CONNECTIONS BETWEEN COMETS AND PLASMAS IN SPACE

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From the point of view of plasma physics, comets are unique and fascinating objects. Many fundamental aspects of cometary structure and dynamics are known to involve plasma processes, but in a large number of areas the basic mechanisms are poorly understood. It seems certain that many of these basic questions about comets will remain open until detailed in situ measurements are available. In terms of general plasma physics, it also seems certain that we will learn much by achieving such detailed understanding of comets, since many of the dynamical processes in the cometary system represent unusual examples of very important, widespread natural phenomena.

I would like to confine attention here to four general areas involving comets and plasma physics. These are:

1. The comet as an obstacle in the solar wind,
2. The nature of the plasma flow,
3. Collisionless shocks,
4. Plasma processes in the comet tail.

In terms of the first of these topics, it has been known for many years that the comet-solar wind interaction is very different in character from the wind interaction with other objects. The bottom part of Figure 1, which is similar to a drawing shown earlier by Dr. Whipple, depicts a widely accepted concept of the comet-wind interaction in terms of development of a contact discontinuity and an upstream collisionless shock. One point that is highly unusual here concerns the scale of the system, since along the sun-nucleus line the contact surface is at $r \simeq 10^5$ km, even though the nucleus itself is presumably only a few kilometers across.

The scale values were derived many years ago by Biermann et al. (1967), and the top panel in Figure 1 shows one of their numerical examples,

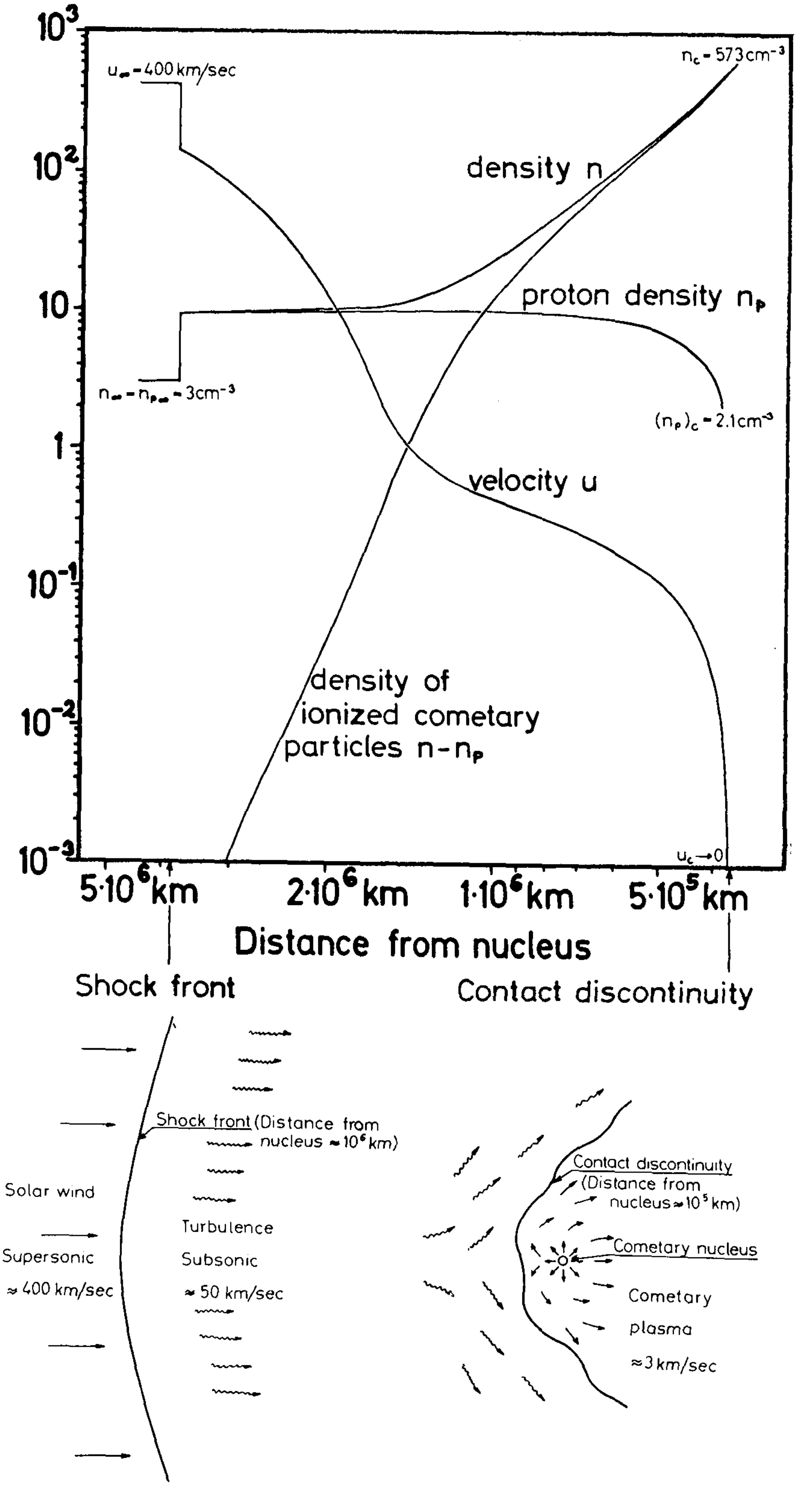

Fig. 1. (Bottom) Configuration of plasma interaction of solar wind with a comet. (Top) Calculated velocity and density profiles upstream of a comet.

calculated using a simplified comet model. One basic point that is unusual has to do with the very low gravity of the nucleus and the associated large scale height. A related feature involves the very large extent of the neutral gas cloud, which leads to continuous production of newly-ionized cometary particles at huge distances from the source. These effects lead to a very gradual decline in plasma density over an enormous distance from the nucleus, and this yields the expected large scale for the comet-wind interaction, as shown in Figure 1.

The top part of Figure 2, taken from the Comet Halley Science Working Group report, shows more details of the expected wind-comet interaction, including the development of an extended plasma tail, and the presence of a very large neutral hydrogen corona. In order to fit all of these important cometary elements on a single drawing, it is necessary to use a logarithmic distance scale, as indicated here. Of course, the logarithmic distance scale does tend to obscure many important and unusual characteristics of the comet-wind interaction. For instance, it must be noted that the outermost H-corona contour shown here passes through the sub-solar point at a radius of about 4×10^7 km $\approx$ 0.25 A.U. Moreover, this sketch indicates a shock-to-contact surface subsolar standoff ratio of about $(2 \times 10^6/10^4) \approx$ 200, but it obscures the fact that this differs greatly from the conventional fluid-dynamics results which leads to a ratio of 1.4. In order to put all of this in a proper perspective, the bottom panels of Figure 2 show corresponding details of the Earth-wind and Venus-wind interactions on the same relatively unfamiliar logarithmic distance scale. It is apparent in the lower panels that the shock forms at a distance that is only 40 percent upstream from the subsolar obstacle distance (magnetopause or ionopause), and that the obstacle itself has a dimension that is comparable (within an

