TRACKING INTERPLANETARY DISTURBANCES USING INTERPLANETARY SCINTILLATIONS

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ABSTRACT

This paper reports the detection and tracking, on a day-to-day basis, of two travelling interplanetary disturbances using observations of interplanetary scintillation in the directions of a large number of spatially well-distributed, compact extragalactic radio sources at 327 MHz using the Ooty Radio Telescope. Solar wind velocities derived from the observed scintillation spectra were used to detect and track the two travelling interplanetary disturbances between 31 October and 5 November 1992 as they propagated away from the sun. The grid of scintillating radio sources were essentially used as a moveable "picket-fence" in the sky to track the disturbances from day-to-day. Both disturbances were traced back to an active region on the sun located close to a large coronal hole. It is shown in the present case that both the coronal hole and the active region were involved in generating the two disturbances. Some evidence, from *Ulysses* data, to indicate that two coronal mass ejections (CME's) might have occured in the same region is also presented.

Key words: Interplanetary Disturbances; Interplanetary Scintillation; Solar Wind Velocities; Coronal holes; Flares; Coronal Mass Ejections.

1. INTRODUCTION

Several techniques have been developed in the past four or five decades for observing the the solar corona and the solar wind. Such studies have yielded a wealth of data regarding the occurrence of disturbances in the sun-earth space environment and their association with discrete ejections of mass and energy from the sun. For concise reviews of these techniques one may refer to Jackson (1991a); Bird & Edenhofer (1990); and Schwenn 1990. While most of these techniques are applicable to the study of the interplanetary medium (IPM) either close to the sun (at heliocentric distances d < 30 $R_\odot$ where $R_\odot$ = radius of the sun) or close to the earth (d$\simeq$200 $R_\odot$), interplanetary scintillation (IPS) of compact extragalactic radio sources at meter wavelengths is the only ground-based technique for remote-sensing the IPM in the distance range 30 $R_\odot$ to 200 $R_\odot$ from the sun.

The phenomenon of IPS arises when electron density irregularities in the solar wind plasma scatter radio waves coming from distant, compact radio sources and produce intensity fluctuations on the ground. IPS at meter wavelengths is thus sensitive to turbulence in the solar wind, causing travelling interplanetary transients which cross the lines-of-sight to compact radio sources to exhibit themselves as enhanced scintillation of the radio sources. IPS is thus a relatively inexpensive and effective ground-based technique to probe the IPM at all distances between 0.1 and 1 AU from the sun, as well as off and on the ecliptic plane. IPS observations have traditionally been made by using large dipole arrays operating as transit instruments to measure the scintillation index (the ratio of the root-mean-square (rms) deviation of signal intensity to the mean signal intensity) of the radio sources as a function of solar elongation (sun-earth-radio source angle, ϵ). It has been shown, Manoharan & Ananthakrishnan (1990), that in addition to scintillation index measurements, reliable estimates of solar wind velocities can also be made using a single telescope (as opposed to using a network of three telescopes separated by approximately the fresnel distance at the observing frequency) by fitting model spectra to the observed spectra of intensity fluctuations due to IPS. The IPS spectra must however. all have large signal to noise ratios and be obtained in the weak scattering regime where the rms phase deviation imposed by the IPM on the wave front from the radio source is much smaller than a radian. At 327 MHz, the weak scattering regime extends beyond $\epsilon > \simeq 10°$. However, IPS observations with the Ooty Radio Telescope (ORT) are generally not carried out beyond $\epsilon = 55°$ as it has been seen, from many years of observation with the ORT that there is no appreciable IPS power beyond these solar offsets.

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Important milestones in the study of the inter relationships amongst the sun, the IPM and the earth were the identification of corotating solar wind streams as the cause of recurring geomagnetic activity, and the identification of coronal holes as the source for such fast streams Hundhausen (1977). However, when it comes to the question of identifying the cause of nonrecurrent geomagnetic storms unambigious answers are not yet available. In a study of 96 interplanetary disturbances (IPD) mapped by using IPS during the period August 1978-September 1979 Hewish & Bravo (1986), have concluded that nonrecurrent geomagnetic disturbances occur due to energetic and large scale transients, usually associated with shocks, which are driven by the eruption of plasma flows similar to high speed streams, but of shorter duration. It has also been argued that the sources of such errupting streams are coronal holes at mid-latitudes on the sun, and that disappearing filaments and flares play only a peripheral role in causing these interplanetary transients. In contrast several arguments have been marshalled by Gosling 1993, in support of the view that the fundamental cause for the occurrence of non recurring geomagnetic storms, travelling interplanetary shocks and solar energetic particle events reside in coronal mass ejections (CME). More recently a bimodal model for solar activity has been proposed by Dryer 1994, in which both CMEs and flares play key roles.

