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Radio Source Scintillations through Comet Tails Revisited: Comet Wilson (1987)

O. B. Slee,[A] *A. D. Bobra,*[B] *D. Waldron*[C] *and J. Lim*[D]

[A] Australia Telescope National Facility, CSIRO,
P.O. Box 76, Epping, N.S.W. 2121, Australia.
[B] Physical Research Laboratory, Ahmedabad 380 009, India.
[C] U.K. Schmidt Telescope Unit, Royal Observatory, Edinburgh.
[D] Department of Mathematics and Physics, Macquarie University,
North Ryde, N.S.W. 2113, Australia.

Abstract

Observations of the quasars 0606–795 and 0637–752 as the tail of Comet Wilson swept across them on May 1 and May 2, 1987, showed a three-fold increase in scintillation index over that of nearby compact radio sources outside the tail. Two scintillation regimes have been identified: (1) small-scale turbulence of 10–40 km develops near the tail-axis; (2) large-scale turbulence of 90–350 km is present in the off-axis transition region between the tail plasma and solar wind. At a distance 0·12 AU downstream from the nucleus the r.m.s. electron-density variation in these turbules is 4–8 cm^{-3} on axis and 0·8–1·7 cm^{-3} in the transition region between the tail and the solar wind. The reported negative results from earlier comets are shown to be of doubtful significance.

1. Introduction

Several groups of observers have made conflicting claims about the existence of enhanced intensity scintillations as the plasma tail of a comet passes in front of a compact radio source. Increases in scintillation were noted for Comet Kohoutek (Ananthakrishnan *et al.* 1975) and Comet Halley (Alurkar *et al.* 1986; Slee *et al.* 1986). Conversely, Ananthakrishnan *et al.* (1987) were unable to confirm an enhancement for Comet Halley while Hajvassiliou and Duffett-Smith (1987) reported negative results for a number of comet-tail occultations. A discussion of two conflicting claims on the presence of enhanced scintillation due to Halley's tail was given in the science correspondence section of *Nature* by Alurkar *et al.* (1989) and Ananthakrishnan *et al.* (1989).

In May 1987, during the apparition of Comet Wilson, an opportunity arose to resolve this controversy. We observed the two compact sources 0606–795 and 0637–752 on three successive days (May 1, 2 and 3) when the comet was near its closest approach to earth. As an additional check on the general state of turbulence in the solar wind we also observed a third compact source 0438–436 about 35° closer to the sun. The parameters of these sources are given in Table 1. Some useful information about Comet Wilson is presented in Table 2.

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Table 1. Radio source parameters

Radio source PKS	Ecliptic coordinates (°)	(°)	408 MHz flux density Total[A] (Jy)	Compact[B] (Jy)	Comments
0438–436	54·2	–64·6	8·1	8·1	IPS control source
0606–795	268·7	–77·0	3·3	3·3	Occulted May 1, IPS control May 2
0637–752	254·9	–80·8	7·9	4·3	Occulted May 2, IPS control May 1

[A] From Molonglo Reference Catalogue (Large *et al.* 1981).
[B] Extrapolated from Parkes–Tidbinbilla Interferometer measurements at 1·67, 2·29 and 8·41 GHz (Norris and White unpublished).

Table 2. Comet Wilson parameters

Date at 04 UT	Nuclear ecliptic coordinates (°)	(°)	Topocen. distance (AU)	Heliocen. distance (AU)	Elong. (°)	PA tail[A] (°)	Project. velocity (km s^{-1})
May 1	292·6	–80·4	0·6234	1·2106	92·8	147·1	70·0
May 2	282·2	–83·6	0·6237	1·2128	93·0	138·6	68·1
May 3	254·2	–86·2	0·6262	1·2152	93·2	132·6	66·8

[A] Includes a correction for tail lag of +3·1°.

2. Observations and Results

The observations were made with the Parkes 64-m telescope at 408 MHz using the same equipment and reduction procedure that were fully described for our observations of Halley (Slee *et al.* 1986). The path of the comet projected onto the plane of the sky is shown for May 1 and May 2 in Fig. 1. The ephemeris for the comet is that published in IAU Circular No. 4364 (April 10, 1987). The position angle of the tail axis, which is shown in Fig. 1 for several values of UT, has been corrected for the apparent 'tail lag' induced by the interaction of the comet's velocity and the radially directed solar wind velocity.