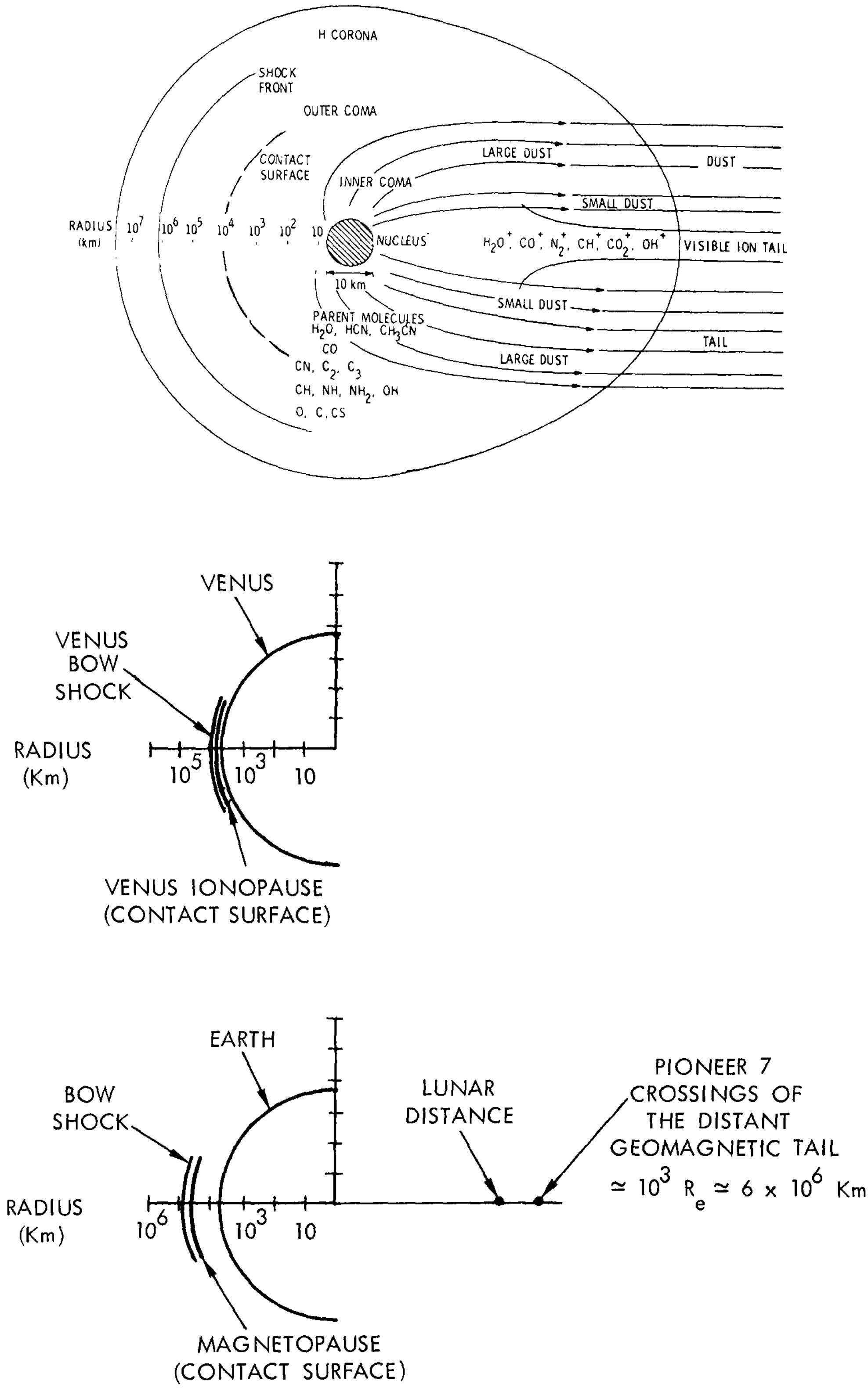

Fig. 2. (Top) Sketch, on a logarithmic scale, of the several regions of the comet-solar wind interaction. (Bottom) Similar logarithmic sketches of the solar-wind interaction processes at Venus and Earth.

order of magnitude) to that of the parent body, in great contrast with the case for the comet. Moreover, the Pioneer-7 information concerning the extent of the Earth's tail shows that the comet tail also has an exceptional length. Recently Intriligator *et al*. (1977) discussed Pioneer-7 data in the anti-solar region at 3000 R_e and showed that tail-related changes in the plasma parameters were measured just beyond the point shown in Figure 2. However, since plasma tails for comets are extremely easy to detect, we know that the cometary structures generally do have huge scales, as indicated at the top of Figure 2.

There is no corresponding firm information, from optical or other remote sensing observations, on the position of the contact surface and bow shock, and there is really no firm knowledge that a well defined shock exists. What we do know is that the H-corona spills out in all directions so that a large population of neutrals from the comet atmosphere will be present in the upstream solar wind. Figure 3, taken from a forthcoming paper by Lillie (1978) shows a photograph of Comet Bennett with superimposed hydrogen intensity contours derived from the University of Colorado ultraviolet instrument on OGO 5. The existence of this huge cloud of neutrals in the upstream region leads to some real uncertainty about the formation and physics of the comet bow shock. Wallis (1973) pointed out that when the neutrals are ionized in the upstream region, these "newly-born" ions are picked up by the solar wind. The high-mass upstream ions then load down the incoming solar wind, and this mass loading can ultimately lead to subsonic flow, which does not produce any collisionless shock at all. Thus, Wallis questioned the conventional assumption that a bow shock forms upstream from the comet. Similar questions have been raised about the wind-Venus interaction, but since the comet gravity is so low, the

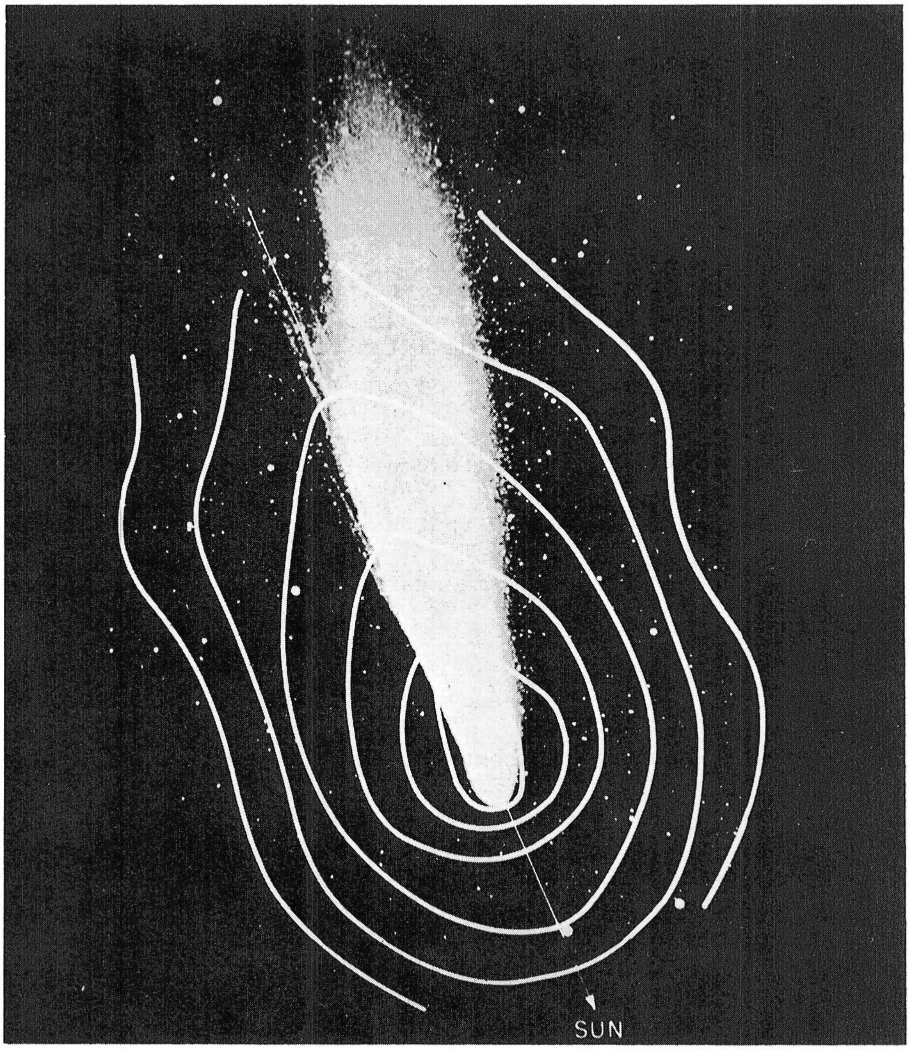

Fig. 3. Lyman-alpha brightness contours superimposed on a photograph of Comet Bennett. (After Lillie)

comet-wind interaction is the one most likely to lead to a thick, neutral-dominated interaction of this type.

