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Plasma structures in comets P/Halley and Giacobini-Zinner

J.C. Brandt[1] **and M.B. Niedner, Jr.**[2]

[1] Laboratory for Atmospheric and Space Sciences, University of Colorado, Boulder, CO 80309, USA
[2] Laboratory for Astronomy and Solar Physics, NASA-Goddard Space Flight Center, Greenbelt, MD 20771, USA

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Summary. An overview of large-scale plasma phenomena is presented based on results of spacecraft probing of comets Halley and Giacobini-Zinner and on worldwide submissions to the Large-Scale Phenomena Discipline Specialist Team of the International Halley Watch. Examples of tail phenomena and science are presented with emphasis on observed disconnection events. The archive of this material will clearly be very valuable for studying the comet/solar-wind interaction during the 1985–1986 apparition of Halley's comet.

Key words: plasma tails – disconnection events – solar wind interaction

1. Introduction

Our pre-encounter view of plasma structures in comets was based on the ideas of Biermann (1951) as extended by Alfvén (1957) to include the effects of the solar-wind magnetic field. The solar wind interacts with bright comets through its magnetic field and the cometary ions which are produced in an extended region around the comet. The field lines away from the comet are unimpeded and thus wrap around the comet to create a magnetic field in a hairpin configuration, i.e., a configuration with lobes of opposite polarity separated by a current sheet. Some part of this total magnetic structure includes the visible plasma tail. Because the comet is an obstacle in a supersonic and super-Alfvénic solar wind, a bow shock was also expected. Despite the sketchiness of many of the details, this picture presented specific tests of the data returned by the flyby spacecraft sent to comets Giacobini-Zinner and Halley.

2. In situ results

Direct exploration of comets began with the International Cometary Explorer (ICE) intercept of comet Giacobini-Zinner on 1985, September 11. The intercept was 7800 km from the nucleus on the tailward side.

Draping of field lines was observed, confirming Alfvén's (1957) basic picture, and the current sheet in the center of the tail was clearly detected. Extensive plasma wave activity was recorded, and the plasma wave experiment also served as a dust impact detector. The composition of the plasma was dominated by water-group ions. As the spacecraft traversed the comet, the flow speed of the plasma decreased from solar-wind values to low speeds on the order of a few tens of km s^{-1} while the density

