The Solar Wind outside the Plane of the Ecliptic

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The scintillation of radio sources caused by the interplanetary medium offers a means of studying the motion of the solar wind well away from the plane of the ecliptic, where direct measurements have so far been confined. Observations from a triangular arrangement of radio receivers (on 81·5 Mc/s) suggest that the solar wind is faster over the solar poles than in the plane of the ecliptic.

DIRECT measurements of the solar wind carried out from space vehicles have, so far, been confined to regions close to the plane of the ecliptic at distances of the order of one astronomical unit from the Sun. Interplanetary scintillation[1] provides a new technique for studying the solar wind over a much wider range of heliocentric latitude and radial distance, and some preliminary measurements of the drift motion of scintillation diffraction patterns across the surface of the Earth using two spaced observing sites have already been reported[2]. In this note an account is given of more extensive observations made between February and July 1966, using three observing sites. Both the magnitude and direction of the solar wind have been measured and evidence has been found that the wind velocity from the polar regions of the solar atmosphere is significantly greater than that in the plane of the ecliptic. A triangular arrangement of observing sites was used as shown in Fig. 1. The antennas at each site were transit instruments with similar collecting areas of about 800 m^2 and operated at a frequency of 81·5 Mc/s. Identical receivers having a time constant of 0·2 sec were used and data from the outstations were returned to Cambridge using G.P.O. telephone lines. Before April 10, a three-track pen recorder was used and the records were analysed as described before[2]. After this date the output of each receiver, sampled at intervals of 0.12 sec, was digitized and punched on a single paper tape. For the latter period, which included more than half the observations, data reduction was carried out entirely automatically.