This uncertainty concerning the cometary bow shock is only one of many open questions involving plasma flows. Figure 4, taken from a paper by Wallis and Dryer (1976), illustrates many of the flow regimes that are possible in the neighborhood of the comet. Table 1 defines the different regions identified in the figure. One very novel flow configuration is indicated here. Specifically, Wallis and Dryer pointed out that the tail-ward flow, which is initially subsonic and sub-Alfvénic, may involve formation of an internal shock at the interface with the supersonic wake. This type of internal shock has recently been discussed in terms of radial outflow models for the Jovian magnetosphere (Kennel and Coroniti, 1975), and it is interesting to speculate that studies of flows around comets may provide direct information on plasma systems dominated by internal energy sources.

The large-scale dynamical phenomena that develop in the ion or plasma tails of comets are known to be controlled to a large extent by microscopic plasma physics processes, and some of the more important areas of investigation are summarized in Table 2. Figure 5, taken from a paper by Niedner and Brandt (1978) vividly illustrates the great complexity and variety of the large scale spatial and temporal variations detected in comet tails. The figure shows Comets Borrelly (upper left), Halley (upper right and lower left), and Bennett again (lower right). It is clear from these photographs that the plasma tails exhibit significant spatial non-uniformities. When the large scale of the comet tail and the relatively slow speed of the solar wind are taken into account, it also becomes clear that local conditions in comet tails exhibit rapid variations with time.

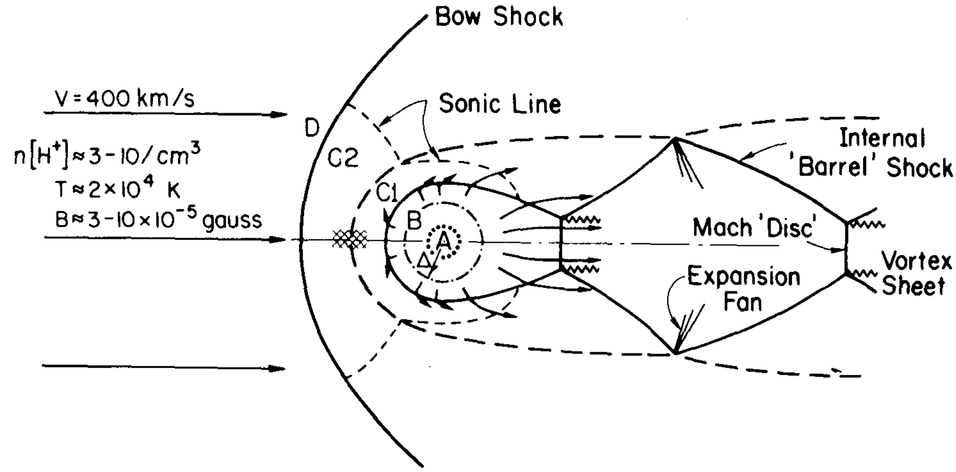

Fig. 4. Wallis and Dryer's (1976) postulated configuration of comet-solar wind interaction processes.

Table 1. Possible Flow Regions Upstream of the Control Source (from Wallis and Dryer, 1976)

Flow Regime	Transition	Comet/Solar Wind
A. Subsonic source flow		Drag and heating of dust; evaporation of icy grains
	Continuous, within a few source radii	
B. Supersonic radial expansion		Photodissociative heating of gas Ionization + cooling + recombination $P_{stag} \approx r^{-1}$, large but finite M
	Shock, where $P_{stag} = O(P_{\infty})$	
C1. Subsonic interior plasma		Enhanced cooling gives a denser and narrower region
	Contact discontinuity (perhaps flute or Kelvin-Helmholz unstable)	
C2. Subsonic exterior plasma		Wide region controlled by mass addition and cooling of new suprathermal ions
	Bow shock	
D. Supersonic (-Alfvénic) streaming		Mass addition reduces effective mach number to $M \lesssim 2$

Table 2. Plasma Processes in Comet Tails

RECONNECTION OF MAGNETIC FIELD LINES

Stability of X-nulls; tail disconnection; particle acceleration in "fireball" regions; substorm analogs

DEVELOPMENT OF INTERNAL TAIL INSTABILITIES

Onset of filaments, rays, helical structures; viscous interactions at the tail boundaries; "amplification" of the piled-up interplanetary magnetic field, current-driven discharges, and ionization enhancements (anomalous resistivity)

LARGE SCALE DYNAMICS AND VARYING INTERPLANETARY CONDITIONS

Plasma tail disconnection and sector boundaries; changes in tail orientation ("windsock"); possible "flareup" in association with interplanetary blast waves