Send offprint requests to: J.C. Brandt

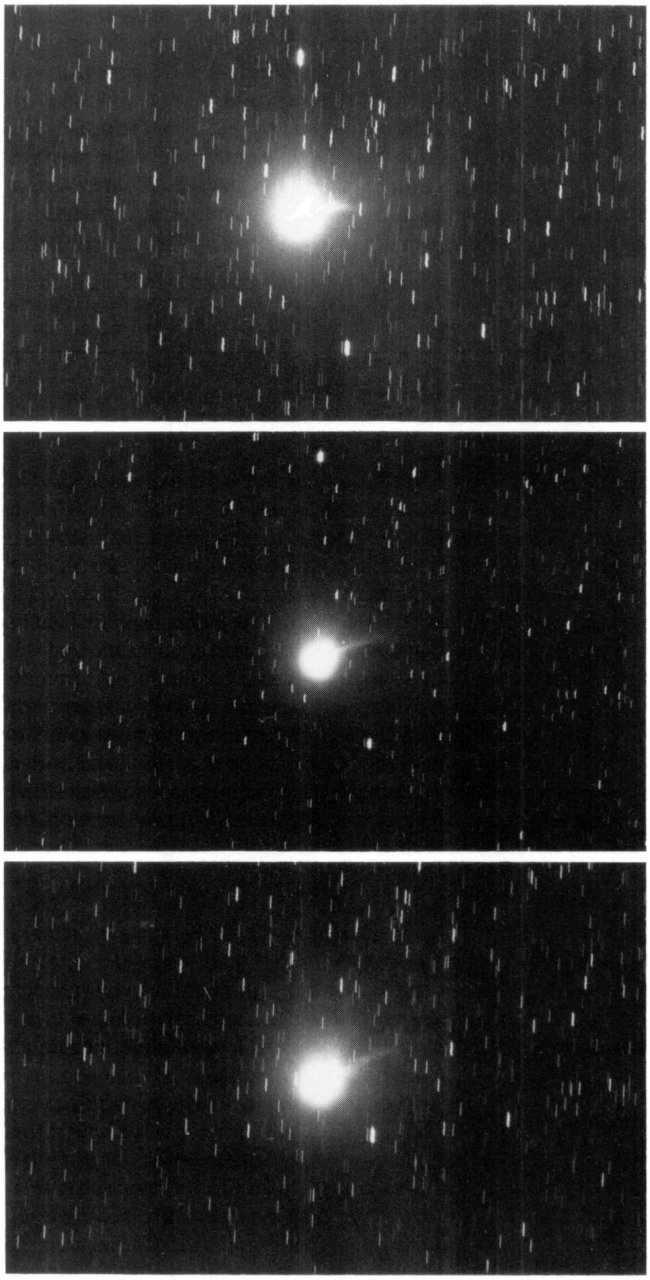

Fig. 1. Several images of Halley's comet on November 15, 1985, showing the beginnings of plasma tail activity (Bulgarian National Observatory photographs)

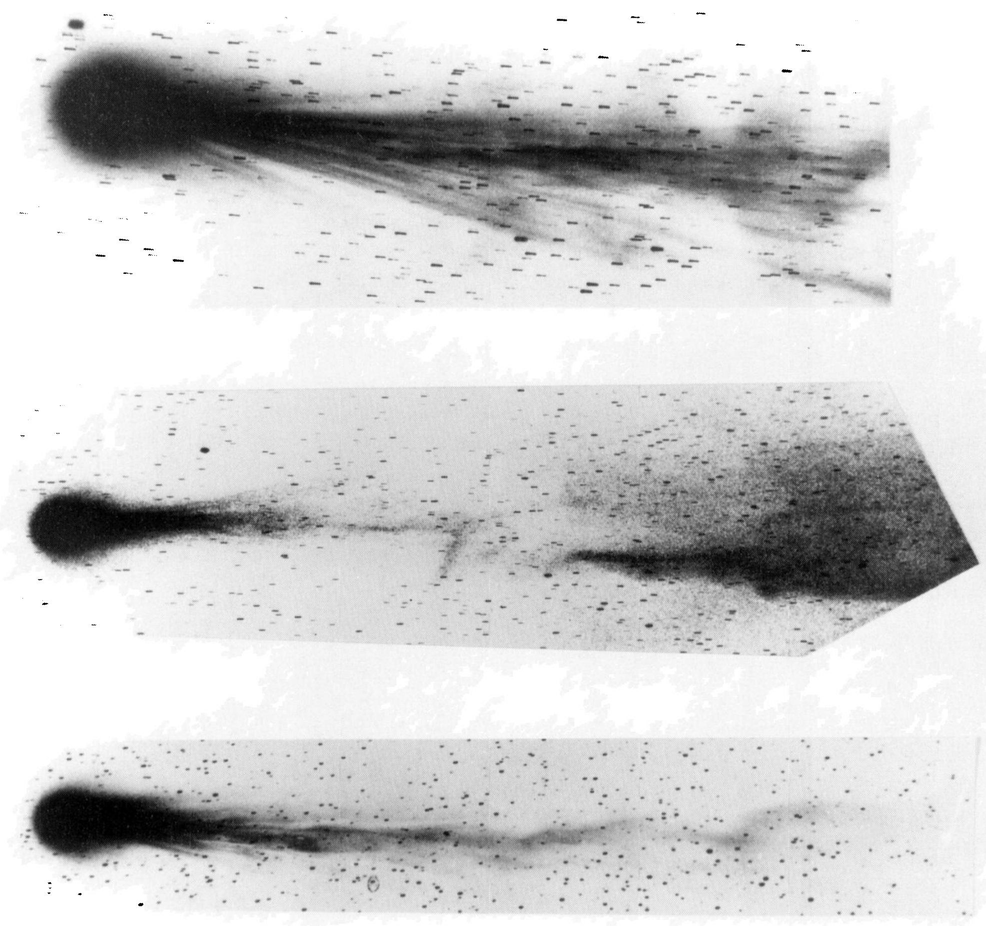

Fig. 2. Images of Halley's comet obtained from the Calar Alto Observatory of the Max-Planck-Institut für Astronomie on 1986 January 9 and 10, (a) and (b); and from the Haute-Provence Observatory on January 11, (c). A Disconnection Event (DE) is clearly shown

increased to a maximum of approximately 600 cm^{-3} in the center of the tail. The dense plasma regions were observed to be cold, ~20,000 K. Away from the central tail region, large fluctuations in most parameters were observed. Energetic ions were observed by two experiments. A substantial fraction of the ions are probably produced by the "pick-up" process involved in the solar-wind interaction, but the existence of ions in the 500 keV energy range requires an additional acceleration process.

