On the observations of radio sources occulted by the ion-tail of comets

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The interaction of interplanetary medium with cometary plasma gives an excellent opportunity for studying the cosmic plasma processes. The occultation of compact radio sources can be used effectively for measuring several characteristic parameters of this interaction. During 1985–86 apparition of comet Halley, a number of groups attempted this experiment around the globe. In this article I present an overview of these, as well as studies made later. On the basis of present knowledge, suggestions are made for effective use of this technique for future observations. A method to estimate plasma density (N) in the ion-tails with the help of its irregularity (ΔN) calculated using interplanetary scintillation is suggested. These values are compared with the values obtained by *Vega-1* and *Vega-2* spacecrafts in the case of comet Halley.

A phase modulation is imposed on the wavefront of the radiations from a compact radio source while passing through an ionized medium (plasma) which gives rise to a variety of scintillation phenomena. The characteristic time-scales or correlation bandwidths of these scintillations provide a valuable means of remote-sensing these plasmas. This technique, if effectively used, can yield a large amount of valuable information regarding the nature of the plasma-tail of comets. During the last few years, a number of attempts have been made to use this technique for the study of cometary plasma. However, the results derived from these studies are limited and not devoid of confusion in their observational aspect. In this article, I present a brief overview and the present state of the art in this field. Attempts have also been made to point out what needs to be done in future for the effective use of this technique in the study of the comets.

Ion-tail of the comets

Comets are made up mainly of ice. The ice is believed to have been produced during the early stages of the solar-system formation. As they come close to the Sun, the ice starts sublimating and is eventually ionized due to solar UV and solar wind. Other ions like CO^+, CO_2^+, etc. have also been identified. This ionized gas closely interacts with the interplanetary magnetic field as well as the solar corpuscular radiation to produce the so-called type-I tail of the comet. The velocities associated with these tail particles are of the order of tens to hundreds of km s^{-1}, which cannot be explained without the interaction with solar wind. The confinement of the plasma in a long cylinder of ratio 10^3 or more without any diffusion can only be possible by trapping the ions in the magnetic field, as Alfven and Biermann in 1953 have rightly pointed out. Rays are directly pointed away from the Sun, which conclusively proves the very strong solar wind interaction with these materials. This type-I tail possesses several fine structures like kinks, helices and knots. They are supposed to be formed due to the interaction between cometary and solar wind plasma, which triggers the K–H instability at the boundary separating the two plasmas. This K–H instability can cause the plasma turbulence at characteristic wave-numbers in the cometary tail. The turbulence so produced can scatter solar wind protons and provide an acceleration mechanism for cometary ions[1]. The compact radio sources occulted by turbulent cometary plasma can be used to study the degree of turbulence. One of the important parameters of these processes is the electron density fluctuation and density gradient of cometary plasma which, in principle, can be derived from interplanetary scintillation (IPS)-like observations. Before discussing the present observations related to this, the basic theory of this technique is overviewed.

Basic theory of scintillation

Plane wave propagating from a distant compact radio source is incident on a thin phase-changing slab of the plasma turbulence. Immediately outside the slab the wavefront gets corrugated owing to phase deviation. After propagating a certain distance, called Fresnel distance $Z_F = 2\pi a^2/\lambda$, (where a is the scale-size of irregularities and λ is the operating wavelength) through free space to the observer, amplitude modulations start building up, forming a spectrum of intensity on the ground.

The statistical quantity of the medium that is of interest here is a three-dimensional spatial spectrum of refractive index fluctuations at the wavelength λ, $M_{3n_e}(\mathbf{q})$. In a plasma it can be related to the three-dimensional electron density spectrum by

$$M_{3N}(\mathbf{q})=r_e^2\lambda^2 M_{3n_e}(q) \tag{1}$$

where $\mathbf{q}=(q_x^2+q_y^2+q_z^2)^{1/2}$ is a three-dimensional wave number, n_e the refractive index and r_e the classical electron radius.