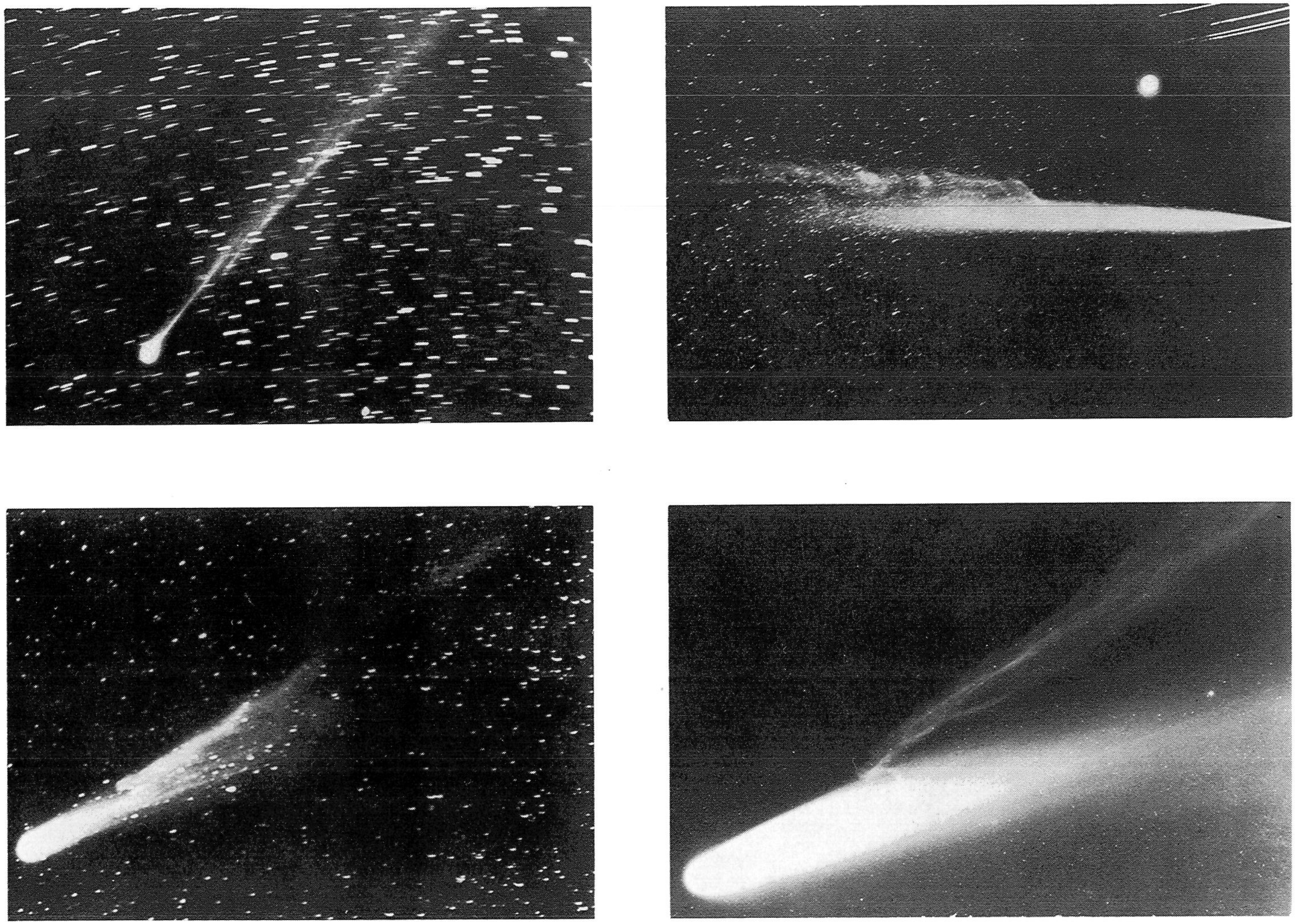

Fig. 5. Photographs of Comets 1903 IV Borrelly on July 24, 1903 (upper left), 1910 II Halley on May 13 and June 6, 1910 (upper right and lower left), and 1970 II Bennett on April 4, 1970 (lower right). The 1903 IV and June 6, 1910 photographs of 1910 II are Yerkes Observatory photos. The May 13, 1910 photograph of 1910 II is from Lowell Observatory and the 1970 II photograph is from K. Lübeck at Hamburg Observatory.

This conclusion should not be very surprising because our present understanding of the Earth's magnetic tail (which was initially conceived to be similar to the tail of a comet) shows that the tail and the plasma sheet are intrinsically non-uniform and non-steady. Figure 6, taken from a recent review by Russell (1976), shows a snapshot of the inhomogeneous structure of the tail (left side), and an idealized sketch of the anticipated large scale temporal changes that are thought to develop during various phases of a substorm (right side). The types of local measurements that lead to these general models are indicated in the next few figures. Figure 7 shows how intense, low-frequency magnetic turbulence levels are detected in association with high proton flow velocities near the neutral sheet in the Earth's tail (Coroniti et al., 1977), and Figure 8 shows Frank's (1976) idealization of the magnetotail "fireball" model, in which field annihilation at an X-type null provides the source of streaming energy for protons. The fireball and the field reconnection mechanism are not completely understood at present, but it is clear that plasma acceleration does occur in the Earth's magnetotail, that the process is a very fundamental one, and that it is associated with large-scale dynamical changes in the entire magnetosphere.

Figure 9 shows other aspects of IMP-7 and -8 magnetotail plasma probe measurements that are indicative of different local acceleration processes. Frank et al. (1976) detected energetic oxygen ions in the distant tail, and they speculated that the appearance of O^+ ions in this region is associated with the acceleration mechanism for those precipitating auroral electrons known as "inverted V" events. All of these plasma acceleration processes in the Earth's magnetosphere may have cometary

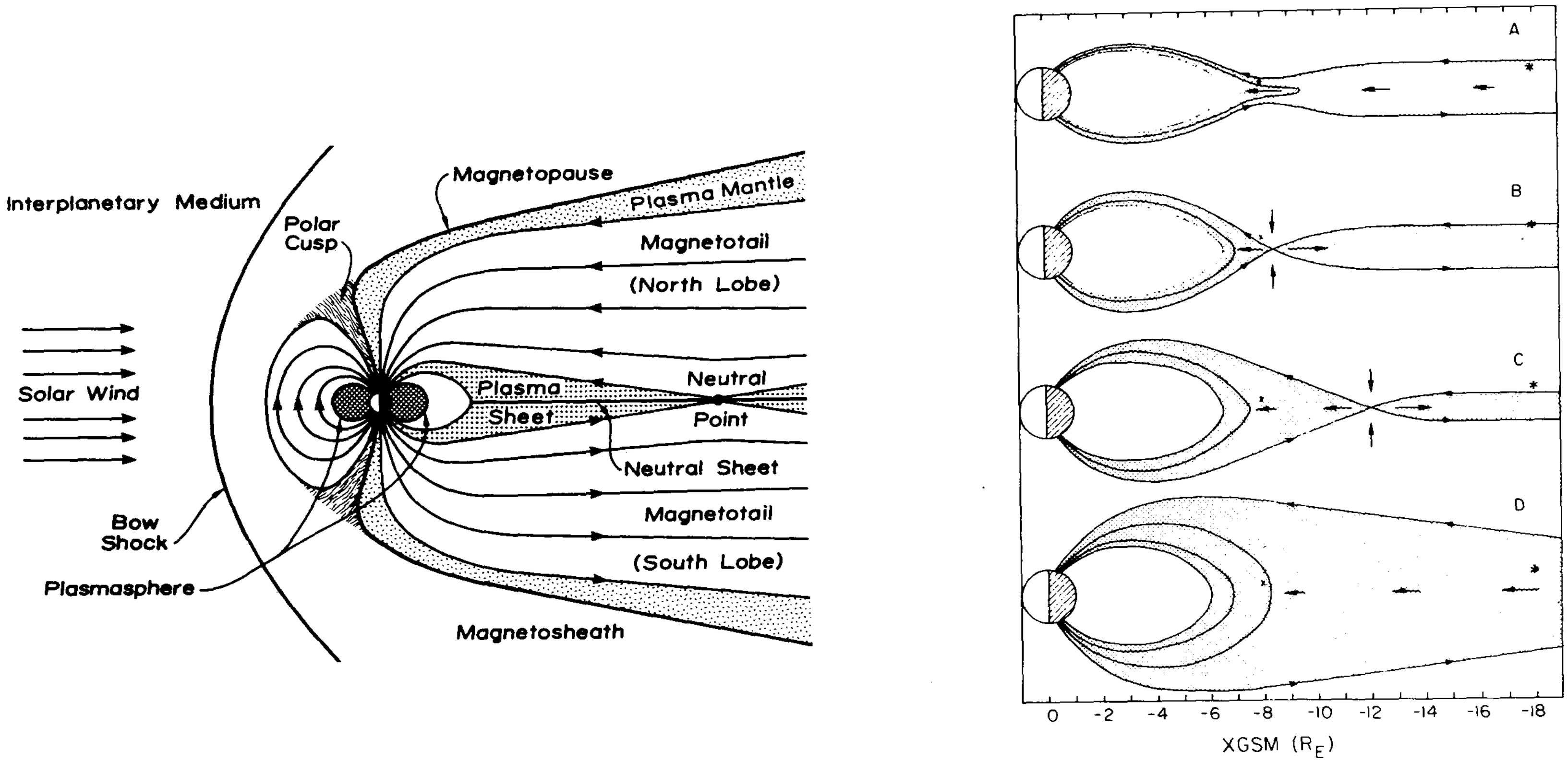

Fig. 6. (Left) Noon-midnight meridional cross-section of the magnetosphere. (Right) Conceptual model of the initiation of the expansion phase and recovery phase of substorms in which a neutral point is formed near the Earth and then recedes. (From Russell, 1976)