The "bow shock" in comet Giacobini-Zinner was not as most investigators expected. It was an extended deceleration region which achieved the same purpose as a true shock, namely, the deceleration of the incident solar wind. Note that this region was sampled only on the flanks, and thus, there may have been a classical bow shock at the nose region. In broad outline, the pre-encounter view of the plasma structure was confirmed, along with a few surprises and many quantitative details. For a summary of ICE results, see the 1986 March and April issues of *Geophysical Research Letters*, and the 18 April 1986 issue of *Science*.

Very roughly, the dimensions of plasma structures in Halley are the comet Giacobini-Zinner values scaled upward by a factor of seven. Two very important differences are as follows. First, the close approach of Giotto enabled it to penetrate the contact surface and establish the existence of a magnetic field free region (radius ~5000 km) around the nucleus; the size of Giacobini-Zinner's ionosphere is unknown because ICE did not traverse it. Second, the bow wave exhibited the characteristics of a shock. Bear in the mind that all spacecraft to comet Halley passed on the sunward side. The large dimensions of the plasma interaction can be illustrated by the ICE measurements at Halley. The spacecraft passed Halley by 0.2 AU sunward in late-March 1986 and clearly detected plasma waves and energetic ions associated with the comet. Preliminary results from the Halley missions were published in the 1986 May 15, issue of *Nature*.

3. Physical framework for plasma morphology

The large-scale plasma morphology and solar-wind interaction for a medium-to-large water ice-dominated comet is dominated by two physical developments: (1) the turn-on of plasma phenomena as the comet appraches the sun (and the turn-off as the comet recedes), and specifically, the development of an ionosphere; and (2) the cyclic building and discarding of plasma structures and tails associated with Disconnection Events, or DE's.

For the turn-on description, we follow Mendis and Flammer (1984), who extended the earlier work of Biermann et al. (1967). The key parameter in the discussion is the mean molecular weight of the mass-loaded solar wind as the flow approaches the nucleus.

