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Simultaneous interplanetary scintillation and optical measurements of the acceleration of the slow solar wind

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Abstract. Simultaneous observations of the slow solar wind off the southeast limb of the Sun were made in May 1999 using optical measurements from the C2 and C3 LASCO coronagraphs on board the SOHO spacecraft and radio-scattering measurements from the MERLIN and EISCAT facilities. The observations show the slow solar wind accelerating outwards from 4.5 solar radii (R), reaching a final velocity of 200–300 km s⁻¹ by 25–30 R. The acceleration profile indicated by these results is more gentle than the average profile seen in earlier LASCO observations of larger scale features, but is within the variation seen in these studies.

Key words: Interplanetary physics (solar wind plasma; sources of the solar wind; instruments and techniques)

1 Introduction

1.1 Interplanetary scintillation observations

Observations of interplanetary scintillation (IPS), in which the diffraction pattern cast across the Earth when a distant compact radio source is observed through the solar wind have been used as a flow tracer in the solar wind for over 35 years (e.g. Hewish *et al.*, 1964; Dennison and Hewish, 1967; Armstrong and Coles, 1972). Provided that the phase changes introduced into the incident radio waves are small (the condition of weak scattering) it is possible to treat contributions to the observed scintillation pattern from different parts of the line-of-sight to the source separately (e.g. Coles, 1995; Grall *et al.*, 1996; Breen *et al.*, 1996b). As the ray-path from the source to the antenna moves closer in to the Sun, the phase changes become larger and the amplitude of the scintillation pattern increases until the

inner limit of weak scattering is reached. Inside this limit, in the “strong scattering” regime where the phase changes introduced by scattering are large, the contributions from different regions of the ray-path do not combine as a simple weighted linear sum, and it becomes very difficult to accurately determine the contributions of different regions of the ray-path to the observed scintillation pattern (e.g. Hewish, 1989; Grall, 1995). The distance from the Sun for the transition from weak to strong scattering depends on the frequency of the radio waves received: for EISCAT observing at 0.93 GHz, the transition takes place at 25–30 solar radii (R) in the slow wind; for MERLIN (Thomasson, 1986) observing at 5 GHz, the transition lies below 7 R, though it is to be noted that the power radiated by most of the strong astronomical radio sources falls off towards higher frequencies, so that fewer “good” IPS sources are available at higher frequencies. A combination of high-frequency observations covering the region close to the Sun and lower-frequency observations covering the outer regions, with overlapping fields-of-view, is ideal. A schematic diagram of the geometry of an IPS observation is given in Fig. 1.

The first IPS observations using the EISCAT facility at a frequency of 0.93 GHz were made in 1982 (Bourgeois *et al.*, 1985) and a regular series of measurements of solar wind velocity have been made every summer since 1993. IPS observations have been made with MERLIN by Rickett (1992), initially in 1989 at 1.658 GHz using several baselines up to 127 km in length, and later in 1992 using the upgraded MERLIN incorporating the new Cambridge antenna which provides baselines of up to 217 km. The results of these observations were encouraging, and provided the impetus for the combined programme of EISCAT and MERLIN observations run in May 1999.

1.2 White-light observations

One of the aims of the coronal instruments on the SOHO spacecraft was the determination of the acceleration profile of the solar wind (Domingo *et al.*, 1995).

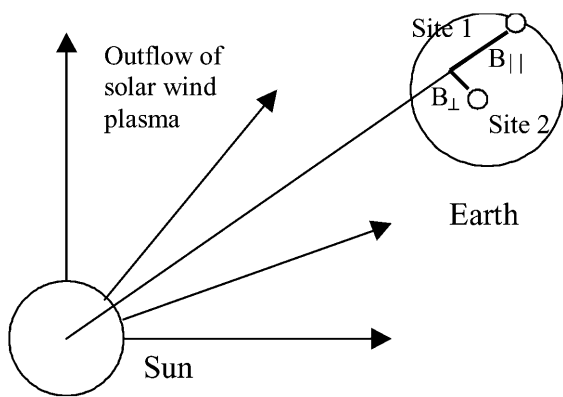


Fig. 1. Schematic diagram of a two-station observation of interplanetary scintillation, viewed from the direction of the radio source (normally a Quasar). The maximum cross-correlation between the scintillations observed at the two sites occurs when the baseline between the two receiving stations is parallel to the weighted average direction of flow of the solar wind across the ray-path (close to radially outwards from the Sun), and at a time-lag determined by the drift velocity of the scintillation pattern between the two ray-paths (e.g. Moran *et al.*, 1998). The baselines radial and tangential to the Sun-Earth direction in the plane of the sky are shown as $B_{||}$ and B_{\perp} respectively