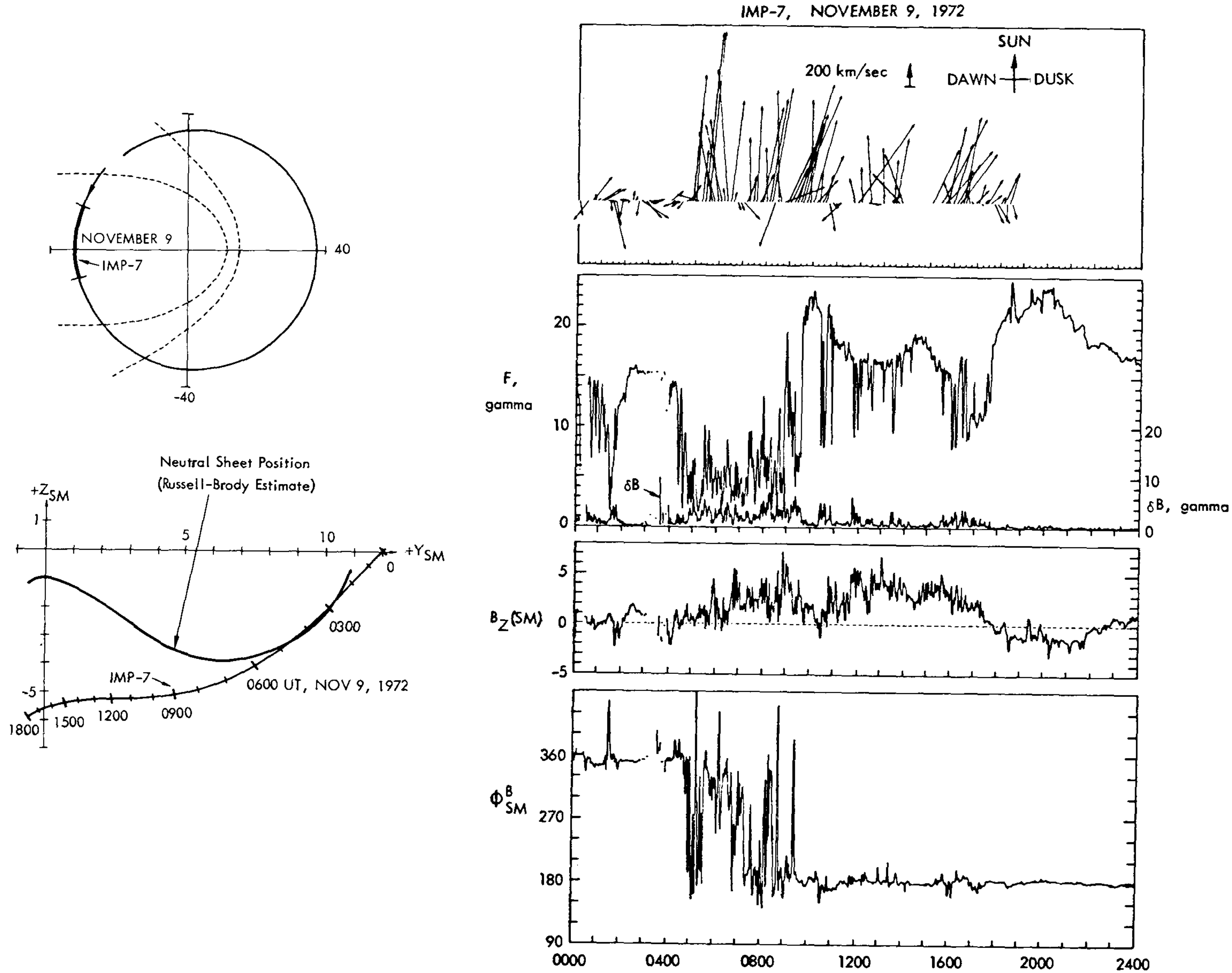

Fig. 7. (Left) The IMP-7 location in the geomagnetic tail. (Right, from top to bottom) The plasma flow velocity vector, the magnitude and disturbance level of the magnetic field, and north-south component of the magnetic field, and the equatorial angle of the magnetic field during a period of intense turbulence observed in the geomagnetic tail by IMP 7.

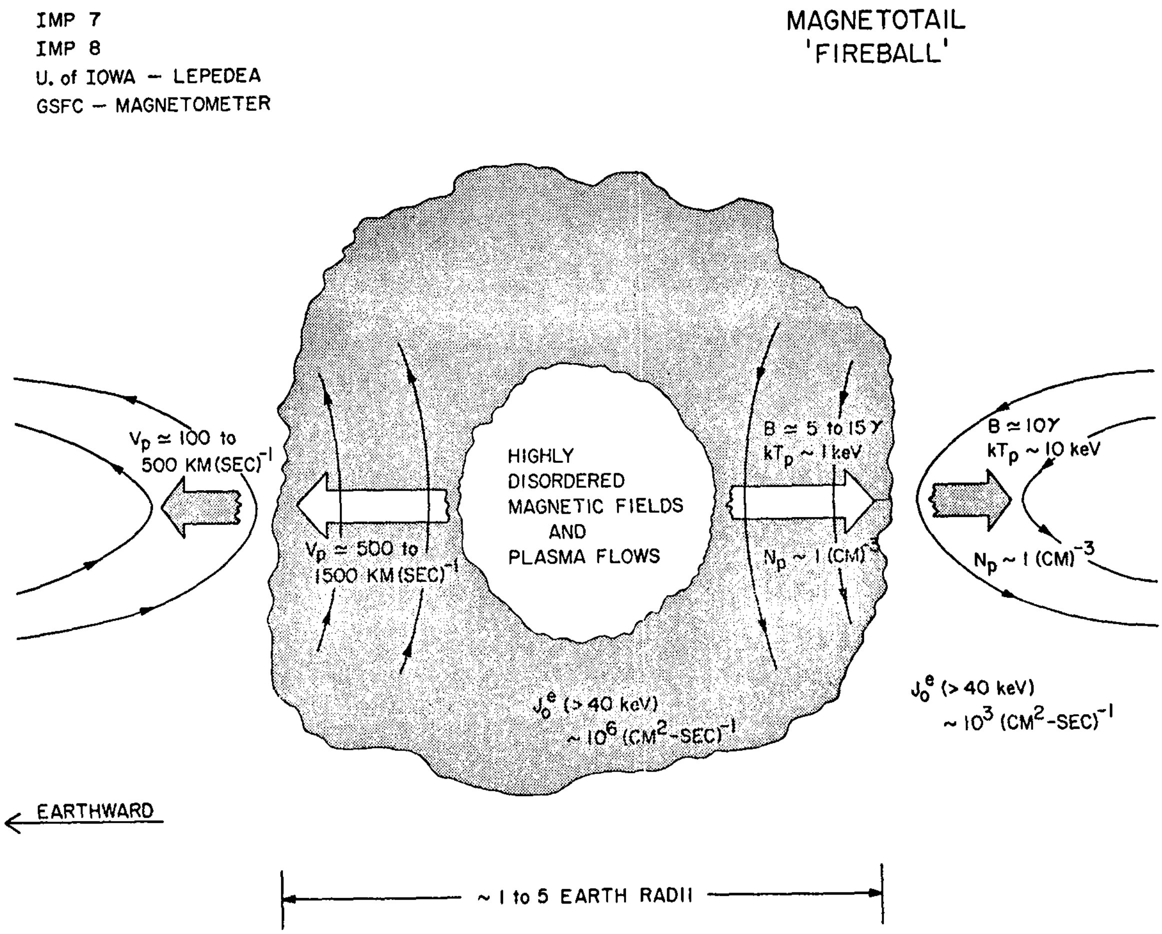

Fig. 8. Frank et al.'s (1976) model of a magnetotail "fireball."