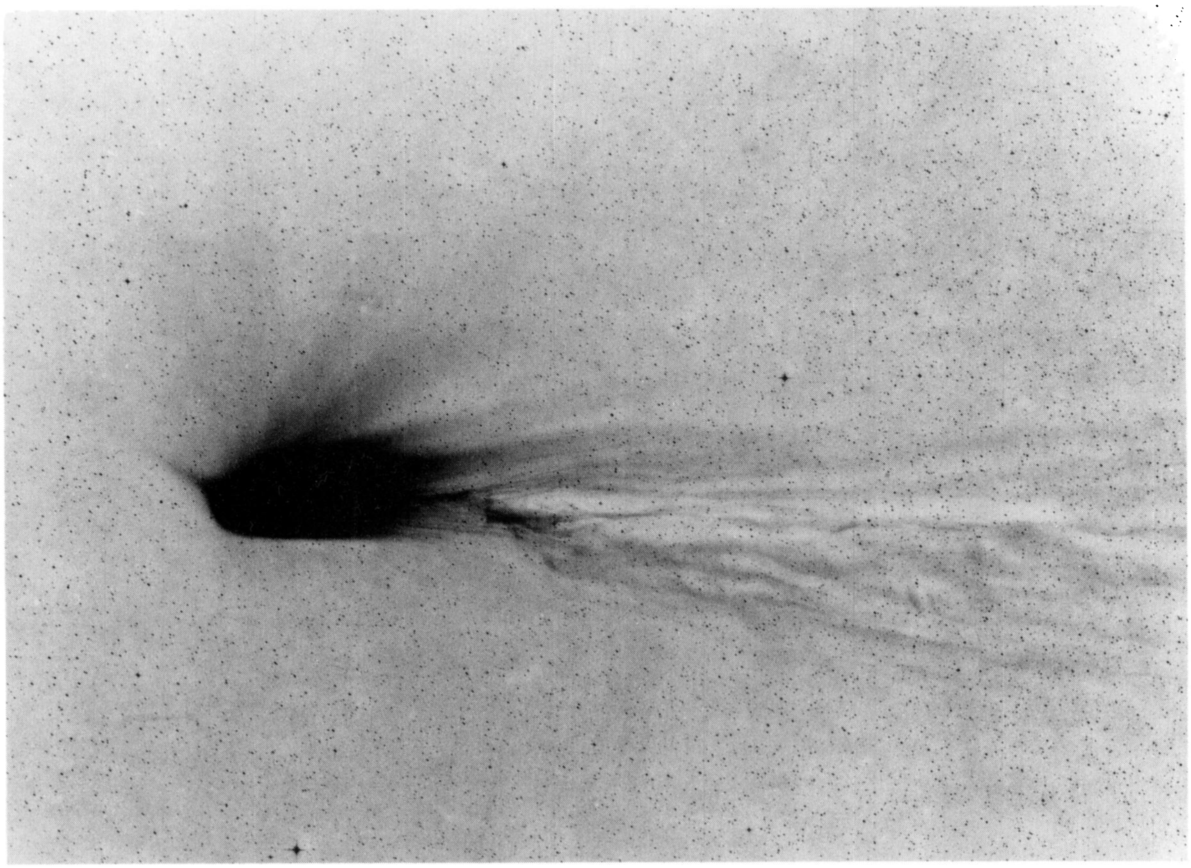

Fig. 3. The comet as photographed by the U.K. Schmidt telescope in Australia on 1986 February 22.78 UT, showing an anti-tail (left), dust structures (above), and the plasma tail (right, below). (photography by B.W. Hadley, ©Royal Observatory, Edinburgh)

According to standard gas dynamic theory, the mean molecular weight, normalized to the value far from the comet, cannot exceed 4/3 without the creation of a shock wave upstream of the nucleus.

The cometary atmosphere is sufficiently tenuous that the solar wind can penetrate to the nuclear surface without violating the critical value (4/3) for comet Halley outside heliocentric distances of about 3 AU. Specifically, this is the distance at which the critical value is reached one ion (solar-wind proton) Larmor radius from the surface. Inside the 3 AU distance, a shock wave forms upstream to divert the flow around the comet, thereby ensuring that the critical value is not exceeded in the supersonic regime. The collisionless shock is expected to have a thickness of an ion Larmor radius, thus leading to the condition described above.

To form an ionopause (separating the mass-loaded solar-wind flow from the pure cometary ions by a tangential discontinuity) requires sufficient momentum in the cometary outflow, which is generally supplied by the neutrals where they are collisionally-coupled to the ions. Houpis and Mendis (1981) showed that the solar wind would penetrate the cometary atmosphere until the proton-cometary neutral momentum transfer mean free path is equal to the radial distance from the nucleus. This is the ionophause distance and the ionopause is well defined when this distance exceeds the Larmor radius. This occurs at a heliocentric of about 2.5 AU or less.

When the ionopause is developed and stable (cf. Ershkovich and Mendis, 1983), a visible tail is formed and is subject to the evolution caused by the solar-wind magnetic sector structure. We follow the description of Niedner and Brandt (1978), who extended the basic physical description of the comet/solar-wind interaction given by Alfvén (1957) to include reversals in the interplanetary magnetic field. The capture of magnetic fields from the solar wind is changed when a sector boundary is traversed and fields of opposite polarity are pressed into the old field rooted into the head region. Magnetic reconnection occurs on the sunward side and ultimately severs the flux looped around the head. Then the old plasma/magnetic structure disconnects from the head to form a DE and the comet forms a new plasma/magnetic tail with the new polarity. Niedner and Brandt (1980) have assembled observational evidence that the DE is the key part of a cyclic evolution with a characteristic morphology before and after the DE. This model of DE's is discussed in the context of Halley imagery in Sect. 5.

In the sections below, we compare the observations of comet Halley with the physical framework.

