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彗星離子尾研究簡史

葉永烜
國立中央大學天文研究所與太空科學研究所

A Brief History of the Study of Cometary Plasma Tails

Wing-Huen Ip
Institutes of Astronomy and Space Science
National Central University
Taiwan

Abstract

A short description is given to the historical development and future prospect of the study of cometary plasma physics. It traces the beginning of cometary research at the dawn of the space age to the present time. It is also suggested that we will soon be able to study commentary activities and dynamical behaviors in other solar systems by space-born observatories.

1. Introduction

The beginning of the study of the physical properties of comets can be traced back to the 1950's during which several basic ideas were proposed. Among them we can count the icy conglomerate model of Whipple (1950, 1951), the theory of corpuscular radiation by Biermann (1951), and the magnetic field line draping model by Alfven (1957). Whipple's icy conglomerate model depicts cometary nuclei as being composed of a mixture of volatile ice (H_2O, NH_3, CH_4, CO_2,…) and dust grains, hence the so-called dirty

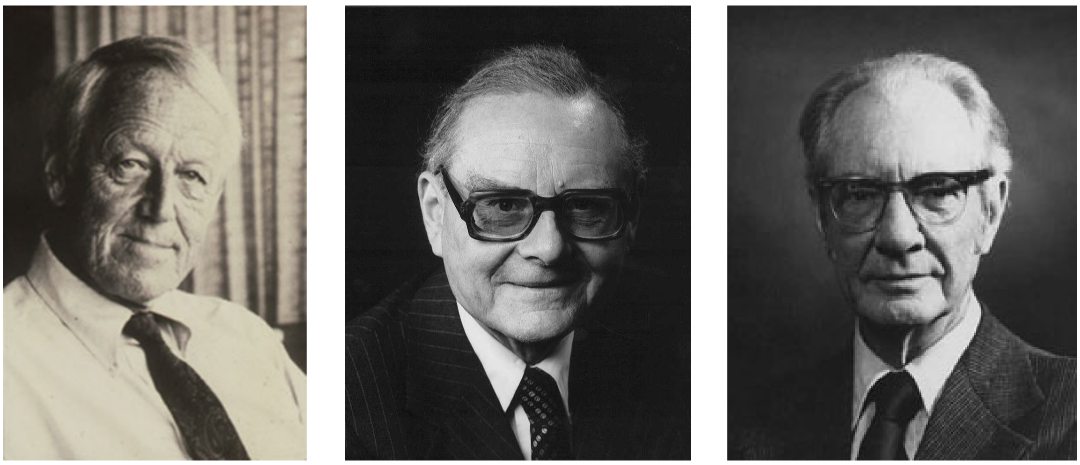

Fig. 1: Heros of cometary research. Left: Hannes Alfven (1908-1995); middle: Ludwig Biermann (1907-1986); right: Fred Whipple (1906-2004).

snow ball model. Such frozen mass should be of monolithic structure. The continuous sublimation of the volatile ice will lead to the formation of a layer of porous dusty mantle of low thermal conductivity, which will eventually choke off the outgassing process of the ice buried below. The gas drag at the nucleus surface will pull the small grains of micron and sub-micron sizes away, forming the elongated dust tails under the effect of solar radiation pressure. But it would have taken more than two decades of scientific efforts and many heated debates before some of the details could be understood. For example, in the period before water ice was confirmed as the main constituent of cometary volatiles by the observation of strong Lyman-alpha line emission of the neutral hydrogen atoms (from photo-dissociation of H_2O molecules), cometary activities like the formation of dust tails and ion tails had once been believed to be controlled by solar wind interactions under the bold but incorrect assumption that the outgassing processing was independent of the solar distance (Belton, 1965). An interesting consequence of such theory was the hypothesis that the solar wind flow should terminate at 2-3 AU from the sun because it was usually at this distance that cometary dust tails were observed to build up. Now we know that the solar wind should stop at about 100 AU after the Voyager 1 spacecraft had finally flown across the so-called termination shock of the heliosphere in December 2004 (Stone et al. 2005). However, battles on the nature of comet solar wind interaction raged on in the 70's. So, what was it all about?