If the slab thickness $L \gg a$, then outside the slab two-dimensional spatial phase spectrum for thin screen ($L \ll Z$) is expressed as[2]

$$M_{2\Phi}(q_x, q_y)=\frac{4\pi^2}{\lambda^2} L M_{3N}(q_x, q_y, q_z=0) \tag{2}$$

The propagation of the phase-distorted waves results in density scintillation (spectrum of intensity) on the observer's plane. Under weak-scattering conditions (i.e. $\Phi_0 \ll 1$ radian, where Φ_0 is rms phase deviation), the two-dimensional intensity spectrum can be written as

$$M_{2I}(q_x, q_y)=4\sin^2\frac{(q^2\lambda Z)}{4\pi}M_{2\Phi}(q_x, q_y), \tag{3}$$

where the term $4\sin^2[(q^2\lambda Z)/4\pi]$ is a 'high-pass propagation filter' that removes the lower spatial frequencies from the spectrum.

Scintillation index, m, is defined as[3]

$$m^2=M_{2I}(q_x, q_y)\,\mathrm{d}q_x, \mathrm{d}q_y. \tag{4}$$

In the direction of propagation along the x-axis one-dimensional intensity temporal spectrum becomes

$$M_I(f)=\frac{4\pi}{V_x}\int_{-\infty}^{\infty} M_{2I}\left(q_x=\frac{2\pi f}{V_x}, q_y\right)\mathrm{d}q_y$$

$$\text{for } f \geqslant 0, \tag{5}$$

where V_x is the x-component of the velocity of the plasma density irregularity.

Actually the pattern received by the observer is made up of contributions from scattering volume all along the line of sight. In the case of weak scattering, the spectrum can be approximated as[4]

$$M_I'(f)=\int_0^Z M_I(f,z)\,\mathrm{d}z. \tag{6}$$

In practice, by scintillation experiments one calculates scintillation index. It depends on the density of the plasma irregularity and its scale-size, operating wavelength and width of the plasma-irregularity slab as shown by the equation below.

For Gaussian electron density correlation function the rms phase deviation introduced by the irregularity to the incoming wavefront can be written as[5]

$$\Phi_0=(2\pi)^{1/4} r_e \lambda (aL)^{1/2}\langle\Delta N\rangle, \tag{7}$$

where

r_e is the classical electron radius,
a the scale-size of the irregularity,
L the width (thickness) of the irregularity slab,
λ the operating wavelength and
$\langle\Delta N\rangle$ the rms change in plasma density irregularity.

For weak scattering the scintillation index[2] m is given by

$$m=\sqrt{2}\,\Phi_0 \tag{8}$$

If one knows about the movement of the plasma irregularity (or one assumes) one can calculate the scale-size of irregularity. In this, scintillation periodicity is also used (which is calculated from the observed scintillation pattern). Then, by equations (7) and (8), ΔN can be calculated.

To have an idea of N, in any slab having ΔN (e.g. cometary plasma tail) an approximation (or assumption) is made that ΔN and N, if they have any dependence over distance from the cometary nucleus, have the same dependence as in the case of solar plasma. At any distance say R (from the Sun), N_{comet} can be calculated in the following way

$$\left(\frac{N}{\Delta N}\right)_{\text{comet}}=\left(\frac{N}{\Delta N}\right)_{\text{solar}}$$

N and ΔN in the case of Sun are known (or can be extrapolated); ΔN_{comet} is calculated from IPS observations, and N_{comet} can be estimated.

Using this method an estimate of N_{comet} has been made for different comets during various IPS observations and this is given in Table 1. It is clear that the plasma density and its irregularity are independent of tailward distance from the nucleus.

Cometary observations

There are a few observations of occultation of radio sources by cometary ion-tails. Important information regarding these observations is summarized in Tables 1 and 2.