Of the imaging coronal instruments, the large-angle spectroscopic coronagraph (LASCO, described by Brueckner *et al.*, 1995) is ideal for investigating outflow velocities from the inner corona out to distances of 25–30 R. Various LASCO studies (Sheeley *et al.*, 1997; Tappin and Simnett, 1998; Tappin *et al.*, 1999) have investigated the speed of identifiable features as they propagated out through the fields-of-view of the two LASCO coronagraphs. The small discrete “knots” or “blobs” studied by Sheeley *et al.* (1997) showed evidence of continuous acceleration from around 2 solar radii (R) out to beyond 20 R. The large-scale features, coronal mass ejections, studied by Tappin and Simnett (1998) were somewhat different. Some showed continuous acceleration, but the majority either moved at constant velocity or underwent a sudden acceleration at distances between 5 and 8 R. This behaviour is similar to that reported by Srivastava *et al.* (1999).

Sheeley *et al.* (1997) derived flow speeds by assuming that the features they studied were drifting at the background solar wind speed “like leaves in a stream”. This assumption can be made with more certainty if smaller features are studied, and particularly if the velocity profiles of features on different scales are compared. Tappin *et al.* (1999) considered very small-scale features in LASCO data and derived outflow velocities by calculating the cross-correlation function of white-light intensity at two radial distances from the limb of the Sun, a method analogous to the 2-site IPS technique (but see Tappin *et al.*, 1999 for a discussion of the differences between the two methods). The results indicated that the slow solar wind had reached its cruising speed by 25–30 R, with most of the acceleration taking place inside 10–15 R. Breen *et al.* (2000) compared the velocity of small-scale variations in intensity

observed in the fast solar wind with velocities obtained from EISCAT IPS measurements, but unfortunately the signal-to-noise ratio in the outer part of the LASCO field-of-view was too low for a direct comparison of velocities derived by the two techniques at the same radial distance. The observations made by Tappin and Simnett (1998), Sheeley *et al.* (1997), Tappin *et al.* (1999), Srivastava *et al.* (1999) and Breen *et al.* (2000) therefore cover four entirely different ranges of irregularity scale, from in excess of 100 000 km to around 100 km. In this study LASCO, MERLIN and EISCAT data from overlapping fields-of-view were compared for three days in May 1999. The scale sizes of the irregularities ranged from ~10 000 km for the LASCO features to ~100 km for the irregularities observed by EISCAT IPS and ~60 km for those observed at 5 GHz by MERLIN.

2 Observations

The observations discussed were made from EISCAT, MERLIN and LASCO between 2 and 15 May, 1999 and were co-ordinated so that the different instruments observed flow along similar stream lines of flow (within $\pm 10^\circ$ latitude and lying off the same limb).

2.1 LASCO observations

The LASCO (Large-Angle Spectroscopic Coronagraph) instruments observed the white-light intensity in the solar corona off the southeast limb of the Sun for 12 h per day on 9 and 11 May, 1999, producing an image from the C2 and C3 coronagraphs every 12 min. This was the finest time resolution possible when using C2 and C3 together, because of limitations in the data transfer rate from SOHO to Earth (Plunkett, private communication, 1999). The results were divided into two overlapping distance ranges from the Sun (Fig. 2) and cross-correlated (using the analysis technique described by Tappin *et al.*, 1999) to obtain estimates of the flow speed. The observations from each day were divided into two 6-h intervals to provide independent estimates of slow speed.

2.2 MERLIN observations

The strong radio source 0318+164 (CTA-21), with its small angular size and well-studied structure, is an ideal source for high-frequency IPS observations of the innermost regions of the solar wind. Lying off the southeast limb of the Sun in early May 1999 and moving closer to the Sun and towards higher latitudes with time, it had ray-paths to the Earth which reached their closest approach to the Sun on 12 May, 1999.

Time was allocated for MERLIN observations on three days (4, 9 and 11 May, 1999). 0318+164 was observed on all three days for approximately 2.5 hours per day. The observations are summarised in Table 1.