2. Solar wind and comet-solar wind interaction

Few students in space physics today know that the existence of solar wind originated from the study of cometary ion tails. From a statistical study of the pointing of the ion tails, Biermann (1951) deduced that the cometary ions must be interacting with a radial outflow of ionized gas emitted from the sun. But the momentum transfer mechanism could not be fully accounted for until Alfven (1957) made the postulation that sweeping of the interplanetary magnetic field by the cometary ionospheres was essential in the formation of cometary ion tails (see Figure 2). This picture was still very much contested until observational confirmation by numerical simulations and eventually in-situ measurements of space probes to comets in the 80's were made (see Ip 2004 and references therein). However, this is only part of the story because the solar wind's interaction with the expanding cometary comas is very different from its interaction with the Earth's magneto- sphere, the latter characterized by the formation of a bow shock. Therefore, it was with good reason that the Munich group embarked on a number of pioneering work to explore the nature

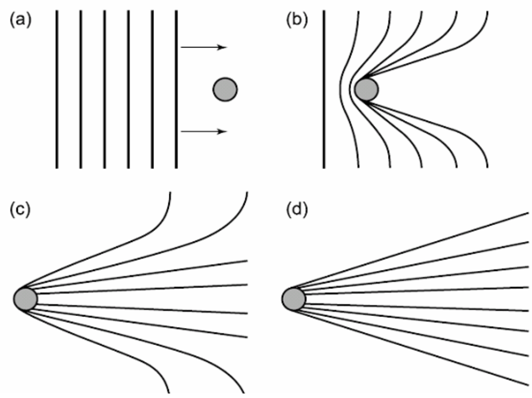

Fig. 2: Alfven's magnetic field draping model, describing different stages of the formation of the ion tail.

of this fundamental plasma process (Brosowski and Wegmann 1972; Schmidt and Wegmann 1980). Wallis and colleagues (Wallis 1971; Wallis and Ong 1975) advocated strongly the scenario of a weak shock or even no shock at all, the physical reason simply being, that with the gradual addition of the new ions of heavier mass (i.e., the water ions) as the supersonic solar wind streams into the extended neutral gas coma, the flow speed will be reduced and the plasma temperature will be correspondingly increased. These effects conspire to make the upstream solar wind flow to take on an ever decreasing Mach number (e.g., the ratio of the bulk flow speed to the local sound speed). According to a one-dimensional treatment (Wallis and Ong 1975), a shock will form when the mass-loading exceeds a certain critical value. The first space probe to a comet, the International Cometary Explorer of NASA to comet Giacobini-Zinner, had not detected any clear sign of a bow shock. Instead, a series of large-amplitude variations in both electron number density and magnetic field magnitudes were observed (Smith et al. 1986). At the encounter of Comet Halley, the Suisei spacecraft of ISAS provided a clear signature of a weak shock (Mukai et al. 1986). The issue which had lingered on for almost twenty years was finally settled by this first wave of space missions to comets. Nevertheless, many intriguing questions remain. For example, the combination of different outgassing rates and solar wind conditions would require not just the magnetohydrostatic formulation treating the cometary ions as one-single species well-mixed with the solar wind but also the kinetic consideration of the finite gyroradius effect and dynamical behaviors of ions of different masses. The coupling of the pickup ions with the plasma wave activity and the resultant particle acceleration are still to be fully understood, and the investigation of cometary plasma physics has just started.

3. Cometary ionospheric structures

Apart from the large-scale structures related to solar wind interaction, much attention had been drawn to the inner region of cometary coma and ionosphere in the early eighties. There are two reasons for doing so. First, the nucleus is the source of all cometary gas and dust. So, the closer one gets to it, the better will one known about the original composition of these pristine icy bodies. Second, the Giotto probe of ESA, having been designed to penetrate to a distance of about one thousand km from the nucleus would permit us to answer basic questions like the formation of cometary ionosphere and the magnetic field structure in the innermost region of the cometary coma. The magnetic field draping model of Alfven would necessarily imply the pile-up of magnetic field in front of the cometary ionosphere. The folding of the magnetic field in the anti-sunward direction would also lead to the formation of a current sheet separating the two regions of different magnetic polarities (Ip and Mendis 1976). The simplest way to estimate the magnetic field strength (B_i) at the frontside cometary ionosphere is to equate the magnetic field pressure to the solar wind ram pressure. This method yields a value of $B_i \sim$ 50-100 nT In fact, the stagnant ionospheric plasma is subject to two opposite forces: one from the magnetic field tension and another from the frictional drag due to collisional interaction with the outward-streaming neutral gas (Ip and Axford 1982). If the force balance equation were solved, the analytical solution would show that there should be a diamagnetic cavity surrounding the central nucleus. However, the existence of the diamagnetic cavity and the theoretical solution had not been known until the flyby observations of the Giotto spacecraft at comet Halley (Neubauer et al. 1987). Figure 3 depicts the comparison of the magnetometer measurements with the analytical model.