Ananthakrishnan *et al.*[6] reported fluctuations in the intensity of the extragalactic source PKS 2025–15 during its occultation by the coma and tail of the comet Kohoutek (1973f) on 5 January 1974 using Ooty radio telescope at 327 MHz. At the time of these observations the solar elongation (Sun-Earth-source angle) of the source was 20°. They concluded that no radio emission above the confusion limit of the telescope could be detected from the comet. (Although they did not uniquely attribute the observed fluctuations in the intensity of the occulted source to the plasma in the ion-tail.) However, Lee[7] interpreted these scintillations as

Table 1. Values of N_{comet} estimated using the values of ΔN_{comet} calculated from IPS observations

Comet	Details of observation	Tailward distance from the nucleus (AU)	ΔN_{comet} cm^{-3}	N_{comet} cm^{-3}	Heliocentric distance r of the comet (AU)	Geocentric distance Δ of comet (AU)
Kohoutek[6]	5 Jan. 1974	0.0005	2	200	0.92	1.04
Halley[8,9]	18–20 Dec. 1985	0.144	1.8	180	1.22	0.88
Halley[11]	29 March 1986	0.036	1.8	180	1.14	0.58
Wilson[14]	1–2 May 1987	0.12	1.7	170	1.21	0.62
Austin[15]	13 May 1990	0.04185	6	600	0.92	0.34

Table 2. Summary of the occultation events discussed in the text

Place and frequency of operation	Observation period	Scintillating sources occulted	ΔS Jy and solar elongation	Comet used	Information on cometary tail	Remarks	Result
Ooty[6] (India) 327 MHZ	5 Jan. 1974	2025–150	20°	Kohoutek	25°	—	Positive
Ahmedabad[8,9] (India) 103 MHz	18–20 Dec. 1985	PKS 2314+03 (3C 459)	11 Jy 85°	Halley	Length 10° No DE	3 Days' observation. Enhancement of scintillation by factor of six over background scintillation	Positive
Parkes[11] (Australia) 408 MHz	29 Mar. 1986	1827–360	10.6 Jy 89°		Halley 10° No DE	Enhancement of four times	Positive
Ooty[13] (India) 327 MHz	11 Feb. 1986	2052–106	0.5 Jy 11.2°	Halley	Nil	Solar wind contribution to scintillation dominating	Negative
	2 Mar. 1986	2021–168	0.3 Jy 37°	Halley	DE on Mar. 1 UT	S/N poor; no observations	—
	24 Mar. 1986	1921–293	5 Jy 74°	Halley	Nil	—	
	1 Apr. 1986	1817–391	1.2 Jy 96	Halley		Confused with 1815–391	—
Cambridge[12] (UK) 81.5 MHz	May 1978—March 1981	35	— 90°–100°	12 comets	None for 6 comets; one comet 5°, rest less than 2°	58% Chance of missing the occultation. No information on DE.	—
Parkes[14] (Australia) 408 MHz	1 May 1987	0606–795	3.3 Jy 92.8°	Wilson	—	Enhancement of 3–4 times	Positive
	2 May 1987	0637–752	4.3 Jy 93°	Wilson	—	Enhancement of 3–4 times	Positive
Ahmedabad[15] (India) 103 MHz	13 May 1990	2204+29 (3C 441)	— 70°	Austin	Length more than 7.3°	Enhancement of 3 times	Positive

caused by the turbulent plasma in the ion-tail of the comet even though their periodicity was about 10 sec.

Alurkar *et al.*[8] and Sharma[9] made IPS observations at 103 MHz when the solar elongation of the occulted source 3C 459 (PKS 2314+03) was ~90°. At such elongations the scintillations recorded, if any, are weak, as the telescope points far away from the Sun where the solar plasma and irregularities are sparse. Any possibility of interference causing such scintillations is ruled out because the scintillations recorded were maximum on 18 December and then progressively decreased on 19 and 20 December. No correlation was observed between the enhancement and ionospheric phenomena such as sporadic E and Spread-F. Solar activity during observations was 'very low', while geomagnetic activity was 'quiet to unsettled' with no Sc-type magnetic storms as reported (Pre. Report and Forecast of Solar Geophysical Data Joint NOAA–USAF Space Environment Service Center, 1985). During this observation period (but not simultaneously), observations of five other scintillating and non-scintillating sources (viz. 3C 298, 3C 318, 3C 324, 3C 368 and 3C 409) were made, some of which were within 8° declination and about 3 h of right ascension of the occulted source. None of these sources, except the quasar 3C 459, showed any enhancement of scintillations. Hewish *et al.*[10] showed that interplanetary transients cover a solid angle of helio longitude and latitude of $\pi/2$ Sr. and also, there is a strong correlation between enhancement in scintillation and mean plasma density along the line of sight to a source. As the enhancements in scintillations were recorded only in the case of 3C 459, the density increase was restricted in that direction only. These authors[8,9] concluded that the observed enhanced scintillations of 3C 459 were caused by the ion-tail of comet Halley as predicted.