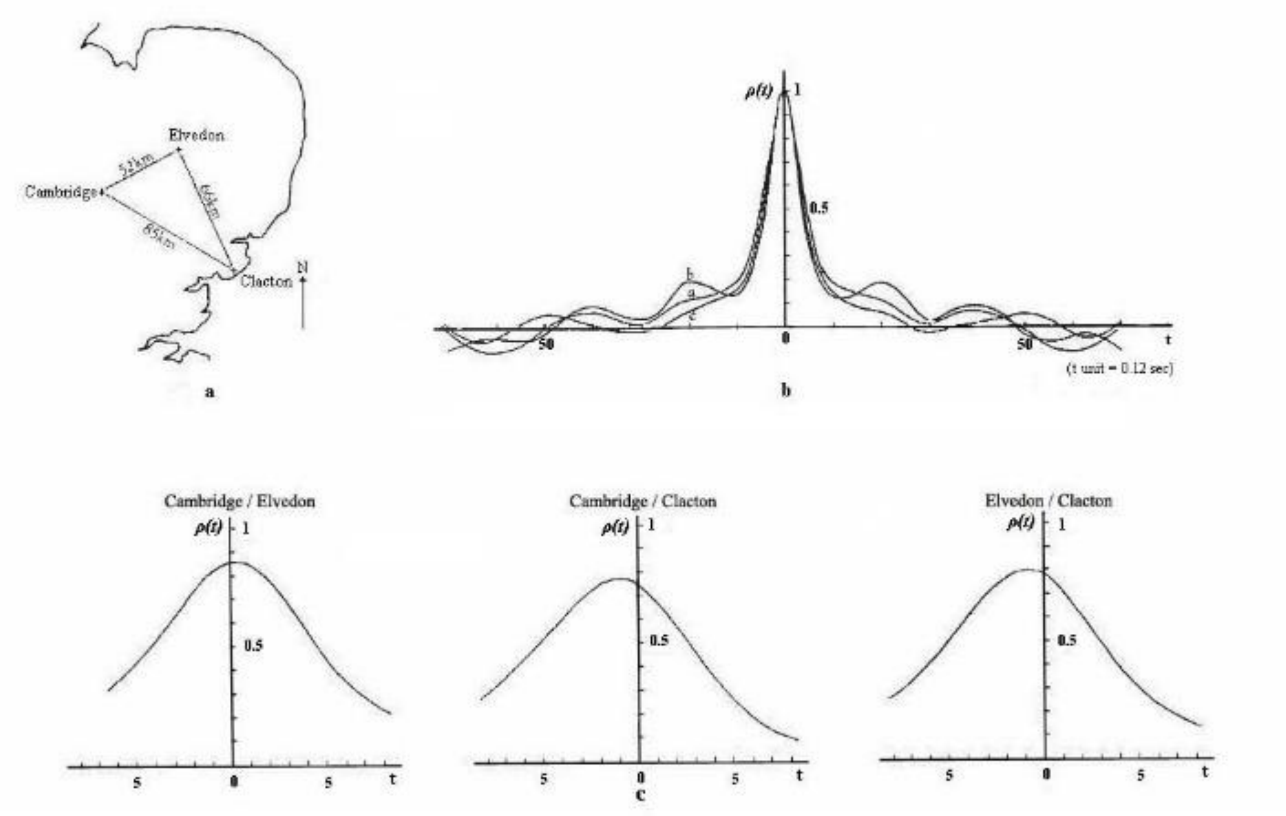

Fig. 1 (a) Location of the observing sites. (b) Typical auto-correlograms, and (c) cross-correlograms derived from observations of May 9, 1966.

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Most of the measurements were confined to the radio source 3C 48; a few observations were also made using the small diameter component[3] of the Crab Nebula.

The analysis was confined to an interval of one or two minutes each day from which the auto-correlogram of each receiver output and the three cross-correlograms were derived. The results for a typical day are shown in Fig. 1. The fluctuations of intensity, the auto-correlogram of which usually decayed to e^{-1} in about 0·6 sec, were found to be highly correlated at the three sites, while the cross-correlograms exhibited systematic displacements of the order 0·1-0·2 sec.

The derivation of the drift velocity of a diffraction pattern using data of this kind is straightforward if the pattern is isotropic, while a slightly more complex analysis is necessary for the anisotropic case[4]. The present results were obtained by assuming that the pattern is isotropic; possible corrections arising from the errors in this assumption are believed to be small for reasons which will be discussed later. Noise fluctuations on the records led to a probable error of ± 0·03 sec in the time displacement derived from the observations on any one day, and this corresponds to an error of about ± 10 per cent in the derived velocity.

The magnitude and direction of the velocity of the diffraction pattern derived from the cross-correlogram data are shown in Fig. 2(a). It is seen that the direction of motion across the ground varied systematically from a position angle of about +50° in February to about -100° in June. The broken curve in Fig. 2(a) shows the expected direction calculated for an assumed radial outflow from the Sun, after making a small correction for aberration caused by the orbital velocity of the Earth, and it is seen to fit the observations within the experimental uncertainty of ± 15°.

The average magnitude of the velocity, which varied from about 300 km/sec when the line of sight passed the Sun at a distance of 0·8 A.U. to 490 km/sec at a distance of 0·36 A.U. where the line of sight crossed the polar region of the solar atmosphere, is shown in Fig. 2(b). In relating the velocity of the diffraction pattern to the solar wind the effect of integration along an extended line of sight must, however, be taken into account. The observed velocity represents a weighted average the value of which is dominated by the regions of greatest scattering which occur where the line of sight is closest to the Sun. On either side of this region apparent motion perpendicular to the line of sight corresponds to a resolved component of the true radial velocity. Estimates based on the observed radial dependence of interplanetary scintillation[1,5] suggest that the true velocity may be 5-10 per cent greater than the values shown in Fig. 2(b). The random day to day changes of velocity are frequently greater than the experimental error and are believed to be real.

During the period of observation the heliocentric co-ordinates (p, θ) of the point of closest approach of the line of sight varied as shown in Fig. 3(a), and in Fig. 3(b) the observed velocities have been plotted as a function of these co-ordinates. There was a significant increase of velocity as 3C 48 approached the Sun, which might be associated either with decreasing radial distance or with increasing heliocentric latitude. The possibility that this increase was caused by temporal changes in the solar atmosphere, rather than by a systematic variation of heliocentric co-ordinates, does not seem likely, because the increase was maintained for a period of at least two weeks during which there was no outstanding solar activity.

Further measurements on other radio sources are needed to show that the increase of velocity is primarily a function of heliocentric latitude, although it seems unreasonable that the velocity should increase with decreasing radial distance since gravitational deceleration is negligible. Some limited data have been obtained from observations of the scintillating component of the Crab Nebula during July 1966, and the results are shown in Fig. 3(d). At this time the line of sight lay close to the plane of the ecliptic, but observations at distances less than 0·4 A.U. were unfortunately not possible because of the decrease of scintillation at small angular separation which has been noted before[3]. For $p \approx 0.4$ A.U. an average velocity of 295 km/sec was obtained as compared with 420 km/sec derived from observation of 3C 48 at the same radial distance. This result strengthens our earlier supposition that the solar wind has a greater magnitude at high helio-centric latitude. Further evidence is provided by the rate of scintillation on other sources[1] which has been shown to increase with heliocentric latitude in a manner consistent with the same picture.

