasingly clear that OH (Swings 1941) as well as O (Swings et al. 1958) were major constituents that had previously been neglected. Malaise (1970) detected pressure effects in a tiny region surrounding the nucleus, at least in five comets of a sample of six, and this implied total densities much larger than believed before.

The large gas productions have also been substantiated by Finson and Probstein's (1968) analysis of the dust drag needed to explain the dust distribution in the tails. But entirely decisive was the discovery of the Lyman α halo of Comets Tago-Sato-Kosaka, Bennett, and Encke. Not only the gas productions were large enough to drag away centimeter- to meter-size grains or boulders from the nuclear region, but also the huge amounts of gas (10^{30} atoms per second) had to come from the vaporization of large amounts of volatile snows, and this was basically Whipple's description of the icy conglomerate.

The Coma

Exotic sources of the Lyman α emissions have been proposed, like a charge-exchange excitation of solar-wind protons in collisions with cometary gases (Tolk et al. 1970), but easily refuted (Mendis et al. 1972) because of the brightness distribution of the Lyman α halo. The Biermann and Trefftz (1964) prediction was based on the mechanism that is currently accepted as the only likely explanation. Their argument was derived from the fact that 10^{30} to 10^{31} transitions per second were observed for the [OI] red line at 1 A.U. on reasonably bright comets. As the line is forbidden, a steady state implying a resonance-fluorescence excited by sunlight (as for all the other radicals observed in comets) would need unacceptably large amounts of oxygen. The alternate possibility is that the oxygen atom is formed already in its excited state, by the very process of photo- or charge-exchange dissociation of its parent molecule. If this possibility be accepted, the observed number of [OI] transitions per second becomes a measure of the rate of production of parent molecules dissociated into excited oxygen atoms. Now, if a large fraction of these parent molecules are hydrides, they must free many hydrogen atoms in the coma. In Biermann's analysis, water was one of the numerous possible hydrides. At the Tucson meeting two years ago, I went further and tried to show that water was likely to be one of the more abundant constituents. At the present time, this position has become even stronger. To quote Code et al. (1972): "The conclusion that water is a major constituent of comets and that the hydrogen envelope must be primarily due to the photo-dissociation of H_2O is strongly supported by the OAO observations". It is interesting to mention that not only OH, H, and [OI] are consistent with the dissociation of H_2O, but also that the resonance line of OI at 1302 A has been identified by the OAO and that its intensity does not contradict its origin as a by-product of water. All of this implies that H_2O is several hundred times as abundant as C_2 or CN, which were the most intense bands of the cometary spectra. The only other major constituent that I would be ready to propose is CO; CO has not yet been detected, but is probably needed in large amounts to explain the CO+ observed in the plasma tails (Wallis 1968).

Since 1965, I have offered several circumstantial proofs of the presence of water ice in the cometary nucleus. First, (Delsemme 1965a and b) I have shown with some success that the appearance of the coma near 3 A.U. requires that the vaporization of the nucleus be controlled by the latent heat of water ice or of gas hydrates. The latent heats of most other possible snows are much too small. More recently (Delsemme 1971), I have proposed that the brightness dependence on the heliocentric distance that has been observed

(Code et al.1970) for the hydrogen and hydroxyl halos of Comet Tago-Sato-Kosaka, can be quantitatively explained by a three-step process, namely, the vaporization of the water snows, the photo-dissociation of the water molecules into the ground states of hydrogen and hydroxyl, and the photo-excitation of hydrogen and hydroxyl by a fluorescence mechanism.

My explanation assumes that the optical-depth effects were not strong enough in this comet to hide the bright central condensation of Lyman α, and that this condensation was observed with a diaphragm much smaller than the scale length of dissociation of water. The Lyman α image of Comet Tago-Sato-Kosaka, as observed by Jenkins et al. (1972), seems indeed to show a sharp maximum of the brightness, with a radius of some 2×10^4 km. My second condition depends on the diaphragm used by Code et al. From the description of the Wisconsin instrument package, it is either 2 or 10 arc min. (photometer) or 2 x 10 arc min. (spectrophotometer). However, Code et al. (1972) in reviewing the scientific results of the OAO, mention that the inverse square dependence of water dissociation should not affect the observed surface brightness. Therefore, they seem to imply that their diaphragm was not much smaller than the scale length of the dissociation of water, in apparent contradiction with the diaphragms quoted before. This argument must wait for the relevant information before being discussed any further. Finally, (Delsemme 1972) I have also recently shown that the vaporization controlled by water snows (and water snows only) gives the dependence of the non-gravitational force on solar distance that gives the smallest residuals in Marsden's study of Comet Schwassmann-Wachmann 2.

In the interpretation of H, OH, and O as fragments coming from the dissociation of water, rather complete models of the coma have been already computed (Keller 1971, Mendis et al. 1972). They explain rather well the brightness distribution (Mendis) and the distortion of the coma (Keller). However, some difficulties still remain. Biermann (1972) has called attention to one of these difficulties, established by Keller. Since the photo-dissociation of water produces two fragments only, the conservation laws imply that the internal energy absorbed by OH sets the kinetic energy of the H atom. Welge and Stuhl (1967) have established that the reaction $H_2O = h\mu \rightarrow H(1^2S) = OH\ (X^2\Pi)$ does not give much rotational or vibrational energy to OH. Therefore, the H atoms must fly away with a velocity of 20 km/sec, set by the energy difference between the absorbed photon and the dissociation energy of H_2O.

However, this high velocity has not been observed. From his model of the coma simulating the distortion observed in the Lyman α halo of Comet Bennett, Keller (1971) has deduced that an initial velocity of 8 km/sec was needed to predict the correct isophotes. Keller's model depends on the assumed acceleration given by the solar light pressure in Lyman α, but cannot be subject to a very large revision. I want, however, to point out that the hydrogen atoms are produced with a scale length of the order of 10^5 km, that is, in a region which is large for the ordinary standards, but very small when compared with the Lyman α halo. A large part of these H atoms is therefore likely to have had a few molecular collisions, sometimes more than 10, but often less, within the 10^5 km radius. Besides, half of the hydrogen atoms probably come from the photo-dissociation of OH. As the dissociation energy of OH is 101 kcal mole^{-1}, most of these hydrogen atoms are produced with a very small residual velocity. This is probably enough to explain that the average velocity of the H atoms went down from 20 to some 8 km/sec. The figure 20 km/sec could probably be lowered also, because of the energy distribution in the solar spectrum. There are many more photons available in the longest wavelength range of the first continuum of water, and therefore, the average energy difference with the dissociation energy, is less than the one predicted from the absorption maximum of the continuum.

The importance of H collisions in the 10^5 kilometer range may also explain the fact that Code et al. (1972) have detected no velocities in excess of 3 km/sec, presumably in the bright central region where the spectra were recorded.

Finally, while the role of the second continuum of water is not important, it is not quite negligible (Delsemme 1970,this volume,p.33f).Despite the fact that it is at shorter wavelengths than the first continuum, it may produce slower H atoms, because much of the excess energy is stored in rotational levels of OH ($A^2\Sigma^+$) as observed in the laboratory by Carrington (1964).

If the possible explanations sketched here do not entirely solve the H velocity discrepancy, we note that Comet Bennett may be a very young comet by Oort's concepts; thus the discrepancy could indicate chemical differences expected between young and old comets, in particular, the presence of large amounts of a constituent snow more volatile than water.

The Inner Coma and the Nuclear Region

When A.Wenger and I (1970a and b) simulated cometary conditions in the laboratory, we discovered a peculiar behavior of the solid hydrates of gases (clathrates). They looked near 200°K like a granular powder with a sharp size distribution. Besides, grains were constantly stripped from the main body of snow and dragged away by vaporizing gases. D. C. Miller and I (1969, 1970, 1971a, b, and c) have developed a model of the inner coma, taking these new results into account. We have proposed (Delsemme 1968) that a halo of icy grains is likely to build up around the nucleus. These particles are steadily stripped from the nucleus by vaporizing gases. Their terminal velocity and their rate of evaporation set the size of the halo; it can reach an order of magnitude of 10^4 km. The existence and size of an icy halo is consistent with the photometric shape of the continuum observed in Comet Burnham. The fact that the icy grains can become an extended source of radicals is consistent with the photometric profile of C_2 in Comet Burnham. These results, reported at the Tucson Meeting, are now published (Delsemme et al. 1970a and b, 1971, 1971a and b). These icy grains do not include the permanent grains of dust that are dragged away by gases and eventually repelled into the dust tail (Finson and Probstein 1968). Our work (Delsemme et al. 1971a) modifies slightly Probstein's analysis and shows that the terminal velocity of the gas is 1.77 times the mean speed as defined in kinetic theory. It also shows that, for large vaporization rates, the dust grains can reach some 80% of the gas velocity. For all practical purposes, as in Larson and Minton (No.26),the dust grain velocity can therefore be taken as 0.6 km/sec^{-1}.

Recent infrared observations of the nuclear region of several comets have detected a thermal flux which seems to come from this cloud of particles (Maas et al. 1970, Kleinmann et al. 1971). By combining infrared and optical wavelength photometry, O'Dell (1971) establishes the albedo (0.3 ± 0.15) of the particles leaving the nucleus. Their optical emissivity diminishes in the infrared regions, and therefore their temperatures are about 50% greater than those found for blackbodies in the same radiation field. Although Myer (1972) claims to have detected a direct infrared measurement from the nucleus of Comet Bennett, he also mentions that his resolving power is of the order of 10" in the scan direction by 4" in the perpendicular direction. This makes a rectangle of 5000 × 2000 km at the comet's distance, and there is little doubt that he also has detected an infrared emission peak coming from the dusty particles that reach almost instantaneously their radiation equilibrium with a temperature near 600°K at the comet's distance from the sun.

As far as the other parent molecules are concerned, it is clear that most of them should be concentrated within 10^4 km of this inner coma; but, apart from the hints given by the recent discoveries of complex molecules in interstellar space, they remain as mysterious as two or twenty years ago. Recent discussions on the origin and formation of the solar system (CNRS, Nice, 1972) stress the importance of the mysterious snows of the cometary nucleus, as a possible sample of the least perturbed material of the primeval solar nebula.

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NO. 26

PHOTOGRAPHIC OBSERVATIONS OF COMET BENNETT, 1970II

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ABSTRACT

Direct photography of Comet Bennett with a range of focal lengths shows structure in the coma and strong Type I and Type II tails. The Type I tail shows motion in 15 minutes. The inner coma contains spiral-shaped jets of a type observed visually on occasion in the past but not photographed before. The spiral shape is apparently due to the rotation of the nucleus. On the assumption that the outward velocity of the jets is 0.6 km/sec, as estimated by Delsemme, a rotation period of 1.4-1.5 days is derived for the nucleus. The rotation is direct (i.e., in the sense of the comet's orbital motion).

Comet Bennett (1969i or 1970II) was discovered on 1969 December 28.8 by J. C. Bennett when it was at far-southern declination and of the eighth magnitude (IAU Circular 2196). The comet was generally well-placed and observed at many localities in part because the location of the perihelion close to the earth's orbital plane. The orbital elements as determined by Marsden (IAU Circular 2234) are:

$$\begin{array}{ll} T = 1970 \text{ March } 20.04586 & \left.\begin{array}{l} \omega = 354^\circ\!.15532 \\ \Omega = 223^\circ\!.96121 \\ i = 90^\circ\!.04504 \end{array}\right\} (1950.0) \\ e = 0.9962715 & \\ q = 0.5376179 \text{ A.U.} & \end{array}$$

Epoch = 1970 April 4.0 ET.

The geometry of the comet orbit in relation to the earth orbit is shown in Fig. 26-1. Comet Bennett exhibited spectacular structure and due to its great brightness could be photographed with short exposures. In general, the Type I and Type II tails were not unlike those of other bright, dusty comets, such as Comet 1957V (Mrkos), and the spiral coma structure was similar to that observed visually in the bright Comets 1835III, 1858VI, 1886III, 1874III, and 1910II (Rahe et al. 1969). This may be seen from

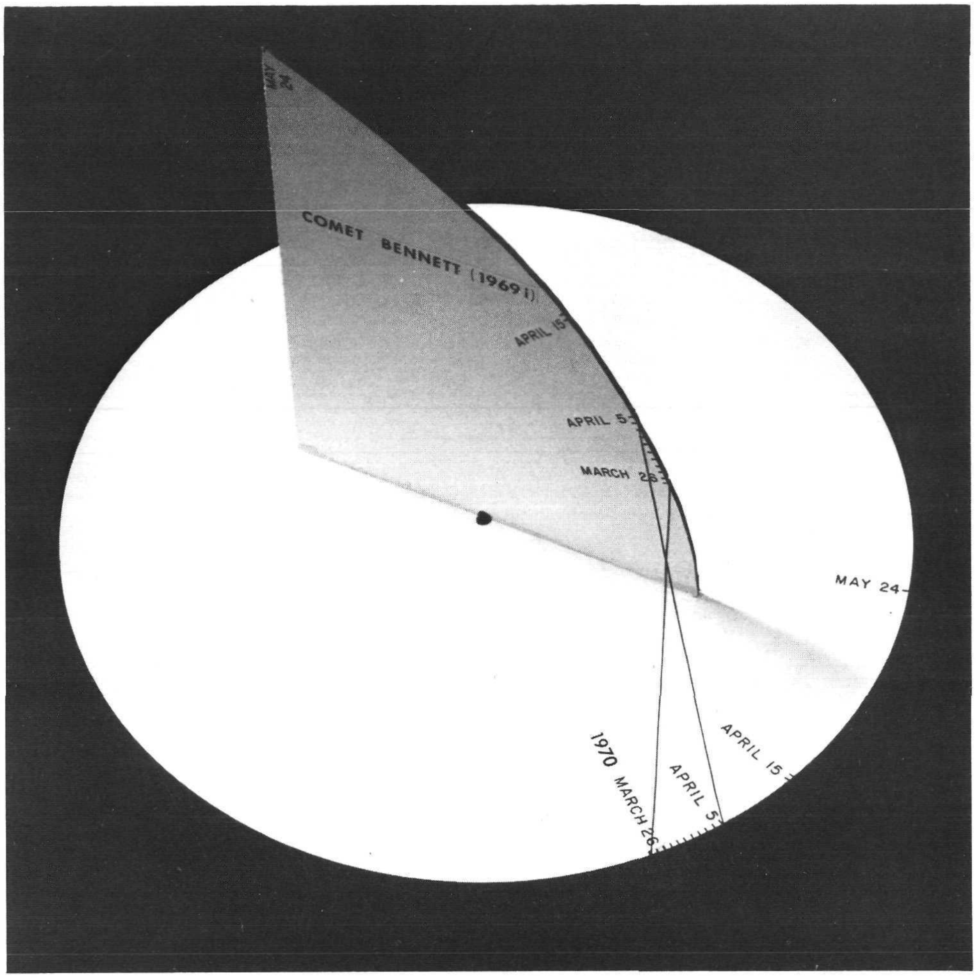

Fig. 26-1 - Model of orbits of Comet Bennett and Earth showing positional relationships on the days of observation.

