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Remote Sensing of the Heliospheric Solar Wind using Radio Astronomy Methods and Numerical Simulations

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Abstract. The ground-based radio astronomy method of interplanetary scintillations (IPS) and spacecraft observations have shown, in the past 25 years, that while coronal holes give rise to stable, recurring high speed solar wind streams during the minimum of the solar activity cycle, the slow speed wind seen more during the solar maximum activity is better associated with the closed field regions, which also give rise to solar flares and coronal mass ejections (CME's). The latter events increase significantly, as the cycle maximum takes place. We have recently shown that in the case of energetic flares one may be able to track the associated disturbances almost on a one to one basis from a distance of 0.2 to 1 AU using IPS methods. Time dependent 3D MHD models which are constrained by IPS observations are being developed. These models are able to simulate general features of the solar-generated disturbances. Advances in this direction may lead to prediction of heliospheric propagation of these disturbances throughout the solar system.

Key words. Sun—heliosphere, solar wind.

1. Introduction

More than 20 years ago we made a detailed analysis of interplanetary scintillation (IPS) data from the 3 station radio observatory in San Diego and showed how the solar wind changes with the solar cycle (Coles *et al.* 1980). In particular we noted that solar phenomena are 'intimately linked to the solar magnetic fields, which exhibit complex but systematic variations'. It was also noted that 'the dominance of the high speed streams during the declining phase of the solar cycle is the most obvious change in the ecliptic wind'. Observations since then, by both ground based IPS and *in situ* spacecraft, including the out-of-the-ecliptic mission by Ulysses spacecraft in 1995 have confirmed these amply. The polar solar wind is dominated by coronal holes. Apart from flares and coronal holes, coronal mass ejections (CMEs) are also an important component of solar activity and all these give rise to phenomena that may be studied by ground based IPS.

IPS arises when the scattered wavefront from a distant quasar gives rise to intensity fluctuations, which as they drift past the observer on a multi-telescope system at the prevailing solar wind speed, produce fluctuations that are correlated with a time lag. Knowledge of the baseline geometry and the time lag enables one to estimate the solar wind speed.