The position angle of the tail axis was measured from contrast-enhanced prints of plates taken with the U.K. Schmidt telescope at Siding Spring, N.S.W., on the evenings of May 1, 2 and 3. On these prints the tail can be traced out to an angular distance of about 5° from the nucleus with most of the plasma contained within a cone of opening angle about 3° at the nucleus. The average tail lag for the three nights was 3·1±0·7°.

An overview of our observations of the occulted sources is presented in Fig. 2. Each plotted value represents the r.m.s. scintillation flux obtained by averaging 10 blocks of data each 41 s long. The r.m.s. flux was obtained by measuring the area under the corresponding average power spectrum—this was computed by subtracting the average spectrum of all off-source blocks for the day from the spectrum of the 10 on-source blocks. This procedure should effectively remove the system noise contribution but it still leaves a small contribution due to the flux density of the source itself. In the case of 0606–795 this amounts to a 1·7% increase in the system temperature of

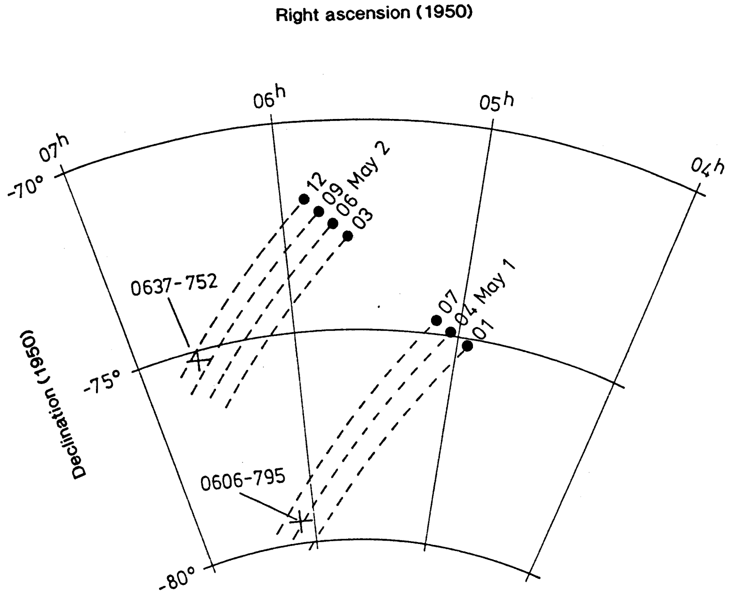

Fig. 1. Equiangular projection onto the plane of the sky of the path of Comet Wilson with respect to the radio sources 0606–795 and 0637–752 (marked with crosses). The position of Wilson's nucleus is shown at selected three-hour intervals of UT on May 1 and 2. The dashed lines represent the extended sun–Wilson vectors, which include a position angle correction for tail-lag of +3·1°.

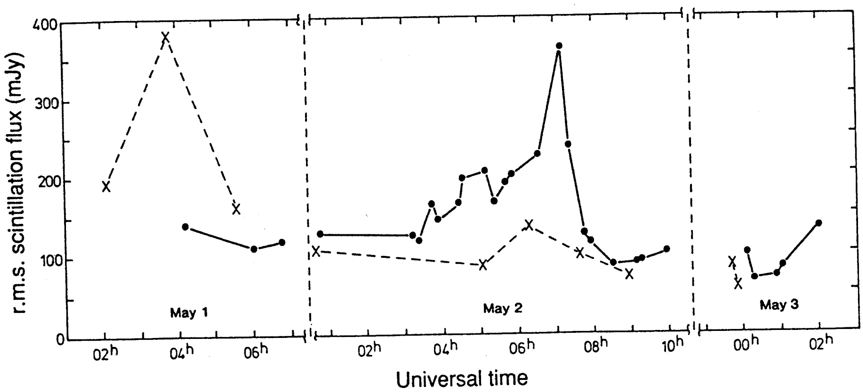

Fig. 2. Scintillation profiles of the occulted sources on May 1, 2 and 3. Each point represents the r.m.s. scintillation flux obtained by averaging 10 blocks (410 s) of data. Quasar 0606–795 (crosses joined by dashed lines) was occulted on May 1 with the tail-axis of Wilson passing in front of the source at about 0400 UT. Quasar 0637–752 (circles joined by full lines) was observed on May 2 with the edge of Wilson's plasma tail passing across the source near the scintillation peak; the tail-axis occultation about 1100 UT was not observed. Both sources were outside the tail on May 3.