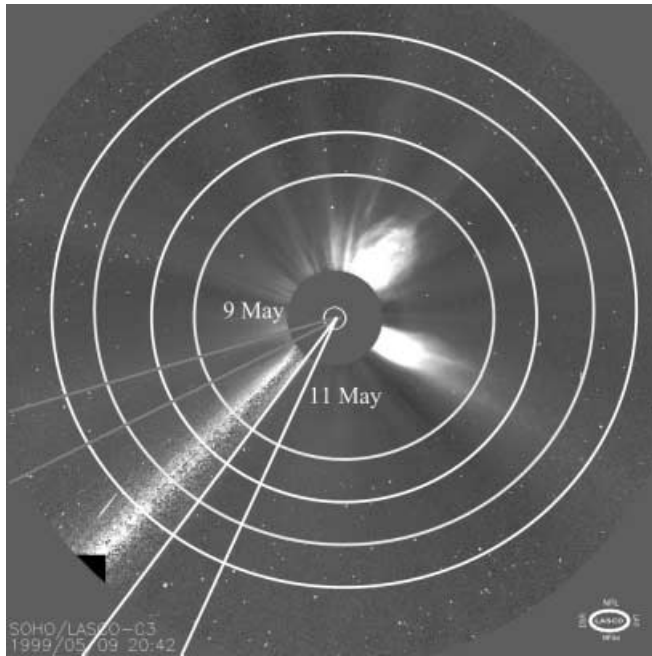


Fig. 2. Schematic diagram showing the regions of the LASC0 field-of-view used to estimate flow speeds on 9 and 11 May, 1999, overlaid on a LASC0 C3 image from 2042 UT on 9 May, 1999. The support for the occulting disc is visible at about 45° South off the east limb. The regions observed were PA 110–125 on 9 May and PA 145–160 on 11 May

Observations were also made of a second radio source, 0321+123, which lay further out from the Sun off the same limb as 0318+164, but unfortunately these proved to be too weak to produce useful scintillation measurements. 3C84 (0316+413) and 0552+398, at sufficiently large distances from the Sun that the degree of scintillation should have been negligible were observed for calibration purposes.

The observations on 4 May were made using the Cambridge and Knockin telescopes of MERLIN, operating at a central frequency of 1.66 GHz, a single polarisation (left circular) of equivalent band width 10 MHz being sampled at 100 Hz. On 9 and 11 May, the Cambridge and Jodrell Bank Mk2 telescopes were used at a central frequency of 5 GHz. Once again the detected equivalent band width was 10 MHz and the signals were sampled at 100 Hz. However, although only the left-circular polarisation was recorded from the Cambridge telescope, both left- and right-circular polarisations were recorded from the Mk2 telescope. Ideally, both polarisations would have been recorded

at all sites. However, in order to preserve the total power information essential for IPS measurements during the microwave link signal transfer from the outstation sites at Cambridge and Knockin to Jodrell Bank the signals had to be frequency modulated onto the links, which restricted them to a single 10 MHz polarisation band. In future experiments we intend to record data locally at each site, which will permit a wider band width and sampling of both polarisations.

Although the Cambridge data were noisy, with significant quasi-periodic interference, the scintillation pattern as the solar wind flowed across the ray-path from 0318+164 was detectable and good correlation was observed between the measurements at the two sites (Fig. 3). Good data were obtained from Knockin on 4 May, 1999, and from the Jodrell Bank Mk.2 telescope on 9 and 11 May, 1999.

The baselines available from MERLIN are significantly shorter than those of EISCAT (Tables 1, 2), but the velocity resolution is still adequate when the solar wind across the ray-path is dominated by a single stream, as was the case for the observations of 0318+164 during early May 1999.

2.3 EISCAT observations

EISCAT made observations of IPS off the southeast limb of the Sun every day from 2 May, 1999, to 15 May, 1999. These observations are summarised in Table 2. The data were received on one polarisation over a 8 MHz band width at the Tromsø and Sodankylä sites (7.5 MHz at the Kiruna site), centred on 931.5 MHz. Initial sampling was at 10 kHz, with the data subsequently averaged to give a sample every 0.01 s (e.g. Breen *et al.*, 1996a). Together with the MERLIN and LASC0 observations, the EISCAT results extended the measured profile of slow wind velocity out to beyond 90 R. Mean velocities throughout the distance range covered by EISCAT were in the range $250\text{--}380\text{ km s}^{-1}$.

