SCIENTIFIC NEED FOR A COMETARY MISSION

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Today is a scientific golden anniversary for me. During the last months, I have been concentrating an attack on periodic comet Schwassman-Wachmann 1, which stays outside of Jupiter's orbit all the time. Looking through the literature over the past 50 years since it was discovered, I notice that on October 17, 1927, in Harvard Announcement Card number 33, my first published scientific contribution appeared. So today is the golden anniversary of my first publication. I don't expect that to impress Dr. Öpik very much, however.

I will be rather simple and direct in this presentation. Two of the speakers asked whether I would describe a comet and give some of the basic information about it, so I shall do so. I admit that this account will be biased to some extent, but I will not have time to be at all complete, nor to give the arguments supporting many of the statements. Figure 1 shows the comet that surprised everybody in 1910 by appearing just before the long expected Comet Halley. That comet, 1910 I, was an extremely dusty comet. In the figure, the dust is off to the upper left, and to the right, you see the gas or ion tail.

Figure 2 shows an extemely different type of comet, a sun-grazer, Ikeya-Seki, 1965 VIII. The following picture (Figure 3), photographed by the Japanese, shows it coming almost to the Sun. It came so close that the entire tail was extremely curved by Kepler's laws.

Next (Figure 4) are four views of Comet Mrkos, 1957 V, showing the difference between the so-called ion or plasma tail, the straight one in the upper left, and the dust tail curving off to the right. These three comets illustrate the enormous differences in physical appearance among various comets.

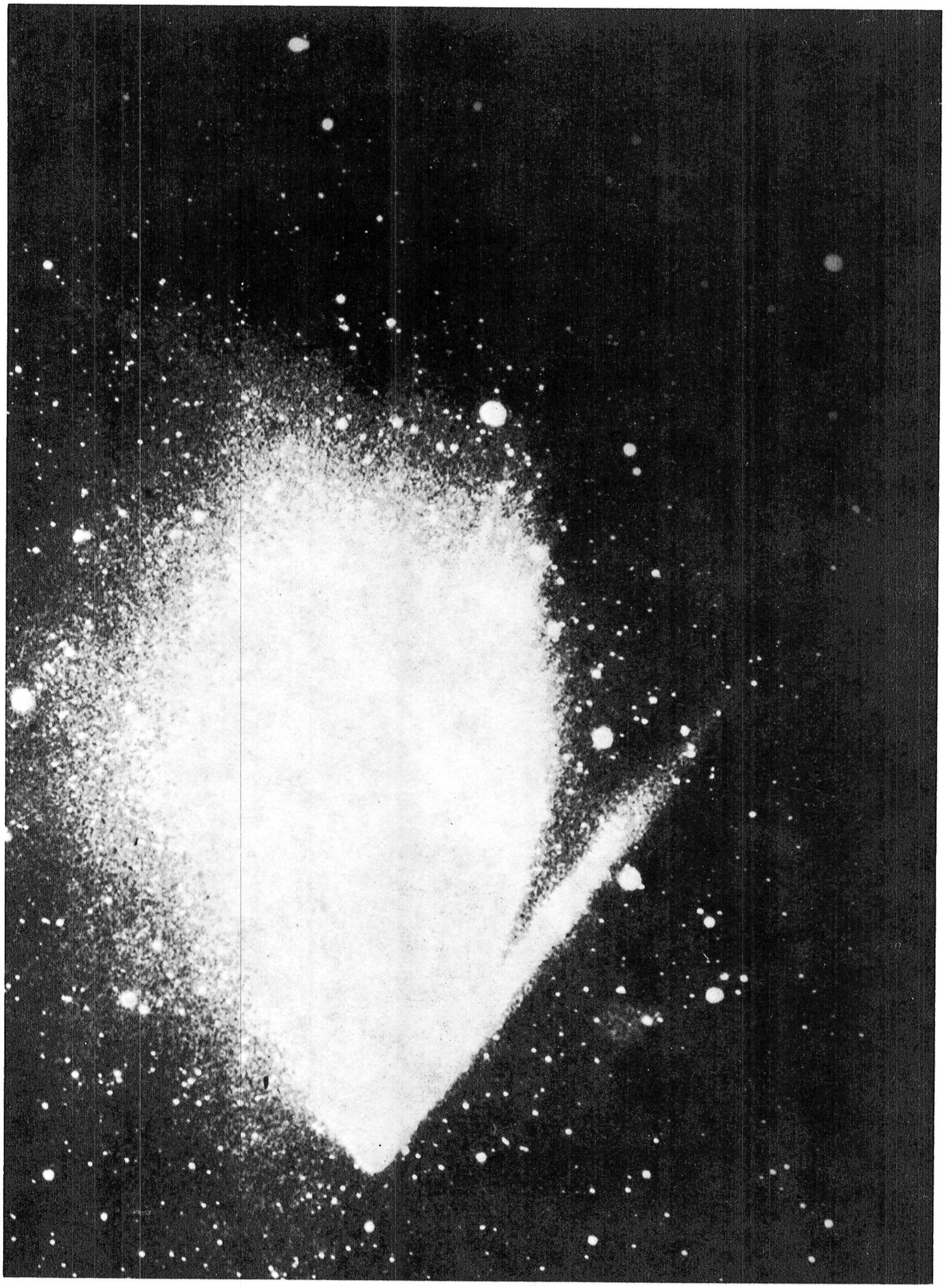


Fig. 1. Comet 1910 I.