In addition to measurements of velocity it is also possible to draw conclusions about the scale and life-time of the diffraction pattern. Precise results require careful consideration of the effects of random noise in the separate records which become important when, as in the present case, the pattern is highly correlated at the three observing sites. Analysis of the cross-correlograms following the method described by

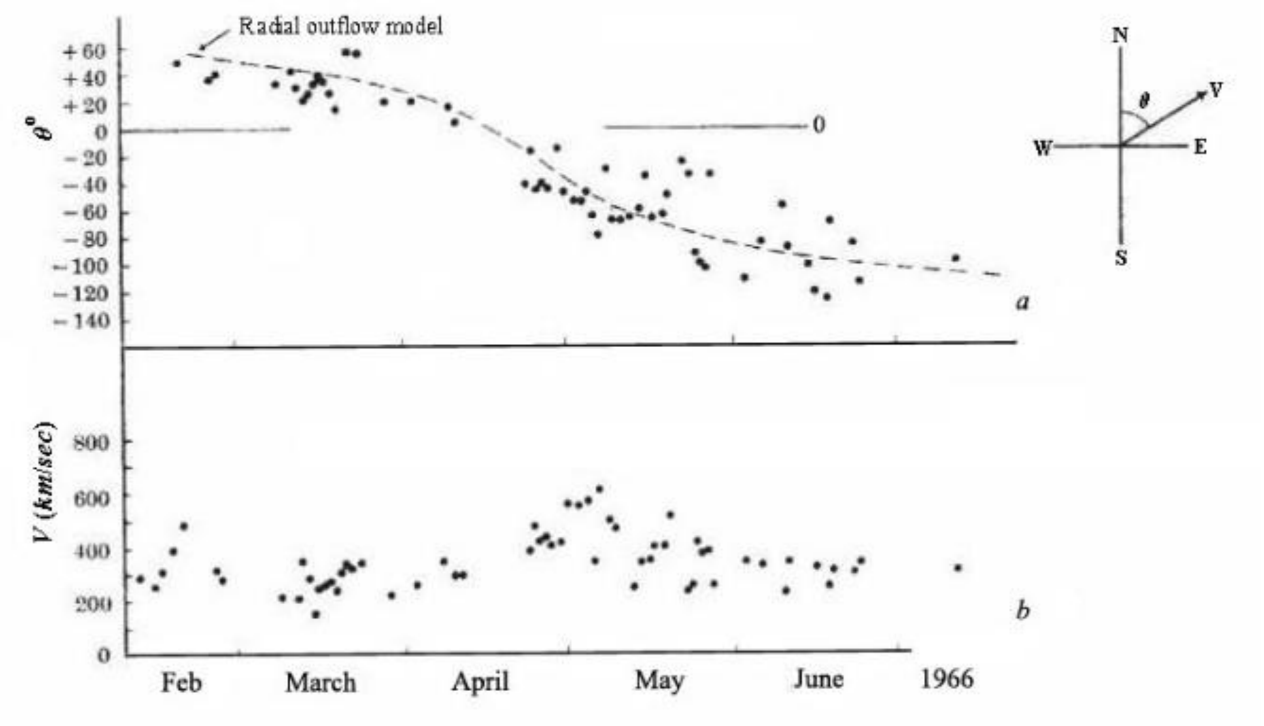

Fig. 2 (a) Observed direction of motion of the diffraction pattern across the ground. The broken curves shows the direction expected for a strictly radial outflow from the sun. (b) The magnitude of the drift velocity.