3 Results

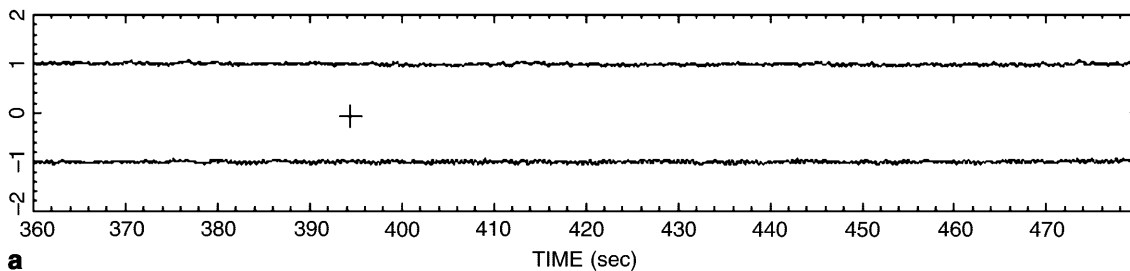
The LASC0 results were dominated by slow flow throughout this period, though a small amount of fast flow was detectable. The IPS results from MERLIN and EISCAT also clearly showed clear slow flow with a weak fast component originating from a coronal hole lying on the anti-Earthward side of the Sun. This was as expected, as the observations lay above a conspicuous

Table 1. MERLIN IPS observations during the slow wind velocity study interval. Latitudes given are heliocentric, longitudes are Carrington and distances are in solar radii: these co-ordinates are

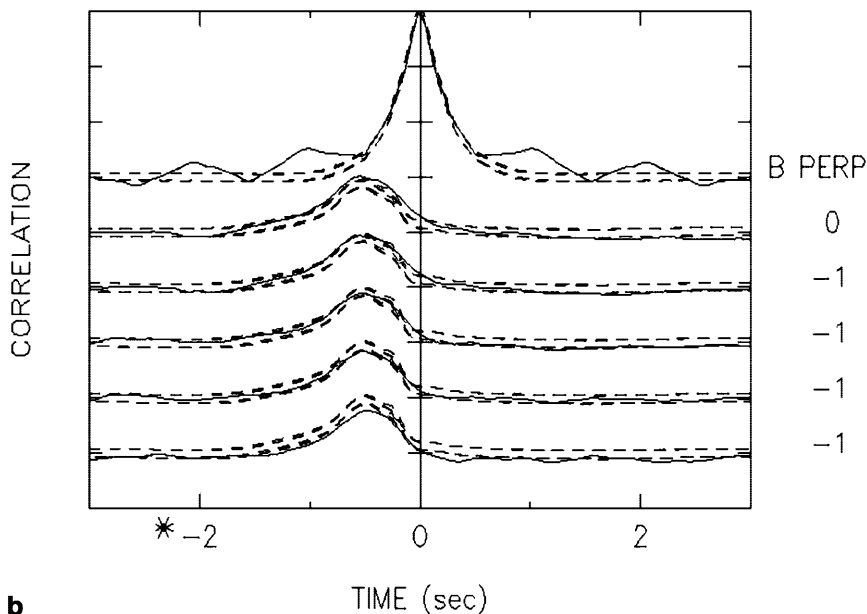
given for the point of closest approach of the IPS ray-path to the Sun. Baseline lengths are in km, velocities are in km s^{-1}

Date	Source	Latitude	Longitude	Distance	Baseline	Baseline _⊥	Velocity	ΔVelocity
990504	0318+164	−19	242	30.8	152	0.8	316	25
990509	0318+164	−36	166	13.6	154	0.2	169	84
990511	0318+164	−60	138	8.4	156	0.2	105	26

s = start f=end x=delete q=done r= reject c=threshold clip p=replot 0318+164 ON 990509 AT 151027 BOT-TOP JMK2 CAMB



a



b

Fig. 3. **a** Raw data from the MERLIN receiving stations at Jodrell Bank (average of scintillations in both polarisations) and Cambridge, 9 May, 1999 1507 UT to 1509 UT. **b** Observed (*solid lines*) and fitted auto- and cross-correlation functions for 75 min of data centred on

1540 UT. The observed scintillation is weak but clearly detectable, and model fitting suggests that the data is best described as dominated by slow flow at an average speed of 160 km s^{-1} , with a significant degree of variation ($\pm 100 \text{ km s}^{-1}$)

east-limb streamer (Fig. 2). Projecting the IPS ray-paths back to 2.5 R using a simple constant-velocity ballistic model shows that the great majority of flow across the ray-paths originated above the bright corona. A typical example (MERLIN observation of 0318+164 on 9 May, 1999) is shown as Fig. 4.