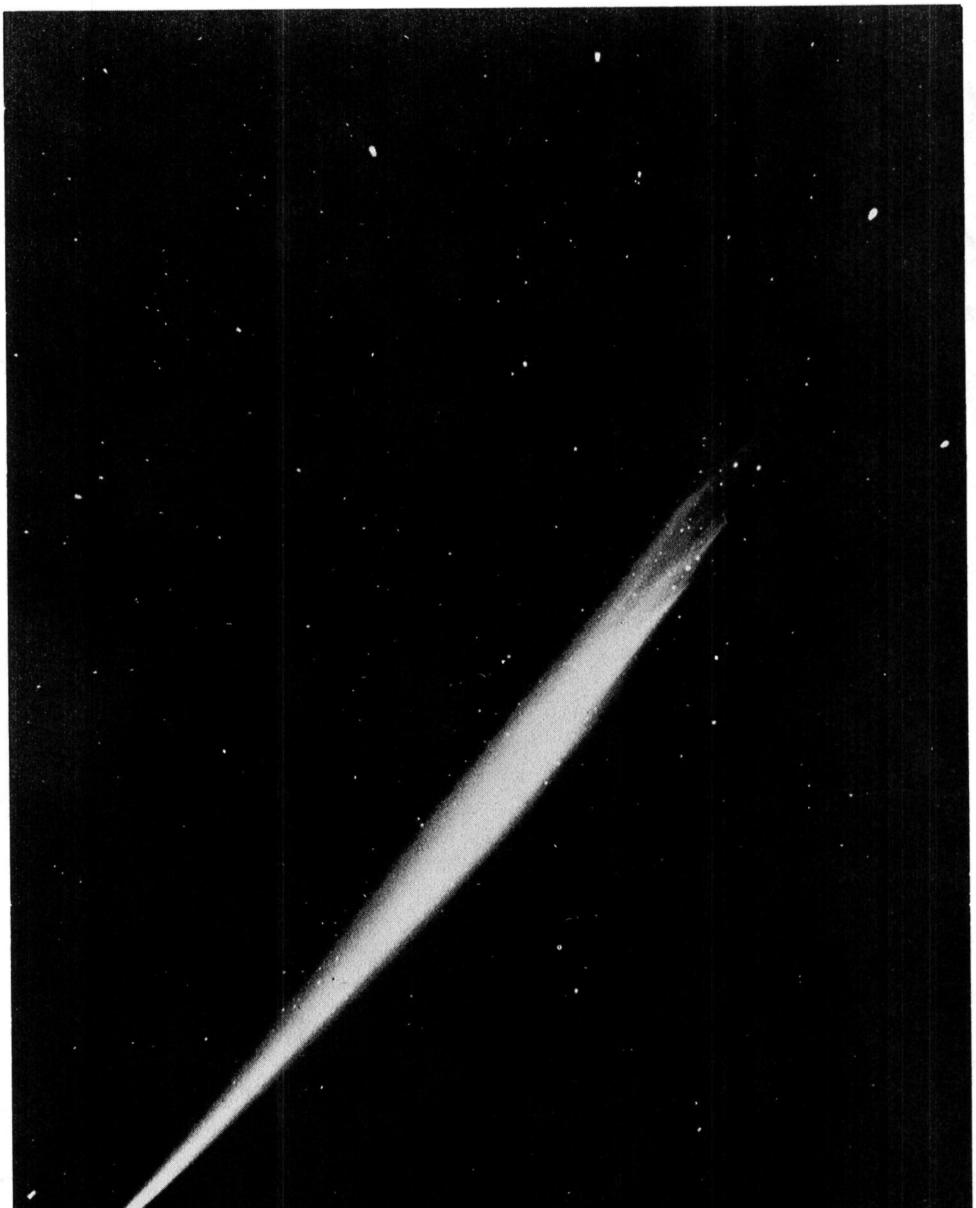


Fig. 2. Comet Ikeya-Seki, 1965 VIII.

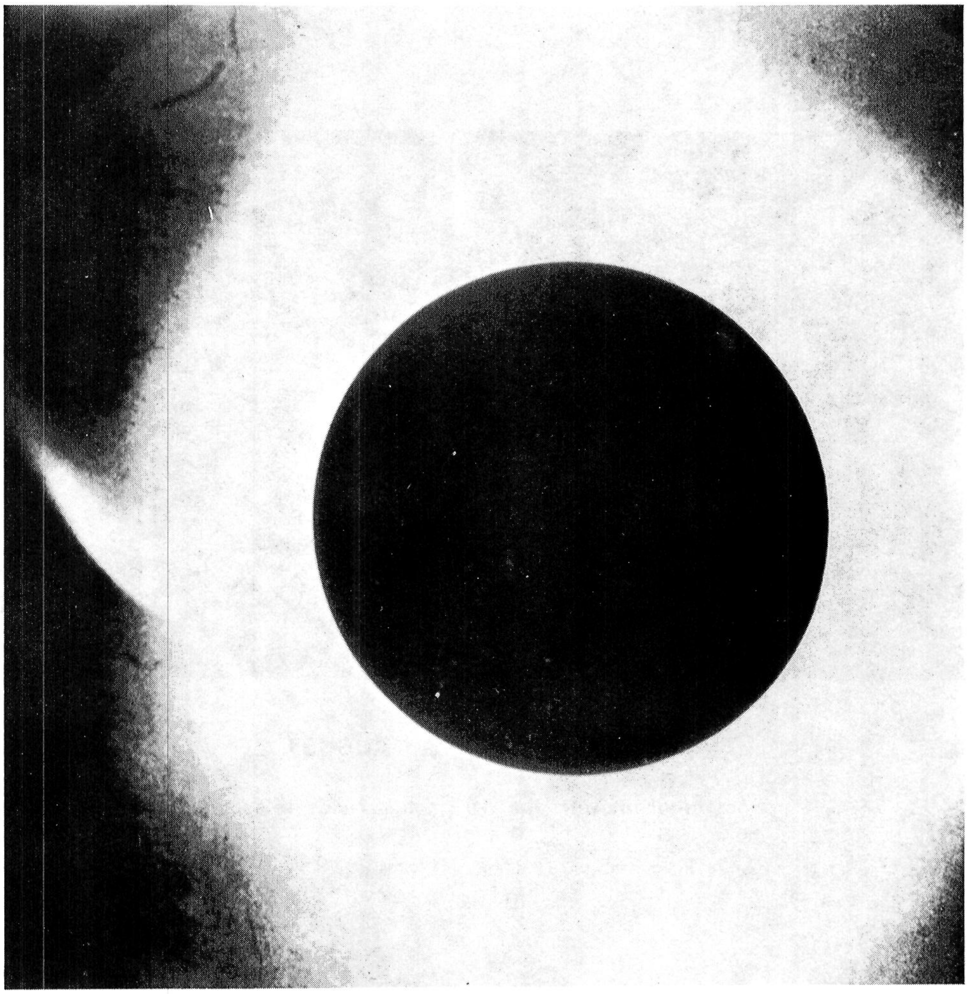
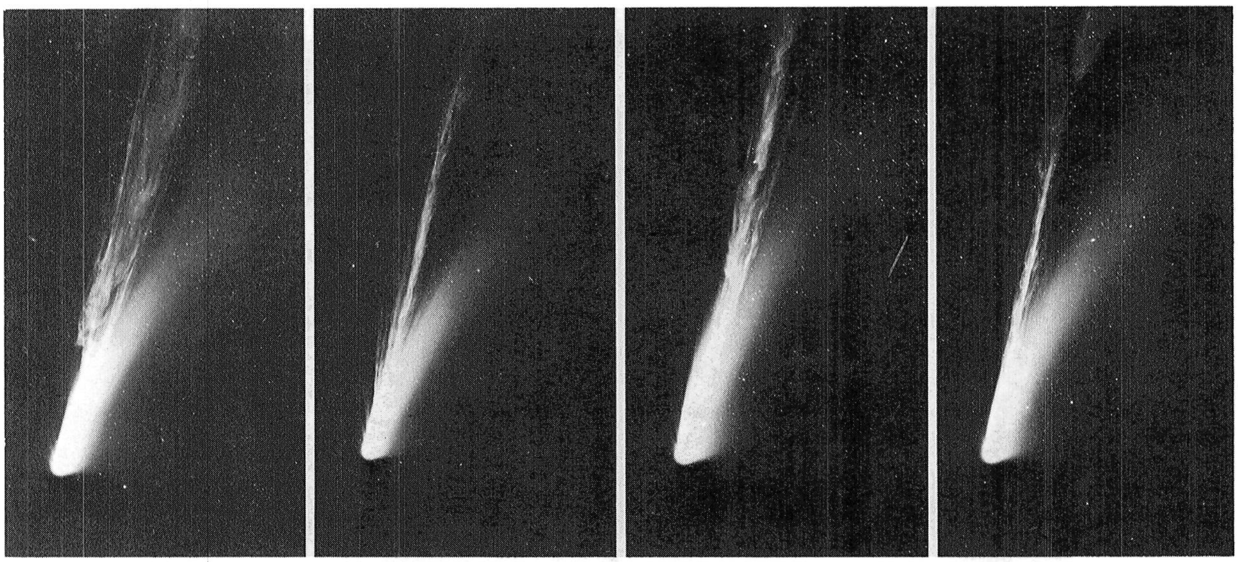


Fig. 3. Comet Ikeya-Seki (1965 VIII) close to the Sun.



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Photographed with the 48-inch schmidt telescope.

Fig. 4. Comet Mrkos, 1957 V.
(Hale Observatories)

We have in Figure 5 a diagram of a comet. First we note the head or a coma which is the order of 30 thousand kilometers in radius. Gas is sublimated from the invisible nucleus carrying dust with it. The dust is pushed back by solar radiation pressure with a small acceleration so that Kepler's Law causes it to swing far behind, producing the highly curved dust tail.

The plasma tail can extend to as much as 10^8 km or more. I was asked by one of the speakers to define "plasma". As I understand it, a plasma is an ionized gas. In many plasmas, such as the solar wind, the energy involved in the electric and magnetic fields is comparable to the kinetic energy of individual random particle motion. For comets, the energy involved in the magnetic fields and the electric currents can be significant.