Fig. 26-2: the left picture resembles Mrkos 1957V; the right picture is typical of a bright comet past perihelion observed around 1.5 A.U.

The Observations.

The photography was carried out with a variety of instruments and emulsions(Table 26-I) to record as many photographic properties of the comet as possible. The high-resolution photography within the coma was done at the F/13.5 Cassegrain focus of the Catalina 154 cm reflector, using the 35-mm camera and film of the planetary program. We succeeded in photographing the inner spiral structure, which in the past had been recorded only visually (Rahe et al. 1969). An effort was made to determine whether this structure was wavelength dependent. Table 26-II summarizes the film-filter combinations used and their effective passbands.

TABLE 26-I

INSTRUMENTS AND EMULSIONS USED

Camera	Focal length	f/No.	Field	Scale (arcmin/mm)	Emulsions Kodak	Figs.
Aero Ektar	0.175 m	2.5	30° x 40°	19.3	Tri-X pan	26-2(right)
Aero Ektar	0.30 m	2.5	5° x 7°	11.2	4-X pan	26-14, 17
Aero Ektar	0.60 m	6.0	8° x 10°	5.6	Royal-X pan	26-2(left)
15-cm Refr.	1.5 m	10.0	1° x 1.5°	2.2	103-a-O	26-6, 11, 14
154-cm Refl.	20.80 m	13.5	4' x 6'	0.16	103a-O,4-X, HSIR	26-3,4,5,7,12, 13,16,18
154-cm Refl.	20.80 m	13.5	32'	0.16	103a-O	26-15
229-cm Refl.	20.8 m	9.0	32'	0.16	103a-O, 103a-E	26-8, 9, 10

Apparently because of the great dust content of the spiral structure, no distinct differences in appearance were noted in the different broadband wavelength regions. Just outside the coma and into the tail, such differences with wavelength were observed, indicating that the dust and gas streams could be distinguished there. A narrow-band filter centered on the sodium-D lines gives an indication of structure difference even in the region of the spiral structure.

TABLE 26-II

FILM-FILTER COMBINATION & EFFECTIVE PASSBANDS

Emulsion	Filter	Effective Passband *	
103a-O	UG-1	.33	.38
	UG-5	.33	.38
	-	.33	.49
4-X	-	.33	.63
	GG-14	.52	.63
	Na(D)	-	-
103a-E	RG-2	.63	.67
HSIR	GG-14	.68	.88
	RG-5	.72	.88

* 50%-of-maximum limits, plus effect of three airmasses.

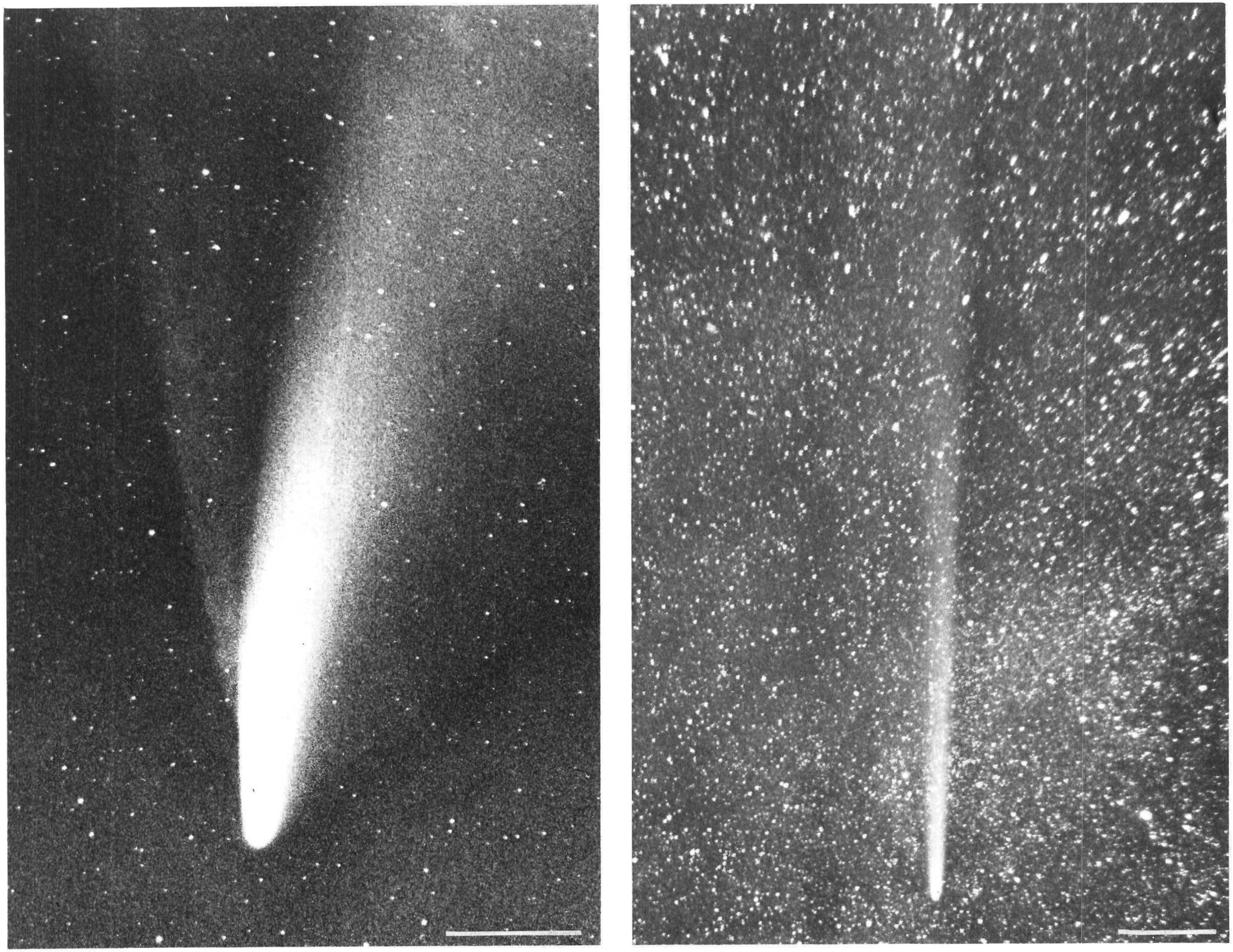

Fig. 26-2 - Left. 1970 March 30.5 UT, Type I and II tails separated, with the Comet 0.59 AU from the sun and 10 days past perihelion. Bar represents 5 x 10^5 km. Right. May 24, Comet faded to 8th magnitude and tail appears long and faint due to larger distance from sun (1.43 AU). Comet observed near the plane of orbit. Bar = 10^6 km. Both images are composites of two images, taken with Aero Ektars of F. L. 60 cm (left) and 17.5 cm (right).

Photographs at different exposure times optimize recording of detail in regions of different intensity. We normally took 5-10 exposures in quick succession, for making film composites. This reduced graininess and allowed higher contrast to be used in the copy. By selecting the best originals, the quality was further improved. Finally, the guiding problems on a moving object resulting from long exposures were avoided. All photographs were taken just before dawn with the comet 20° - 30° above the horizon. This, of course, reduced the average seeing quality and caused some atmospheric dispersion (which was not compensated for as in our planetary photography program since it would have unduly limited the field). On the best short exposures the apparent nucleus is about 2 arc-sec diameter which is regarded "seeing-limited".

Composites were also made of the images taken on 103a-O film with the 15-cm f/10 finder telescope (of the 154 cm). Its field was 1°.5 by 1°, and the records showed the hoods around the coma as well as filaments in the tail.

We are indebted to Dr. E. Roemer for allowing us to reproduce some of her photographs taken with the Steward Observatory 229-cm reflector on Kitt Peak; and the 154-cm reflector, Catalina Observatory. Her exposures are generally longer than ours and show the fainter envelopes as well the tail.

Supplementary records were obtained with smaller wide-field cameras having portable mounts used at suitable locations, whenever the 154-cm telescope was not available. The emulsions used are listed in Table 26-I. Figs. 26-2, 26-14, and 26-17 show selected records.

Interpretations.

When our first short exposures with the Catalina telescope just before dawn on March 26, U.T. showed some spiral structure emanating from the comet's nucleus (Fig. 26-3), we decided to continue observations daily, as often as feasible. We found that, particularly on one day, March 28, the jets were almost uniformly curved up to about 20,000 km from the nucleus, beyond which they began to conform to the outer envelope. The spiral structure is shown for 6 days in Figs. 26-3, 26-4, 26-5, 26-7, 26-12 and 26-13; on April 15 and 16 it was no longer clearly visible (Fig. 26-16a and 26-16b). The dimensions in km may be derived from the scales. Our reproductions are made from undodged composites unless otherwise noted in

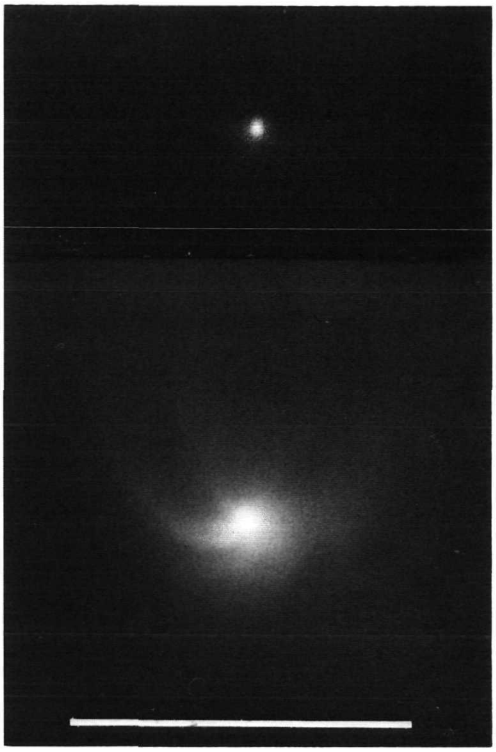

Fig. 26-3 - 1970 March 26, 12:41 UT. Advancing daylight prevented recording full extent of spiral structure. Composite of 17 images, exposure range 1/4 to 5 sec. Single image of nucleus 1/125 sec at 12:50 UT. Bar = 5 x 10^4 km.

the captions. For the outer envelopes, we refer to Figs. 26-4, 26-6, 26-8, 26-9, 26-10, 26-11, and 26-15. The entire set, with exposure times varying from 1/125 sec to 20 min, a ratio of 150,000x, shows the enormous intensity range to be covered, actually in excess of 10^8.

Electromagnetic forces are not expected to be important in the inner coma (e.g., Chapt. 25), and the Coriolis force due to orbital motion would in this case lead to periods in the ejection spirals of several months. Since instead a period somewhat over 1 day is indicated, the rotation of the nucleus itself is held responsible for the observed spiral trajectories. (The spirals are merely the locus of the particles ejected linearly and continuously, thus resembling the pattern caused by a lawn sprinkler). Since, as stated above, in our broad-band photography from 3300-8800 Å the geometry of the jets appears independent of wavelength, it is inferred that the visible jets are indeed mainly composed of particles reflecting sunlight. Some deviation in the jet pattern was observed in Na 5893 Å (Figs. 26-7 and 26-12), attributed to the release of Na atoms from the particles in flight.