The LASCO velocities are shown in Fig. 5. The large error bars at heliocentric distances beyond 25 R are a result of the poor signal-to-noise ratio in the outer regions of the LASCO field-of-view, which are caused by the low electron densities (and thus poor contrast between the white-light corona and the background) at these distances.

Figure 6 shows the velocities derived from MERLIN and EISCAT IPS observations on 4, 9 and 11 May, 1999. There is considerable scatter between data points, which is probably a result of different streams of slow wind lying across the ray-paths of the different observations, but the overall trend, with acceleration from velocities of $100\text{--}200 \text{ km s}^{-1}$ at distances of 9–11 R to $250\text{--}300 \text{ km s}^{-1}$ by 30 R, is clear. The velocities observed on 4 May, 1999, at 31 R by MERLIN (at 1.66 GHz) and

EISCAT (at 931.5 MHz) agree to within the uncertainties in the measurements. There is good reason to believe that a significant proportion of these uncertainties reflect real, physical differences in the velocities of different streams of slow wind across the ray-paths.

4 Slow wind velocity profiles

Figure 7 shows a plot of the velocities derived from all of the observations made by LASCO, MERLIN and EISCAT between 2 and 15 May, 1999. There is very good overall agreement between the LASCO and IPS velocities, indicating that the irregularities observed by the two techniques are drifting at the same speed. As the scale sizes of the irregularities observed by LASCO and IPS are so different ($\sim 10\,000 \text{ km}$ for LASCO, $\sim 100 \text{ km}$ for IPS) this suggests that the irregularities are drifting at the background flow speed.

The observations made on 4, 9 and 11 May covered different latitudes and longitudes on the Sun, so any direct comparison of results from different distances on

Table 2. EISCAT IPS observations during the slow wind velocity study interval. Latitudes given are heliocentric, longitudes are Carrington and distances are in solar radii: these co-ordinates are given for the point of closest approach of the IPS ray-path to the Sun. Velocities are in km s^{-1} . Observations shown in normal type lie along similar stream lines of flow to that observed using MERLIN on 4 May, 1999, observations shown in **bold type** lie along similar

stream lines of flow to that observed using MERLIN on 9 May, 1999, and observations shown in *italic type* lie along similar stream lines of flow to that observed with MERLIN on 11 May, 1999. The observation shown in ***italic bold type*** lies on a stream line between those observed by MERLIN on 9 and 11 May, 1999, but is included as it covers a distance and latitude region otherwise unrepresented in the LASCO/MERLIN/EISCAT dataset

Date	Source	Latitude	Longitude	Distance	Baseline	Baseline _⊥	Velocity (slow)	Δ Velocity (slow)
990502	0318+164	-17	273	37.7	225	1	391	110
	0321+123	-38	279	42.6	210	1	338	16
990503	0321+123	-40	265	39.5	192	2	344	43
990504	0318+164	-19	244	30.8	239	1	319	18
990505	0318+164	-21	228	27.2	250	0	345	38
	0431+206	-10	263	89.4	233	1	339	42
990506	0318+164	-23	214	23.9	255	1	367	117
	<i>0321+123</i>	<i>-52</i>	<i>220</i>	<i>31.1</i>	<i>297</i>	<i>4</i>	<i>340</i>	<i>90</i>
	0431+206	-10	248	86.1	241	3	300	32
990507	<i>0321+123</i>	<i>-57</i>	<i>206</i>	<i>28.7</i>	<i>273</i>	<i>6</i>	<i>384</i>	<i>67</i>
	0431+206	-10	233	82.8	239	0	295	128
990508	<i>0321+123</i>	<i>-63</i>	<i>193</i>	<i>26.7</i>	<i>243</i>	<i>1</i>	<i>306</i>	<i>171</i>
990509	<i>0321+123</i>	<i>-70</i>	<i>271</i>	<i>24.9</i>	<i>223</i>	<i>5</i>	<i>287</i>	<i>150</i>
990511	<i>0433+053</i>	<i>-48</i>	<i>193</i>	<i>85.9</i>	<i>221</i>	<i>1</i>	<i>295</i>	<i>69</i>
990514	<i>0433+053</i>	<i>-53</i>	<i>152</i>	<i>79.1</i>	<i>193</i>	<i>1</i>	<i>254</i>	<i>85</i>
990515	0431+206	-12	112	56	247	3	395	15

The large error bars in the velocities determined from observations of 0431+206 at large distances from the Sun are caused by the low scintillation power received when the ray-path to the source does not pass close to the Sun. The large uncertainties in velocities determined from observations from inside 28 R may arise from real

differences in flow speeds in adjacent streams of slow wind, or may be a result of uncertainties in the modelling process as the ray-path approaches strong scattering. Further analysis is necessary before the contributions of these sources of uncertainty can be separated

different days can be misleading. Figure 8 shows the velocities measured along the stream lines of flow observed by MERLIN and LASCO on 9 May at 36° South (Fig. 8a) and 11 May at 60° South (Fig. 8b).