For comets, as Biermann showed long ago, the solar wind with its million tons a day of million-degree ionized gas, mostly hydrogen, coming out at some 400 kilometers per second is a plasma that interacts with the outgoing gas from the comet. The comet gas is partially ionized, mostly by the solar wind and somewhat by solar radiation. The first discontinuity in the flow of the solar wind is broad and irregular, the bow wave (Figure 6). Perhaps it is not a real discontinuity. In any case the solar ions first notice the comet near the region of the bow wave. That causes chaotic magnetic fields. Then there is a contact surface near, perhaps very near, the coma in which the ions of the comet strongly interact with solar wind and its magnetic fields. The result is a pressure on the comet ions that carries them away from the Sun with very high accelerations. The accelerations, sometimes more than 100 times solar gravity, remained a puzzle for a

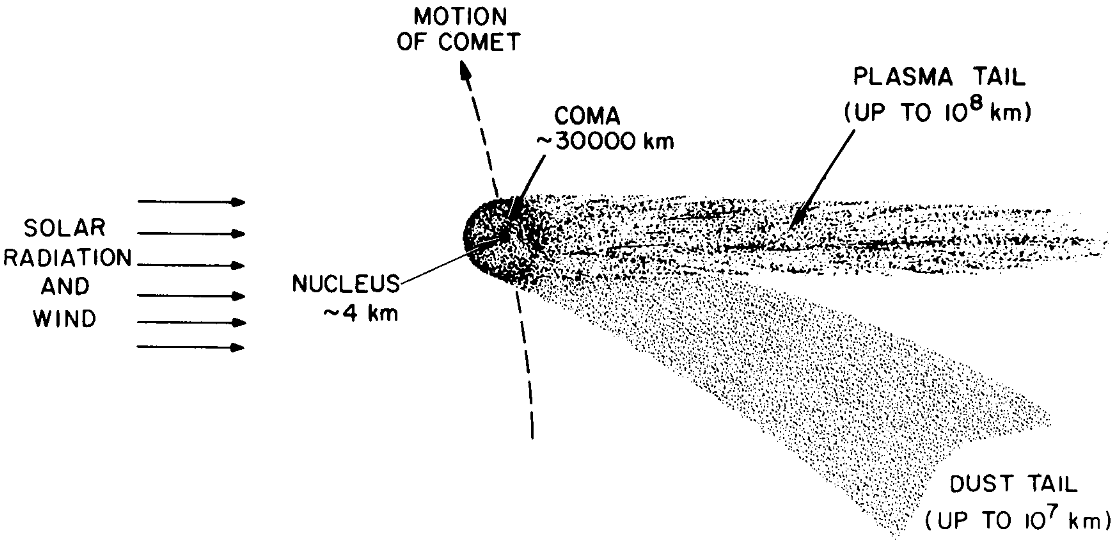

Fig. 5. Sketch of cometary dimensions.

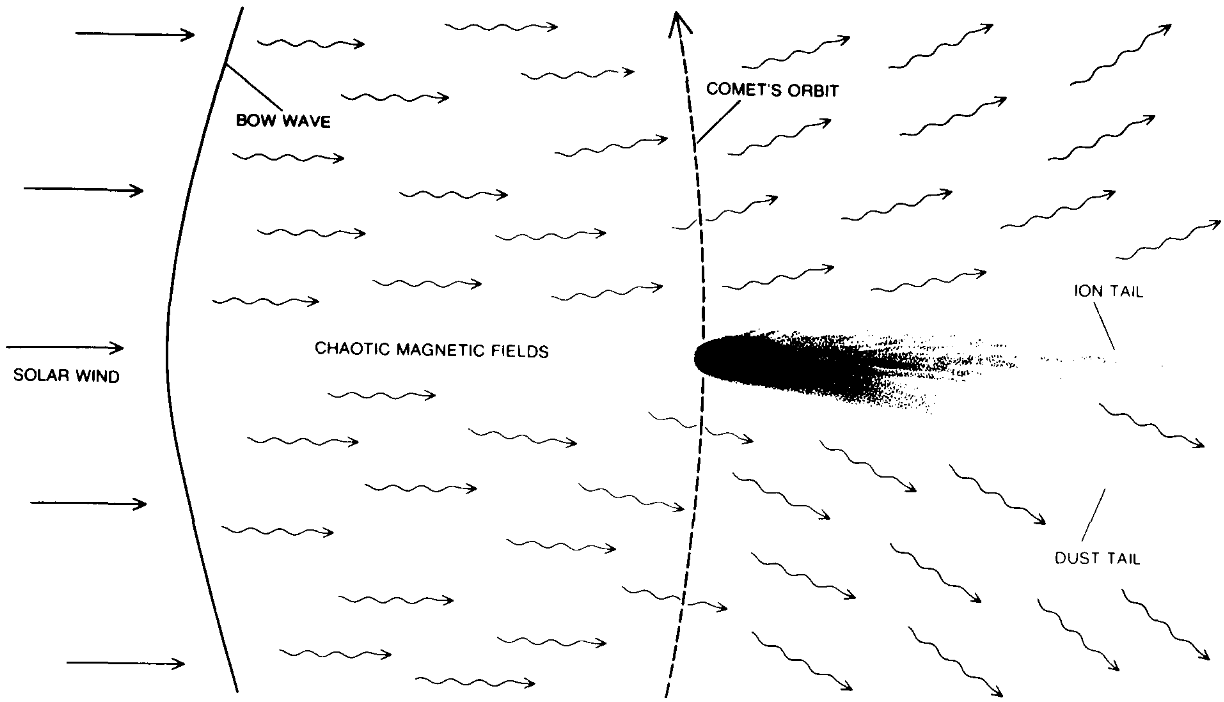

Fig. 6. Sketch of the large-scale features associated with the solar wind.

century, until it was finally understood that the solar wind is the cause of these phenomena.

So we have the nucleus, the cause of it all, only a kilometer to few kilometers in diameter. I think that the comets are the greatest little deceivers in the solar system. A tiny body puts on a magnificent show by ejecting vapor and particles so that the solar radiation reflecting from the particles and being re-radiated from the gases produces a conspicuous comet. A 5 to 10-km diameter body can produce phenomena that stretch out visibly over a hundred million kilometers or more.

Comet Kohoutek, 1973 XII, was a great disappointment for the public, but a huge success for scientists. Figure 7 shows, for example, the twisted nature of the ion tail near the head of comet Kohoutek. In Figure 8 is comet West, 1976 VI. It is an extremely dusty comet, but near the head there is a bit of ion tail up at the top. This looks enormously different from one picture to the next. Figure 9 was taken in blue light and the ion tail shows up much more strongly to the right; the dust is again on the left. Figure 10 shows comet West in the red and therefore accentuates the dust. The striations in the dust tail are quite complicated to explain. They are much like those of 1910 I, the comet in Figure 1.

Now comet West was by no means unique, but relatively rare in that its nucleus split. There are four components showing in Figure 11. These slowly separated. Sekanina discovered a remarkable fact about split comets; those pieces that survive the shortest time are accelerated away from the original orbit with the greatest velocity. Among multiple nuclei in split comets, differential non-gravitational forces arising from the jet action of the sublimating gases control the relative motions.