A stability analysis has been given to the interface between the magnetized ionospheric plasma magnetic field-free region (Ershkovich and Mendis 1983). It is interesting to note that the diamagnetic boundary was found to be extremely unstable. This result renders the formation of the diamagnetic cavity a puzzle. A possible explanation might be that comet-solar interaction could

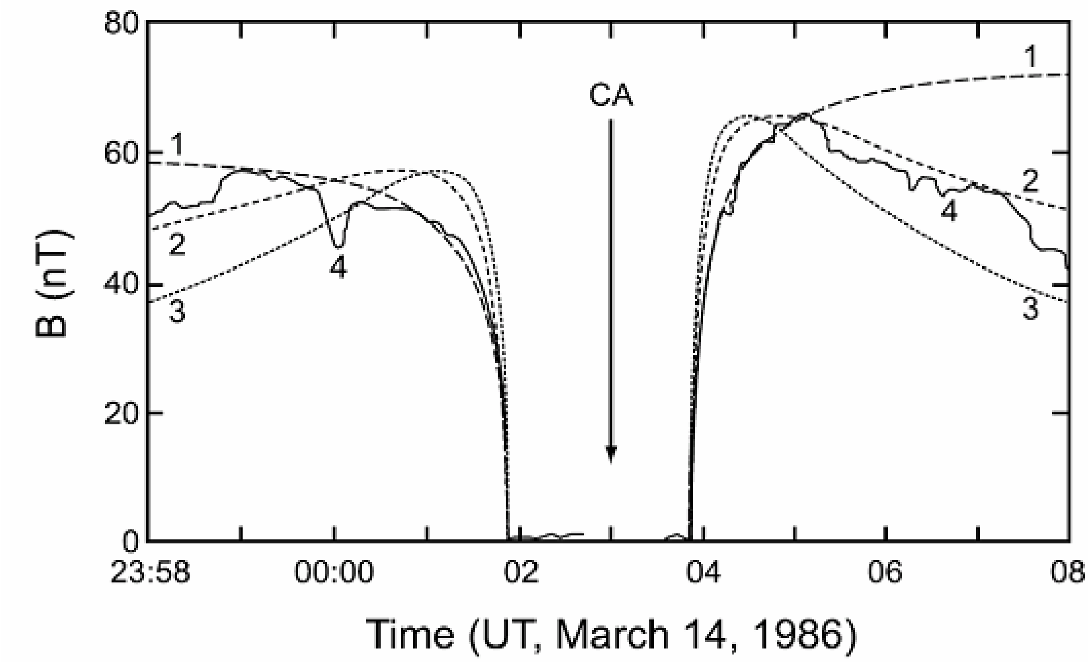

Fig. 3: Comparison of the theoretical curves by Wu (1987) with the magnetic field measurements made by the magnetometer experiment on Giotto showing the inner pileup region inbound and outbound and the magnetic cavity region.