120 K, and for 0637–752 a 4% increase. Thus, with no scintillation in the source itself, there will be an apparent increase in r.m.s. level of 7 mJy for 0606–795 and 17 mJy for 0637–752. It is clear from Fig. 2 that the minimum observed r.m.s. level was about 50 mJy, so that the contribution of the source's flux density is not very significant; the observed minimum is probably due to the addition of a small amount of normal interplanetary scintillation, a small contribution from ionospheric scintillation and a component due to unsubtracted gain variations in the receiver.

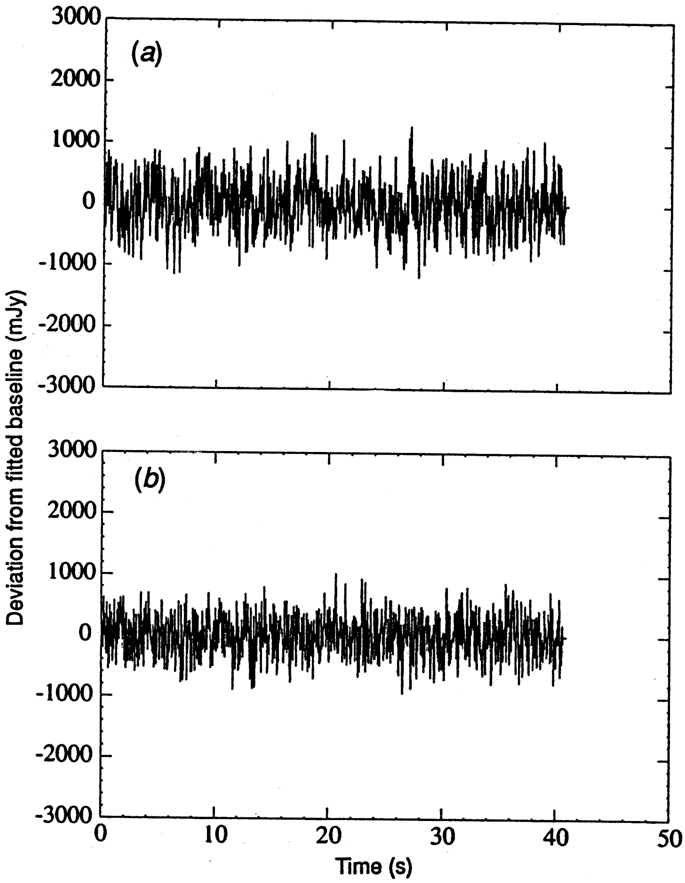

Fig. 3. Samples of data taken during the occultation of 0606–795: (*a*) data recorded on-source at 0354 UT on May 1 near the time of tail-axis occultation; (*b*) a block of data recorded off-source shortly before that of (*a*).

The important features of Fig. 2 are the peaks in scintillation flux on 0606–795 at about 0400 UT on May 1 and on 0637–752 at about 0700 UT on May 2. At the same times (or as close as circumstances permitted) the scintillation fluxes of the control sources (0637–752 on May 1 and 0606–795 on May 2) were comparatively low.

It can be seen from Fig. 1 that the axis of Wilson's plasma tail passed across 0606–795 at about 0400 UT on May 1, corresponding to the peak in

Fig. 2. One of the 41 s data blocks taken on-source during this peak is shown in Fig. 3*a*; for comparison a block of data taken with the telescope one degree off-source is shown in the lower panel. It is clear that the fluctuations have a noticeably higher amplitude in the on-source data.

Fig. 1 shows that the tail axis of Comet Wilson did not pass in front of 0637–752 on May 2 until about 1100 UT, about one hour after the elevation limit of the telescope terminated our observations. Nevertheless, Fig. 2 shows that we recorded enhanced scintillation from 0400 to 0730 UT while the low-density edge of the plasma tail was passing across the source. (We note that our observations of 0606–795 on May 1 did not encompass the passage of the source behind either edge of the tail.) Fig. 4*a* shows a 41 s block of data near the peak at about 0700 UT and Fig. 4*b* illustrates the receiver output one degree off-source. There is an important difference between the enhanced scintillations seen in Figs 3*a* and 4*a*—the scintillation in the latter contains a much more pronounced low frequency component.