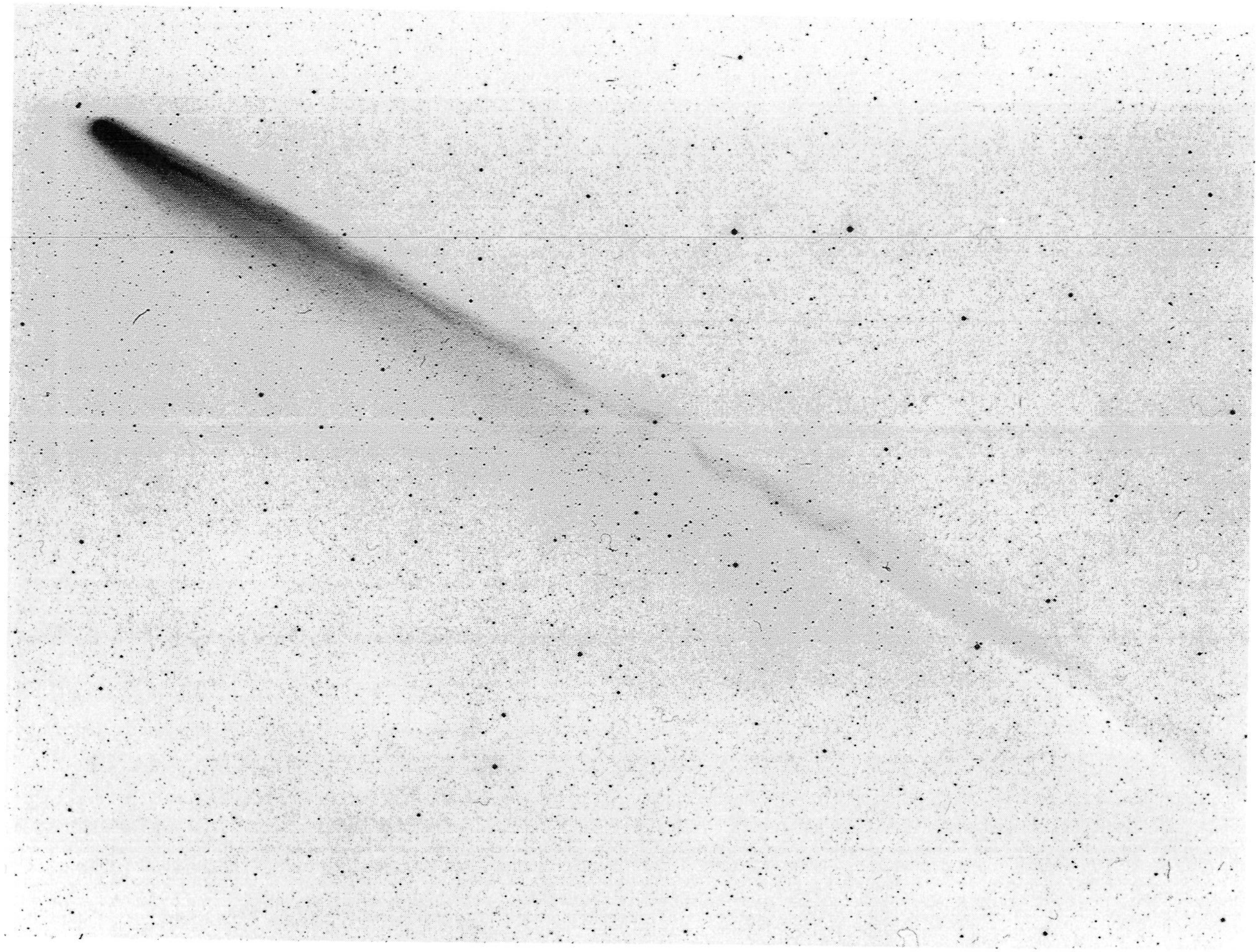

Fig. 7. Comet Kohoutek, 1973 XII.
(Joint Observatory for Cometary
Research photograph)

Fig. 8. Comet West, 1976 VI.

Fig. 9. Photograph of Comet West (1976 VI) taken in blue light.

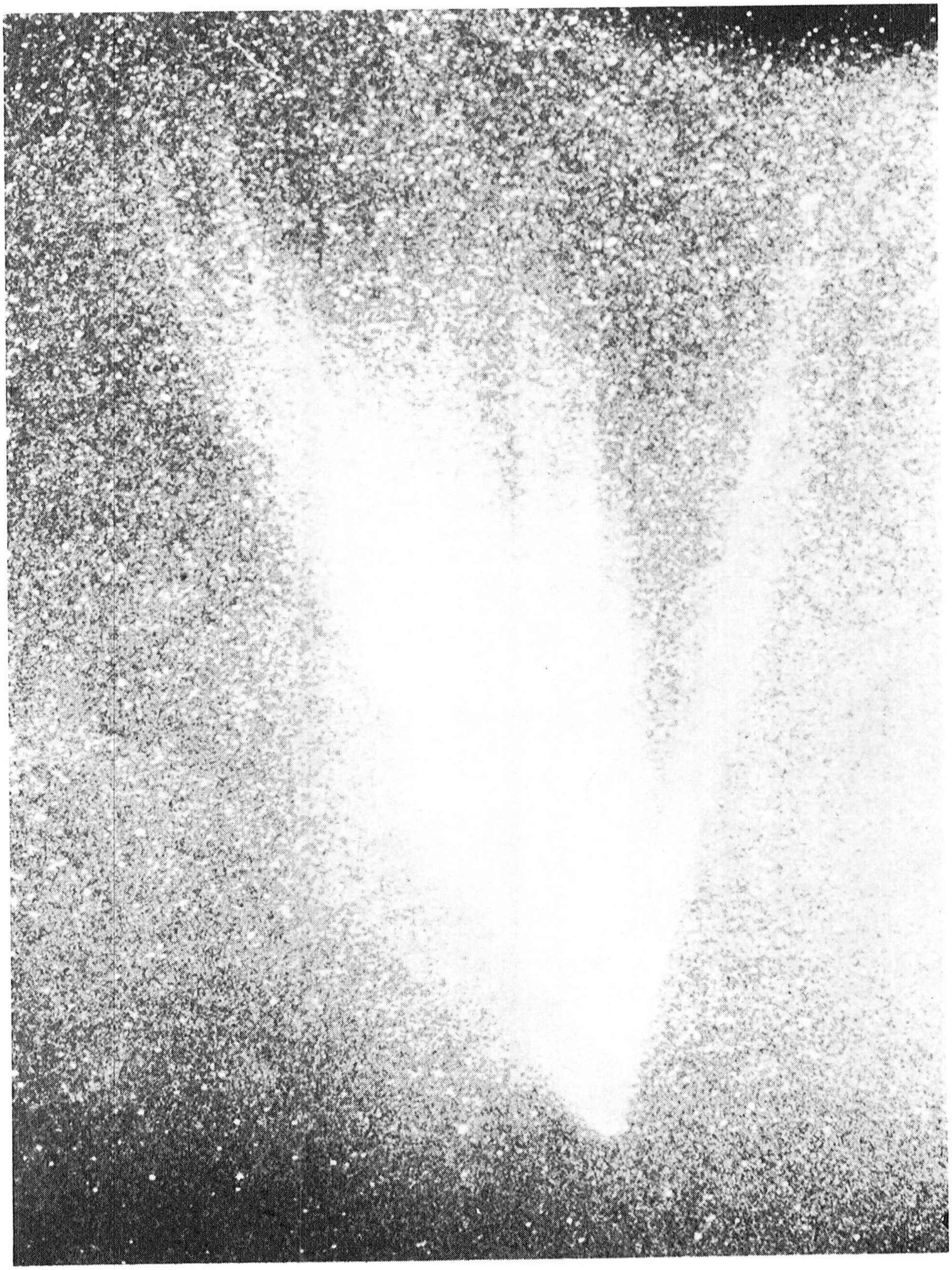

Fig. 10. Photograph of Comet West (1976 VI) taken in red light.

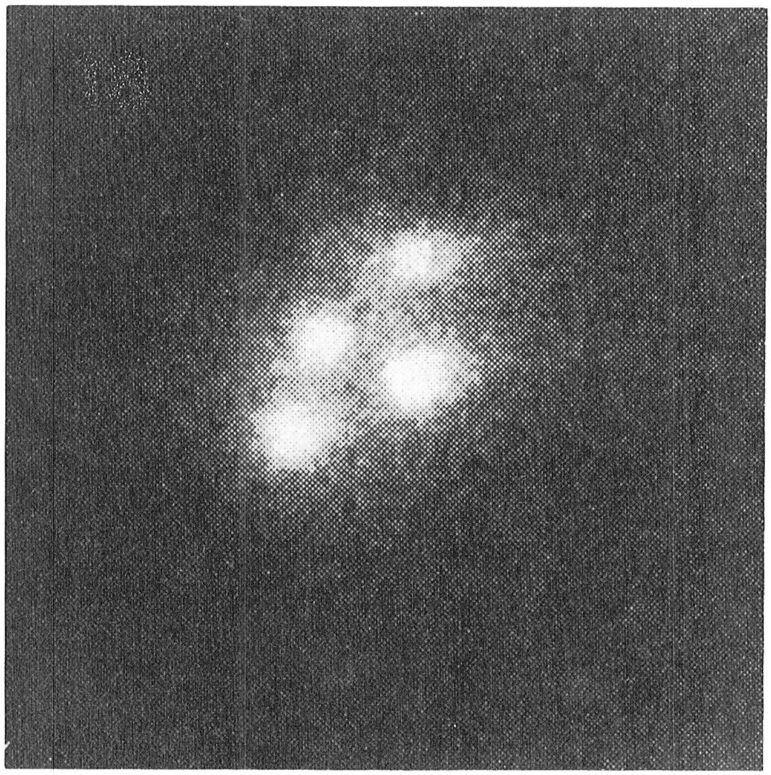

Fig. 11. View of Comet West (1976 VI) after its nucleus has split into four components.