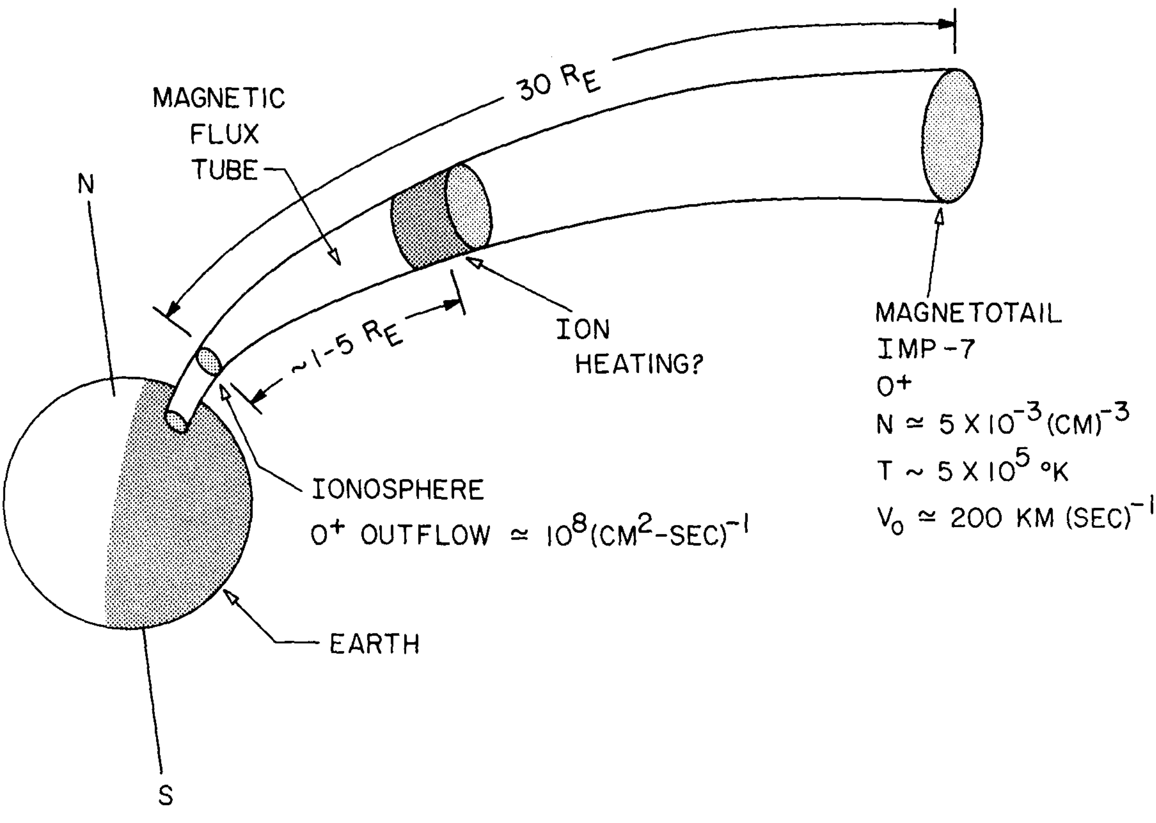

Fig. 9. Model of ion acceleration associated with auroral phenomena. (From Frank et al., 1977)

analogs since cometary "outbursts" or "discharges" are thought to have origins related to substorms and aurora on Earth (Ip and Mendis, 1976).

By now it should be apparent that the data displays involving the geomagnetic tail are primarily concerned with the region fairly close to Earth. These regions, where "fireballs" have been detected, are certainly very important and very interesting, but in terms of the scale of a comet, the IMP-7 and -8 measurements are scarcely in the tail at all. The Pioneer-7 and -8 deep space probes did yield a few crossings of the distant geomagnetic tail, as shown in the top panel of Figure 10 (Intriligator et al., 1969), during which plasma probes measured very rapid changes in the distribution functions, as shown in the bottom of Figure 10. However, it has never been clear whether or not these plasma variations represented spatial or temporal changes, or whether they were associated with internal plasma instabilities or changes in the solar wind itself.

Of course, the geomagnetic tail is not luminous, and we can only carry out multiple point measurements with an expensive array of spacecraft observing platforms. However, the natural luminosity of a comet tail provides an exceptional opportunity to study the dynamics of an enormous plasma "column," and to separate spatial and temporal variations, as well as to distinguish changes driven by solar-wind fluctuations from those associated with local instabilities.

An example of the possibilities is shown in Figure 11. Notice the large "bend" in the comet's tail (Brandt and Rothe, 1976). Niedner et al. (1978) tested the wind-sock theory of comet tails by relating changes in solar wind properties (measured on IMP 8) to this large-scale

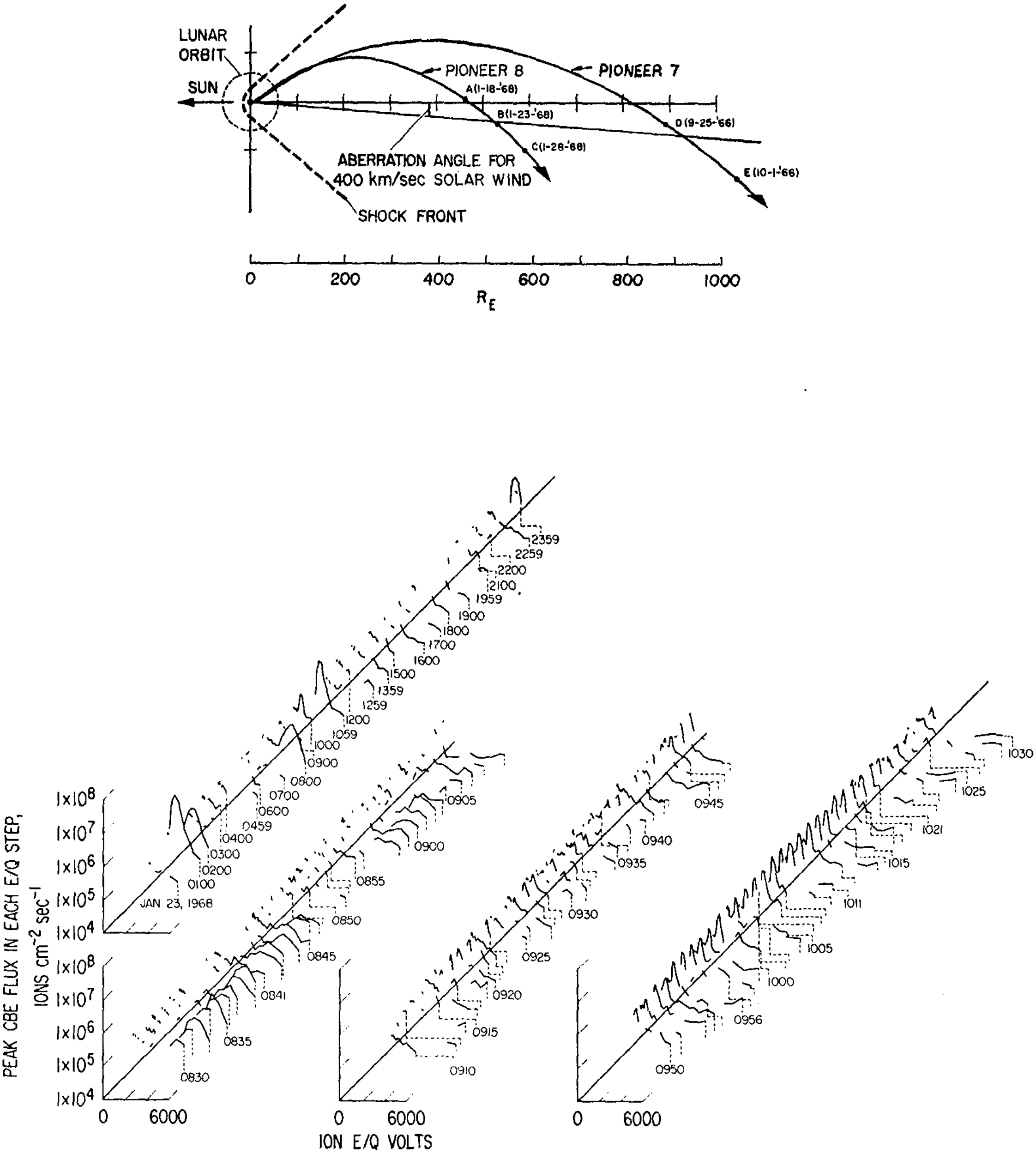

Fig. 10. (Top) Ecliptic projection of trajectories of Pioneers 7 and 8. (Bottom) Ion spectra in the geomagnetic wake observed by Pioneer 8 on January 23, 1968.