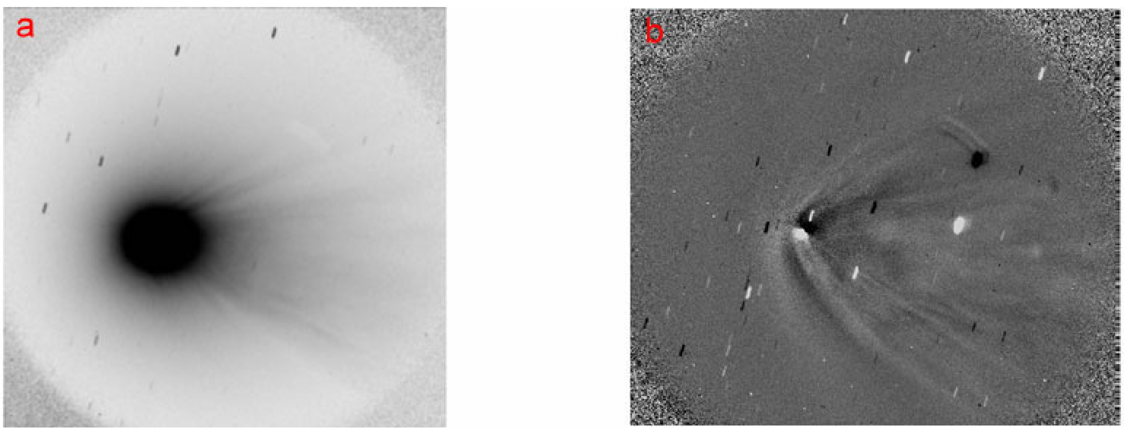

Fig. 4: Narrow-band filter images of comet Machholz (H2O+ ion image before (a) and after (b) continuum subtraction) taken by Zhong-Yi Lin on Lulin Observatory on January 6, 2005.

be characterized by large time variability. If the gas production rate and neutral gas flux were high and the solar wind pressure was low, the expansion of the neutral coma might then expel the magnetized ionospheric plasma leading to a diamagnetic cavity of transient nature. We, of course, do not know whether this was the situation when the Giotto spacecraft flew by comet Halley. But we do know that the cometary ion tails were often very filamentary, filled with fine structures (Figure 4). Such effect could be the result of either collapse (or reformation) of the ionospheric diamagnetic cavity or turning on (or off) of the ion source (Ip 1994).

How should we clarify these issues in the future? The Rosetta mission to comet will certainly help by virtue of the long-term monitoring capability during its rendezvous phase. However, the Rosetta observations will nevertheless be short of a global view of the solar wind interaction and ionospheric structures. Ground-based observations of the behaviors of the neutral coma and cometary plasma tail of Comet 67P/ Churyumov-Gerasimenko will therefore be very important in completing the general picture. As for the solar wind condition, we should plan coordinated X-ray imaging and spectroscopic measurements since they will provide very useful