It is clear from the foregoing evidence that the plasma tail of Comet Wilson contained an excess of plasma turbulence over the normal solar wind. More information on the structure of this turbulence can be obtained from the power

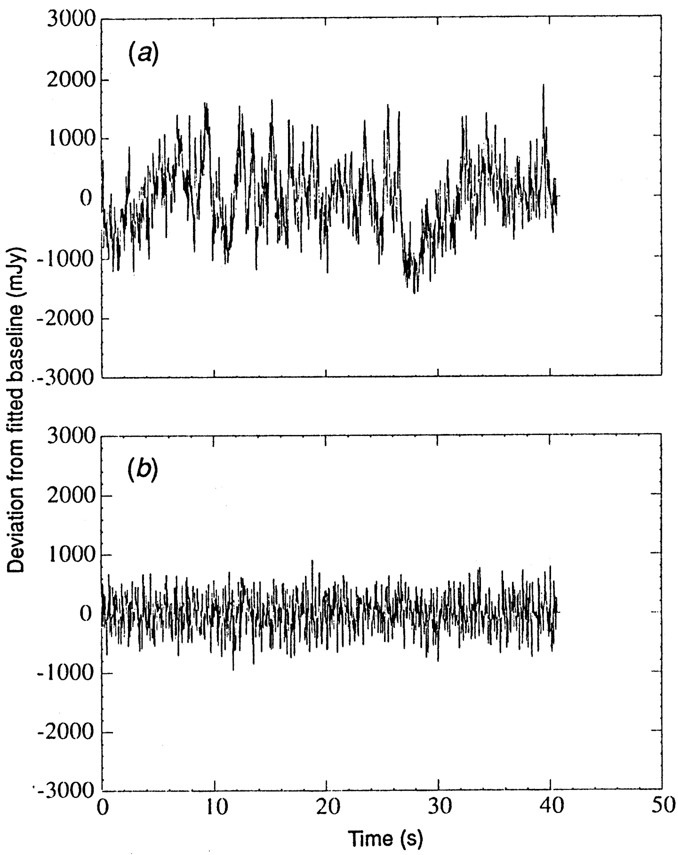

Fig. 4. Samples of data taken during the occultation of 0637–752: (*a*) data recorded on-source at 0620 UT on May 2 while the source was shining through the edge of Wilson's tail; (*b*) a block of data recorded off-source at 0635 UT.

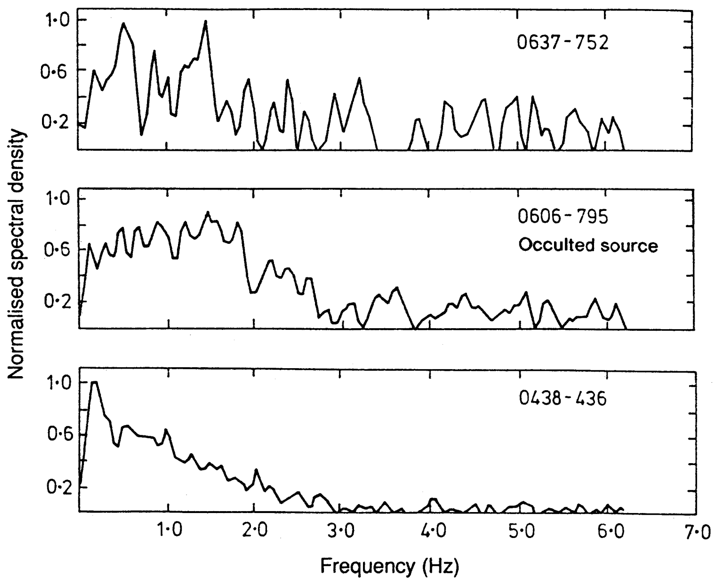

Fig. 5. Power spectra for the three sources computed from 410 s of data taken near the time of tail-axis occultation of 0606–795 on May 1. The frequency resolution before Hanning was 0·0488 Hz. Spectral estimates have been normalised to the maximum value in each spectrum.