2. THE OOTY IPS SURVEY

The ORT operates at 327 MHz and is an equatorially mounted steerable instrument with a collecting area of $\simeq$ 8000 m^2. With the refurbishing of the ORT in 1991, Selvanayagam *et al.* (1993), scintillating fluxes as low as 0.25 Jy could be detected easily with it using data stretches as short as three minutes (1 Jy = 10^{-26} W m^{-2}). This sensitivity made it possible to to observe around 150 scintillating sources in a day in the elongation range 10° $< \epsilon \leq$ 55°. An IPS survey was carried out during the period August 1992-August 1993, Balasubramanian *et al.* (1993), in order to detect compact radio sources in the 7 steradian of the sky visible to the ORT, in the declination range -35° $\leq \delta \leq$ 35°. Of about 5000 known radio sources observed during this survey, around 2100 were found to exhibit scintillation, while approximately 1050 sources were found to be strong scintillators. The sequence of observations during any given day was such that sources with smaller ϵ were observed progressively at later epochs of time. The list of sources selected for the IPS observations were chosen from the catalogues of radio sources in the Texas survey at 365 MHz and the Molonglo survey at 408 MHz such that their flux densities S_ν were larger than or equal to 1.5 Jy at the respective frequencies (ν = 365 or 408 MHz). Figure 1 is an all-sky plot in right ascension and declination of the grid of scintillating sources identified during the IPS survey in 1992-1993. The thick sinusoidal line marks the ecliptic. The depletion of sources at right ascensions between 240° and 300° is due to the ORT being non-operational during that period for maintainence. The survey observations were continued in 1994-1995 to reconfirm and classify the sources already observed and to observe sources missed in the first attempt. The analysis of this second round of survey observations are still underway.

3. TRACKING INTERPLANETARY DISTURBANCES

During the early part of the IPS survey in 1992-93, two IPD's were clearly identified, tracked from day-to-day and traced back to a location on the solar surface which was seen to contain an active region and a large coronal hole. The observations were based on advance information (made available, in real time, to observers at ORT) about the time and location of two flare generated shocks fronts. The observation and analysis of the two events have been described in detail by Janardhan *et al.* (1996). Due to having the advance predictions on the time and location of the two flare generated shock fronts, the schedule of the IPS survey observations were adjusted so that the lines-of-sight to the observed sources lay to the west of the sun-earth line in the region to be traversed by the interplanetary transients. Figure 2, reproduced from Janardhan *et al.* (1996), shows velocity maps for each of the six days of observations. The finely dotted semi-circles are loci of equal ϵ with the sun at the center. The small filled circles represent solar wind speeds in the range 200 km s^{-1} < V $\leq$ 600 km s^{-1}, while the open circles represent velocity values in the range 600 km s^{-1} < V $\leq$ 1500 km s^{-1}. The location of each point is given by the position angle, measured north through east, of the solar wind across the source. North is indicated at the top of each map by a large 'N'. The velocities were derived by fitting model spectra to the observed IPS spectra using the method developed by Manoharan & Ananthakrishnan (1990). It is very easy to identify from the maps two high velocity disturbances propagating outwards from day to day. The first IPD, on 31 October, is seen to be lying between 15° $< \epsilon <$ 35° and has moved to elongations > 35° on 1 November. On 2 November it has moved out beyond ϵ = 55°. Bearing in mind that the sequence of observations on each day is such that smaller ϵ are probed at progressively later times, the maps indicate that the leading edge of the disturbance was intercepted on 31 October as the lines-of-sight swept to smaller ϵ. The second disturbance, seen on the map of 3 November is located at elongations > 35° and has propagated beyond ϵ = 55° by 4 November leaving behind predominantly low velocities that persist into 5 November. The well-defined separation of the high and low velocities on 3 November indicate that one is seeing the trailing edge of the second high velocity event as it moved out of the observation limits set for IPS observations with the ORT.