4. Summary of imaging results

Plasma tail activity for comet Halley was observed to commence in mid-November 1985 (Fig. 1), when $r = 1.8$ AU; such a "turn on" distance is in basic agreement with the theory of Mendis and Flammer (1984) when the uncertainties in the observations and the theory are considered. The plasma tail was fully developed by

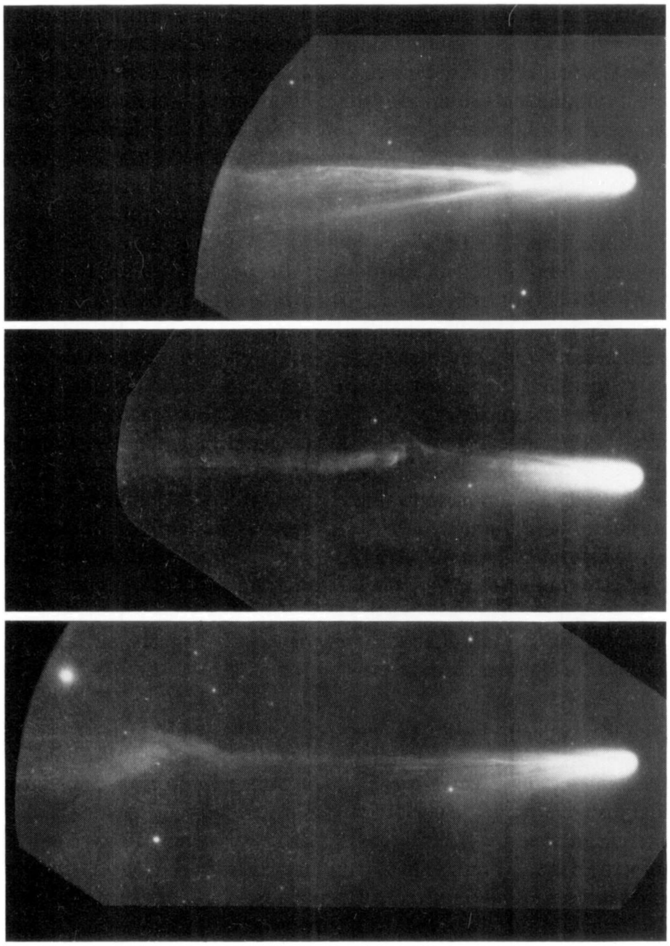

Fig. 4. A prominent DE developed in the plasma tail of Halley on March 20, as shown in this 3-day sequence spanning, top to bottom, March 20–22. All photographs were obtained at about 12 h UT with the 18″ Palomar Schmidt Camera

early December 1985. Perhaps the first *dramatic* DE for comet Halley was centered on 1986 January 10, (Fig. 2).

Early post-perihelion images from Schmidt telescopes in the southern hemisphere were spectacular. Multiple dust dails and a probable DE were seen on February 22 (Fig. 3) as was a DE on 1986, March 10. The DE of 1986 March 20–22, is shown in Fig. 4, and an even more spectacular event on April 12 is shown in Fig. 5. Activity continued at least to June 14 and the photograph taken on June 14 (Fig. 6) is currently one of the last ones available to us.

5. Disconnection events

Niedner and Brandt (1978, 1979) rediscovered DE's (known in the early-1900's) and proposed the sector boundary/magnetic reconnection model discussed above. We have extensively advertised this apparition as a potentially rich source of DE's and as a test bed for this hypothesis; Niedner (1986) has presented a list of 16 prominent DE's occurring from December to April. Thus, our first expectation has been amply fulfilled. Verification of the physical model is more complex although initial results (Niedner, 1986; Niedner and Schwingenschuh, 1987) from this apparition of Halley's Comet indicate that the sector boundary/magnetic reconnection model of DE's (Niedner and Brandt, 1978) is consistent with the times of known DE's in Halley and with the magnetic polarity data available from interplanetary and near-earth satellites, and from solar data.

The DE of March 8, 1986 illustrates the exceptional power of both *in situ* data and wide-field images; here we follow Niedner (1986) and Niedner and Schwingenschuh (1987). Figure 7 shows the sector boundary/current sheet location during the week of spacecraft encounters. The DE clearly visible on March 10 (see imagery of West et al., 1986) probably detached from the head close to March 8.4 UT. As Fig. 7 shows, the current sheet was nearly a parallel of solar latitude during this period. Thus, circumstances would appear to be very unfavorable for determining a crossing. However, the time of detachment falls between two times of "Space Truth" as determined by Vega's 1 and 2. The polarity of the draped magnetic field around Halley's Comet had reversed between March 6 and March 9. Therefore, a reasonable scenario involves the passage of a reversal in the polarity of the solar-wind magnetic field circa March 8, ultimately resulting in the field reversal measured by Vega's 1 and 2 and the spectacular DE of March 8.4 UT.

