

Comets as probes of the interplanetary medium

T. Chandrasekhar

Comets are natural probes of the interplanetary medium spanning it three dimensionally at all inclinations to the ecliptic plane and the extent of coverage stretching well beyond the orbits of the planets. They are also the main contributors to interplanetary dust. The ion tail structures in comets are sensitive indicators of the state of interplanetary magnetic field and solar wind structure in the region. The importance of ion tail transient events in comets, which can be monitored by dedicated small telescopes, is brought out and their relation to the sector boundary crossings of the interplanetary magnetic field discussed.

A comet has often been described as 'The nearest approach to nothing that can still be something'. From a popular point of view this may sound surprising as a comet is often visualized as a huge body spanning over a large portion of the twilight skies with a fiery head and a long tail. In reality both the viewpoints are essentially correct. A comet in full bloom does occupy a large angular extent of the sky but it is so tenuous that the mass contained in it is by astronomical standards negligibly small. For instance, for a Halley type comet with a nuclear size of ~ 10 km, assuming a density of $\sim 1 \text{ g cm}^{-3}$ consistent with the fragile nature of the nucleus we get a cometary mass $\sim 5 \times 10^{17} \text{ g} \sim 10^{-10} M_{\oplus} \sim 10^{-16} M_{\odot}$, where M_{\oplus} and M_{\odot} refer to the mass of earth and sun respectively. It is only a small portion of this cometary mass which is released during its passage through the inner solar system. The interaction of this small mass with the solar radiation field, solar wind and the interplanetary magnetic field gives rise to the familiar cometary characteristics—coma and tails (type 1 and type 2) (Figure 1).

Interplanetary coverage

Comets are natural probes of the interplanetary medium. They criss-cross the medium extensively and three dimensionally. It is unlikely that any spacecraft in the near future or any other planetary body can cover such a vast extent of the interplanetary medium, particularly outside the ecliptic plane. Comets can broadly be classified into two types:

Periodic comets, with periods < 200 years. Comets Halley, Giacobini-Zinner, Encke, Swift-Tuttle (1992t) fall into this category. Even in this class, the

interplanetary coverage is substantial. Comet Halley, for example, travels beyond the orbit of Neptune.

Aperiodic comets, appear without notice, generally exhibit greater activity, arrive at all inclinations, isotropically and are generally more interesting objects than those of periodic comets. These comets with highly eccentric elliptical orbits (nearly parabolic) are supposed to originate in the Oort cloud $\sim 50,000$ AU ($1 \text{ AU} = 150 \times 10^6 \text{ km}$) from the sun, nearly one-third the distance to the nearest star and are perturbed by a passing star into the inner solar system. Comets Kohoutek, Ikeya Seki are a few examples of this type.

Typically a comet begins to exhibit signs of activity spectroscopically (generally CN emission is the first to be seen) when it comes within ~ 3 AU of the sun and develops a coma or head. Coma development at ~ 3 AU is a strong indirect evidence that the main constituent of a comet is water-ice, for it is at temperatures encountered at 3 AU that water-ice begins to sublime. Beyond 3 AU comets do not generally show any activity but there are important exceptions.



Figure 1. Comet Kohoutek on 13 January 1974 showing a helical structure in its ion tail. The dust tail is featureless. (JOGR photograph, courtesy of J. C. Brandt)

T. Chandrasekhar is in the Astronomy and Astrophysics Division, Physical Research Laboratory, Ahmedabad 380 009, India

Comet P/Schwassmann-Wachmann I with a period of 16.5 years at a distance of ~ 5 AU in a nearly circular orbit ($e=0.13$) exhibits sudden flares of activity, especially in CO^+ when it can brighten by as much as 8 magnitudes (a factor of ~ 1600 in intensity)¹.

Chiron (Astroid 1060), a 200-km body, exhibits a definite coma, suggesting an origin in the trans-Neptunian population of comets or in the inner Oort cloud.

Comet Halley has recently (February 1991) shown spectacular activity with a coma of extent 200,000 km at a distance of 14.3 AU, i.e. beyond the orbit of Saturn (IAUC 5189)².

The exact mechanism for this kind of activity at large distances from the sun is not known. It is worth investigating if the activity could be some kind of internal effect triggered by an external source like the encounter with a high speed solar wind stream or a sector boundary crossing of the interplanetary magnetic field. Comets could then well serve as probes of activity in the interplanetary medium much beyond the orbit of Jupiter—a region largely unexplored.