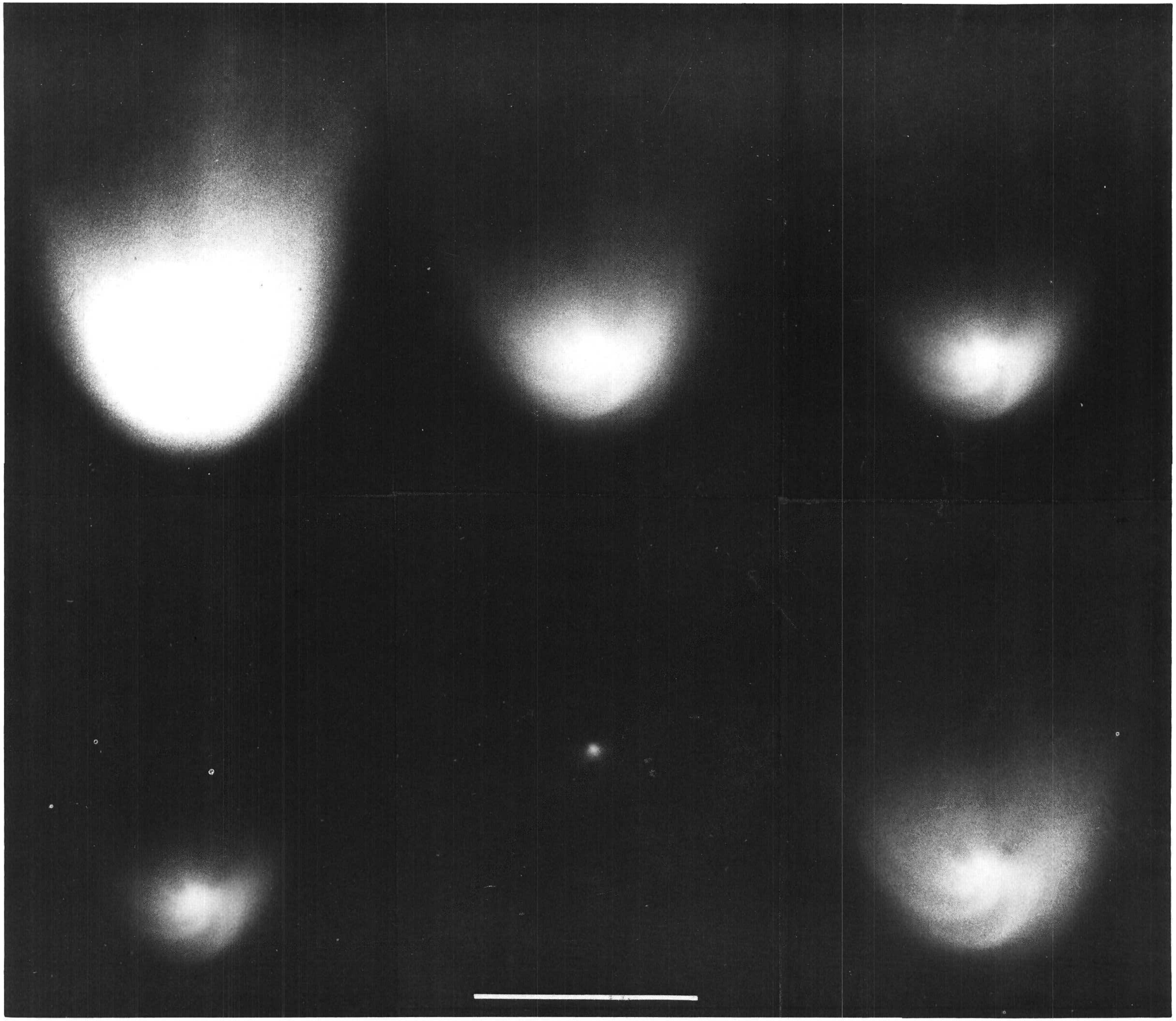

Fig. 26-4 - 1970 March 28, 12:06.5 UT. Composite of 10 images, exposures 4-8 sec. Film composite printed here at four different densities to cover its dynamic range. (Same technique used in other figures). Spiral structure is quite strong. Lower right dodged to emphasize structure. Lower middle image single frame (exposure, 1 sec) at 12:42.8 UT. Bar = 5 x 10^4 km.

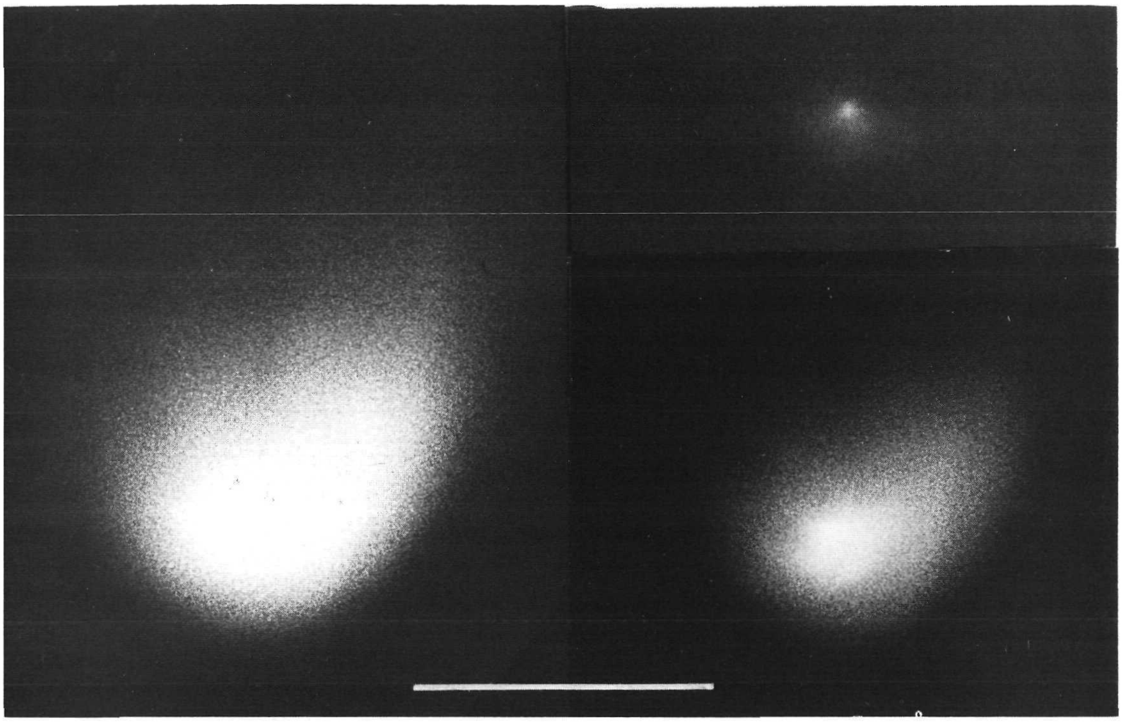

Fig. 26-5 - 1970 March 29, 12:13 UT. Composite of 4 images, exposures 30-60 sec. Single image, 1/60 sec exposure at 12:34.5 UT. Bar = 5 x 10^4 km.

The observed spiral structure clearly consists of jet-like streamers coming from the nucleus. The jets are seen to change from day to day over the period March 26 to April 5, with less prominent streamers present on April 15 and 16.

During the period March 26 to April 5 the most prominent jets showed rather similar curvatures, though additional streamers were often present that complicated the pattern. The March 28 data are the simplest to interpret, showing a pattern that appears to be nearly at right angles to the line of sight, with at least 4 streamers showing essentially constant curvature along their tracks. By contrast, on April 2, 3, and 4 a set of streamers is seen that cannot possibly be assumed to lie all in one plane; some streamers even cover part of the nuclear region. The model pictured in Fig. 26-1 shows that on March 28 the tilt of the comet's orbital plane to the sky at the position of the comet was about 30°. Because the four spirals shown on that day had all the same curvature, all along their tracks, and were thus seen essentially unforeshortened, it is assumed that their common plane was at right angles to the line of sight and that this plane

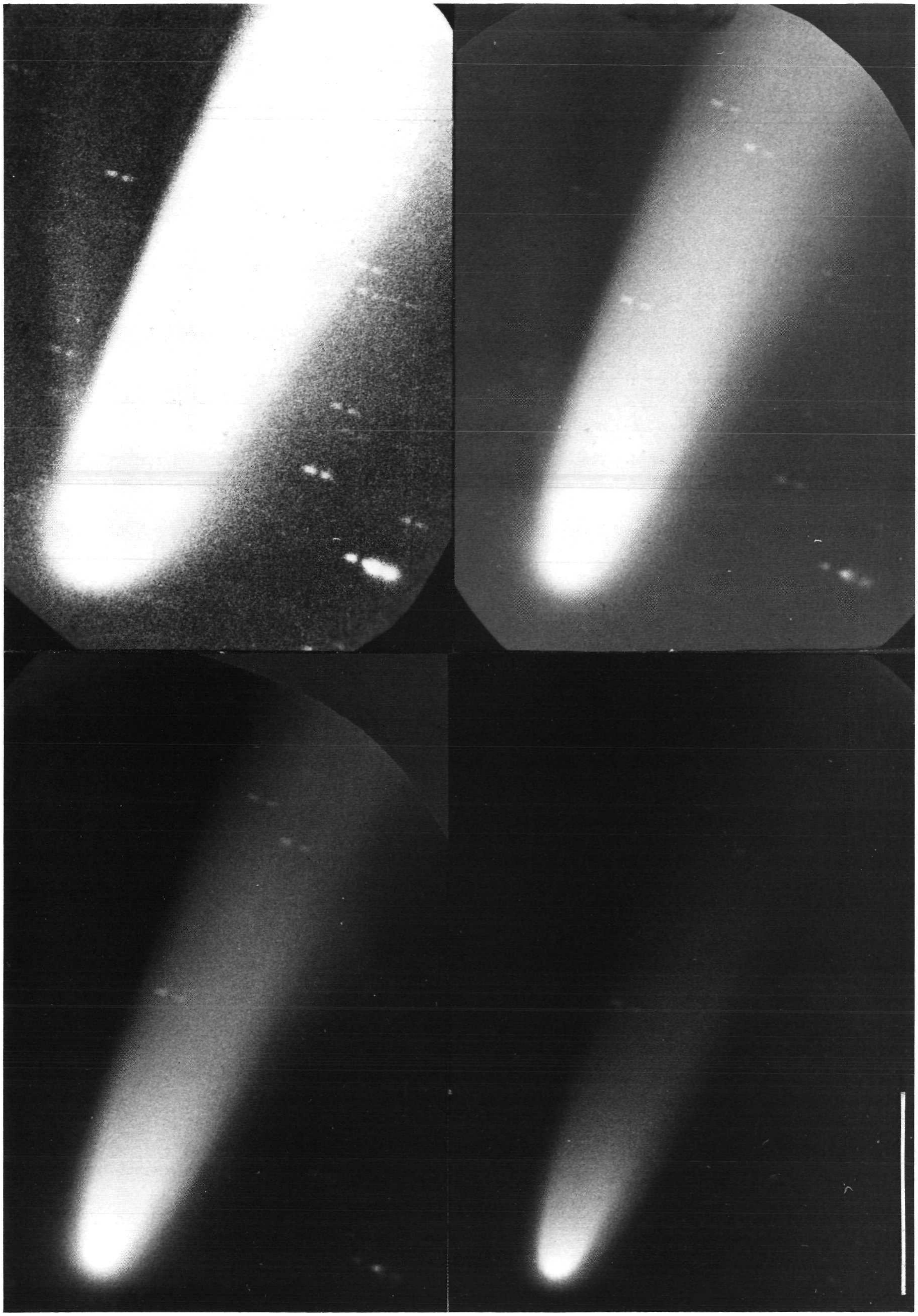

Fig. 26-6 - 1970 March 29, 12:39.9 UT. Composite of 6 images, exposures 3-10 min. Streamers of Type I tail project towards upper left from the Tppe II tail. Note multiple envelopes. Bar = 5 x 10^5 km.