The velocities determined from LASCO and IPS measurements agree well, and on both days the acceleration region of the slow wind appears to lie between 5 and 20 R. This is within the variation of the velocity profiles for large-scale drifting structures ($\sim 100\,000$ km scale size) determined by Sheeley *et al.* (1997), although the 1999 IPS/LASCO results indicate rather lower speeds than the average of the Sheeley *et al.* (1997) profiles. The Sheeley *et al.* (1997) profiles showed a large

degree of variation, so that this difference does not imply inconsistency between the studies. The slow solar wind is known to be highly variable in density and velocity so it would not be surprising if different streams had slightly different acceleration profiles too.

5 Conclusions

The results of these simultaneous overlapping optical and IPS observations of the slow wind are most satisfactory. There is good agreement between the velocities observed in the same regions by LASCO,

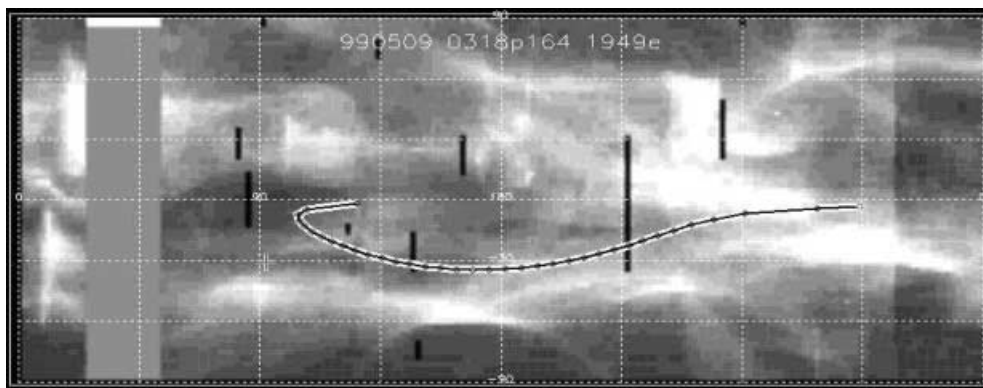


Fig. 4. Ray-path for the MERLIN observation of 0318+164 on 9 May, 1999, projected back ballistically to 2.5 R and overlaid on a white-light map constructed from east-limb LASCO C2 data. Only a very small portion of the ray-path lies above a coronal hole, which is

consistent with the observation being dominated by slow flow. The white-light map covers Carrington longitudes from -180° to 180° and heliographic latitudes from 90° South to 90° North, with the centre of the map at 0° heliographic latitude and 0° Carrington longitude