Tail activity

Besides developing a coma, a comet coming within ~ 1 AU of the sun will usually exhibit a dust tail (type II tail) and also a plasma or ion tail (type I tail).

The dust tail

The dust tail is composed of dust grains which have been embedded in the nucleus and released along with the evaporating ices in a solar radiation field. The dust grain is acted upon by two opposing forces both of which vary as $1/r^2$...: solar gravity and solar radiation pressure.

The ratio of radiation pressure to gravitational force is denoted by $(1-\mu)$, where

$$\beta = (1-\mu) = \frac{F_{\text{rad}}}{F_{\text{grav}}}$$

For a spherical dust grain

$$\beta = (1-\mu) = \frac{\frac{\pi d^2}{4} Q \frac{F_{\odot}}{4\pi r^2 c}}{\frac{GM_{\odot}}{r^2} \left[\frac{\rho_d \pi d^3}{6} \right]},$$

where $F_{\odot}/4\pi r^2 c$ is the solar radiation field impinging

on the grain of density ρ_d and diameter d ; Q the efficiency factor for radiation pressure.

Therefore

$$(1-\mu) \propto \frac{C}{(\rho_d d)}; \quad C = \frac{3QF_{\odot}}{8\pi cGM_{\odot}}$$

The net effect is to make the dust tail curved and lag behind the comet in its passage around the sun. The locus of particles with the same value of β is called a Syndyne. The dust tail is composed of various Syndynes each with its value of β . The maximum value of β fixes minimum size of particles in the observed dust tail. Smaller-sized particles will essentially be pushed away from the system. A survey of β_{max} for a few comets shows that typically $\beta_{\text{max}} \approx 2.5$. The corresponding size of particles in the dust tail is $\sim 1 \mu\text{m}$. Larger particles $> 5 \mu\text{m}$ can sometimes be seen in the antitail, a sunward spike of dust that does not show any signature of silicate absorption at $\sim 10 \mu\text{m}$ in the infrared.

The ion or plasma tail

This cometary tail is formed by the interaction of the ions in the coma with solar wind magnetic field which folds onto the cometary ionosphere and accelerates the ions from the coma in a nearly antisolar direction.

Nearly 75% of all comets which come within 1.2 AU develop an ion tail which generally appears blue compared to the yellow appearance of the dust tail. The blue colour is due to the predominant CO^+ emission in the ion tail at $\sim 4260 \text{ \AA}$.

The very existence of a continuous corpuscular emission (solar wind) from the sun was inferred from the study of cometary ion tails by Biermann in 1951. The observed accelerations in ion tails of 13 comets in the emissions of CO^+ , N_2^+ , CO_2^+ , CH^+ , ... were 30–100 times local solar gravity and could not be explained by radiation pressure. Solar corpuscular emission with velocities up to 1000 km s^{-1} needed to be postulated to explain the observed accelerations.

The ion tails when carefully observed were not exactly antisolar in direction but exhibited an aberration angle ϵ ranging from 3° to 6° . Taking typical tangential velocity component of comets (V_{comet}) in the range $30\text{--}50 \text{ km s}^{-1}$, we get $\tan \epsilon = V_{\text{comet}}/V_{\text{sw}}$ and $V_{\text{sw}} = 300\text{--}500 \text{ km s}^{-1}$.

Thus sudden large changes in solar wind velocity V_{sw} (high speed streams) can produce an observable kink in the plasma tail. Observations of plasma tails of comets thus provide a simple yet elegant means of studying solar wind behaviour at various distances above and below the ecliptic plane as dictated by the cometary orbit.

Plasma tail structures

The plasma tail, unlike the featureless dust tail, is highly structured and shows changes over periods of a few hours or less. The structures in the ion tail include helical structures, ray folding, side rays, kinks, irregularities and disconnection events (DE). Tail streamers are compelling evidence for importance of magnetic fields in comets. But for the magnetic fields the thermal motion of the ions would wash out the structures in a very short time.