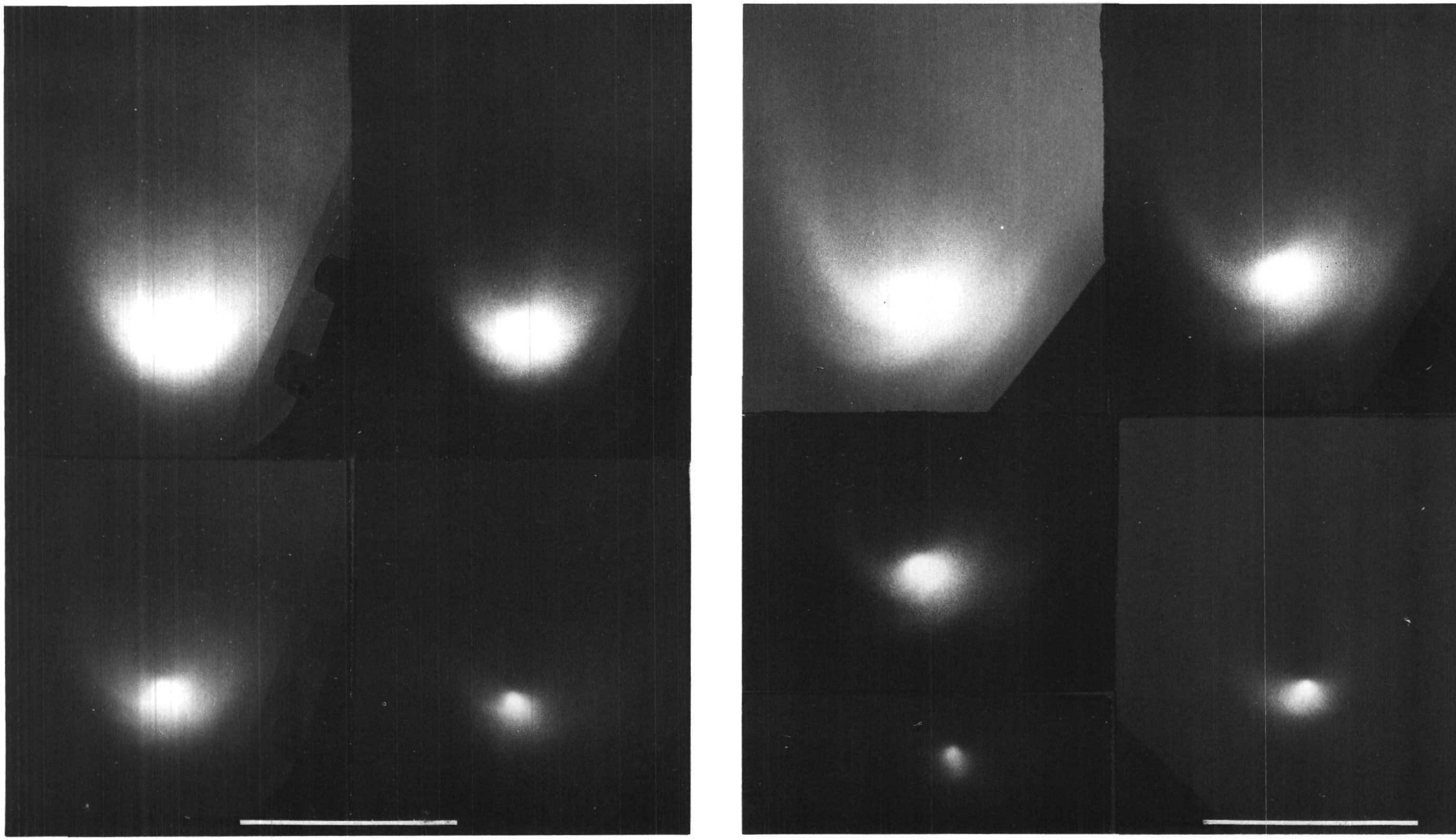

Fig. 26-7 - Left. 1970 April 1, 12:03.8 UT. Composite of 9 images, exposures 15-30 sec. Single image of nucleus, 2 sec exposure, at 12:31.1 UT. Right. 1970 April 2, 11:30.5 UT. Composite of 8 images, exposure 8-30 sec. Lower right taken at 12:14.0 UT through Na filter (composite of 4 images of 1-5 min exposure). Lower left single image 1 sec exposure at 11:33.9 UT. Bar = 5 x 10^4 km.

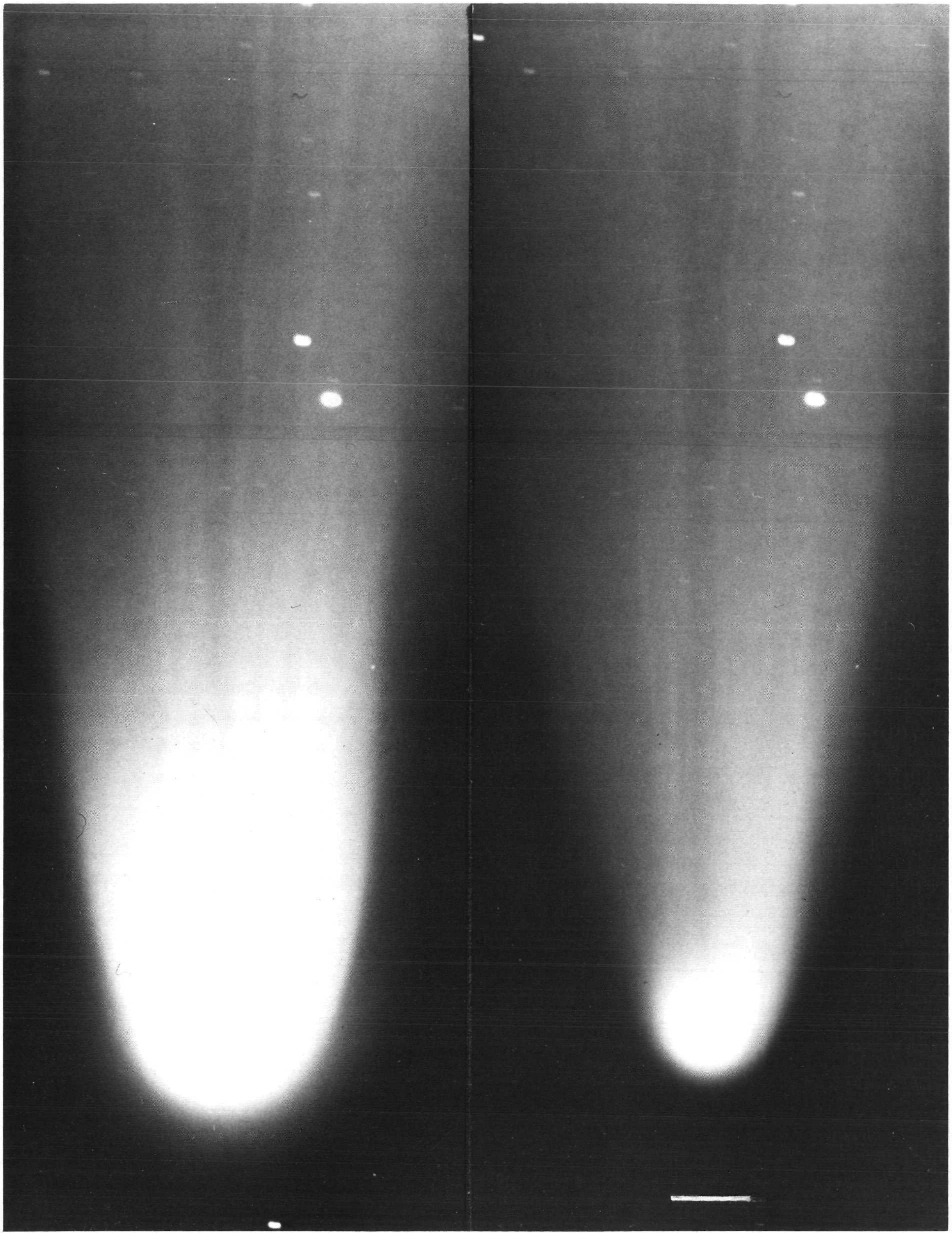

Fig. 26-8 - 1970 April 1, 12:22.1 UT, by Dr. E. Roemer using 229-cm Steward telescope. 103a-O, no filter. Note abundant streamer detail. Right print dodged. Bar = 5 x 10^4 km.

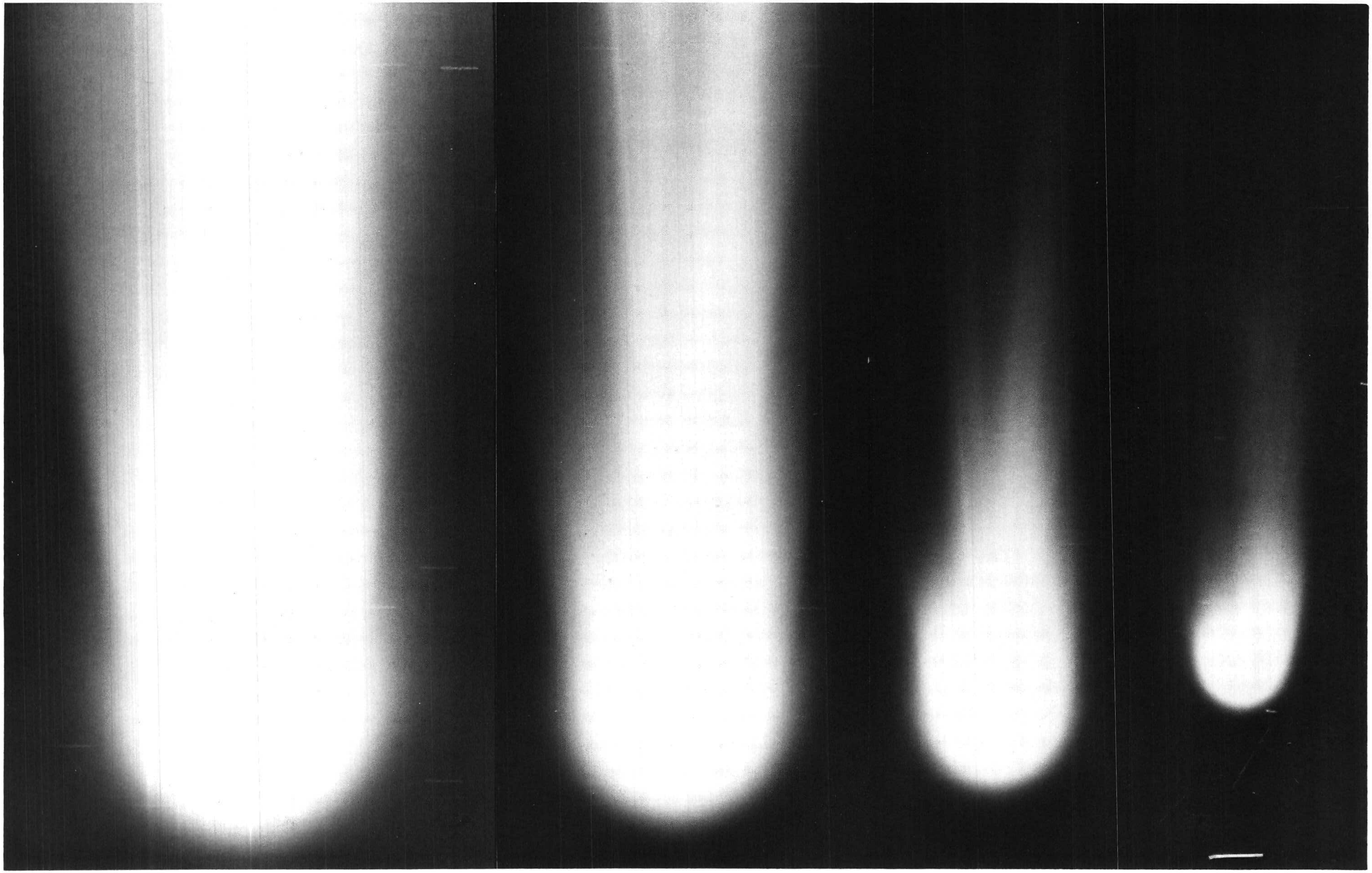

Fig. 26-9 - 1970 April 2, 11:59.6 UT. Single exposure 10 min, by Dr. Roemer, 229-cm reflector on 103a-O plus UG-1 (.33μ-.39μ); printed in four densities. Type I tail prominent. Bar = 5 x 10^4 km.

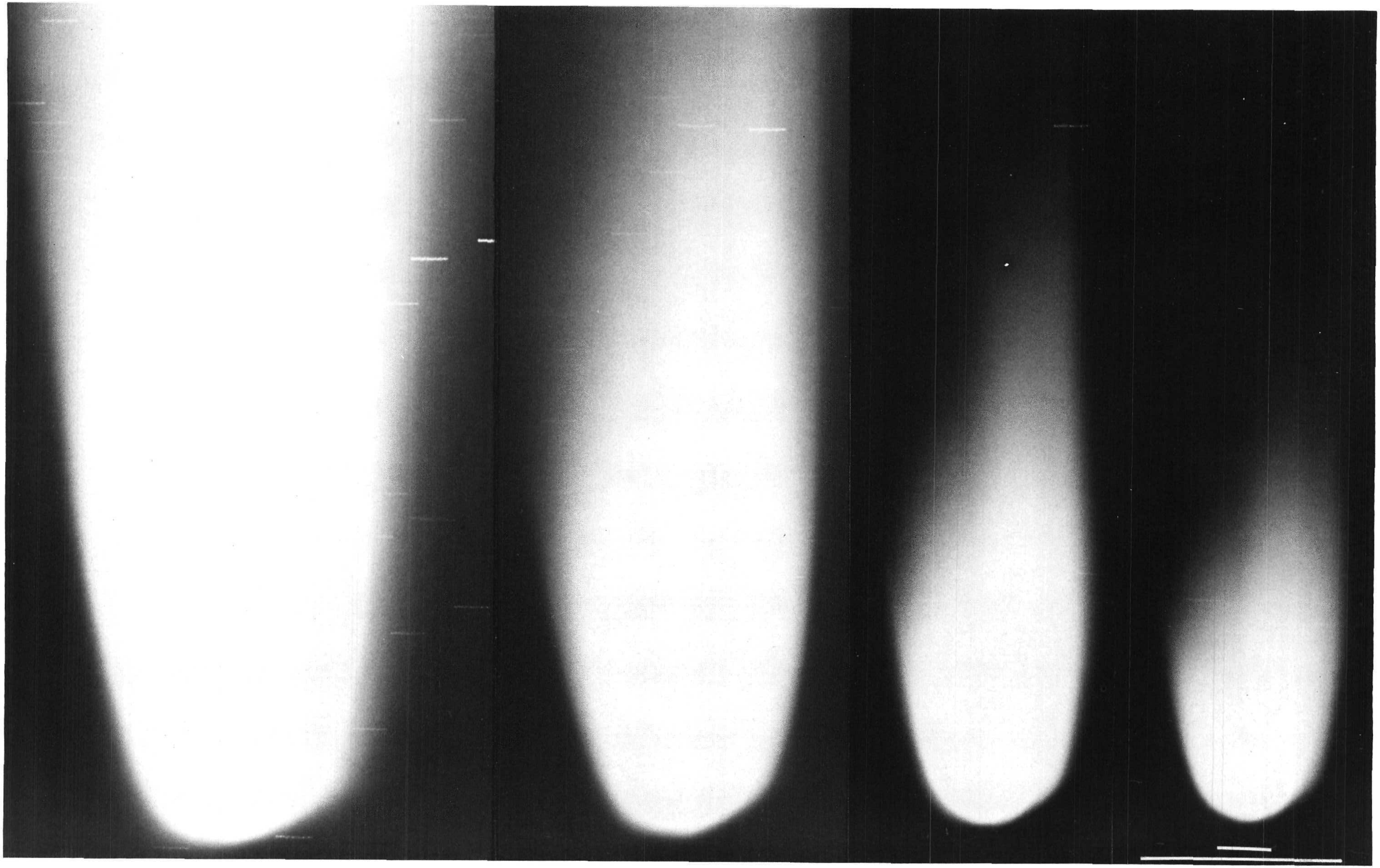

Fig. 26-10 - 1970 April 2, 11:24.7 UT. Single exposure 10 min, by Dr. Roemer, 229-cm reflector. An RG-2 filter with 103a-E emulsion shows reflected sunlight (near absence of gas emissions) and envelopes produced by the spiral structure. Note dark lane found to point precisely away from the sun, apparently shadow cone behind nucleus. Distance from sun 0.62 AU. Bar = 5 x 10^4 km, 2 x 10^5 km.