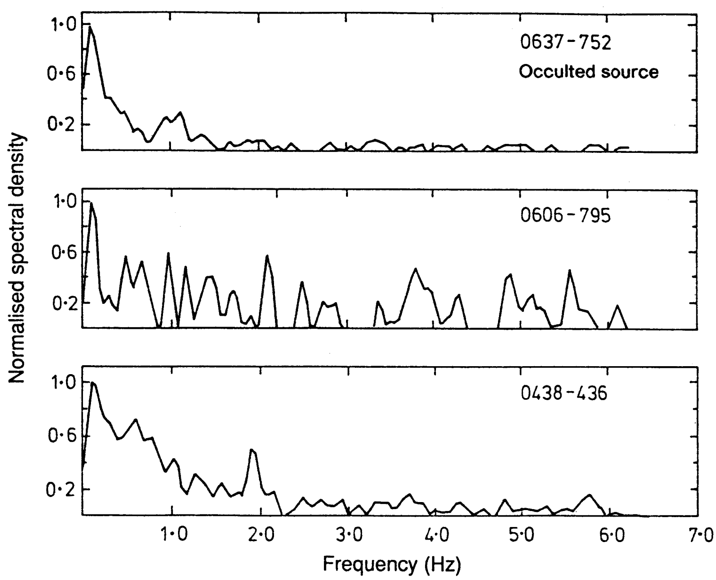

Fig. 6. Power spectra for the three sources computed from 410 s of data taken near the time of maximum scintillation in 0637–752 on May 2. The frequency resolution before Hanning was 0·0488 Hz. Spectral estimates have been normalised to the maximum value in each spectrum.

spectra. Figs 5 and 6 show the power spectra for the sources on May 1 and May 2 respectively, obtained in each case by subtracting a Hanned spectrum of 1200–2000 s of data off-source, from a Hanned spectrum of 410 s of data on-source; the spectra have been normalised to the highest spectral density.

There are important qualitative differences between these spectra. An examination of the spectra for May 1 (Fig. 5) near the time of tail occultation of 0606–795 shows that the spectrum of the occulted source possessed a broad peak in the 1–2 Hz range; 0438–436 (much nearer the sun) had a typical IPS spectrum with a peak near 0·1 Hz and slowly decaying out to 3 Hz. The control source 0637–752, situated well outside the tail on May 1 and 4·6° from 0606–795, shows little evidence of scintillation.

The power spectra of Fig. 6 are applicable to the sources on May 2 near the time of maximum scintillation on 0637–752 as it was entering the comet's tail. Here we see that although 0637–752 and 0438–436 both have spectral peaks near 0·11 Hz, the spectrum of the occulted source decays much more quickly than the IPS spectrum of 0438–436. The control source 0606–795, which was outside the tail at an angular distance of 4·6° from the occulted source, shows no clear evidence of scintillation.

Before any quantitative estimates can be made of the electron content of the plasma turbules one must convert the r.m.s. scintillation flux to a scintillation index, m = (r.m.s. flux)/(compact source flux density). In Table 1, we give our best estimates of compact flux density (the fraction of the total flux density contained within an angular diameter much less than 1 arcsec and therefore able to participate in the diffraction process). These values were obtained by extrapolating measurements with the Parkes–Tidbinbilla Interferometer at 1·6, 2·3 and 8·4 GHz to our observing frequency of 408 MHz. The values so obtained are not accurate because of the temporal variability in compact sources and the large extrapolation involved, but they are unlikely to be in error by more than 25%.

Table 3. Scintillation indices

Date	Source	Scintillation index[A] m
May 1	0438–436	0·030
	0606–795[B]	0·115
	0637–752	0·032
May 1/2	0438–436	0·025
	0606–795	0·030
	0637–752[B]	0·083
May 2/3	0438–436	0·020
	0606–795	0·023
	0637–752	0·030

[A] From 410 s integrations.
[B] Occulted source.

Table 3 summarises the scintillation indices for the three sources on May 1, 2 and 3. For the occulted sources on May 1 and 2 we list the scintillation indices corresponding to the peaks in Fig. 2. The scintillation indices for the two unocculted sources (0438–436 and 0637–752 on May 1 and 0438–436 and 0606–795 on May 2) are those applying to the data nearest the times of the peaks. On May 3, when all sources were clear of the tail, we give the median scintillation index of each source.

It is clear from Table 3 that on May 1 the scintillation index of the occulted source (0606–795) is 3–4 times higher than that of the nearby control source 0637–752. The occulted source is also 3–4 times higher in scintillation index than 0438–436, which is 45° closer to the sun and displays a spectrum in Fig. 5 typical of the normal solar wind. It is therefore reasonable to deduce from this evidence that the contribution of the normal solar wind to the index of the occulted source is not very significant.

On May 2 the scintillation index of the occulted source (0637–752) is almost three times higher than that of the nearby control source 0606–795 and more than three times that of 0438–436, which again displays a typical IPS spectrum (Fig. 6).