The DE's of March 20–22 (shown in Fig. 4) and April 11–12 (shown in Fig. 5) have been investigated by Brosius et al. (1987), who used ICE plasma and magnetometer data taken at a time when the comet and spacecraft were relatively close together, to examine possible solar-wind causes of these two DE's. The results are that: (1) the March 20–22 event occurred at a time of sector boundary crossing and uncharacteristically low solar-wind proton densities; (2) the April 11–12 event was associated both with magnetic reversals in the interplanetary magnetic field and with compression regions in the solar-wind plasma. The results are hence consistent with the sector boundary model (Niedner and Brandt 1978) of DE's, but compression effects and tailside reconnection (Ip, 1985; Russell et al. 1986) probably cannot be completely ruled our for the April 11–12 event.

6. Conclusion

The activities associated with the 1985–1986 return of Halley's Comet have provided us with good imaging coverage of rich tail phenomena and extensive *in situ* data. When fully archived, these will be an invaluable data base for studies of large-scale and related phenomena.

To date, the data show that: (1) the basic mechanism for the comet's interaction with the solar wind (Alfvén, 1957) is correct; (2) that the turn-on and turn-off of plasma activity follows the description of Mendis and Flammer (1984); and (3) that disconnection events are associated with sector boundary crossings and are an essential element in the morphology of developed plasma tails (Niedner and Brandt 1978).

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Fig. 5. Halley's comet as photographed by F.D. Miller on April 12.1042 UT with the University of Michigan Curtis Schmidt, La Serena, Chile. Note the spectacular DE

Fig. 6. Halley's comet on June 14, 1986 (photograph taken by E.P. Moore, Joint Observatory for Cometary Research, NASA-Goddard Space Flight Center, and New Mexico Institute of Mining and Technology)

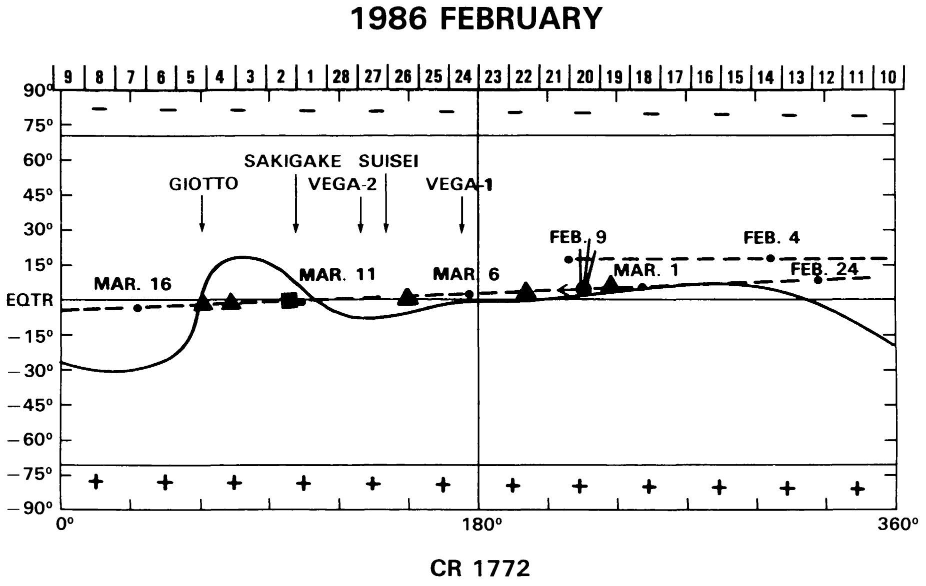

Fig. 7. Synoptic map of the coronal "source surface" of the solar wind and interplanetary magnetic field for Carrington Rotation 1772 (after Niedner, 1986). The heavy wavy line is the coronal neutral line across which magnetic polarity reverses and which is convected out into interplanetary space, giving rise to magnetic sectors. The track of the comet across the corona was obtained by computing the foot point longitude and latitude of the Archmidean spiral connecting the sun and comet for a constant solar-wind speed of 400 km s^{-1}. The times of the Halley spacecraft encounters are indicated, and the triangles and squares along the comet track denote the times of prominent and suspected DE's, respectively. The dates along the top of the figure are the times of central meridian passage at Earth (the coronal neutral line coordinates were kindly provided by Dr. J. T. Hoeksema, Stanford University)

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