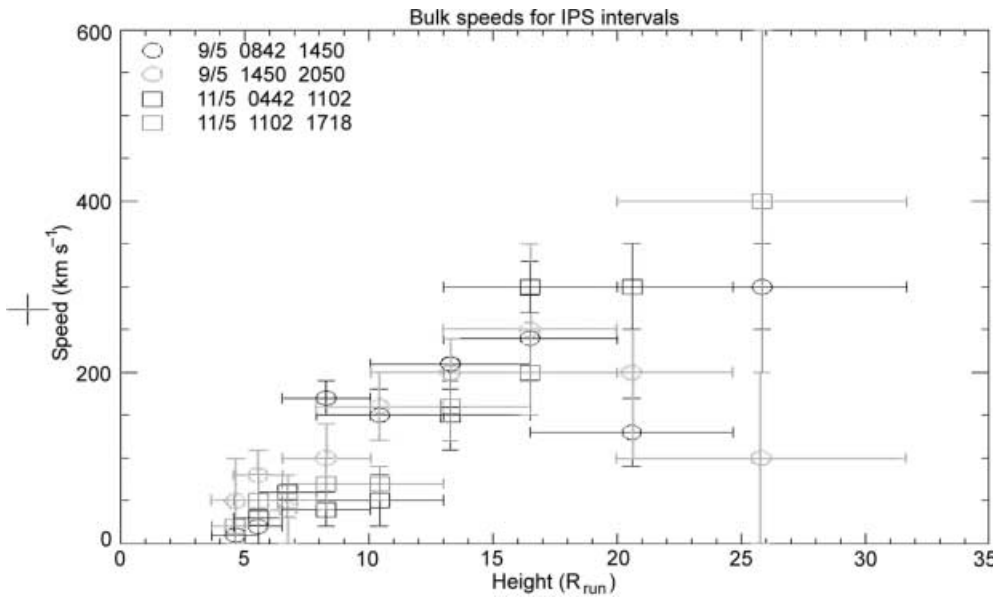


Fig. 5. Slow wind velocities measured by LASCO on 9 and 11 May, 1999. The *large error bars* for measurements outside 25 R are a result of the low signal-to-noise ratio in the outermost regions of the LASCO field-of-view

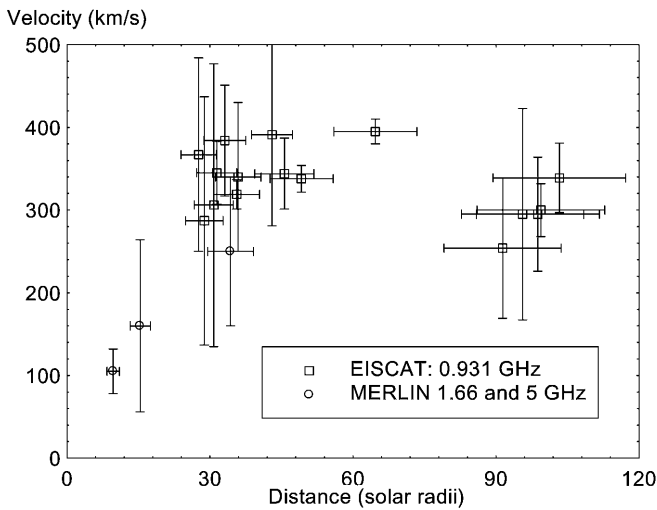


Fig. 6. Velocities determined from EISCAT \square and MERLIN \circ IPS observations off the southeast limb of the Sun between 2 and 15 May, 1999

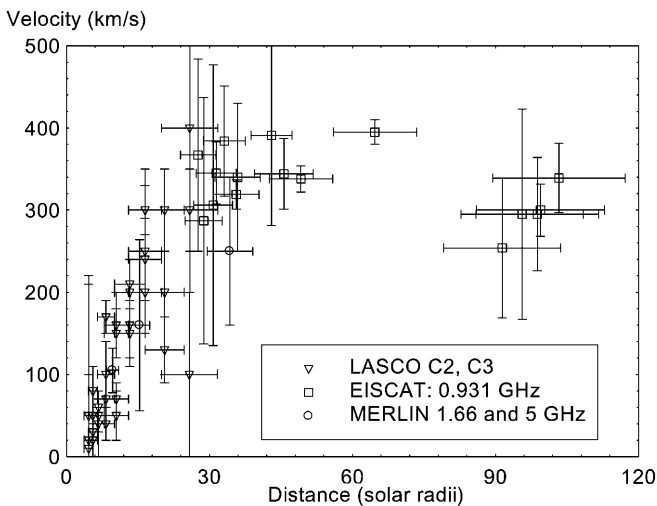


Fig. 7. Combined plot showing LASCO and IPS velocities off the southeast limb of the Sun between 2 and 15 May, 1999