4. RELATED SOLAR SURFACE EVENTS

The IPS velocities derived for the two events were traced back to the active region AR7321 (located at S25L71 in Carrington coordinates) on Carrington Rotation CR 1861. The active region was located within 10° of a large coronal hole. The back projection was carried out using the measured values of the

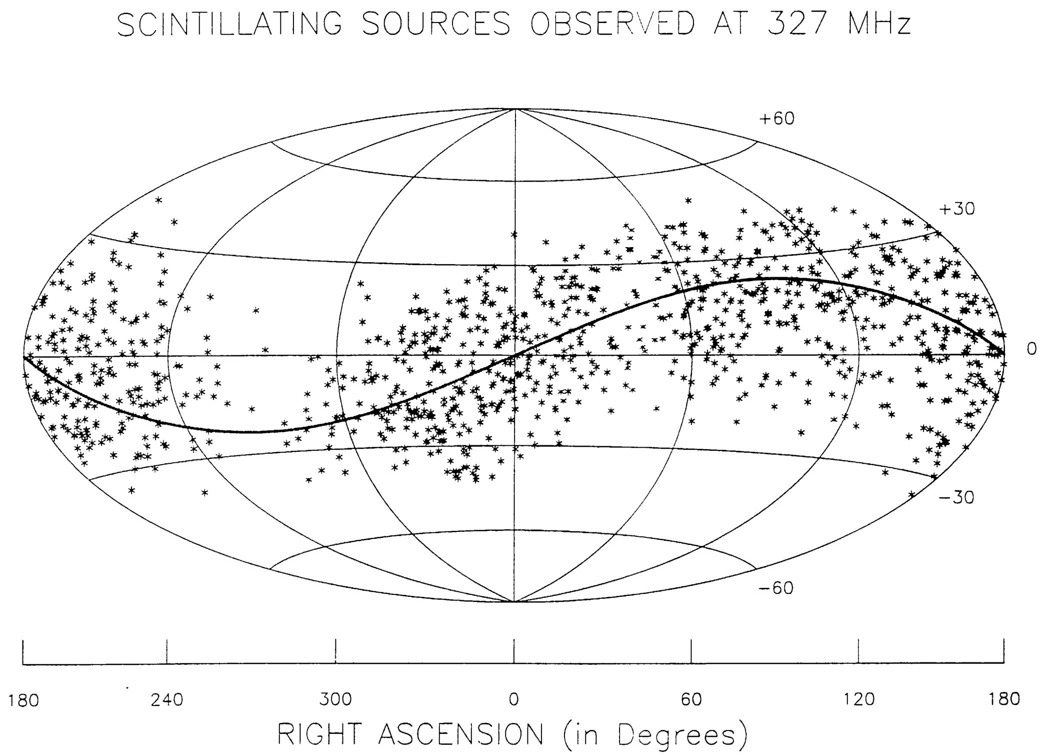

Figure 1. Shows an all sky map of the distribution, in right ascension and declination, of the grid of scintillating sources identified in the Ooty IPS survey in 1992-1993. The dark sinusoidal line marks the ecliptic. The depletion of sources at right ascensions between 240° and 300° is due to lack of observations because of problems with the ORT.

solar wind velocity for each source and due to the inherent uncertainties in such a method, the origin of the disturbances could be pinpointed with an accuracy of only a few tens of degrees - see Janardhan *et al.* (1996) for details. H_α pictures of the solar disk, taken at the Udaipur Solar Observatory, India, indicated that a filament eruption had also taken place from active region AR7321 on 30 October. In addition, the active region was also seen to grow in size from 60 to 1650 millionths of the solar hemisphere between 24 and 30 October, while the area of the coronal hole reduced rapidly. All of this activity observed on the solar surface indicate that large scale rearrangements of the magnetic fields in the region were taking place. Thus the possibility for the occurance of a CME from the region cannot be ruled out.

A large number of transient shock waves, generally associated with fast CME's, were identified between 1990 and 1994 using solar wind plasma and magnetic field high time resolution data from *Ulysses*. See , eg., González-Esparza *et al.* (1996) and references therein.