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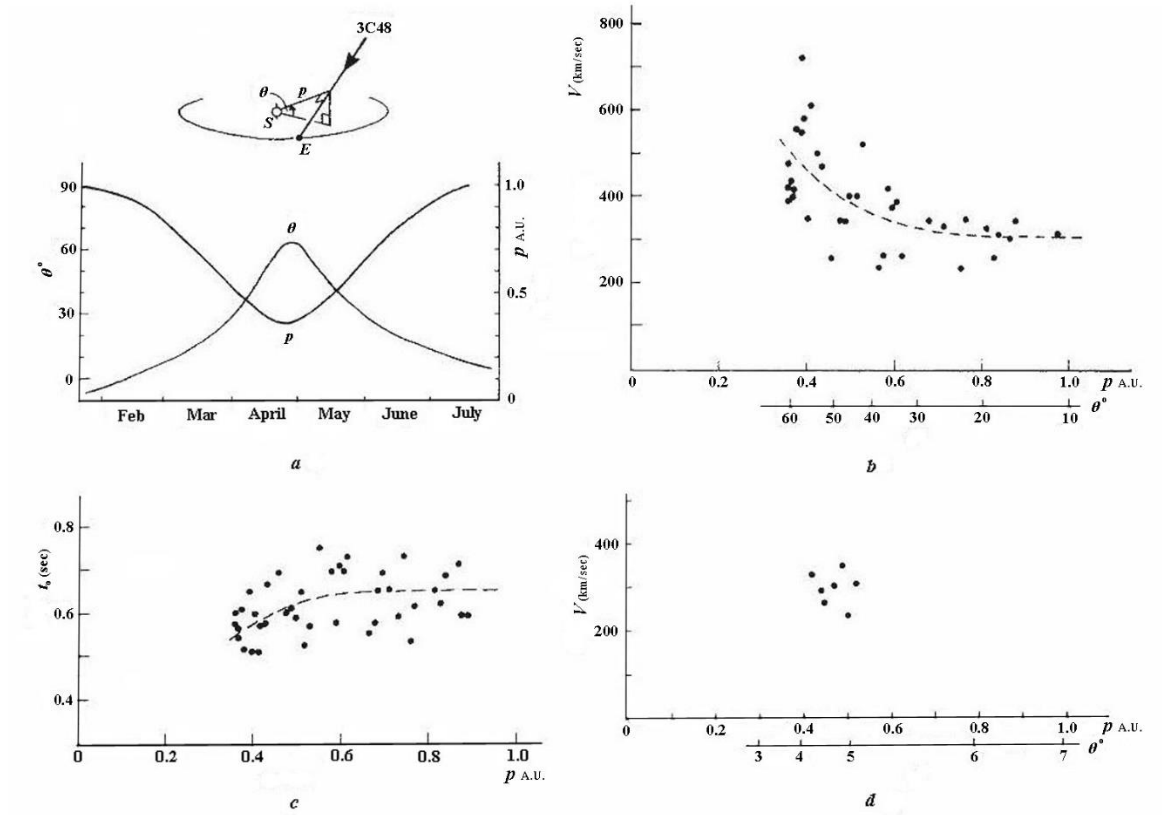

Fig. 3 (a) Heliocentric co-ordinates of the point closest to the Sun on the line of sight to 3C 48. (b) The observed velocity as a function of heliocentric co-ordinates for 3C 48. (c) Width (to a^{-1}) of the auto-correlogram of the temporal fluctuations of intensity. (d) Observed velocity derived from observations of the Crab Nebula.

Phillips and Spencer[4] indicates that the spatial correlation falls to e^{-1} in a distance of about 160 km. Since it has been shown that the interplanetary medium is a weak scatterer for $p > 0{\cdot}5$ A.U. (ref. 8), it follows that this remarkably small scale reflects the true size of the plasma density fluctuations themselves. The scale derived from cross-correlation does not differ significantly from estimates of the scale derived from auto-correlation on the assumption that the temporal fluctuations at one site are caused entirely by the drift motion of an unchanging pattern. It follows that the life-time of the pattern must be longer than the correlation time of 0·6 sec. The correlation time observed for various positions of 3C 48 relative to the Sun is shown in Fig. 3(c) where the heliocentric co-ordinates refer to the point on the line of sight closest to the Sun. It is seen that the correlation time decreased as 3C 48 approached the Sun, a result which is anticipated in view of the observed increase of velocity of the diffraction pattern. The decrease of correlation time is, however, not as large as would be expected and this leads to the conclusion that the scale of the diffraction pattern is somewhat greater when the line of sight is closest to the Sun. This effect is probably associated with the changing distance of the Earth from the dominant diffracting region and does not necessarily imply that the plasma irregularities themselves are larger when close to the Sun. For a line of sight such that $p \approx 0{\cdot}4$ A.U., the strongest irregularities are 0·9 A.U. distant from the Earth while for $p \approx 0{\cdot}9$ A.U. their distance is only 0·4 A.U. Now the diffraction pattern can only contain amplitude variations the lateral scale of which is smaller than the Fresnel zone radius, and it follows that, if the irregularities in the medium have a range of sizes, then the scale of the pattern will tend to increase as the distance from the diffracting region is increased. This phenomenon could readily account for an increase of scale for small values of *p*.