On May 3, when all three sources were clear of the tail, the formerly occulted sources have low scintillation indices, as does 0438–436, which continued to display a typical IPS spectrum.

In summary, the scintillation indices in Table 3 reinforce the impression given by Fig. 2 that most of the scintillation seen near the peaks on May 1 and 2 is due to excess turbulence in the plasma tail of Wilson and is not due to patches of higher-than-normal turbulence in the solar wind. It is reasonable to conclude that the scintillation indices of the occulted sources are at least three times higher than those expected from turbulence in the solar wind at elongations of about 93°.

The occultation of 0606–795 on May 1 occurred at an angular distance of 5·7° downstream from Wilson's nucleus, corresponding to a projected linear distance of 0·120 AU. The tail with opening angle of 3° had a projected linear width of 0·0063 AU ($9 \cdot 4 \times 10^5$ km) at the source's position and swept across the source in 3·7 h. We shall assume that the thin screen scattering theory developed by Salpeter (1967) is valid for our observations. The correlation length or scale size of the turbulence is given by $a = v/2\pi f_2$, where v is the velocity of the diffraction pattern across the observer and f_2 is the width of the scintillation power spectrum at the exp(−0·5) points. From Fig. 4, f_2 is about 1·7 Hz and, assuming that the plasma turbules at this point in the tail had not yet been accelerated to typical solar wind velocities [see e.g. Jockers (1981) study of plasma condensations in Comet Kohoutek], we assign a translational velocity of $v = 100$ km s^{-1}. Thus $a = 10$ km, which is a much finer scale than has hitherto been considered for interplanetary turbulence. Even if the plasma turbules had been accelerated to a typical solar wind velocity of 400 km s^{-1} the resulting scale size of about 40 km is still considerably lower than the 100–200 km over which IPS is known to be correlated.

For a Gaussian electron density correlation function the r.m.s. phase deviation across the wavefront emerging from the screen is

$$\phi = (2\pi)^{\frac{1}{4}} r_e \lambda (aL)^{\frac{1}{2}} \Delta N,$$

where $r_e = 2 \cdot 82 \times 10^{-13}$ cm is the classical electron radius, λ is the wavelength, L is the screen thickness, a is the scale size and ΔN is the r.m.s. electron density deviation. For weak scattering, the scintillation index is $m = \surd 2\phi$, from which in the present case ($m = 0 \cdot 11$ on the tail axis) $\phi = 0 \cdot 078$ rad. Then with $a = 10$ km and making the reasonable assumption that the screen thickness is equal to its width of $9 \cdot 4 \times 10^5$ km, we deduce that $\Delta N = 7 \cdot 8\ \mathrm{cm}^{-3}$. If the scale size is increased to 40 km corresponding to the normal solar wind velocity then $\Delta N = 3 \cdot 9\ \mathrm{cm}^{-3}$. Despite the uncertainty in the scale size it is clear that the electron density turbulence near Wilson's tail axis is of considerably smaller scale and at least an order of magnitude stronger than the corresponding quantities in the normal solar wind at a distance of 1·2 AU from the sun (Cohen *et al.* 1967).

The occultation of 0637–752 on May 2 took place 0·099 AU downstream from Wilson's nucleus and the strongest scintillations were seen near the edge of the plasma tail at a projected linear distance of 0·0084 AU ($1 \cdot 25 \times 10^6$ km) from the tail axis. The width of the power spectrum is $f_2 = 0 \cdot 18$ Hz and assuming a velocity of $v = 100\ \mathrm{km\,s^{-1}}$ for the plasma turbules the scale size is $a = 88$ km; a plasma velocity of $400\ \mathrm{km\,s^{-1}}$ would give $a = 352$ km. The maximum scintillation index of 0·083 results in an r.m.s. phase deviation of 0·059 rad. With the depth of the screen equal to the projected linear distance from the axis the r.m.s. electron density variation is $\Delta N = 1 \cdot 7\ \mathrm{cm}^{-3}$. If the scale size is increased to 352 km corresponding to a typical solar wind speed then $\Delta N = 0 \cdot 8\ \mathrm{cm}^{-3}$.