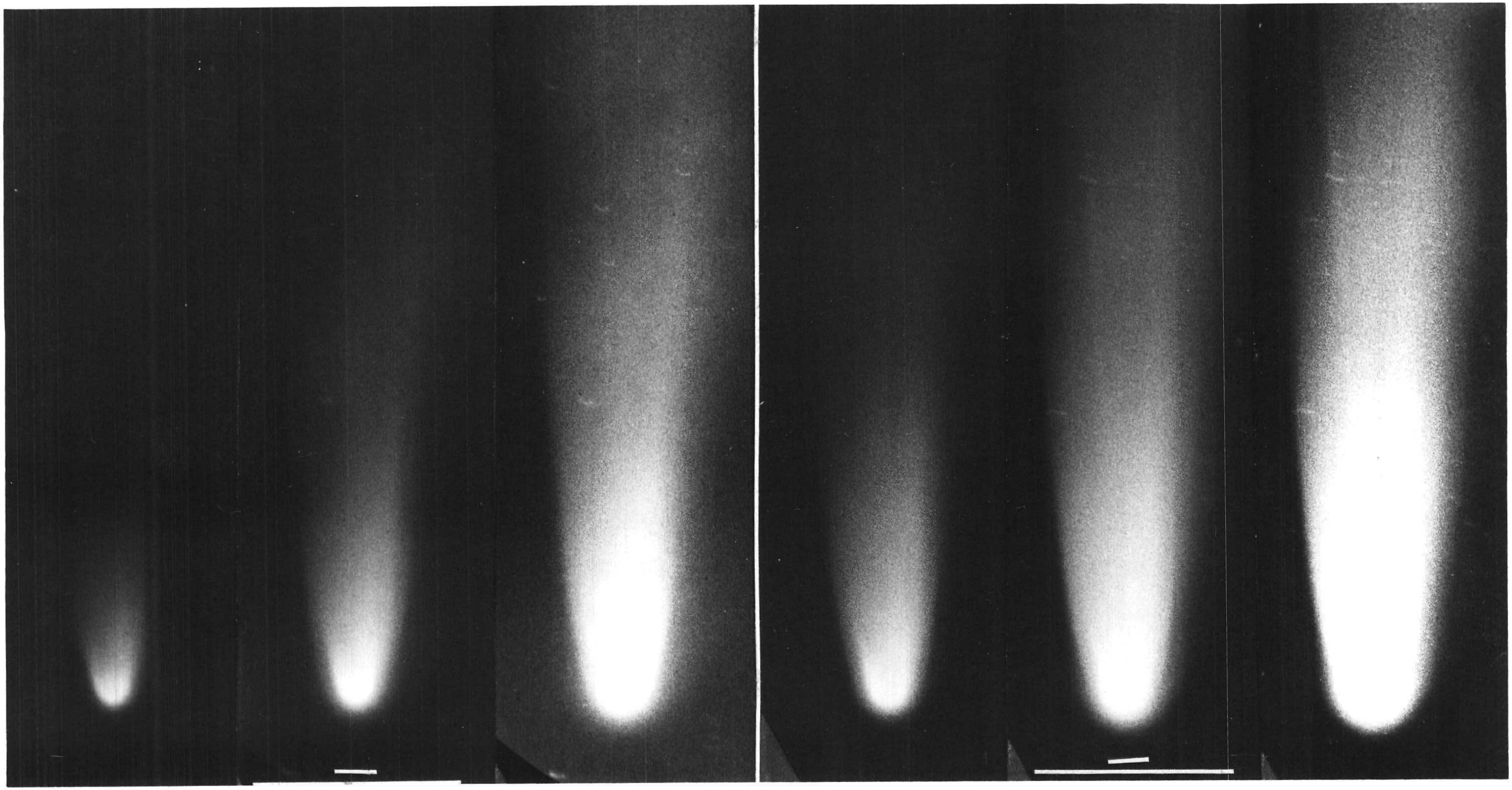

Fig. 26-11 - Left. 1970 April 2, 11:57 UT. Composite of 8 panchromatic images; each exposure 5 min, 15-cm refractor. Note bright spine in tail also visible on April 4. Right. 1970 April 4, 11:45 UT. Composite of 12 images, 3-10 min. Bar = 10^6 km, 2×10^5 km.

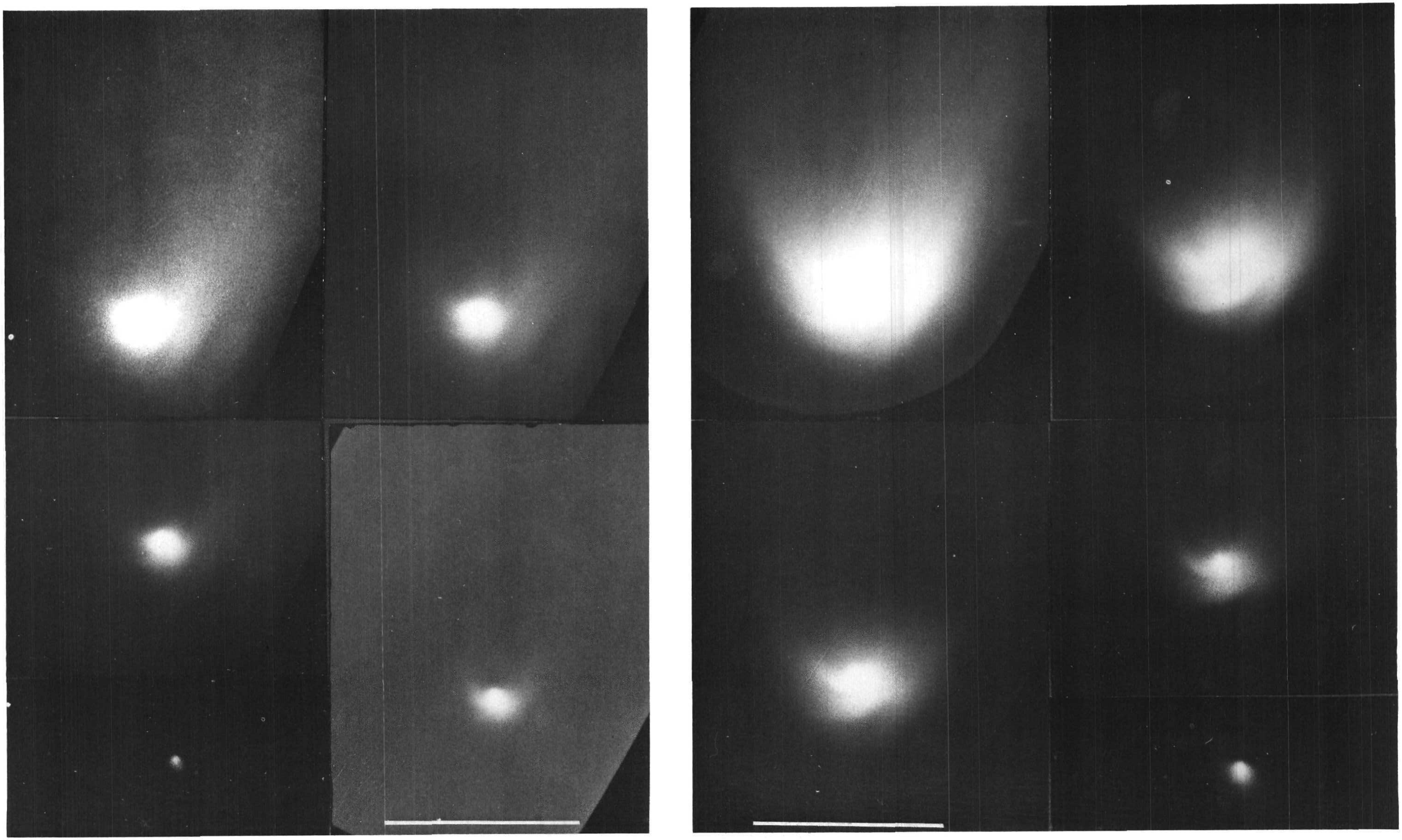

Fig. 26-12 - Left. 1970 April 3, 12:05.4 UT. Composite of 3 images, each 30 sec. Lower right through Na filter at 11:54.9 UT, composite of 3 images 2-5 min. Lower left, single image 8 sec at 12:09.3 UT. Right. 1970 April 4, 12:13.8 UT. Composite of 3 images, 15-30 sec. Spiral structure is again strong. Lower right, single image of nucleus, 2 sec at 12:32 UT. Bar = 5×10^4 km.

was likely to represent the equatorial plane of the nucleus. The model shows moreover that the sun seen at the comet was just 90° from the line of sight. Thus the sun was very near the equinox for the rotating nucleus. The subsolar point on the nucleus was therefore near its equator, and the emissions could indeed have been roughly equatorial (allowing for various lags in the emissions, as the photographs definitely suggest). Thus, there is no contradiction in assuming that on March 28 essentially equatorial ejections were observed; and that the equatorial tilt was around 30° on the orbit.

The March 28 set was therefore used to determine the period of rotation of the comet nucleus; the result was later verified as to order of magnitude from the records on other dates. The measures themselves are summarized in the following section. On the assumption that the outward velocity of the jets is close to 0.6 km/sec (cf. Delsemme and Miller 1971), a rotation period of 1.4-1.5 days is found. For a different velocity the derived period varies inversely. The derived curvature of the March 28 spirals is compatible with

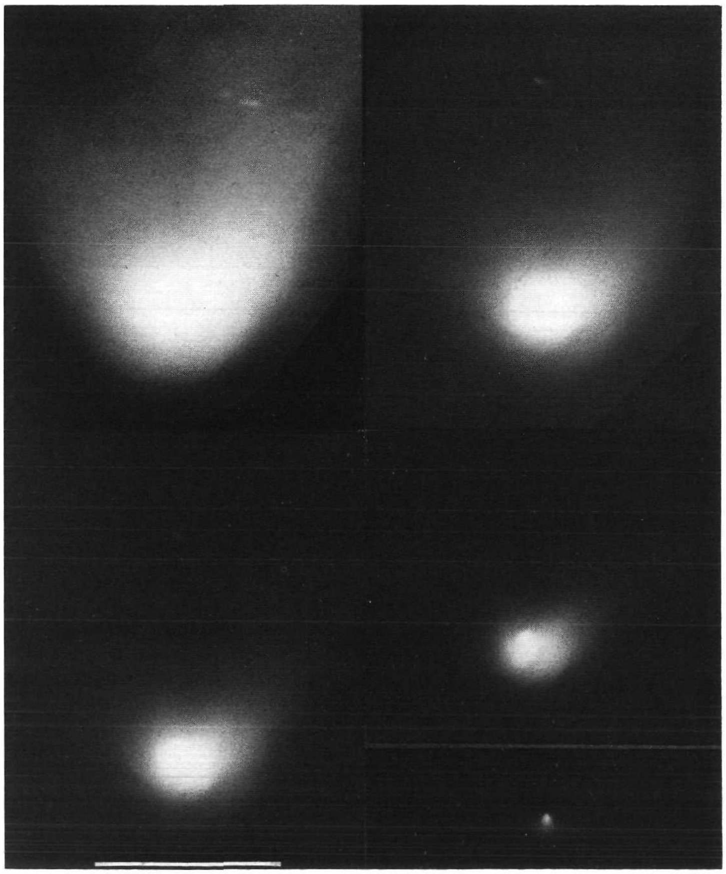

Fig. 26-13 - 1970 April 5, 12:19.9 UT. Upper left, composite of 3 images, 30-60 sec at 12:08.7 UT, showing broken star trails. Others, composite of 10 images, 4-30 sec. Lower right, single image of nucleus, 8 sec at 12:37.6 UT. Bar = 5 x 10^4 km.