The scale of the diffraction pattern derived from cross-correlation is slightly elongated in a direction parallel to its motion, but the mean axial ratio of the characteristic ellipse is less than 2:1. Such an elongation might be expected since earlier measurements of the angular spectrum of radio waves scattered by the interplanetary medium have given evidence for decreased scattering in a radial direction[6,7]. The possibility that the elongation of the pattern is caused by the shape of 3C 48 itself cannot, however, be eliminated. A detailed consideration of the effects of source diameter has been given elsewhere[5], and it has been shown that a source extended preferentially in one direction can give rise to an elongated pattern. There is evidence that the angular dimensions of 3C 48 are critical in this respect, since this source scintillates somewhat less than other sources, and further information is needed before the elongation of the pattern can be ascribed to the interplanetary medium. Phillips and Spencer[4] have shown that the simple auto-correlogram analysis can give rise to errors of up to 20 per cent in the derived velocity when applied to a pattern which is elongated by a factor of 2:1. The errors fall to zero when the elongation is along the direction of motion, however, and it follows that the assumption, mentioned earlier, of an isotropic pattern for deriving velocities is justified. Further attempts have been made to relate the occurrence of scintillation with solar activity. It is possible that a small correlation with sunspot number

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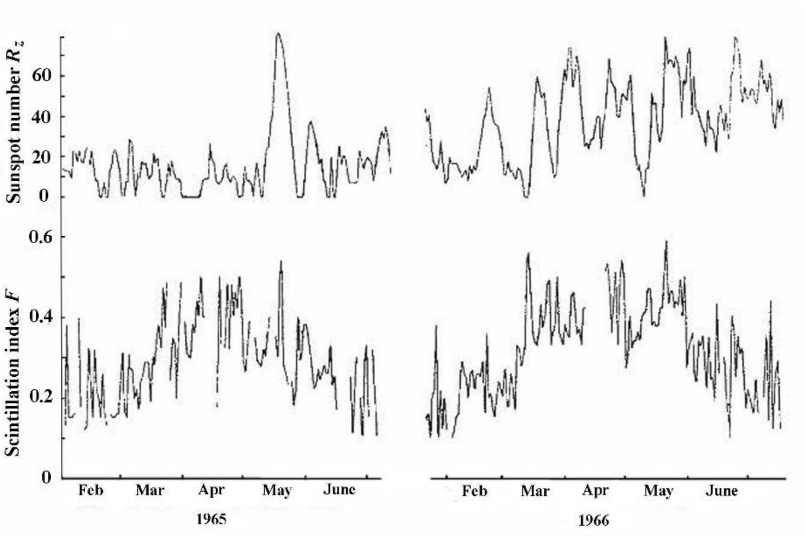

Fig. 4 Day to day variation of scintillation index F and sunspot number.

exists, but the present data are barely significant. In Fig. 4 the scintillation index observed during 1965 and 1966 is shown together with sunspot number for the same period. The scintillation index on March 13 and 14, 1966, increased to about twice its average value and this may be connected with a limb-flare which appeared on the eastern edge of the disk at heliographic latitude 20° N. on March 14. Radial ejection of material from such a point would have passed close to the centre of the line of sight. Further events of this kind are needed, however, before a definite association may be regarded as established.

While the scintillation index varies considerably from day to day, the observed velocities, particularly at low heliocentric latitude, are remarkably constant. This result contrasts with space-probe measurements of the solar wind which have shown larger variations strongly correlated with R_z. It appears that variations of this kind must be averaged out by integration along a line of sight which implies that the differences of velocity are confined to relatively narrow streams in the interplanetary medium.

In an earlier paper[6] it was found necessary to assume a slight convergence of the solar wind towards the plane of the ecliptic. This suggestion was put forward to explain the slow radial variation of the measured width of the angular spectrum of radiation scattered by irregularities for $p < 0{\cdot}4$ A.U. The present measurements are not sufficiently accurate to detect the difference (about 10°) from a strictly radial direction predicted by this model.

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