Slee *et al.*[11] using Parkes 64-m telescope reported enhancement of scintillations by as much as four times that of the background when the compact radio source 1827–360 was occulted by Halley's comet during its post-perihelion period. The geocentric velocity of the comet Halley was $\sim 40\ \mathrm{km\ s^{-1}}$. The projected distance from the nucleus, at which the tail passed in front of the source, was 5.4×10^6 km. They deduced ΔN in the ion-tail to be $1.8\ \mathrm{cm^{-3}}$ for a gaussian electron density correlation function. The same for a Kolmogorov power-law spectrum, with an inner scale of 100 km and an outer scale of 4.8×10^5 km, was estimated to be $1.4\ \mathrm{cm^{-3}}$.

Hajivassilliou and Duffett-Smith[12] used the data recorded at Cambridge during the IPS survey at 81.5 MHz to make a retrospective search for enhanced scintillation caused by cometary tails. The data comprised daily measurements of the rms scintillating flux density on about 2000 radio sources at all values of right ascension north of declination $-10°$. From this data base they found a sample of 35 comets, out of which 12 were identified as sufficiently bright to promise an effect and whose tails occulted about 45 bright scintillating sources observed in the survey. They[12] concluded that there was no convincing evidence for enhanced scintillations of radio sources due to plasma density irregularities in the ion-tails of the comets.

These observations were not really planned for occultation events by cometary ion-tails. The visual magnitudes of 8 out of 12 comets were in excess of 10 and had no reports on tail lengths of six comets; the remaining five comets had tail lengths of less than 2° and only one comet had a tail length of 5°. Their[12] telescope could observe each source only for 2 min. In addition, the comet's slow proper motion which implied large uncertainties in the calculated moments of the occultations confused their data. They therefore concluded that the observations did not entirely rule out the possibility of scintillations caused by cometary tails, since the comets used by them were faint and many of them carried no report of a tail being observed.

Ananthakrishnan *et al.*[13] attempted to observe scintillations of four radio sources occulted by the ion-tail of comet Halley at 327 MHz, using the Ooty radio telescope. However, the description of only three sources, viz. 2052–106, 1921–293 and 1817–391, is given. The last source was confused with 1815-391. Each occulted source, together with the corresponding nearby control source, was observed for 15-20 min, alternated between 10 min of observations of each of the control sources. Each observation was made for three days, the middle one being the day of occultation spread over 6–9 h. Based on these observations, they concluded that no significant increase in the level of turbulence was observed attributable to the plasma tail.

The solar elongation of the source 2052–106 during the observations was approximately 10° which is improper as at 327 MHz the maximum scintillation of a source due to solar plasma occurs around 14° solar elongation. Consequently, the bulk of the scattering took place in a relatively thin layer of the solar plasma centred around the point of closest approach to the source 2052–106. Corresponding control sources were also within 12° of the Sun. Therefore, the enhancement due to the cometary tail was not detected. The source also got broadened owing to the strong scattering, resulting in reduction of the scintillations. Furthermore, due to the nearly 18° inclination angle between the ecliptic and the orbital plane of the Halley's comet, this line of sight might intersect the cometary tail at a point much towards its far end; and it will not intersect at all if the two planes were coincident. But this effect is only 5%. Thus, the event reported by Ananthakrishnan *et al.*[13] was unsuitable to observe any enhancement of scintillations that would have been caused by an active comet like Halley. Due to poor signal-to-noise ratio in the case of source 2021–168 no observations are reported in their[13] paper. This is very likely due to a disconnection (of tail) event (DE) on 1 March UT which might have made the occultation ineffective[9]. During the observation of the occulted source, 1921–293, an enhancement of 10% in scintillation was shown when it was within 10 arcmin of the ion-tail. The last occulted source in their investigation was 1817–391 with its control source 1827-360. From their[13] Figure 3(a), it can be estimated that the enhancement in the case of the occulted source was about 60%, while that for the control source (1827–360) was about 20%. Despite this, they described these two enhancements as similar.