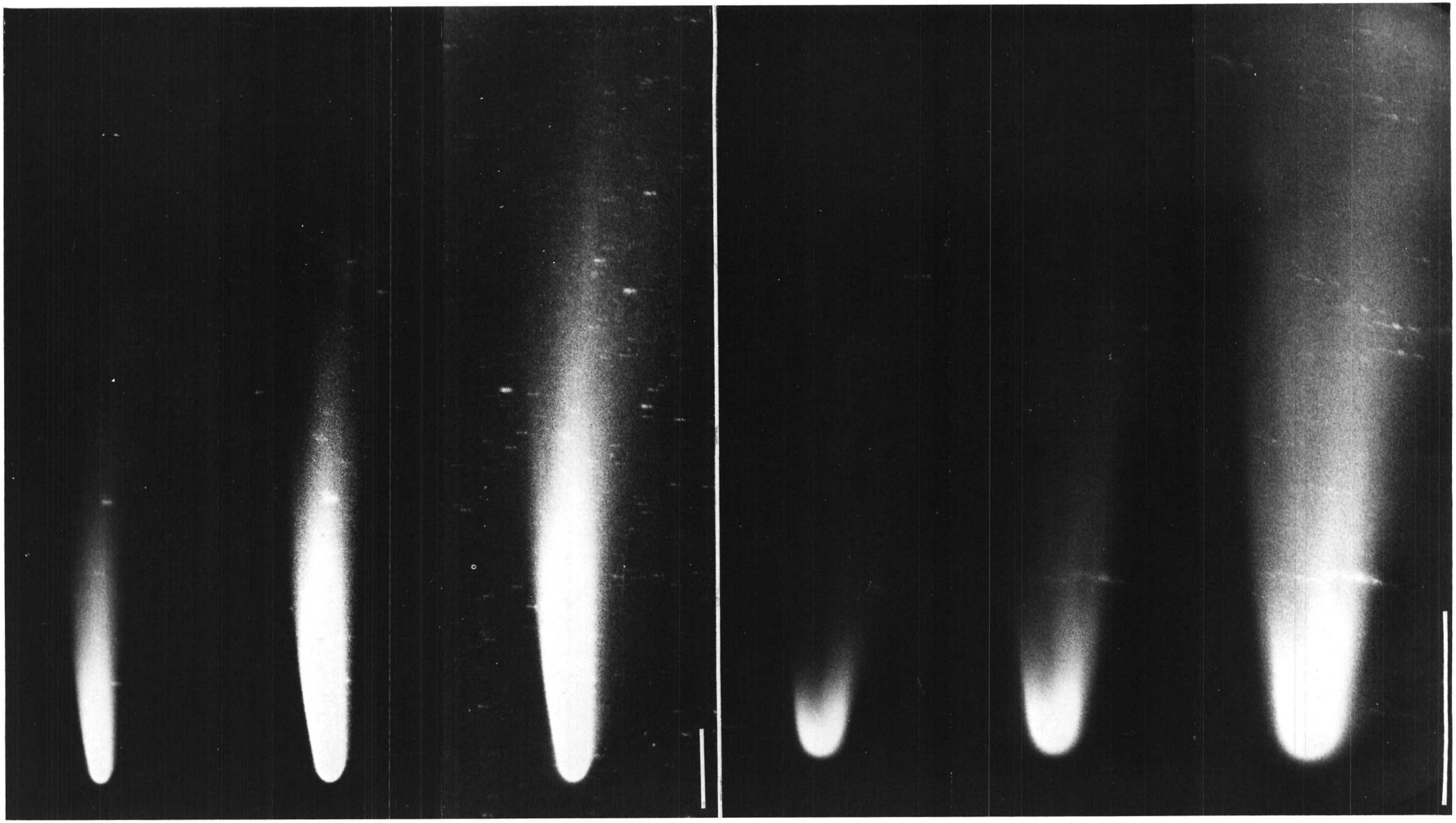

Fig. 26-14 - Left. 1970 April 5.5 UT. Composite of 7 images, 15-30 sec, taken with F = 30-cm Aero Ektar. Bar = 10^6 km. Right. 1970 April 5, 11:35 UT. 15-cm refractor. Composite of 9 images, 3-5 min. Bar = 5 x 10^5 km.

the records obtained on April 2, etc., but these later photographs cannot be explained simply by ejection near the comet's equatorial plane only. Instead, in early April, a clearly three-dimensional array of streams is observed. By April 5, the line of sight to the comet was inclined about 45° to the plane of its orbit, and the sun was some 10° from the equator estimated above. Whether these altered circumstances can fully account for the projected 3-dimensional complexity of streamers is not clear without a more thorough investigation. It was a happy accident that around March 26-28, 1970 a geometric simplicity existed and that a corresponding simplicity was actually observed on March 28, thus suggesting a straightforward interpretation of the spiral jets. The direction of the rotation of the nucleus is found to be in the sense of the comet's orbital motion. The above conclusions (which pertain of course to one comet only) are of interest in connection with the dynamic (nongravitational) evidence assembled by Marsden (1969) for the pole orientations of several short-period and one long-period comet. He found these to be strongly concentrated to the normals of their orbital planes. The question thus arises how much a single passage at $q = 0.5$ A.U. (for a new comet) can do to reorient its axis of rotation. Another question is whether the poles of such asteroids as are assumed to be old comet nuclei, show an orientation preference of the type suggested by Marsden's studies.

Measurements.

The outward velocity of the particles emitted with the gases by the nucleus probably averages about 0.6 km/sec (Delsemme and Miller 1971). The true curvature of the spiral jets will be proportional to the rotational velocity of the nucleus and inversely to the outward radial velocity of the particles.

The authors determined the period of rotation by two methods. Mr. Larson measured suitably-sharp original images from 4 dates over a 9-day interval, March 26-April 4. The spirals were plotted on polar graph paper by projecting original images and tracing points. It was decided to test the plotted spirals for foreshortening by requiring that the radial velocity on the curved track be found constant along the entire spiral. This test eliminated all but two dates, March 28 and one of the April 4 spirals. The derived periods were 1.47 and 1.50 days for March 28 and April 4, based on the adopted $V = 0.6$ km/sec and the linear distances of pairs of

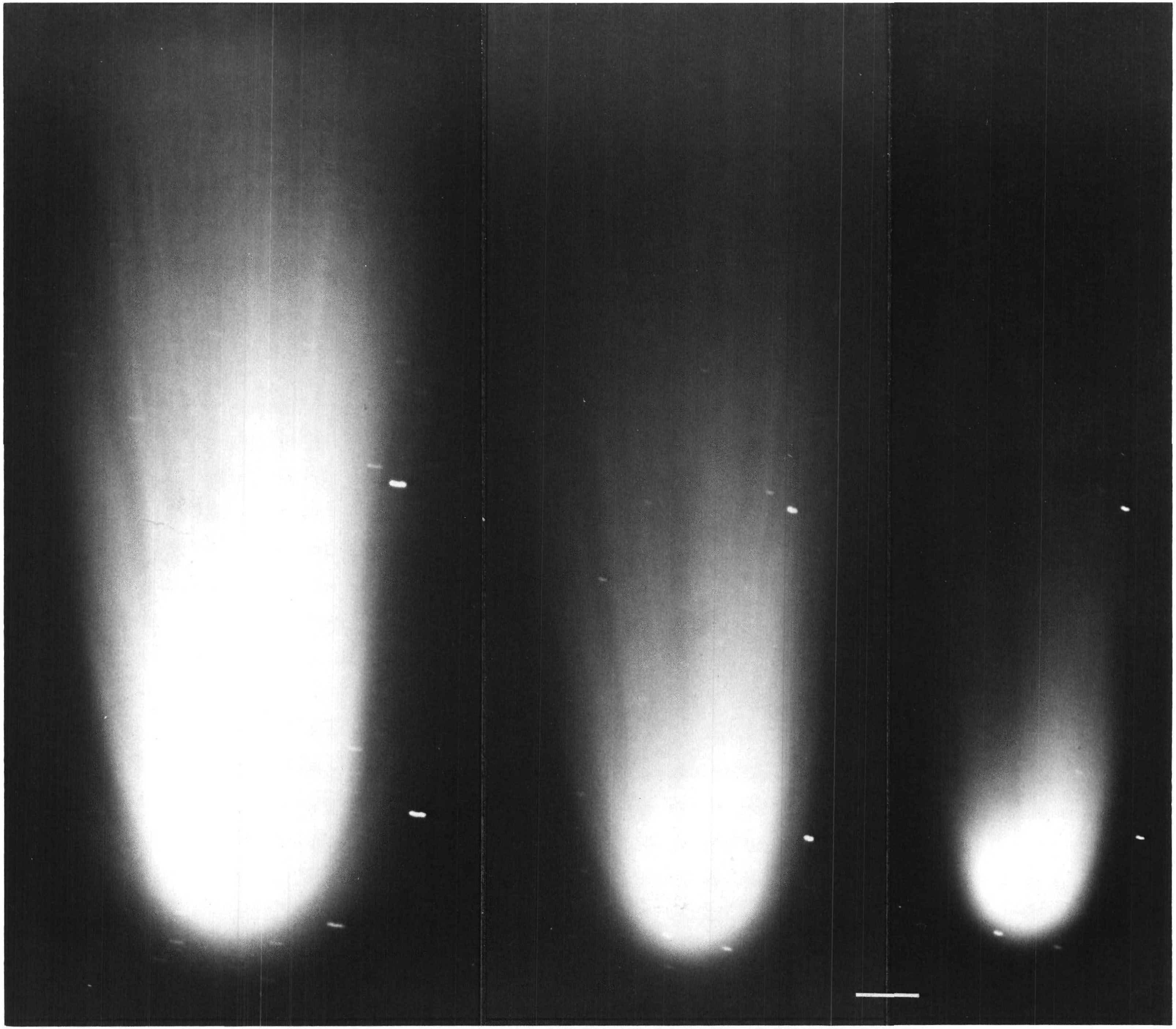

Fig. 26-15 - 1970 April 6, 11:40.9 UT, by Dr. Roemer with 154-cm reflector. Note many streamers; 103a-0, no filter. Right print shows shadow cone best, cf. also Fig. 26-18. Bar = 5 x 10^4 km.

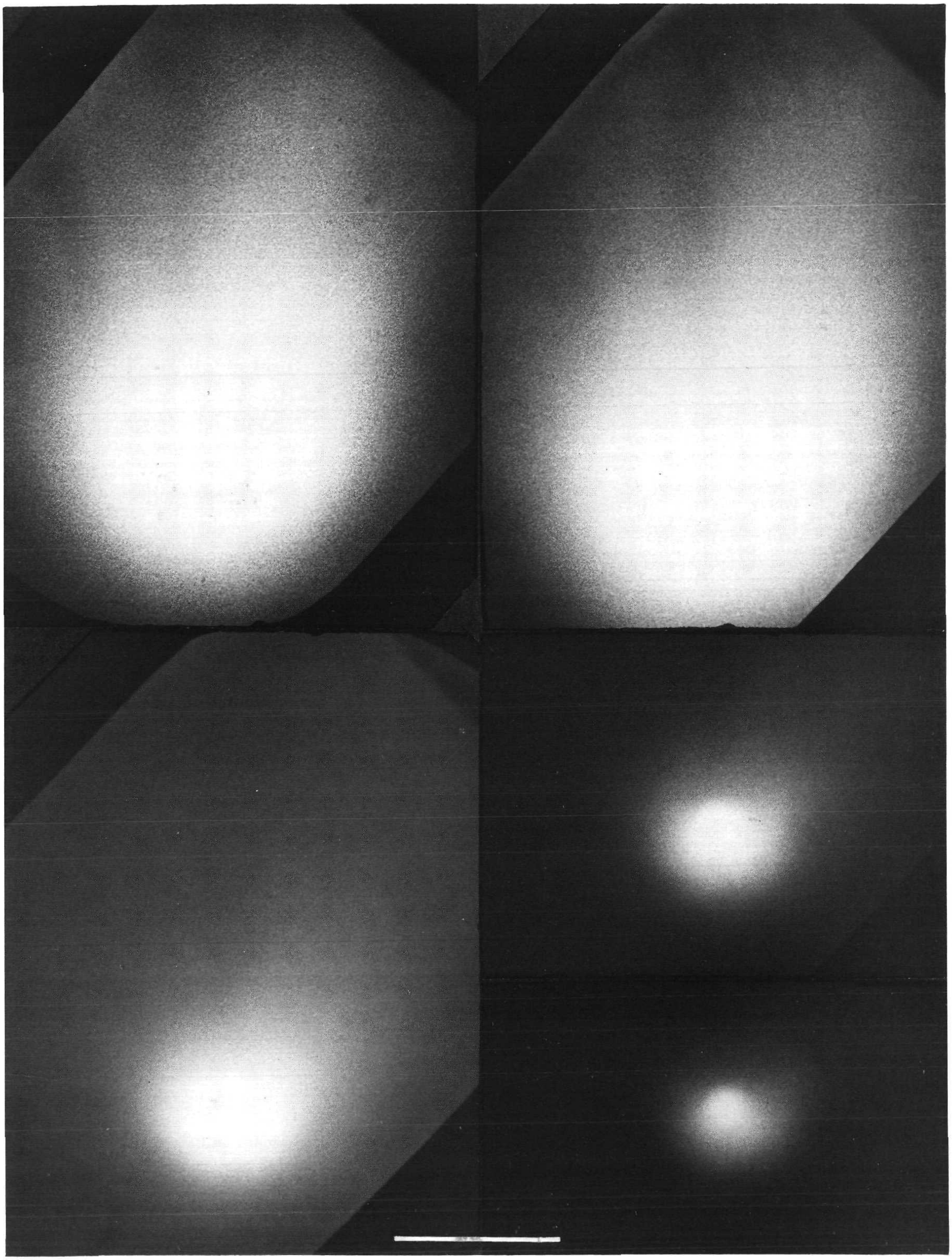

Fig. 26-16a - Left. 1970 April 15, 11:33.5 UT. Upper left, composite of 3 images, 1-5 min exp., on 103a-0 showing streamer detail. Upper right is panchromatic composite of 13 images, 3-5 min exp.; single image of nucleus, 60 sec at 11:18.3 UT.