Around 30 October 1992, *Ulysses* was at a distance of a little over 5 AU and was favourably situated well behind the west limb of the sun at $\simeq$ 19.4° S and $\simeq$ 122° west of earth and by 14 November it was at $\simeq$ 20.2° S and $\simeq$ 108° west of earth (González-Esparza *et al.* (1996)). In this period there is evidence for two CME's that could be related to the events detected by IPS velocity mapping. The first disturbance arrived at *Ulysses* on 9th November and was of short duration. This event produced unusually high solar wind velocities (close to 1000 km s^{-1}). At the time of the event *Ulysses* was at a distance of 5.17 AU and at a latitude of 19.9° S. Rough estimates, using mapping back calculations based on the measured solar wind speed at *Ulysses*, put the source time in the region of 29-30 October at Carrington longitudes 110°−140° (Forsyth. R.J. private communication). The second disturbance arrived late on 14 November and lasted about 3 days. Speeds within the event ranged from about 700 km s^{-1} down to about 580 km s^{-1}. At this time *Ulysses* was at 5.15 AU and 20.2°S. The estimated source time is $\simeq$ 31 October-2 November from Carrington longitudes 90°−110° (Forsyth, R.J. pri-

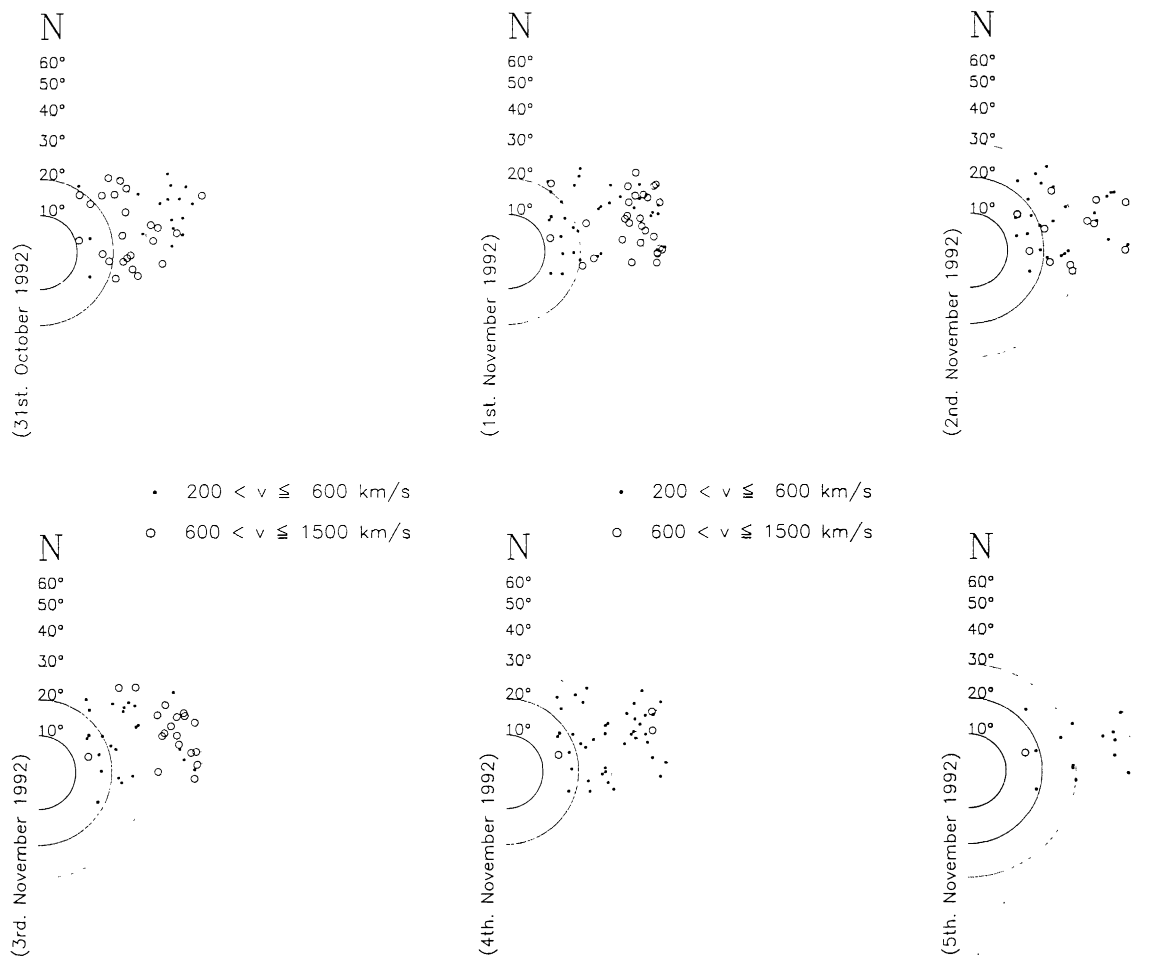

Figure 2. Show velocity maps on each of the days from 31 October to 5 November, 1992. The finely dotted semi-circles are loci of equal solar elongation with the sun at the center. The small filled circles represent solar wind speeds in the range 200 km s^{-1} < $V \leq$ 600 km s^{-1}, while the open circles represent velocity values in the range 600 km s^{-1} < $V \leq$ 1500 km s^{-1}. The location of each point is given by the position angle, measured north through east, of the solar wind across the source. North is indicated at the top of each map by a large 'N'.

vate communication). Even though these estimates of the source location are only preliminary and may have large errors, the fact that they trace back to roughly the location of the active region AR7321 is encouraging and indicative that the CME too was probably involved in the events.

5. DISCUSSION AND CONCLUSIONS

It is important to note that these observations were carried out in the early part of the IPS survey when the grid of scintillating sources (Fig. 1) were still being identified. Thus about 70% of the sources observed on each day were non-scintillators. In spite of this velocity maps of sufficient spatial resolution could be made to clearly identify the two events. This was possible because real time observations of the optical location of the two flares, which probably caused the events, were combined with Type II radio drift observations and a theoretical model to predict the approximate time and location of the associated shock fronts (see Janardhan *et al.* (1996), for details of the flares associated with these two events). Thus observations could be made on appropriately located sources, thereby increasing the spatial resolution of the maps, rather than looking at sources randomly distributed over the entire sky. The implications of this are that the grid of IPS sources can essentially be used as a moveable "picket-fence" for the identification and tracking of IPD's. In conjunction with other ground based observations like Type II drift observations, optical observations of solar surface transients and spacecraft data like LASCO, this can be a very effective method of tracking IPD's all the way from the sun to 1 AU. It must be noted that IPS observations have been traced back to solar events by other workers like Rickett 1975; Gapper *et al.