The kinks and knots of material seen in type I tails show motion and acceleration away from the head with typical velocities near the head of $\sim 10 \text{ km s}^{-1}$ accelerating to velocities $\sim 250 \text{ km s}^{-1}$ down the tail. The accelerations required are $(1-\mu) \sim 100$, i.e. about 100 times the local solar gravity. The tendency at present is to interpret the motions and accelerations of structural details as real physical motions. However it is possible to interpret the moving structures as a magneto hydrodynamic wave (MHD) moving down the tail with an Alfvén speed $V_A = B/(4\pi\rho)^{1/2}$. If magnetic field is approximately constant in the main part of the tail, a variation of density ρ from high values near the nucleus to lower values down the tail can reproduce the observed speeds and accelerations. The question whether the observed moving features in the plasma tails of comets are due to wave motion or particle motion can be convincingly answered by direct observations of Doppler shifts of the emitting ions, mainly CO^+ . A positive detection of Doppler shifts down the tail would clearly indicate particle motion.

So far observations of Doppler shifts of cometary ions in the tail have been very scarce.

Huppler *et al.*³ have reported Doppler velocities of $20\text{--}40 \text{ km s}^{-1}$ in H_2O^+ emission in Comet Kohoutek. With an imaging Fabry-Perot interferometer Debi Prasad *et al.*⁴ have observed highly structured motions in a plasma blob near the head of Comet Halley with Doppler velocities $30 \pm 10 \text{ km s}^{-1}$. It is clear that while a few observations—all taken with Fabry-Perot based high resolution spectroscopic systems—indicate mass motion in ionic structures, a convincing answer requires more detailed observations. Imaging Fabry-Perot observations down the ion tail of a future bright comet in CO^+ emission (4260 \AA) which would be very valuable are planned to be carried out by the PRL group from their observatory at Gurushikhar, Mt. Abu.

Cometary dust in the solar system

Comets through dissipation of the dust tail contribute significantly to the dusty component of the interplanetary medium: zodiacal light, *F* corona, and meteor streams. While the particles in the $1\text{--}10 \mu\text{m}$ region are

efficient scatterers of visible light and leave an imprint as the dust tail, for studies of meteor streams the important sizes are larger,—it is the centimetre- and decimetre-sized particles released from the cometary nucleus that are of interest. While space probes to Comet Halley did see particles from 1000 \AA to several mm in size, the distribution of these particles in the interplanetary medium is unknown.

The Infrared Astronomical Satellite (IRAS) surveys of the interplanetary medium in the 25 and $60 \mu\text{m}$ sky flux maps revealed hitherto unknown narrow trails of dust. Several of the bright trails coincided with the projection on the sky of cometary orbits. Bright dust trails of comets Temple 2, Encke and Gunn exhibited material in front of and behind cometary orbital positions over several degrees⁵.

The dust in the interplanetary medium is not stable. Dust particles in the size range ($1\text{--}10 \mu\text{m}$) spiral inward into the sun by Poynting-Robertson effect over a time-scale of $\sim 10^4$ years. Early work by Whipple⁶ indicated that to sustain the zodiacal cloud, a quasi continuous production of dust from comets at a rate $\sim 10^7 \text{ g s}^{-1}$ is needed. It has been pointed out that dust production of short period comets is substantially lower $\sim 300 \text{ kg s}^{-1}$. Further the cometary dust is of low density which can account for only 30% of the existing interplanetary dust. An important role has been suggested for long period comets for keeping the dust within the solar system and for maintaining the zodiacal cloud⁷.

Comet Swift-Tuttle (1992) and the Perseid Meteor stream

The recent recovery (IAUC 5620)⁸ of the long expected Comet Swift-Tuttle, last seen in 1862, has provided a unique opportunity of studying directly the interaction of comet with its associated Meteor stream, the Perseids. The comet is now also identified with Comet Kegler which was extensively observed in China in 1737. During the 1862 apparition the comet came within 32 million miles of earth ($\sim 0.13 \text{ AU}$), brightened to magnitude ~ 2 and developed a 30° tail. It would be very profitable to closely monitor the dust tail of the comet during its present passage (Perihelion on 1992 Dec. 12.3) through regular high resolution pictures of the tail, IR observations, etc. so that the dust ejected can be estimated. Observations of the Perseid Meteor shower of 1993 Aug. 12 which is expected to be intense for the number of meteors per hour and meteor spectra would be very valuable (IAUC 5621)⁹. In view of the monsoon weather conditions in our country during this crucial period one could consider radio observations of the ionic trails caused by the meteors impinging on our atmosphere. Local Ham enthusiasts could possibly help out, their amateur astronomy counterparts in making this important observation.