The sublimating gases cause a small piece to move away at a greater relative velocity than a larger piece, because of the difference in surface-to-mass ratio.

A multiple nucleus will always separate. There is no force adequate to bring the pieces back together again. This, I think, is the most conclusive proof that a long-lasting comet must possess a single coherent nucleus. The observations show, indeed, that most comets do persist for a long time. Most of the short period comets show non-gravitational forces, either acceleration forward in the orbit, increasing the period, or backwards, shortening the period. About equal numbers show period increases or decreases, indicating a random character to polar axis directions. A calculation of the forces shows that the nuclei must be rather small to enable the sublimation, the jet action of escaping gases, to change the orbits perceptibly. Radii of periodic comet nuclei are the order of 1 km.

Figure 12 is my favorite comet picture; it is Comet Kohoutek taken from space. One is in ordinary light and the other is from neutral hydrogen, Lyman-alpha light in the very far ultraviolet undetectable through the Earth's atmosphere. The circle represents the Sun at the distance of the comet to illustrate the size of the neutral hydrogen cloud. Although not the first, this was an exciting verification of Biermann's deduction from my icy comet model. If water is one of the major constituents of a comet, there should be a huge hydrogen cloud. The loss rate of water is on the order of ten tons per second for brighter comets.

Earlier I mentioned the great scientific gains from Comet Kohoutek, due largely from research carried out with the aid of generous support by NASA. They are listed in Table 1. The radio observers first found

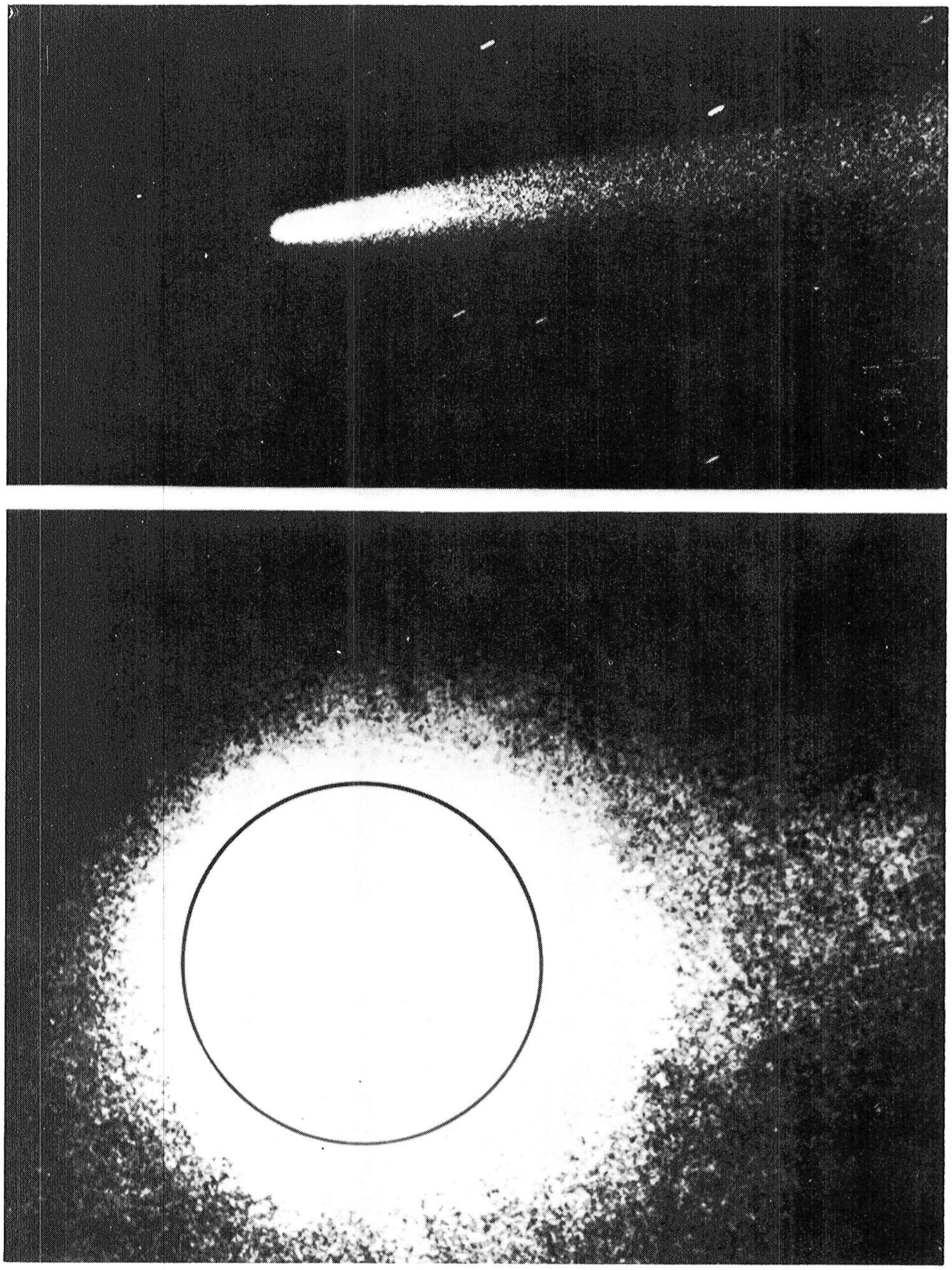

Fig. 12. Comet Kohoutek (1973 XII) as seen from space. (Top) Photograph in white light. (Bottom) Photograph in Lyman-alpha radiation. The circle represents the size of the solar disk.

TABLE 1

MOLECULES ADDED BY STUDY OF COMET KOHOUTEK (1963 f)

By radio	CH_3CN Methyl Cyanide
	HCN Hydrogen Cyanide
	also observed OH and CH
By optical	H_2O^+ in tail
By ultraviolet	C and O
By infrared observed	Silicate Band in tail
Not observed	CH_4, Methane
	NH_3, Ammonia
	Helium

methyl cyanide and hydrogen cyanide and also observed OH and CH, and more recently H_2O. Optically, for the first time, the water molecule was first identified via the H_2O^+ ion while the ultraviolet registered atomic transitions of neutral carbon and oxygen atoms.

In the infrared, the dust particles showed the ten-micron band of silicon, indicating that the particles are, indeed, silicates, as we would expect from meteors. Their nature and size has come more recently from Ney's work; they are usually smaller than one or a few microns and they have a slightly imaginary index of refraction, making them slightly absorbing. In the antitail (dust in the orbit plane seen sunward from the comet), Ney observes that the silicon band is absent, proving that the particles are larger.

Not observed are methane and ammonia which, although difficult to observe, one would expect to be among the primary substances in the comet. We really didn't expect much, if any, helium in comets, but it was looked for and not found.