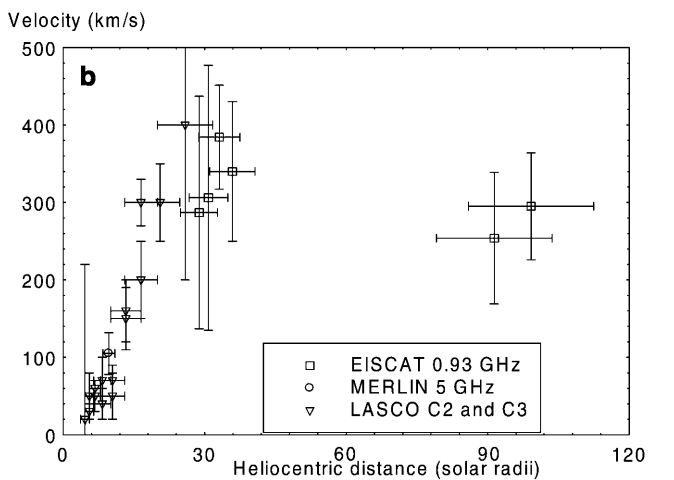
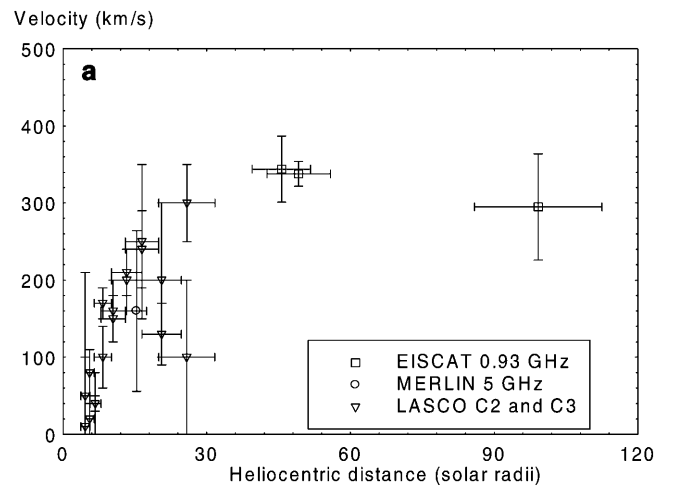


Fig. 8. a Solar wind velocities measured by LASCO, MERLIN and EISCAT along the stream lines of flow observed by LASCO and MERLIN on 9 May, 1999. **b** As Figure 8a but showing velocities measured by LASCO, MERLIN and EISCAT along the stream lines observed by LASCO and MERLIN on 11 May, 1999

MERLIN and EISCAT, considering scale sizes of between 10 000 km and 100 km. Together with the similar results of Sheeley *et al.* (1997) considering “knots” and “blobs” of plasma with scale sizes of ~100 000 km, and of Tappin and Simnett (1998) and Srivastava *et al.* (1999) considering slow-rising CMEs with larger scale sizes, this strongly suggests that density irregularities of very different scale sizes drift at the same speed. This, in turn, supports the Sheeley *et al.* (1997) picture of density irregularities drifting with the background plasma flow “like leaves in a stream”.

The observations made in May 1999 suggest that the slow solar wind begins to accelerate somewhat inside of 4–5 R and reaches its cruising speed by 20–30 R, with most acceleration taking place between 10 and 20 R. This is very different from the fast wind, which reaches its cruising velocity inside 15 R (Grall *et al.*, 1996; Breen *et al.*, 2000). There is considerable scatter in the measured velocities, and this may reflect differences in speed between adjacent streams of slow wind. The slow wind is known to be highly variable in velocity and density outside 30 R (e.g. Breen *et al.*, 1996b; Axford and McKenzie, 1997) and we would expect these variations to be even more marked close to the Sun, when stream-stream interaction will not have had any significant smoothing effect. The variations seen between observations made on 9 and 11 May, 1999, at $36 \pm 10^\circ$ and $60 \pm 10^\circ$ south latitudes tend to support this view.

The uncertainties in velocities estimated from IPS measurements reflect variation in flow speed across the ray-path. The large uncertainties in measurements made close to the Sun suggest that inside 25 R there is considerable variation in slow wind speed. The very slow lower velocity limits and low coefficients of cross-correlation seen in the innermost MERLIN observations suggest that quasi-static plasma may be present in the ray-path, coronal streamers are known from LASCO images (Fig. 2) to extend out beyond 8 R, so it is possible that very low-speed flow in the body of the streamer may contribute to the wide variation in flow speeds. More observations will be required to confirm or deny this supposition, and we intend to carry out a further sequence of co-ordinated LASCO-MERLIN-EISCAT measurements in May 2000.

The very good agreement between the drift velocities observed for irregularities of a wide range of scale sizes is an important result. The observations do not explicitly confirm that the irregularity drift velocity is the same as the background flow speed (it is unlikely that anything other than in-situ measurements could unambiguously measure the bulk flow speed in this region), but the agreement seen between the drift velocities of irregularities of such different scale sizes does suggest that these features are indeed drifting with the background flow. The slow and variable nature of the acceleration profile observed is very different to that seen in the fast wind, and will provide valuable information for modellers seeking to understand the origin and acceleration of the slow solar wind.

A small amount of the ray-paths of all of these observations above dark regions in the white-light maps,

and LASCO, MERLIN and EISCAT all detected small proportions of fast flow. More analysis is required to accurately determine the precise velocities in these regions, and we hope to present these results in a future paper.

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