Transient features in comets

An important aspect of cometary behaviour which could be directly related to its interaction with the interplanetary magnetic field are the cometary transient events which last a few hours or less. Though such features had been noticed as early as 1882 by Barnard, a systematic and complete study of transient events in comets is yet to be done. It would require a very close monitoring of the comet on an hourly basis.

On 13 March 1986 we recorded one such transient event in Comet Halley. A specially designed imaging Fabry-Perot system, incorporating an image intensifier and an optically contacted Fabry-Perot etalon, was used for this purpose. Figure 2 shows the ionic blob detached from Comet Halley in H_2O^+ emission. Figure 3 shows Fabry-Perot interferogram in 6563 \AA in the blob region.

Another blob-like feature was seen in Comet Halley by Lynch and Russel¹⁰ which required again a dissipation time-scale, of $\leq 1 \text{ h}$. Here again there is evidence of the comet passing through the interplanetary sector boundary crossing just prior to these observations.

While detailed theoretical understanding of transient events in comets is yet to be reached, it is clear that interplanetary magnetic field reversals play an important role in triggering the events—some kind of magnetic reconnection process must be responsible for most if not all events.



Figure 2. Ionic blob in the emission of H_2O^+ at 7000 \AA on 13 March 1986 seen adjacent to Comet Halley.

Conclusions

Comets are true and natural interplanetary probes covering the interplanetary medium in a three dimensional manner; comets contribute effectively to the dusty component of the interplanetary medium. The