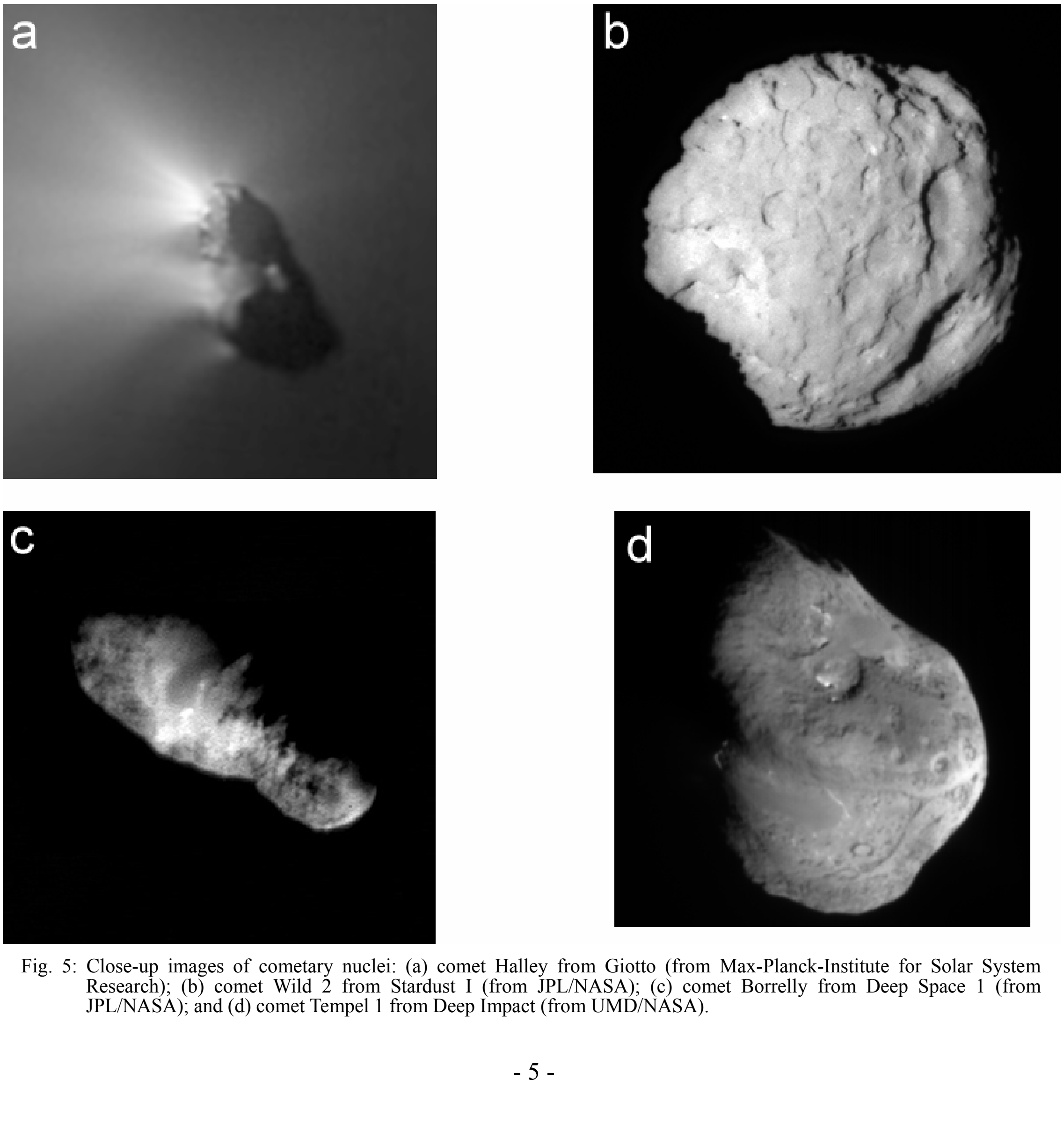

Fig. 5: Close-up images of cometary nuclei: (a) comet Halley from Giotto (from Max-Planck-Institute for Solar System Research); (b) comet Wild 2 from Stardust I (from JPL/NASA); (c) comet Borrelly from Deep Space 1 (from JPL/NASA); and (d) comet Tempel 1 from Deep Impact (from UMD/NASA).

information on the local solar wind environment, as demonstrated by Lisse et al. (2004).

4. Conclusion

As discussed in the previous sections, the development of cometary research had followed the same steps as space exploration of our solar system. After the Giotto project to comet Halley, we have witnessed several successful and some unsuccessful cometary missions. Figure 5 is a summary of the images of cometary nuclei obtained in various missions. Due to the fact that most of these missions emphasized on the physical properties of the nuclei and dust, as in the case of the Stardust project, little progress has been made in the study of cometary plasma. In order to do so, we will have to wait for the data from the Rosetta mission in just a few more years. Looking ahead, we envisage the exciting possibility of observing the dynamical behavior of cometary comas and dust and ion tails in other solar systems. This is because, within twenty years if not earlier, there will likely be space observatories like Darwin capable of imaging exoplanets. Such systems would probably supply precious glimpses of the activities of orbiting comets in these systems. Furthermore, it is quite possible that at that time someone will be working on the statistics of the coma activities and structures of the dust tails just like what had been done 40 years ago (Belton 1965). Cometary research will continue as Man searches across the new horizon.

Finally, we would like to take this opportunity to mention the importance of the study of comets and planets and of space exploration in natural science. We should not be discouraged by the fact that so far only a few Nobel prizes have been awarded to researchers in this field. After all, comet study is not like elementary particle physics, which relies heavily on finding the basic structures of matter by particle smashing machines – even though it has also become popular in space projects like Deep Impact and Don Quixote. Space exploration is important in the sense that it has become a key component of the human spirit and an essential part of our culture. Just like the voyage of the Beagle, the scientific findings from spaceships have the power to change our concept of the world we are living in, the world as we know it, a world we think we know. This we should always remember.

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