3. Discussion

A comparison of these results with earlier (but disputed) claims to have detected enhanced scintillation through Halley's plasma tail is instructive. The experiment of Slee *et al.* (1986) did not use control sources nor were the effects of tail lag on the occultation geometry taken into account. However, the scintillations of the occulted source (1827–360), again observed as it was entering Halley's tail, possessed a similarly high proportion of low-frequency components ($f_2 = 0 \cdot 14$ Hz); this leads to a similar scale size and r.m.s. electron density variation to that observed during the entry of 0637–752 into Wilson's plasma tail on May 2. We note, however, that the Halley occultation took place at only 0·036 AU from the nucleus; it would be imprudent to suggest from this scanty evidence that the turbulence remains constant both in strength and in scale size along much of a comet's tail.

We note also that Slee *et al.* (1986) show in their Fig. 3 a short-lived enhancement in scintillation index about 4·5 hours after the broader first peak. Assuming a tail lag of about 3° (there were no optical plates taken for several days either side because of a full moon), this secondary peak would have coincided with the tail-axis occultation of 1827–360—such a peak would be expected from our present positive result on 0606–795 on May 1. We computed the power spectrum of the on-source data over the secondary peak and found its width to exp(−0·5) was $f_2 = 0 \cdot 33$ Hz with components of appreciable spectral density out to 2·5 Hz. This compares with $f_2 = 0 \cdot 14$ Hz with components out to 1·0 Hz for the main peak. Therefore, although the scale size for the on-axis plasma of Halley is not as small as that for Wilson, there has been a decrease by a factor of 2·5 in going from the tail edge to the tail axis with a minimum of turbulence between the two regimes.

The observations of Alurkar *et al.* (1986) used suitable control sources and showed that a large increase in scintillation index was accompanied by an upward shift in the peak frequency of the power spectrum to 0·6 Hz. Although in their experiment the effect of tail lag may not have been important because of the special occultation geometry, it would be well worth their making a further analysis taking into account the opening angle of the tail and the tail lag, both of which may be available from the photographs of Halley. It is sufficient to point out here that their computation of r.m.s. electron density of 10 cm^{-3} agrees reasonably well with our value of 4–8 cm^{-3} at a similar distance from the nucleus.

We can probably account for the majority of the negative results reported by Hajivassiliou and Duffett-Smith (1987) and Ananthakhrishnan *et al.* (1987). Hajivassiliou and Duffett-Smith admit that the errors in their source positions, assumed tail widths and tail lags, combined with their very small observing time slot meant that there was a 60% chance of missing an occultation. In nine of the twelve observed comets the visual tail lengths were $<1°$, further reducing the possibility of a tail occultation. Their most detailed negative result was obtained with comet Bradfield (1979X) from Feb 1 to Feb 22, 1980, when they obtained twenty-one 2-min observations of a grid of compact sources surrounding the plasma tail; they failed to witness a single definite case of excess scintillation due to tail plasma. However, we note that in addition to the high probability of missing the occultation of each individual source, in only one or two cases was there a compact source both within 3° of the nucleus (the optical tail length was only 1·7°) and within a cone of opening angle 3° centred on the nucleus (seen from the Schmidt plates of Halley and Wilson to contain most of the plasma).

The negative results of Ananthakrishnan *et al.* (1987) may be interpreted differently in two of the three occultations of compact sources by Halleys tail. First, the occultation of 2052–106 took place at an elongation from the sun of only 11·2° where the normal IPS is strong enough to obscure the expected small increase due to the tail plasma. Secondly, the occultation of 1817–391 on April 1, 1986, appears in our opinion to yield a positive result. The authors plot the scintillation flux which was normalised to the average value for the day (their Fig. 3*a*), rather than the more informative raw values. However, it is clear that halfway through this 9-hour observation the scintillation flux of the occulted source rises much more rapidly than that of the control source. As the axis of the comet tail was about to pass over the source at the end of the observation, the scintillations of the occulted source were ~1·8 times stronger than the average over the observing interval, while those of the control source were of average strength. The scintillation index of the occulted source may well have been higher than that of the control source by an even larger factor. The authors' most credible negative result came from the occultation of 1921–293 on March 24, 1986. However, some doubt remains, because their lack of knowledge of the tail lag may have shifted the main phase of the occultation outside their relatively short observing window.

4. Conclusions

The present experiment, aided by earlier positive results on Comet Halley, has 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. The reasons for the existence of either regime are not clear but are probably connected with the presence of velocity gradients across the plasma tail. Further theoretical studies in magneto-hydrodynamics may serve to interpret our results.

Acknowledgments

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