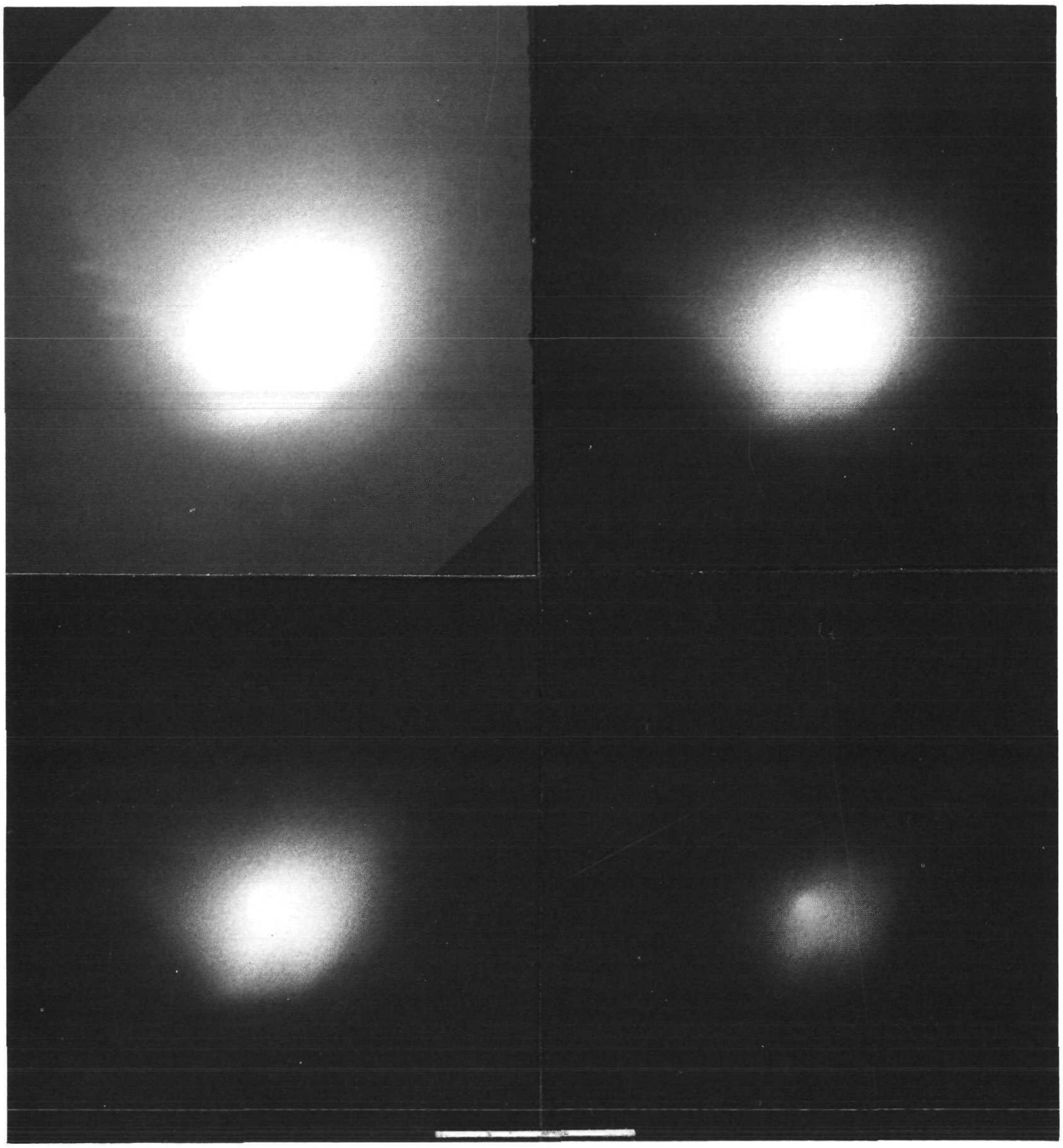

Fig. 26-16b. Right. 1970 April 16, 11:23.0 UT. Composite of 2 images of 3 min. exposure. Note unusual configuration of jets. Two star trails at upper left. Bar = 5 x 10^4 km.

points on the spirals that subtended 45° as seen from the nucleus (and thus represented 1/8 revolution).

Mr. Minton used the Mann measuring machine to obtain the distances traversed in 90° arcs starting at the nucleus. From measures of 3 composites of March 28, he derived $P = 1.38 \pm 0.015$ days (internal accuracy only). Unfortunately, all nightly observing runs had to be short, with a maximum rotation of the nucleus of only 14° covered on April 5. Rotational changes in the pattern could not be established apparently because the image quality varied (improved) as the comet rose.

On April 9 (Fig. 26-17), features in the gas tail were observed. Four exposures were taken with the 30-cm, F/1 Aero Ektar, and all showed the same detail, but in slightly different positions. Fig. 26-17 shows the first and fourth exposures, separated by 15 minutes in time, and combinations of the two showing the extent of the motion. By moving the two images such that the features were superimposed (Fig. 26-17d), the angular displacement of the images of the stars ($2\overset{\prime}{.}2$) could be easily measured. The velocity corrected for foreshortening was about 115 km/sec.

Concluding Remarks.

The photographs reproduced are oriented with the sun below the frames. Fig. 26-8 best shows a narrow dark lane which is found to point away from the sun; it appears to be a shadow cone caused either by absorption of visual radiation or of UV radiation by the coma preventing excitation in the tail. This matter will be pursued elsewhere. Fig. 26-18 shows a composite made of a longer exposure.

Our reproductions have inevitably lost some information that is secured by stereoscopic (= binocular) inspection of pairs of the original records. This inspection not only eliminates minor defects on one frame, but reinforces features present on both frames and takes advantage of areas of best resolution in either frame. Besides, original films have a much larger dynamic range than paper copies. For these reasons, we show in Fig. 19 our best estimate of the streamer patterns on 7 days. This figure may be consulted when inspecting Figs. 26-3 to 16. The present studies could be extended by use of additional photographs that were taken at other longitudes.

Reference is made to some interesting considerations of rotating comet nuclei by Sekanina (1967).

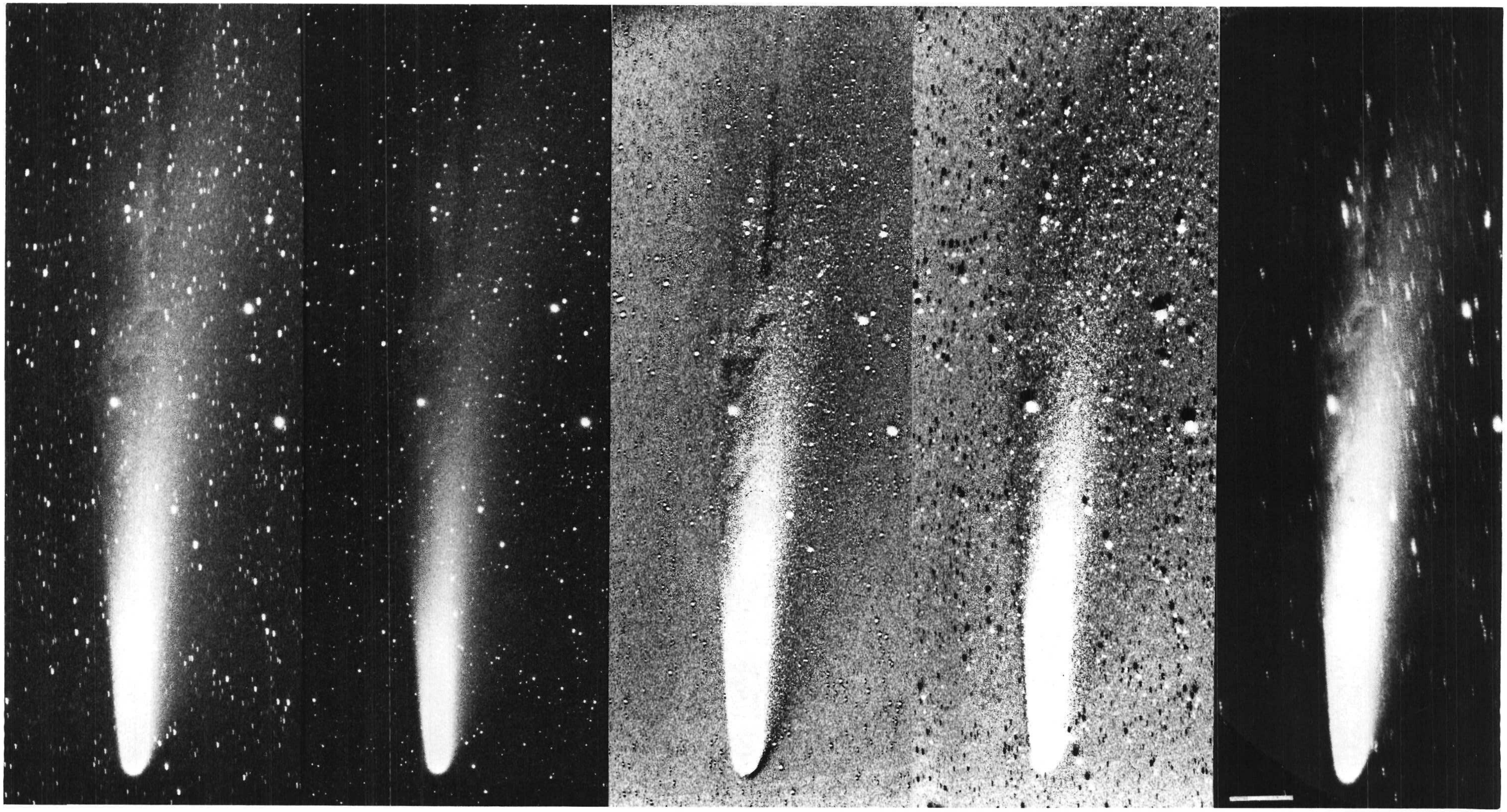

Fig. 26-17 - 1970 April 9.5 UT. Images 1 and 2: 30 and 15 sec exp., 15 minutes apart, with F=30-cm Aero Ektar. Image 3: combination of positive and negative of the two, showing displacement of features in gas tail. Image 4: combination of positive and negative, with one image displaced such that moving features are superimposed and thus disappear. The amount of displacement was measured by the displaced star images. Image 5: composite of 4 images taken within the 15-min period with careful registration on the gas features. Star trails indicate amount of displacement. Bar = 10^6 km.

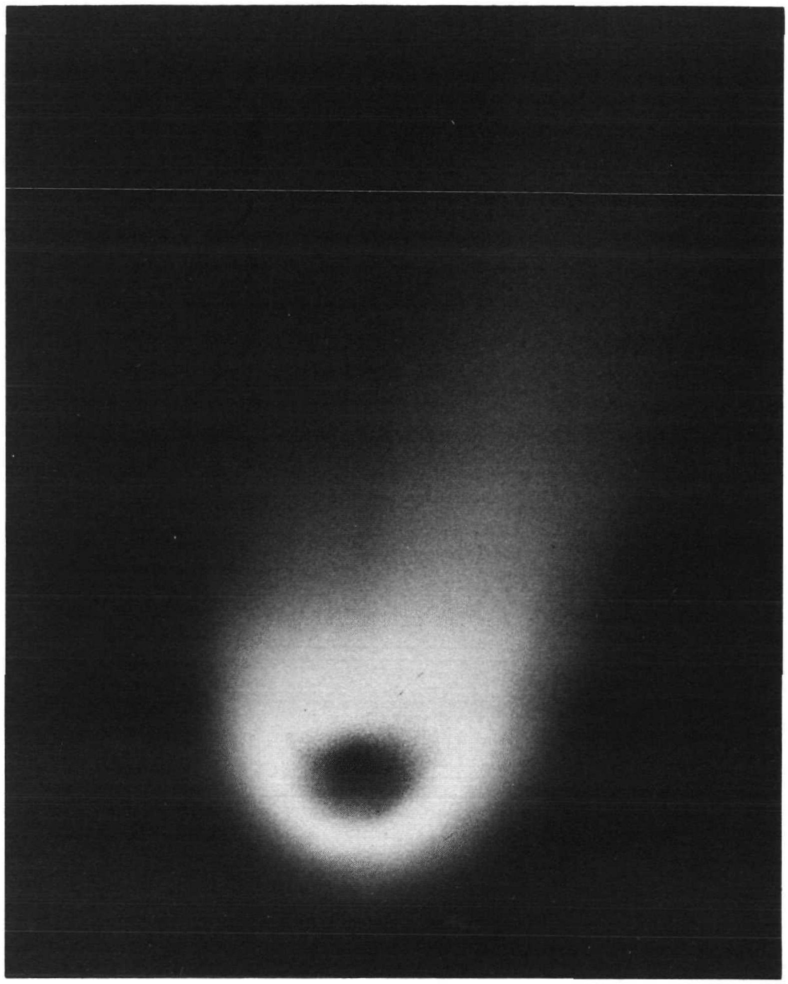

Fig. 26-18 - Same as Fig. 26-15 with negative
of inner portion carefully superimposed.

The authors and Dr. E. Roemer have inquired on the existence of additional photographs of Comet Bennett's spiral coma structure. We were informed that Dale Vrabec and Sara Smith obtained records with the Aerospace Corp. 24" solar telescope in the San Fernando Valley and the Stony Ridge 30" telescope, intermittently from March 28 to April 13, 1970; and that Dr. F. D. Miller obtained photographs with the University of Michigan 52" reflector on April 5, 1970. We gratefully acknowledge the copies received for comparative studies, for the dates March 31, April 2, and April 6; and April 5, 1970, respectively; the quality of these four records was comparable to our own. However, the respective dates and times did not provide additional information on structure changes.