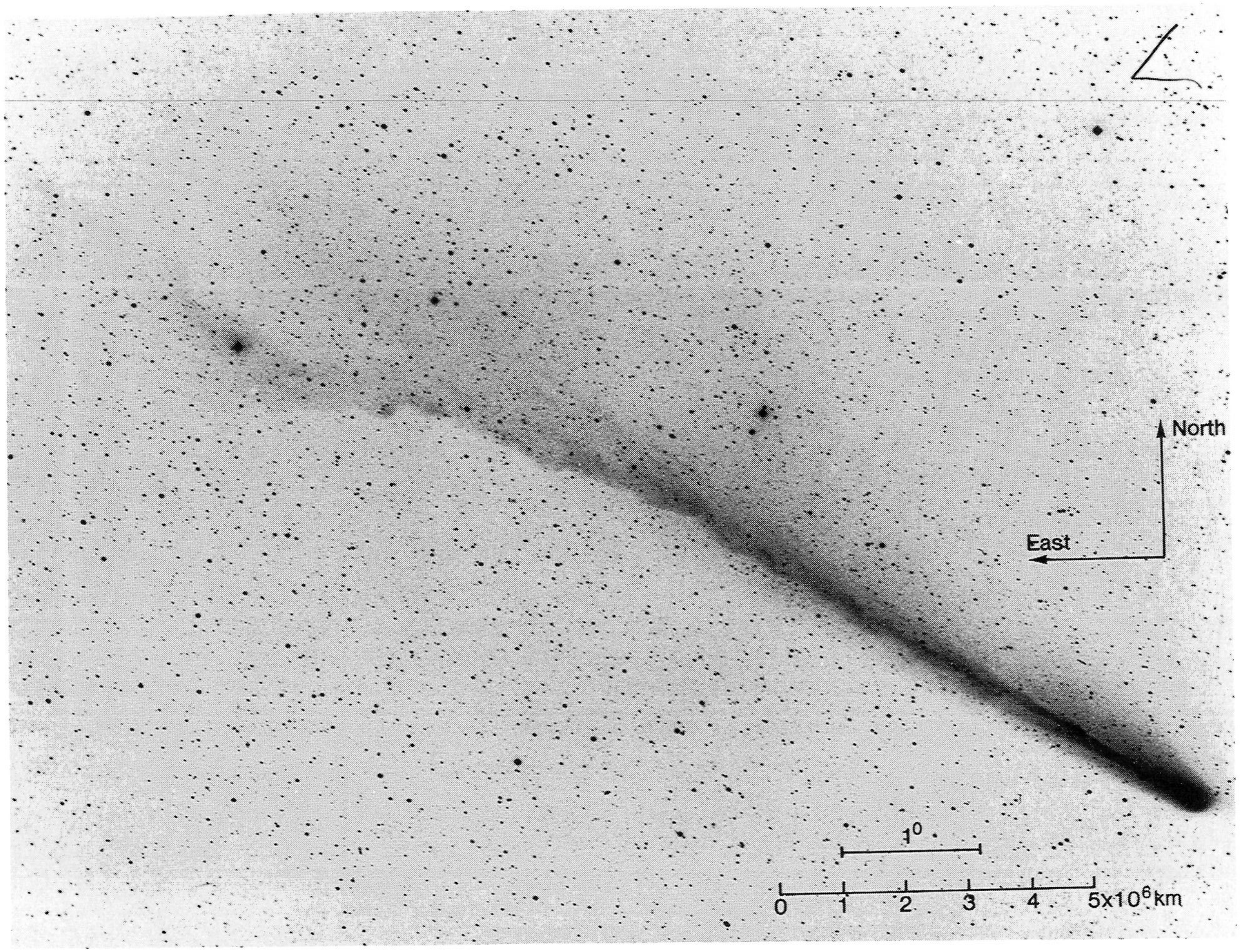

Fig. 11. JOCR photograph of Comet Kohoutek on January 20, 1974.

disturbance in tail direction. Excellent agreement was obtained. It seems that comet tails are very effective and sensitive probes of changing conditions in the interplanetary plasma.

Niedner and Brandt (1978) also demonstrated that extremely important and exciting plasma physics, involving magnetic field merging, reconnection, and "disconnection" can be uniquely studied in cometary ion tails. Figure 12 shows the fundamental points, which are based on the concept that the interplanetary mangetic field is "hung up" in the ionosphere of the comet. For a given interplanetary field orientation, this piled-up field becomes extended and it drapes around the comet to form a plasma tail, as shown in the upper left panel. The concept of "disconnection" is associated with the fact that the piled up field orientation must change if the interplanetary field orientation changes. Thus an advancing null field, such as the sector boundary indicated here, will induce a momentary null in the piled-up field, the existing tail will become disconnected, it will move off in the anti-solar direction as shown, and a new tail with opposite field orientation will form. Figure 13, taken from the paper by Niedner and Brandt (1978), shows an example of the formation of a severed or disconnected tail for Comet Morehouse; the top photograph was taken at 20^h57^m GMT on September 30, 1908 and the lower one at 19^h43^m GMT on October 1. Niedner and Brandt analyzed a number of other cases (including the tail structural changes shown in Figure 5) and they presented convincing evidence for magnetic field line reconnection in response to sector boundaries. When remote sensing observations of this type are combined with *in situ* measurements, it is clear that comet studies will provide new fundamental information on the field annihilation mechanism.