For the materials in Table 2 I have used the term non-organic although the chemists correct me very quickly. Everything with carbon isn't necessarily organic. In any case the non-carbon material identified in the comets consists basically of the most abundant solar atoms that can form compounds -- hydrogen, nitrogen and oxygen. Near the Sun, at about three quarters of an astronomical unit, sodium shows in cometary spectra. In the sungrazing comets very near the Sun, all the lines appear that you would expect to find from heavier, fairly abundant atoms, such as found in meteorites or meteor spectra. Then, in the ion tails, are N_2^+, OH^+, and the water ion.

In the carbon category (Table 3), we again have quite an array of materials, mostly composed of carbon, nitrogen, oxygen and hydrogen.

TABLE 2

NON-ORGANIC MATTER IN COMETS

	NH, NH_2, O, OH, H_2O, H
Near Sun:	Na, Ca, Cr, Co, Mn, Fe, Ni, Cu, V
In Tail:	N_2^+, OH^+, H_2O^+ and silicate particles

TABLE 3

ORGANIC MATTER IN COMETS

C, C_2, C_3, CH, CN, CO

CH_3CN, HCN, CS

AND IN TAIL

CH^+, CO^+, CO_2^+

Clearly this material makes up the primary icy structure of the comet. We still have this mystery of identifying the parent molecules other than H_2O that produce the observed radicals.

I think Kohoutek, although it was a disappointment to the public, is a remarkable example of how much can be learned by concentrated effort. When everyone is excited and using his best observing techniques, whatever they are, and when all are working cooperatively, the result can be magnificent. We are all very grateful to NASA for the support they gave to that program. It did make it possible for so many observations and so many new results to be obtained from Kohoutek.

The physical structure of comets is still poorly known. The only tangible particles that we believe to come from comets are those collected in high altitude balloons and U-2's by Brownlee and his associates. Figure 13 depicts one of those aggregates from the high atmosphere that come in as micrometeorites. Öpik and I predicted long ago that tiny particles could sneak into the atmosphere without losing too much by heating. Note the one-micron scale at the bottom. The material looks like fish roe of sub-micron particles. I wish we had time to discuss them. They seem to be unique. Robert Walker was saying this morning that everytime you see one of those particles, you can predict what the composition is going to be.

Now a brief word about cometary orbits. Figure 14 shows the orbits of a few of the periodic comets going just beyond Jupiter. I won't persist with this except to say that these comets of short period have been disturbed by the planets, mostly Jupiter, from orbits with periods of millions of years which went out to something like 40,000 astronomical units from the Sun, as shown long ago by Oort. New comets, those that are making their first appearance in the inner solar system, have been proven conclusively by Marsden and his associates to have

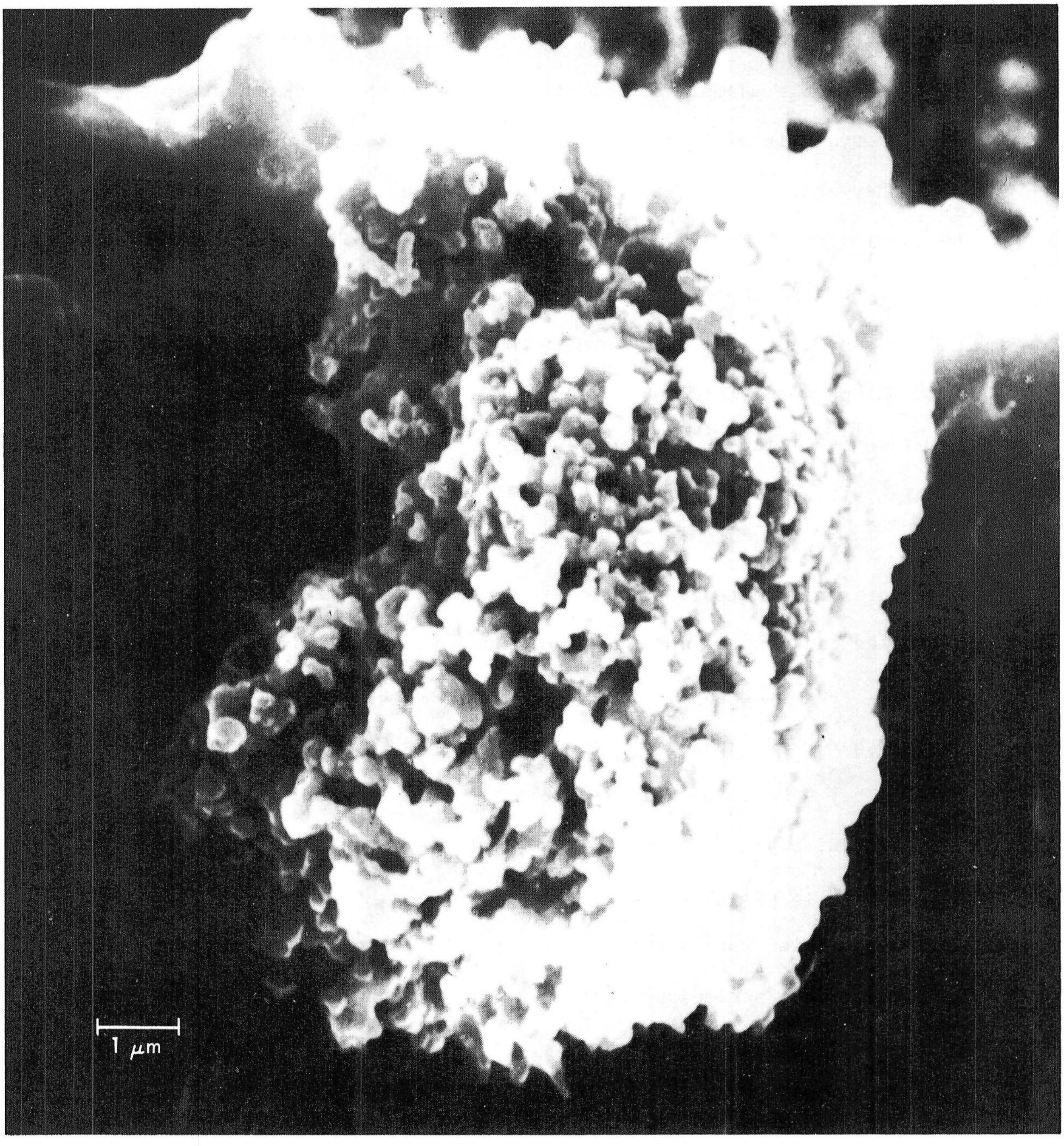

Fig. 13. Photomicrograph of meteoritic material collected on U-2 flight.