Slee *et al.*[14] using the Parkes telescope reported an enhancement of scintillations of the occulted quasars 0606–795 and 0637–752. This enhancement was as much as three times that of the scintillations recorded over the nearby compact source 0438–436 outside the tail. The projected distance from the nucleus at which the tail passed in front of the source was 0.12 and 0.099 AU ($1\ \mathrm{AU} = 1.5 \times 10^8$ km) and the projected linear width of the tail was about 9.4×10^5 km. From this experiment they established that comet tails present two main regimes of plasma turbulence with strength well above that in the surrounding solar wind. Near the tail axis there is a fine-scale structure with scale size 10–40 km; along the tail's edge, where the comet's plasma merges with the solar wind, large-scale turbulence (90-

350 km) appears to develop. They also found the plasma density irregularity to be in the range 1-8 cm^{-3}.

Recently, Janardhan *et al.*[15] using the Ahmedabad telescope made observations of the quasar 2204+29 (3C 441) occulted by comet Austin. They reported an enhancement of about 2.5 times that of the average scintillation of nearby radio sources outside the ion-tail. In a slab of thickness of 10^6 km, they found the scale size of the irregularity to be about 17 km.

It is interesting to compare the estimated values of N_{comet} (Table 1) with the values obtained in March 1986 from *in situ* measurements. Gard *et al.*[16] (using Langmuir probe, *Vega*-2) reported these values in the range 10^2–10^3 cm^{-3} at a distance of 2×10^5 km–6.5×10^4 km from the nucleus of the comet Halley. Vaisberg *et al.*[17] (*Vega*-1) reported maximum density of $\sim 4\times10^3$ cm^{-3}, at $\sim 1.2\times10^4$ km from nucleus. However, Pedersan *et al.*[18] (*Vega* 1 & 2) reported these values in the range 50–25 cm^{-3} in the outer coma and about 10^3 cm^{-3} at a distance of 1.5×10^5 cm from the nucleus.

Conclusions

As has been described earlier, a few attempts were made to record the enhanced scintillations of compact radio sources attributable to density irregularities in the occulting cometary plasma tails. In addition, Hajivassiliou and Duffett-Smith[12] analysed an extensive data base of IPS of about 2000 sources recorded during 1978–81. They came across many events of occultations of scintillating sources by several comets. Most of these comets were faint and there was no information on their cometary tails. Also, due to their very short time (2 min) of observation on each source, nearly 58% of the occultation events were missed[12]. Due to these uncertainties of observations, they concluded that they could not entirely rule out the possibility of cometary plasma tails giving rise to enhanced scintillations of radio sources.

The observations of Ananthakrishnan *et al.*[13] studied in reality three events of occultations of radio sources by the Halley's plasma tail. Sharma[9] has indicated that one of the events reported by these authors failed to observe enhanced scintillations attributable to the cometary tail owing to very unfavourable geometry during that event. In the case of the events during 1–3 April 1986, their observations do indicate enhanced scintillations[13]. On 1 April, there was substantial enhancement in the scintillations and on 24 March, this enhancement was 10%. In both these cases the ion-tail was within 10 arcmin of the line of sight. These were misinterpreted in terms of reasons other than the cometary plasma tail.