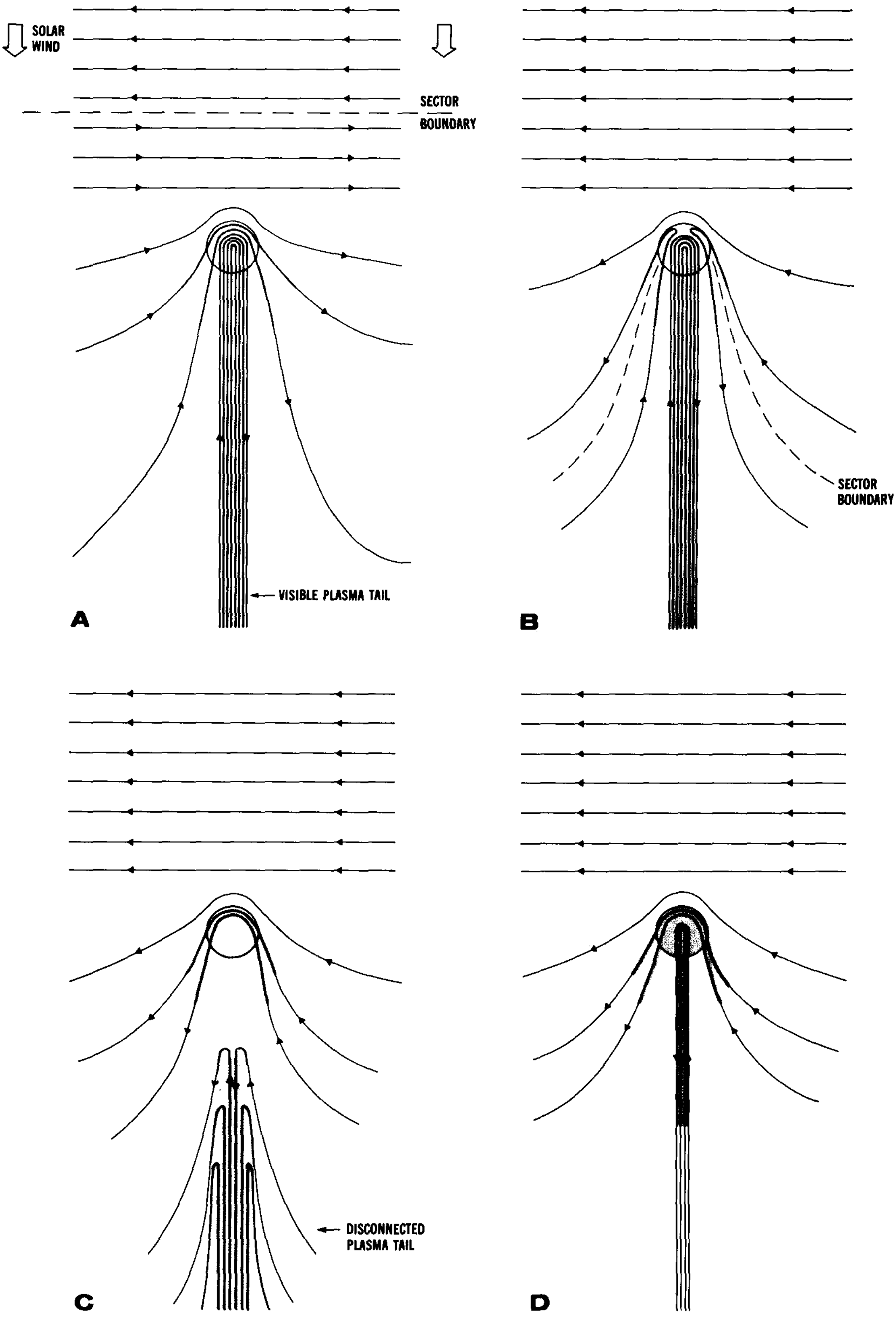

Fig. 12. Process of disconnection of a comet tail in response to the passage of an interplanetary sector boundary. (From Niedner and Brandt, 1978)

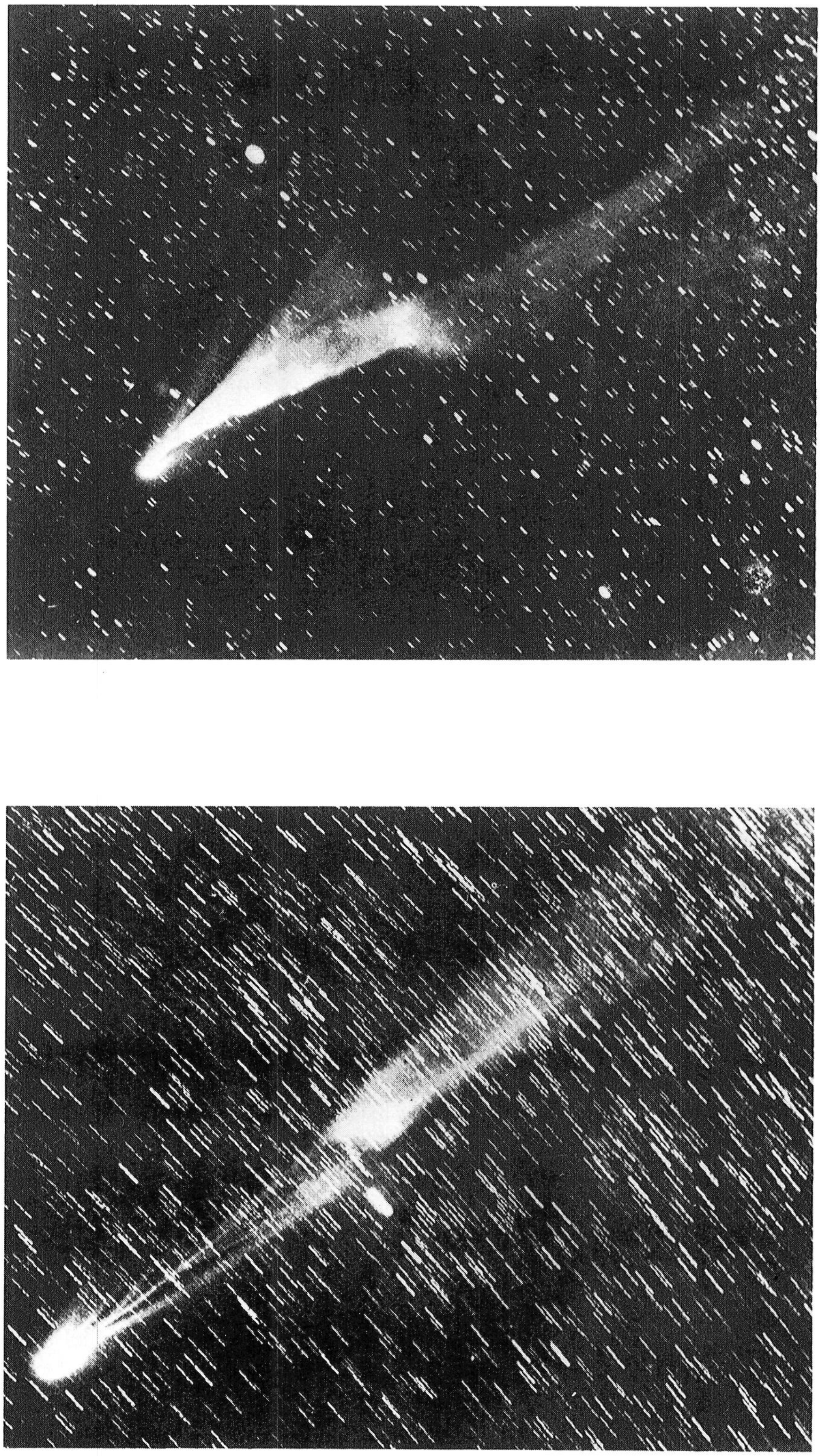

Fig. 13. Two photographs of Comet 1908 III Morehouse, showing a tail disconnection event. The upper photograph was taken on September 30, 1908, the lower one on October 1, 1908. Both photographs taken at Yerkes Observatory. (From Niedner and Brandt, 1978)

In order to summarize the possible science return from a mission to a comet, I reproduce in Table 3 a chart made up by our Chairman, Dr. Belton. This chart contains a listing of outstanding questions about comets that involve plasma physics studies, and it is clear that these questions must be answered if we are to understand comets. It is also worth summarizing the extent to which in situ comet studies will provide general understanding of space plasmas that have important implications beyond the study of solar system plasmas. In this context it seems clear that comet studies can provide fundamental information of general interest in the areas of magnetic field reconnection, the interaction of turbulence with magnetic fields, the behavior of large scale plasma flows, particle acceleration, charged particle transport, and collisionless shocks.

ACKNOWLEDGMENTS

I am very grateful to Jack Brandt, Malcolm Niedner, Jr. and Chuck Lillie for allowing me to discuss their reports and to display figures from them in advance of publication.

Table 3. Science Return from a Comet Rendezvous Mission

SCIENCE OBJECTIVE	SCIENCE RETURN
Characterize the interaction of a comet with the interplanetary plasma and determine the origin and physical nature of comet tails.	The physical nature of tail phenomena observed from the ground.
	Insight into energetic geomagnetic and astrophysical phenomena.
	Whether there is a bow shock. Where it is. What its physical character is.
	Whether there is a contact surface. Where it is. What its physical character is.
	How ions are accelerated into the tail.
	Evidence on whether strong magnetic fields develop near the comet.
	The role wave motions and dissipation play in production of ionization and tail phenomena.
	Whether electric currents are induced in the atmosphere?
	An explanation of the "filaments" and "motions" seen in the plasma tail.

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