* (1982) and Jackson *et al.* (1991b) in the past. However, what makes this method more efficient is the combination of a large fully steerable radio telescope like the ORT along with a large grid of compact radio sources that can be selected and observed at short notice. The "picket-fence technique" has also been used earlier by Manoharan *et al.* (1995), to detect and model a fast moving disturbance overtaking a slower disturbance however, this was the first time that daily velocity maps of sufficient spatial resolution could be produced to track the two disturbances over many days.

From the events described in this paper it is difficult to rule out or support just single solar surface phenomenon as the sole cause for the IPD's observed by IPS at 327 MHz. The events show that a multiplicity of phenomena like flares, filament erruptions, coronal holes and CME's were probably involved in causing the two events. Separating all these events and pinpointing the solar sources of IP transients will thus require a much larger data base using both ground-based and *in-situ* observations. Also, collaborative multi-station IPS observations using the "picket-fence" technique will be of considerable value.

Density maps or "g-maps" of the IPM have been produced for many years now from Cambridge by observing a large grid of scintillating sources and making daily maps of an enhancement factor $g = \Delta S/\overline{\Delta S}$ where ΔS is the scintillating flux and $\overline{\Delta S}$ is the long-term mean scintillating flux of the source see eg. Gapper *et al.* (1982); Hewish, Tappin and Gapper (1985) and Hewish, & Duffett-Smith (1987). Currently, scintillation index measurements on most of the sources, with the ORT, are insufficient to determing the long-term mean scintillating flux of each source and hence produce reliable g-maps. This is because the number of observations on each source during the IPS survey were limited. Thus reliable g-maps cannot be produced with the ORT at present. However, this situation will change as the sources are observed more and more often over the coming years. Furthermore, the ability to obtain power spectra also eleminates contamination of data by ionospheric scintillation which remains a problem with the Cambridge data.

One of the principle shortcomings of the IPS technique using the "picket-fence" method is that it is not sensitive to the polarity of the magnetic field associated with the transients. Thus, it is impossible to predict if a certian transient will cause geomagnetic disturbances on earth. Nevertheless, the IPS technique can detect transients at considerable distances from the earth giving lead times of typically several tens of hours. In combination with spacecraft data and collaborative multi-station IPS observations such a method will be very effective in detecting and tracking interplanetary disturbances.

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