The important requirements of favourable geometry of occultation, monitoring of background level of scintillations during and after an occultation event, covering of a sufficiently large region around the occulted source to monitor effects of interplanetary transients, geomagnetic storms and ionospheric phenomena and complete information on the cometary plasma tail were satisfied during the observations at 103 MHz in December 1985. Sharma[9] and Alurkar *et al.*[19] therefore concluded that the enhanced scintillations observed by them were caused by Halley's plasma tail. Although during the observations of Slee *et al.*[11,14] and Janardhan *et al.*[15] the geometry was favourable, the enhancement in the scintillation of the occulted sources was only about 3–4 times that of the scintillation of a source outside the tail. This enhancement is not very convincing as the variation in the scattering power of the IPM itself could be as much as a factor of three[20]. Unfortunately the observations of Slee *et al.*[14] and Janardhan *et al.*[15] were only single-shot observations.

Table 1 shows that there is no clear dependence of N and ΔN on the tailward distance from the nucleus. However, to reach any conclusion various observations of the radio source occulted by the same comet tail should be made.

Suggestions for future observations

As it is evident that such occultation observations give scintillations when the geometry is favourable as in the case of observations of Halley's comet, Alurkar *et al.*[8] and Sharma[9]. To decide it once and for all, simultaneous observations of scintillating radio sources occulted by the ion-tail of some active comets should be made. Unfortunately this has not been possible so far.

The favourable conditions are:

1. The radio source to be observed should be sufficiently away from the Sun to minimize the background scintillation (IPS) produced by solar plasma irregularities as in the case of Alurkar *et al.*[8], Slee *et al.*[11,14] and Janardhan *et al.*[15].
2. The comets should have well-developed ion-tails. Generally ion-tails of about 10° are developed when comets are within 1–1.5 AU of the Sun.
3. In view of the importance of studying the plasma tail of a comet, it would be preferable to make such observations simultaneously as more than one spaced sites. These frequencies should be $\leqslant 300$ MHz as scintillations are inversely proportional to the operating frequency and are good at metre wavelengths as a result of the characteristics of the IPM.

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Remnants of greenstone sequence from the Archaean rocks of Rajasthan

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An interesting association of granitoid-amphibolite-metasediments occurs around Jagat, southeast of Udaipur in Rajasthan. Lying a little south of the area from where 3.3-billion-year-old gneisses have been reported, these rocks compare well with the known greenstone associations of Archaean age. The mafic and granitoid rocks show chemical affinity with the modern volcanic arc rocks.

THE geological map of southeastern Rajasthan prepared by Heron[1] shows a number of metasedimentary-metavolcanic units separated by outcrops of gneiss-granite rocks, the latter described as Banded Gneissic Complex (BGC). The stratigraphic position of BGC in relation to the metasedimentary metavolcanic units belonging to the Aravalli system, Delhi system and the Raialo series[1] has been debated over the last four decades or so[2,3]. Recently available isotopic dates[4,5], however, confirm that the gneiss-granite rocks mapped as the BGC over a large area, are truly Archaean in age, and have undergone extensive ductile deformation and reconstitution during the Proterozoic[3]. The 3.3-billion-year-old gneisses, the oldest known so far from this part of the Indian shield, occur near Jhamarkotra, southeast of Udaipur. Detailed mapping by us in the area a little south of Jhamarkotra revealed an association of gneiss-granite–amphibolite–metasedimentary rocks which compares well with the well-known granite-greenstone belts around the world. Here we report field and chemical characteristics of these rocks. This might help in understanding the early crustal evolution in the region. A reference may be made in this connection to the report of Sargur-type banded iron formation by Sahoo and Mathur[6] from the neighbourhood of the study area around Jagat (Figure 1) about 30 km southeast of Udaipur.

Lithology and field relationship

Lithologically, the rocks of the Jagat area can be divided into three main groups, namely the granitoids, the amphibolites (including poorly metamorphosed dolerite) and the metasediments. The granitoids cover by far the largest area, followed by the amphibolites. The metasedimentary units, which include carbonates, calc-silicate rocks, quartzite, iron formations and pelitic schists, on the other hand, occur as small bands and irregular enclaves within the granitoid rocks.

The granitoids are of three different types: pink granites, leucogranites and grey gneisses. The last one seems to be the most common of the three. The pink granite, because of its colour and composition, can be