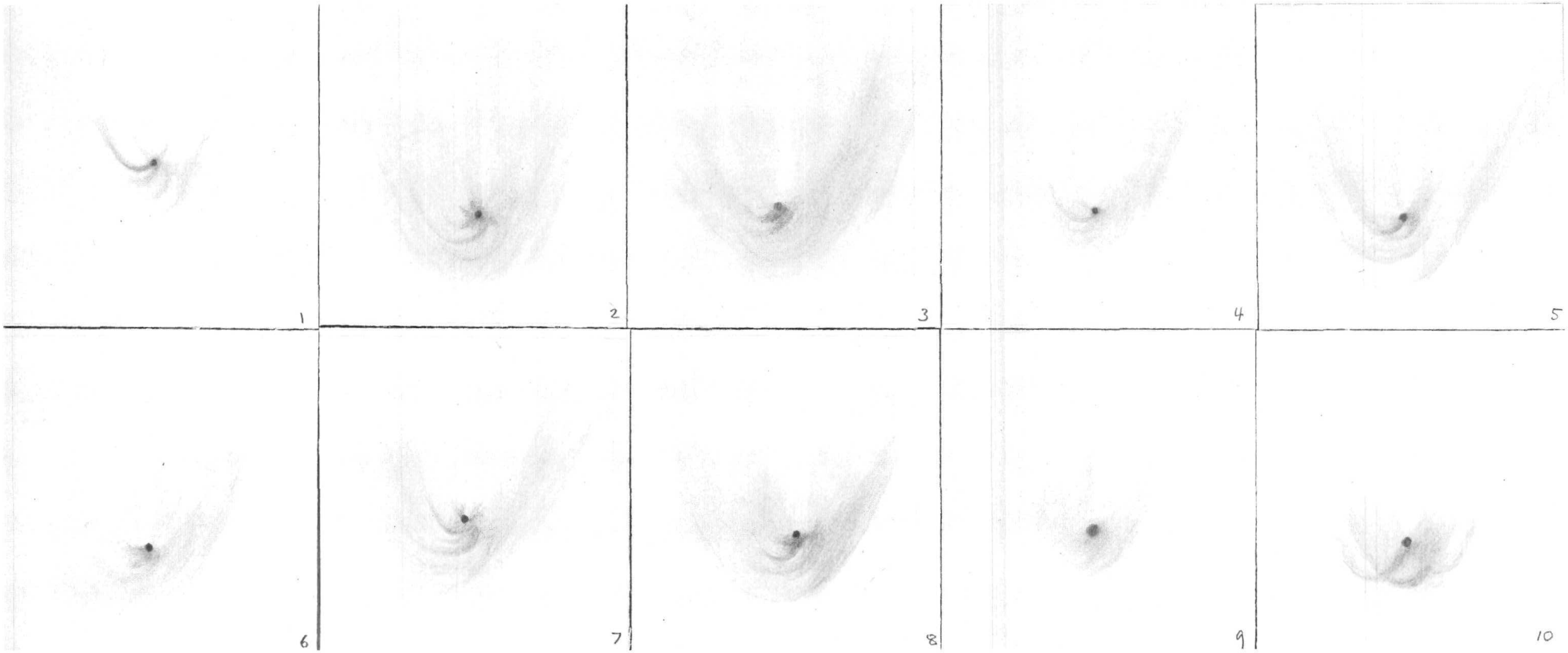

Fig. 26-19 - Sketches of coma structure, based on binocular inspection of pairs of selected original images. Dates and lengths of 50,000 km scale: 1) March 26, 1970, 19 mm; 2) March 28, 18.5 mm; 3) March 29, 18 mm; 4) April 1, 18 mm; 5) April 2, 17.5 mm; 6) April 3, 17 mm; 7) April 4, 17 mm; 8) April 5, 16 mm; 9) April 15, 13.5 mm; 10) April 16, 13 mm.

Acknowledgments.

This research was supported by NASA Grant NGL 03-002-002. Mr. J. Fountain participated in about half the observations and in the earlier phases of preparing the material for publication. We appreciated having the opportunity to discuss the work in progress with Dr. Delsemme. Thanks are due to Dr. E. Roemer for permission to reproduce her Figs. 26-8, 9, and 10; and for her helpful assistance with the preparation of this paper. Dr. Kuiper assisted with the composition of the text.

References.

Delsemme, A. H. and Miller, D. C. 1971, Planet. Space Sci., 19, 1229-1258.

Marsden, B. G. 1969, "Comets and Nongravitational Forces. II", Astron. J., 74, 720.

Rahe, J., Donn, B., and Wurm, K. 1969, Atlas of Cometary Forms, NASA SP-198, Washington, D. C.

Sekanina, Z. 1967, "Non-Gravitational Effects in Comet Motions and a Model of an Arbitrarily Rotating Comet Nucleus, III. Comet Halley, IV. Comet Splits, V. General Rotation of Comet Nuclei", Bul. Astron. Inst. Czech., 18, 286-296, 206-302, 347-355.

NO. 27

CONCLUDING REMARKS

by Gerard P. Kuiper

Lunar and Planetary Laboratory

Papers 1 to 24 of this Volume were presented during the first 1-1/2 days of meetings. The texts of Papers 1-20 here reproduced are in part manuscripts subsequently submitted by the authors or, in most cases, condensed versions of the Conference tape record. Papers 21 and 22 covered important mission studies by JPL and IITRI. They were presented at the Conference as finished manuscripts; but the studies were still to be continued and both were published in final form in 1971. In consultation with the authors, reference is here made to the final versions of these contributions.

The remaining half day of the Tucson Conference was presided over by Dr. Sirri of NASA-JPL. It provided additional opportunities for questioning and exchange between the two groups at the Conference, the scientists-comet-specialists and the JPL and IITRI mission-planners. These discussions were tape-recorded in the same manner as the other Proceedings and comprise 43 pages in type. However, their contents were not deemed of sufficient permanent interest to be included here, especially since these very topics were re-examined in more detail at the Conference at the Yerkes Observatory, June 1971; its Proceedings are available as a 113-page report by IITRI.

As a result, the present Volume deals mostly with current scientific knowledge on comets. The rapid recent advances made it desirable to add in Part III the Papers 25 and 26, both written just before the Volume went to press.

Attention is called to Paper 24 (p. 170) which demonstrates the heavy responsibility to science carried in this area by very few persons. Clearly, an increased professional effort and additional telescopic facilities are called for to provide some measure of balance to the comet missions now being considered. The assigned observing time now is only 2 or 3 nights a month on the part of 2 or 3 major U. S. telescopes. For brighter comets, smaller instruments suffice and more observers do participate. Even here, however, the number of active observers remains small, as is seen below.

Mrs. Faye Larson has assisted us by examining the trend during the 20th Century of the observational activity on comets. She drew the statistics from Vsekhsvyatskii (1958) who gives concise accounts of the observations and physical characteristics for each apparition, with reference to the sources from which the descriptions were taken. A total of 803 cometary apparitions are included, of which 223 are returns. We define a "major comet observer" as one who has observed 10 or more cometary apparitions. Each such major observer has, of course, a time span of observational activity. Fig. 27-1 shows the counts per decade of the number of such major observers. The last entries,1957-1970, extend beyond Vsekhsvyatskii's listing; here Mrs. Larson used the R. A. S. Reports on the Progress of Astronomy, 1950-1970. The two sources agree well where they overlap, 1950-1957, with derived numbers 12 and 13. It is seen that the number of major comet observers has declined from approximately 36 at the beginning of the Century to 8 during the past decade, with an indication of a slight upturn during the early 1970's. As stated before, the situation is even

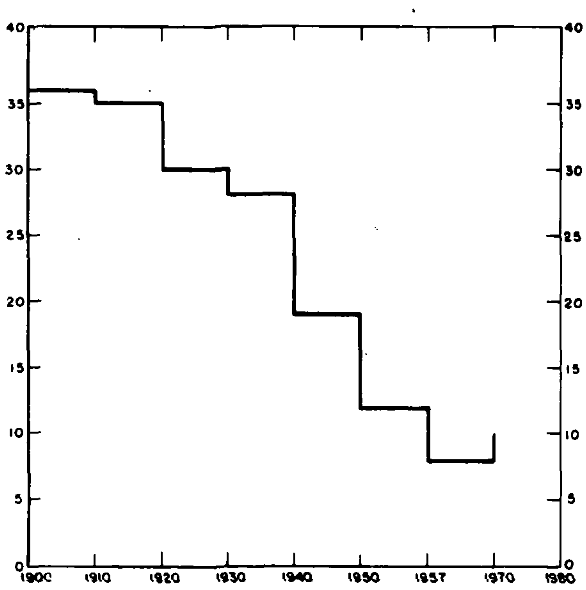

Fig. 27-1 - The number of major comet observers more precarious for the "recoveries" around the 20th mag., which are so vital in planning comet missions.

As these Proceedings stress repeatedly, well-planned cometary missions would yield very basic data on such fundamental problems as the origin and the earliest history of the Solar System.

Table I, due to Dr. Delsemme, gives a summary listing of ground-based programs that need intensified development in the coming decade. A fuller presentation is found in the Proceedings of the Yerkes Observatory 1971 Conference. No doubt important results may also be expected from continued study of non-gravitational forces, stressing the great importance of observing comet apparitions over the maximum possible arcs, as Dr. Roemer has pursued consistently. Dr. Roemer is also preparing a separate publication on cometary nuclei and jets, based on her large and probably unique plate collection obtained with several telescopes over a number of years.

As an aid to ready reference, Table II lists the principal catalogues of cometary orbits, spectra, appearances, and some recent monographs and summarizing chapters.

TABLE 27-I

GROUND-BASED ACTIVITIES RELEVANT TO COMET PROBES

A. H. Delsemme

The Yerkes meeting in June 1971 of the Cometary Science Working Group has emphasized the need to support comet missons, by careful planning of ground-based activities. Here is a short summary of what was deemed to be important in this respect.

1. Astrometry - Observations are critical, in particular for predictions of positions from which to direct the probes. There is a need for a comet astrometric telescope with a continuing program.
2. Nucleus - Photometry of nucleus proper with large focal lengths, polarimetry and phase angle effects; IR measurements of nuclear region.
3. Coma -
   (a) Study of optical thickness of coma in different λ.
   (b) Photometric profiles of molecular bands and atomic lines with emphasis on high space resolution.
   (c) Brightness laws of monochromatic emissions versus solar distance.
   (d) High-resolution spectroscopy extended to more comets.
   (e) Monochromatic polarization studies.
   (f) Monochromatic isophotes through selected filters.
4. Tail - Spectral coverage in IR and UV.
5. Meteor stream studies - Radio and optical measurements.
6. Laboratory experiments -
   (a) Laboratory simulation of cometary conditions in snow.
   (b) Photochemistry studies.
   (c) Study of carbonaceous chondrites possibly having cometary origin.
7. Theory -
   (a) Studies of models of the coma and of its interaction with solar wind.
   (b) Studies of particle scattering.
   (c) Spectroscopic studies, measures of f values of cometary transitions.

TABLE 27-II

LISTING OF RECENT COMET MONOGRAPHS AND ATLASES

IAU Symposium 45, Leningrad 1970, "The Motion, Orbit Evolution, and Origin of Comets", D. Reidel, Dordrecht, The Netherlands (in press).

IAU Colloquium 22, Nice, April 1972, "Asteroids, Comets, Meteoric Matter", to be published.

Liège, Univ. de 1966, Nature et Origin des Comètes, Colloq. Internat'l. Univ. de Liège, 5-7 July 1965, Mém. Liège, 5th Series, V. XII.

Marsden, B. G. 1972, Catalogue of Cometary Orbits, Smithsonian Astrophysical Observatory, Cambridge.

Middlehurst, B. M. and Kuiper, G. P., eds. 1963, Moon, Meteorites, and Comets, U. Chicago Press, Chicago (The Solar System Series V.IV); in particular:

- Chapter 15, "Comets, Discovery, Orbits, Astrometric Observations", E. Roemer, 527-549.
- Chapter 16, "The Statistics of Comet Orbits", J. G. Porter, 550-571.
- Chapter 17, "The Physics of Comets", K. Wurm, 573-615.
- Chapter 18, "Comets: Structure and Dynamics of Tails", L. Biermann and Rh. Lüst, 618-636.
- Chapter 19, "On the Structure of the Cometary Nucleus", F. L. Whipple, 639-662.
- Chapter 20, "Empirical Data on the Origin of Comets", J. H. Oort, 665-673.
- Chapter 22, "Meteors, Meteorites, and Comets: Interrelations", L. G. Jacchia, 774-799.

Rahe, V., Donn, B., Wurm, K. 1969, Atlas of Cometary Forms, Structures Near the Nucleus, NASA SP-198, USGPO. Washington. (This publication also contains a list of general references, p. 127).

Richter, N. B. 1963, The Nature of Comets, Methuen, London.

Swings, P. and Haser, L. 1961, Atlas of Representative Cometary Spectra, Liège, Univ. de, Inst. d'Astrophys.

Transactions, IAU: Reports of Commission 15 (Comets).

Vsekhsvyatskii, S. K. 1964, Physical Characteristics of Comets, NASA TT F-80, USGPO, Washington (translation of Russian text of 1958).

Yerkes Observatory 1971, The Proceedings of the Cometary Working Group, Yerkes Obs., Williams Bay, Wisconsin.

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