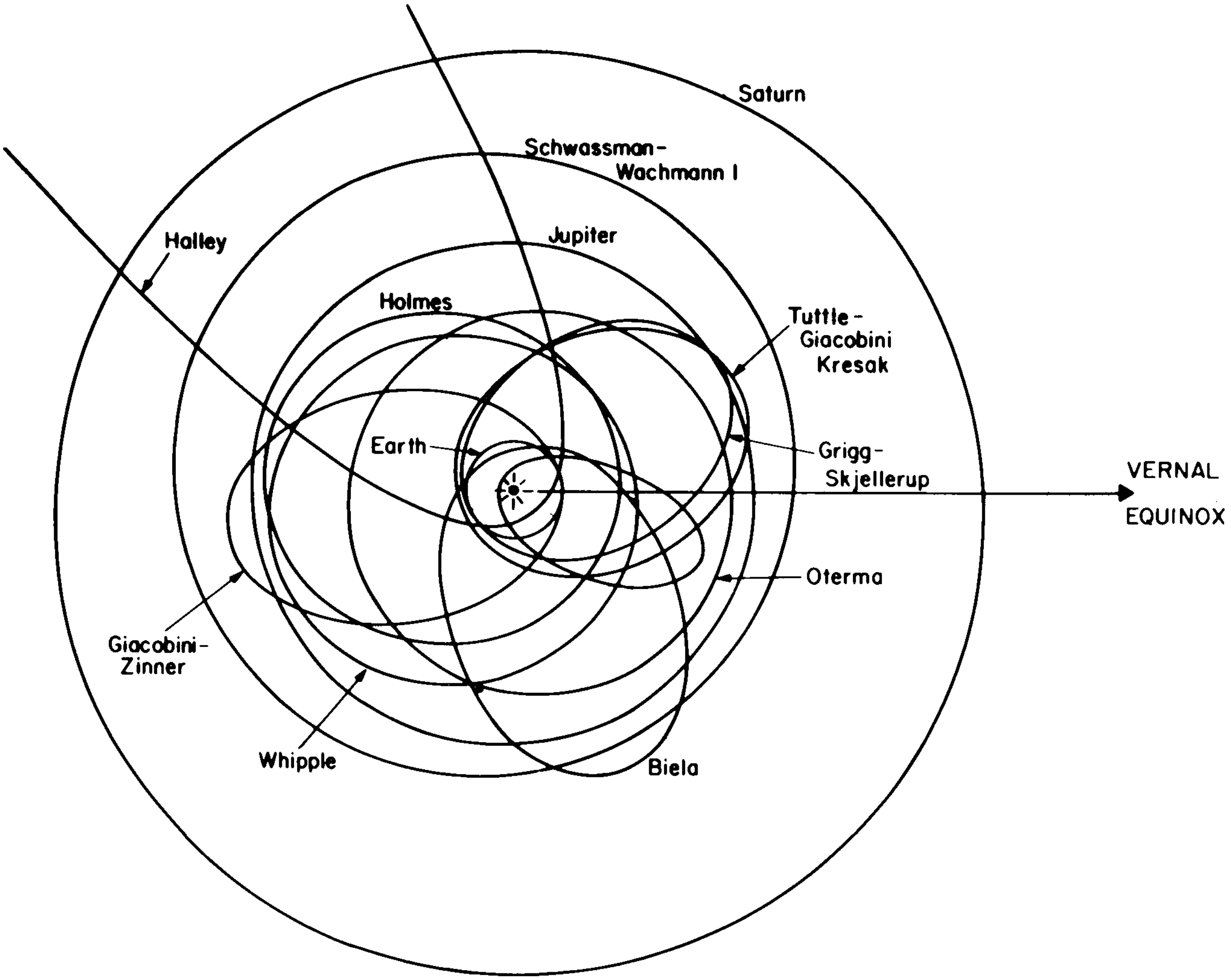

Fig. 14. Orbits of selected short period comets.

come from such great distances. The questions are: Where did they originate? How did they get into this great Öpik-Oort cloud which we know encompasses a solar centered volume of some 40,000 astronomical units radius?

In Figure 15 we see the great Trifid nebula, typical of many in interstellar space. They are huge gas-dust aggregates which we now know to be, indeed, the birth place of stars, clusters of stars, and, surely, of some solar-type systems. Such great clouds can collapse, perhaps from gravitational instability alone, perhaps helped by pressures from very bright stars or supernovae. The Trifid nebula is a beautiful example of one of these gas-dust, stellar incubators, illuminated by newly hatched stars.

For discussion let us look at an interpretation (Figures 16a and b) of the old Laplacian hypothesis. Since nobody has demonstrated a much better picture, I like these old drawings. The first shows the collapsing cloud and the second shows the planets developing in rings. Now we know that can't be true, at least directly from the nebula, but nevertheless, we do know that large clouds collapse. They must have great angular momentum. Therefore, they must develop flattened discs. Perhaps there actually was a Jupiter ring formed, as Larson suggested from early calculations.

We find that within Jupiter's orbit the materials of the terrestrial planets and the asteroids are earthy solids. The temperature must have been too high for ice to freeze out. When we go out beyond Saturn to Uranus and Neptune, the mean composition turns out to be just what you would expect if comets were the building blocks of these great planets. A much lower temperature would be expected to freeze out ices more

Fig. 15. The Trifid nebula.

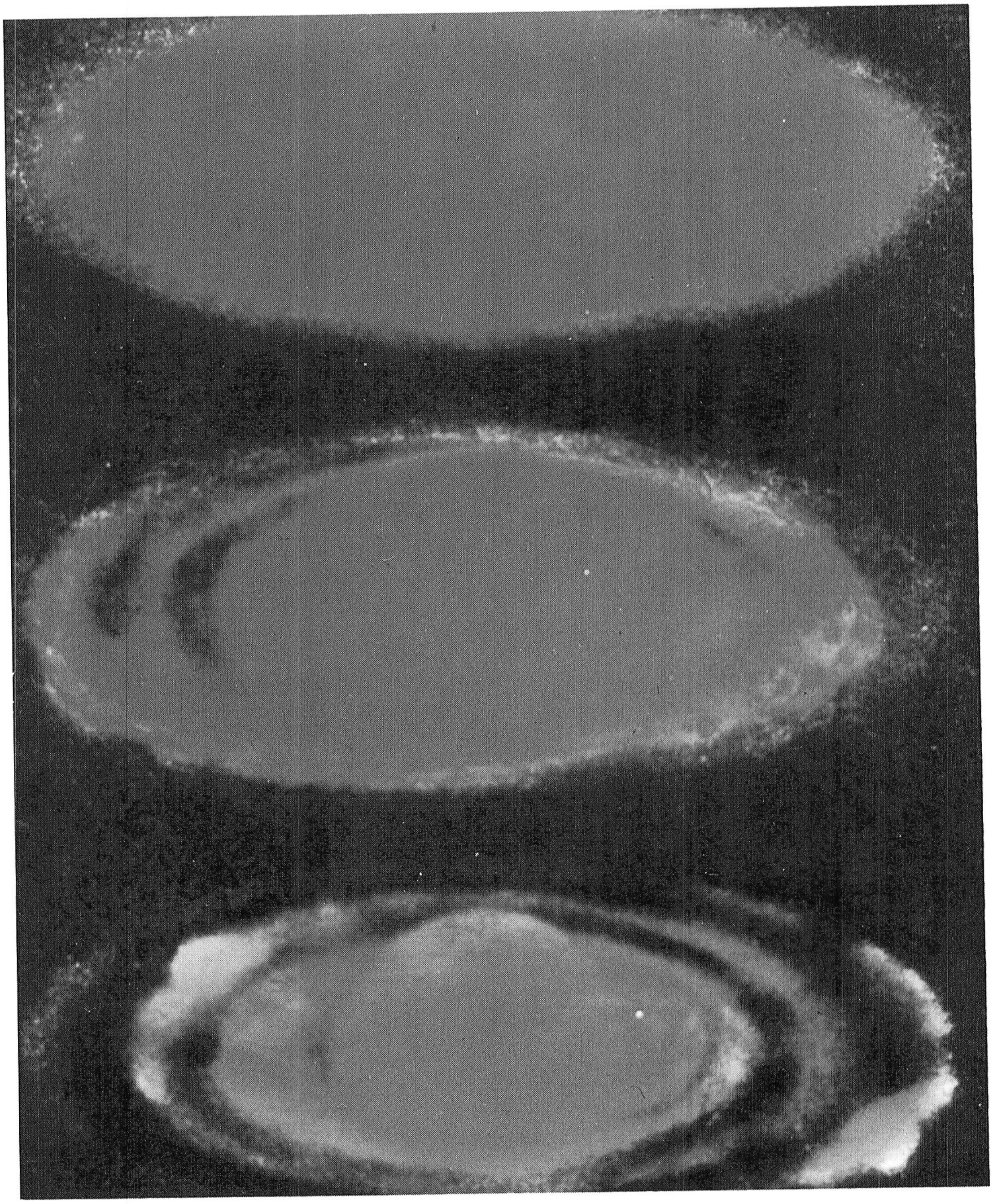

Fig. 16a. Model of Laplacian hypothesis of solar system formation: Collapsing cloud.