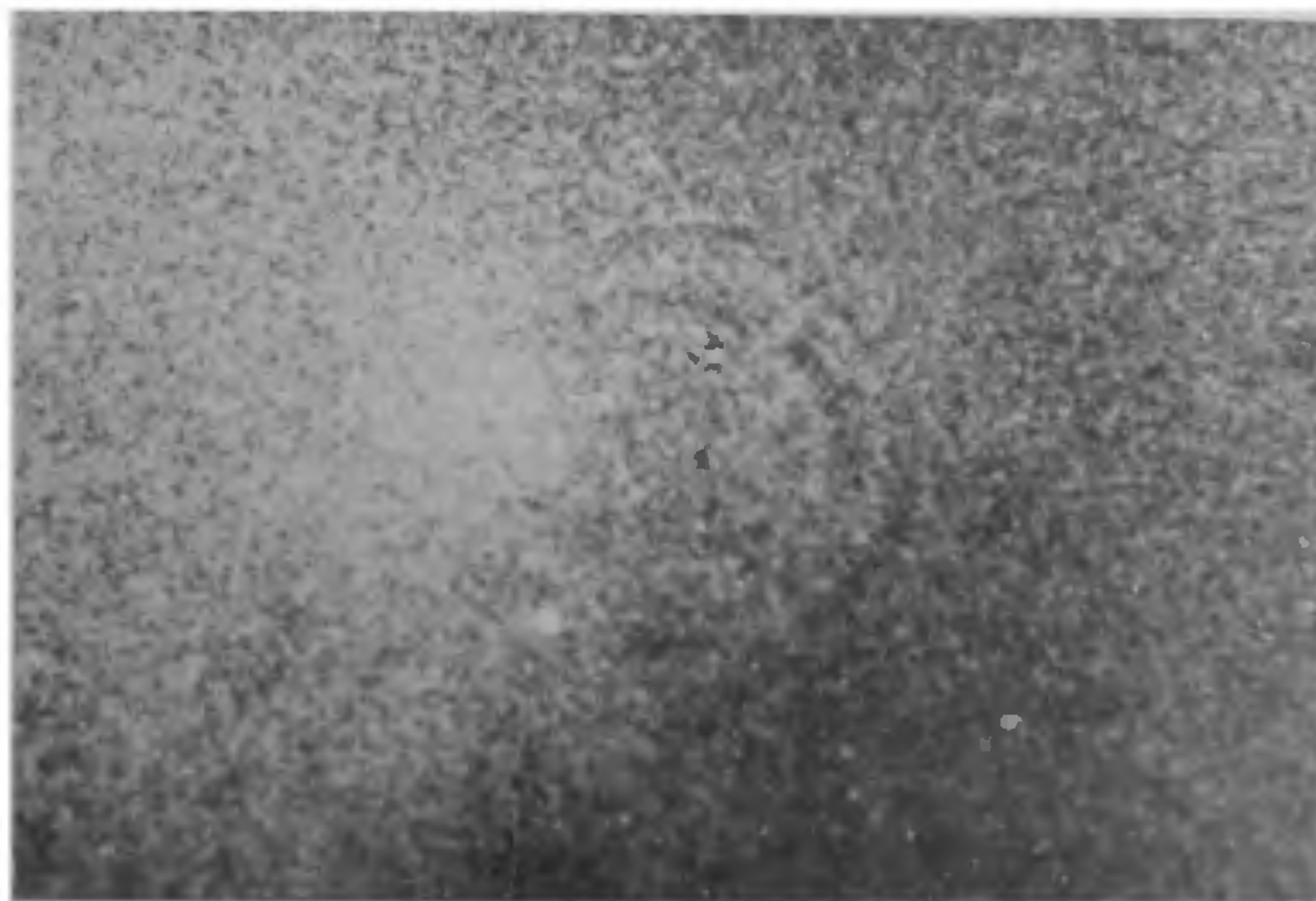


Figure 3. Fabry-Perot interferogram taken in the ionic blob region at 6563 \AA on 13 March 1986. Fringes can be seen as arcs of concentric circles. Microdensitometric radial scan of the fringes leads to the elucidation of velocity structure in the blob.

study of moving structures and transient events which occur largely in the plasma tail of comets clearly reveal interaction with the changing interplanetary magnetic field.

1. Keller, H. U., in *Physics and Chemistry of Comets* (ed. Huebner, W.), Springer-Verlag, 1990, pp. 59–60.
2. Hainant, O., Smette, A. and West, R. M., *IAU Circular No. 5189*, dated 15 Feb. 1991.
3. Huppler, D., Reynolds, R. J., Roesler, F. L., Scherb, F. and Traunger, J., *Astrophys. J.*, 1975, **202**, 276–282.
4. Debi Prasad, C., Chandrasekher, T., Desai, J. N. and Ashok, N. M., *J. Astron. Astrophys.*, 1989, **10**, 1–20.
5. Grün, E., Jessberger, E. K., in *Physics and Chemistry of Comets* (ed. Huebner, W.), Springer-Verlag, 1990, pp. 148–149.
6. Whipple, F., in *The Zodiacal Light and the Interplanetary Medium*

- (ed. Weinberg), Washington, NASA SP-150, 1967, pp. 409–426.
7. Fechtig, H., in *Comets* (ed. Laurel Wilkening), The University of Arizona Press, 1982, pp. 370–382.
8. Kosai, H., Kiuchi, T., Tatum, J. B., Suge, A. and Scotti, J. V., *IAU Circulars No. 5620*, dated 27 Sept. 1992.
9. Brown, P. and Rendtel, J., *IAU Circulars No. 5621*, dated 27 Sept. 1992.
10. Lynch, D. K. and Russel, R. W., *Publ. Astron. Soc. Pac.*, 1988, **100**, 1122–1128.

ACKNOWLEDGEMENTS. It is a pleasure to acknowledge the interaction and discussions on this subject with my colleagues Prof. J. N. Desai, Dr Debi Prasad and Dr N. M. Ashok who have been closely associated with the cometary studies by Fabry-Perot techniques at PRL.

Received 18 December 1992; accepted 21 December 1992

INSA Medal for Young Scientists — 1994

Instituted by the Indian National Science Academy in 1974 the Medal is awarded annually in recognition of outstanding work of scientists below the age of 32 (as reckoned on 31 December preceding the year of award). Only those born on or after 1 January 1962 are eligible for consideration in 1994. The work done in India by the nominee will be taken into consideration for the award.

The awardee is presented a medal and a cash award of Rs 10,000. In addition, the recipient is considered for a research grant by the Academy not exceeding Rs 40,000 per year.

Nominations for the awards for 1994 may be made by Fellows of the Academy, and by the established scientific societies of all-India character, University faculties and departments, and the research institutions. The last date for the receipt of nominations in the Academy is 15 October 1993.

Nomination proforma can be obtained from the Indian National Science Academy, Bahadur Shah Zafar Marg, New Delhi 110 002 by sending a self-addressed envelope of size 25 cm × 12 cm.