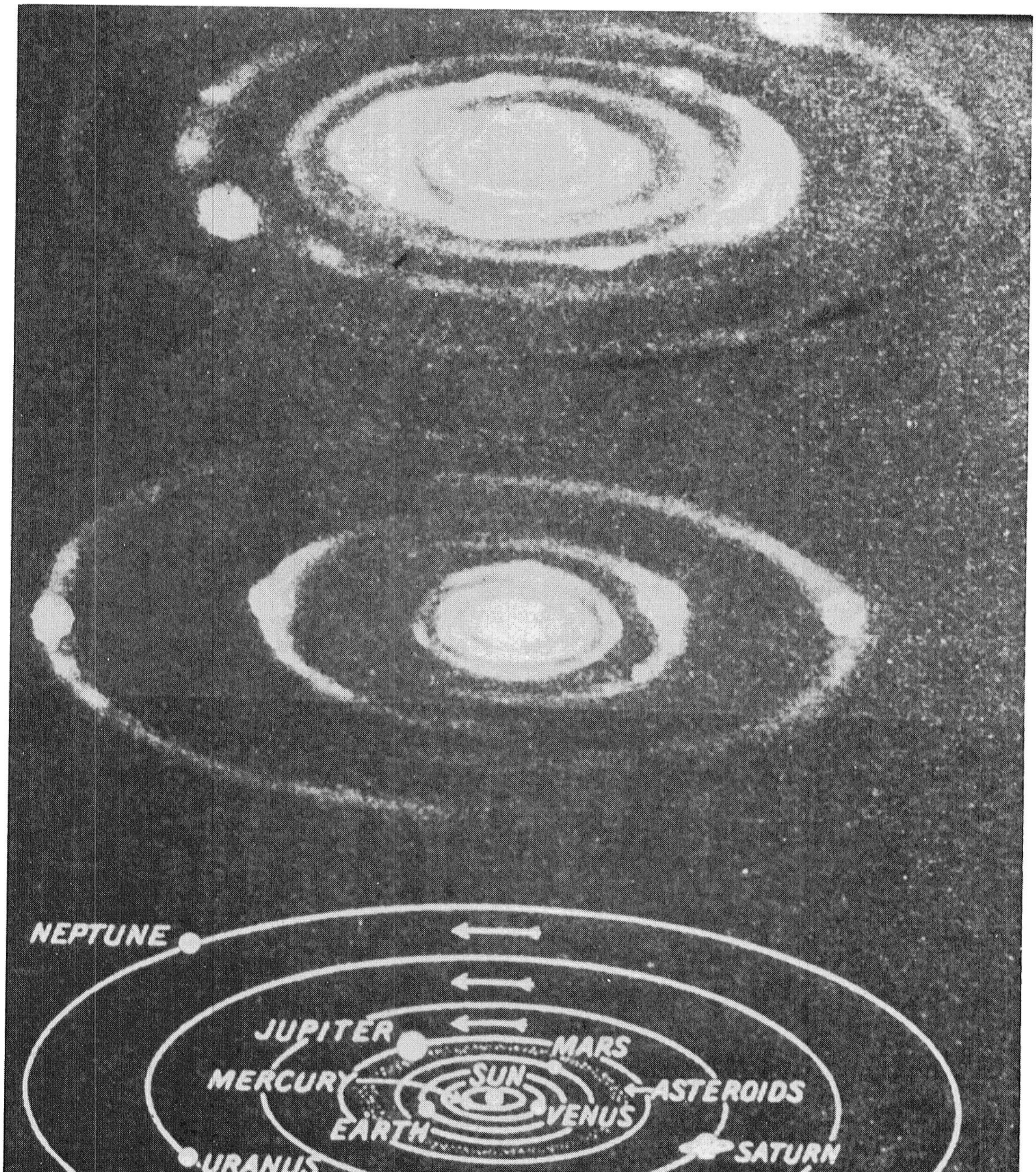

Fig. 16b. Model of Laplacian hypothesis of solar system formation: Planet development.

volatile than H_2O ice. I hope the missions to Uranus will give us the J_2 terms and other terms describing the distribution of mass with respect to the equator of Uranus so that we can learn more about the internal structure. At present, within the accuracy of the theory, the composition is almost exactly that of a frozen mix of solar material, about 98 percent hydrogen and helium, with carbon, nitrogen, oxygen, and heavier atoms as contaminants, retaining only the compounds that would freeze out at 50 to 80 K or at a somewhat lower temperature -- comets for all practical purposes.

If the inner planets, the terrestrial planets, are made up of planetesimals, then Uranus and Neptune are made of what I like to call cometesimals, dirty ice masses up to small and large comets. The question remains as to whether or not Uranus and Neptune formed first and then threw the remaining comets into bigger and bigger orbits by gravitational interactions. Öpik has done a number of important calculations on this problem.

As an alternative, Cameron is now suggesting that the Sun and the planets all formed concurrently in time. The entire system shrank as the Sun's increasing mass reduced the orbits of the growing planets. The solar nebula was quite massive. Finally mass was thrown out very quickly leaving comets in larger orbits because of the reduced central mass. The ejection took place in a fraction of a period for comets which were several hundreds of astronomical units from the Sun. Thus the distant comets were thrown into extremely elongated orbits that constitute the Öpik-Oort cloud.

In any case, I think we can say without any question that comet-like bodies, whether or not they are represented exactly by the comets we see today, were, indeed, the source of the outer planetary system. They were the building blocks beyond Saturn. They are the most fundamental material we know of, left over in the construction of the solar system. I believe the comets we see today are representative of this material, which must have amounted originally to hundreds of earth masses; we do not know how much. Certainly comets contributed significantly to Saturn. Saturn contains more of this type of material than Jupiter, which is nearer to a pure solar mix.

Much evidence points to the Earth's having lost its primitive atmosphere, requiring a later replacement. Some people believe the volatiles came from within. Possibly they came from comets. Suppose that the solar nebula was removed quickly and that there were a great many comets. I have suggested, but not yet proven, that they could have formed a temporary cometary nebula inside the orbit of Jupiter. This nebula could have contributed the volatiles to the Earth and quite possibly also the atmospheres of the other terrestrial planets. The only supporting evidence we have at the moment can also be explained in other ways. It is the lack of the light noble gases. We do not expect noble gases to be abundant in comets unless the temperatures were unbelievably low, freezing the gases. Knowledge of the basic elemental chemistry of comets will answer the question.

The chemistry and the physical structure of comets, including isotopic studies will be highly desirable to answer other questions such as the oxygen anomaly, the oxygen 16, 17, and 18 ratios, as Clayton has discussed, and the carbon 13 and 12 ratios. The studies of these materials will tell us much about how the comets originated.

Now a word about the philosophy of the study of comets. In mission planning there is a tendency to say that the study of the phenomena should play a secondary role as distinguished from the study of the nucleus and the actual matter in the comet. I dislike this philosophy because the phenomena themselves, such as the plasma physics, do tell us something about the nature of the material. In planning cometary research, I do not think one should properly distinguish between the phenomena and the body itself, the nucleus of the comet, any more than in the study of the human body one should separate the mind and nervous system from the chemistry of the physical body. They are all a part of the same grand problem. Anything new learned about the phenomena is important in understanding the nature and orgin of comets.

The rotation of comets, for example, may not be a basic property indicative of the original conditions, because it can be induced by jet action. Nevertheless, rotation is important to study. We know the periods, possibly, of two comets. My current work on P/Schwassmann-Wachmann 1 places its period at just about five days and gives the orientation of the pole. Recently, Fay and Wisniewsky have photometrically found a period of about five hours for P/D'Arrest, but not the polar orientation. Of 34 comets, about half are turning retrograde and half prograde.

The study of the phenomena of distant comets such as P/Schwassmann-Wachmann 1 provides considerable evidence that much cometary material is in an amorphous icy state. When cometary material is heated to a relatively low temperature, somewhat over 100 K, copious sublimation occurs. I find evidence also that a crust forms, suggesting cementing action by heat, even at these low temperatures. This seems to happen in comets generally.

Finally, in summary, the study of comets, particularly space missions to comets, provides the opportunity to learn a great deal about the sequence of events that led to their formation and will provide major clues about the formation of our solar system. We should be able to learn how volatiles arrived on the Earth and, indeed, the basis for the existence of life on the Earth.