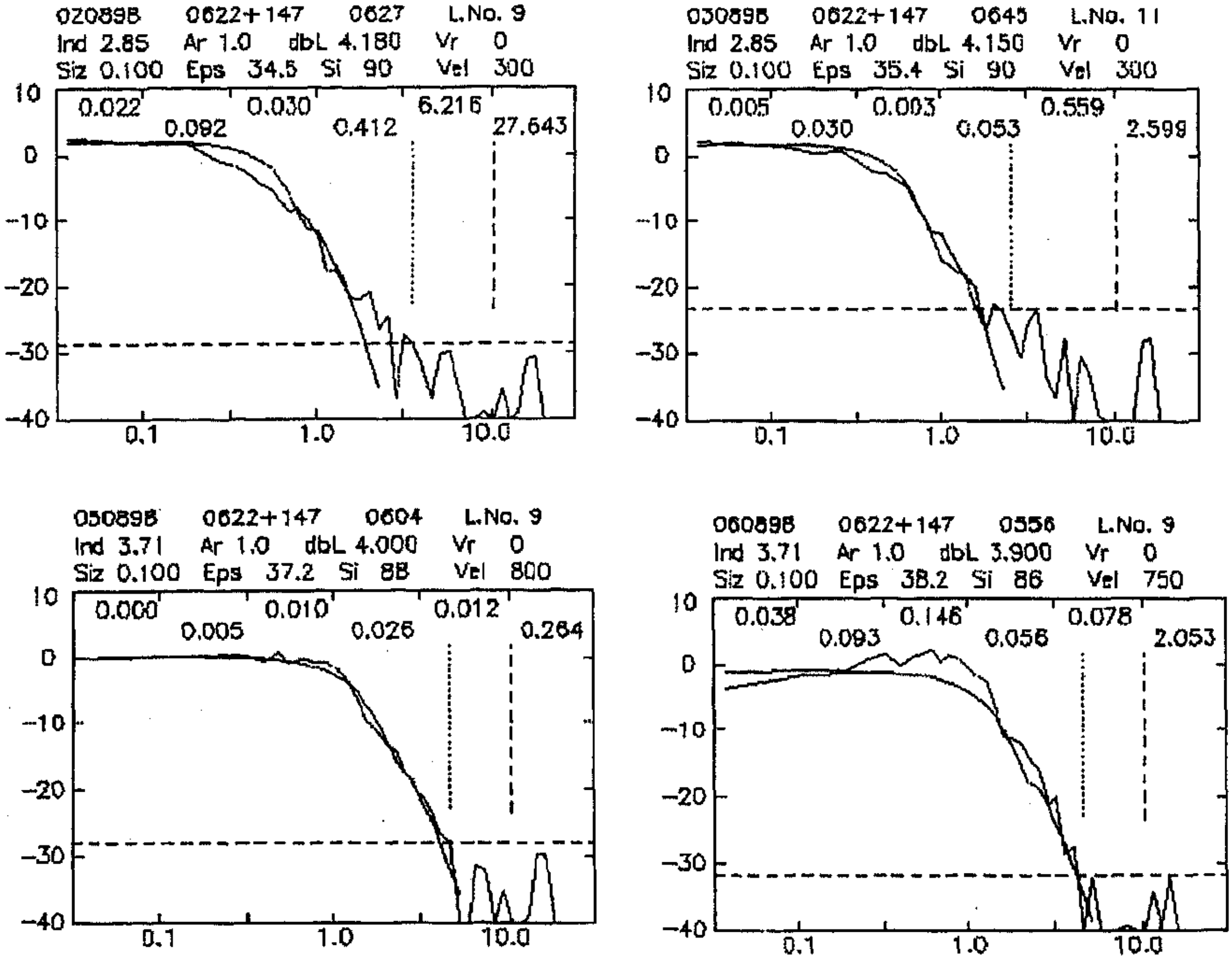

Figure 1. Temporal spectra of compact radio sources 0622 +147 on four days in August 1998. The captions show the date, source name and time of observation in the first line, the fitted spectral index (Ind), axial ratio (AR), power level (dbl), random velocity (Vr) in the second line and size of the source (siz), solar elongation during observation (Eps), the fitted inner scale of the irregularities (Si) and the best fitted value for the solar wind velocity in the third line. The Y coordinate shows relative power in log scale and X-coordinate gives temporal frequencies in Hz. The observed temporal spectrum shown by the fluctuating line is overplotted with the smooth fitted model spectrum.

It is also possible to find a reasonable estimate of the solar wind speed based on the temporal spectra recorded in a single station, provided one has observations with good signal to noise ratio. While this was initially shown by Scott, Coles & Bourgois (1984), Manoharan & Ananthakrishnan (1990) developed this for systematically estimating the solar wind velocity by observing daily a large number of compact radio sources at 327 MHz using the large collecting area of the Ooty Radio Telescope.

A number of temporal spectra (Fig. 1) are shown on a compact radio source 0622 + 147 observed using the Ooty telescope for several days which show how the solar wind velocity changes from day to day (Balasubramanian *et al.* 2000). If one uses reasonable model parameters for the temporal spectral index, angular size of the compact component in the radio source and the axial ratio of the irregularities and estimate the solar wind velocity, the values are found to be in good agreement with three or more station velocities (Manoharan *et al.* 1995).

Further, as the Sun's apparent position changes in the sky, the elongation angle formed by the Sun-Earth-Source line keeps changing. This leads to a change in the scattering/scintillation strength for the same source. Hence, if one plots the scintillation vs elongation curve, one sees a systematic variation (Manoharan *et al.* 1995). The resulting plot is known as the m-p curve, '*m*' denoting the scintillation index (rms fluctuation normalised by the mean source intensity) and '*p*', the sine of the elongation angle.

Instead of using the scintillation index, Gapper *et al.* (1982) preferred to use a scintillation enhancement factor '*g*'. The *g* value is defined as the ratio of the scintillation index of the date normalized by the averaged scintillation index at that elongation. When the solar wind is quiet, the value of *g* is around unity. Thus, one may use both the estimated velocity, V and the scintillation enhancement factor, g to study the heliospheric solar wind.

2. Observations

During the past several years we have used the Ooty telescope to observe a number of solar transient events which show a significant increase in velocity as well as enhanced g. While tracing their origin back to the Sun, we find that a majority of them appear to be associated with energetic flares accompanied by Type II/IV radio bursts. A few of them could also be associated with CME's and a fewer with transient coronal holes. Many of these events are discussed in Janardhan *et al.* (1996) and Ananthakrishnan *et al.* (1999). We term these transient events as inter planetary disturbances (IPD's). In this brief review we refer to only the recent global campaign in August 1998 called the whole sun month (WSM II) campaign, in which IPS observations were also made using the Ooty telescope (Balasubramanian *et al.* 2000). Several IPD's were tracked during WSM II. The most interesting period during the campaign was, when an energetic flare event occurred on August 24th, 1998 with a maximum at 2204 UT in the active region AR 8307 at N35E09. Moreton waves were reported by MLSO from a nearby region. The most impulsive Type II during this period also occurred at 2207 UT on the same day. Shock speeds of 1300 km/s were reported by Culgoora radio observatory. This solar event was seen as a clear IPD in our IPS observations. The IPD propagated over a range of heliographic latitude and radial distance from 0.2 AU onwards to 1 AU (Fig. 2). This IPD was also detected by the ACE spacecraft at L1 at 0620 UT on August 26th, 1998. A geo-effective ssc was observed at the earth at 0651 UT on the same day. The shock speed derived by estimating the time interval between the flare maximum time and the ssc seen on the earth is in good agreement with the IPS velocities as well as the enhancement seen in g values, the details of which are given in Balasubramanian *et al.* (2000). Near simultaneous observations were also made by the Toyokawa four station IPS observatory and are reported in Tokumaru *et al.* (2000). IPS observations are therefore seen to be a useful tool for the remote sensing of heliospheric space weather. Currently, efforts are being made to predict the propagation of such IPDs and also model them using simulations.

3. Discussions

Energetic flare timings appear to be good markers for the beginning of a disturbance. In the last few years, we have shown that based on a simple shock time of arrival

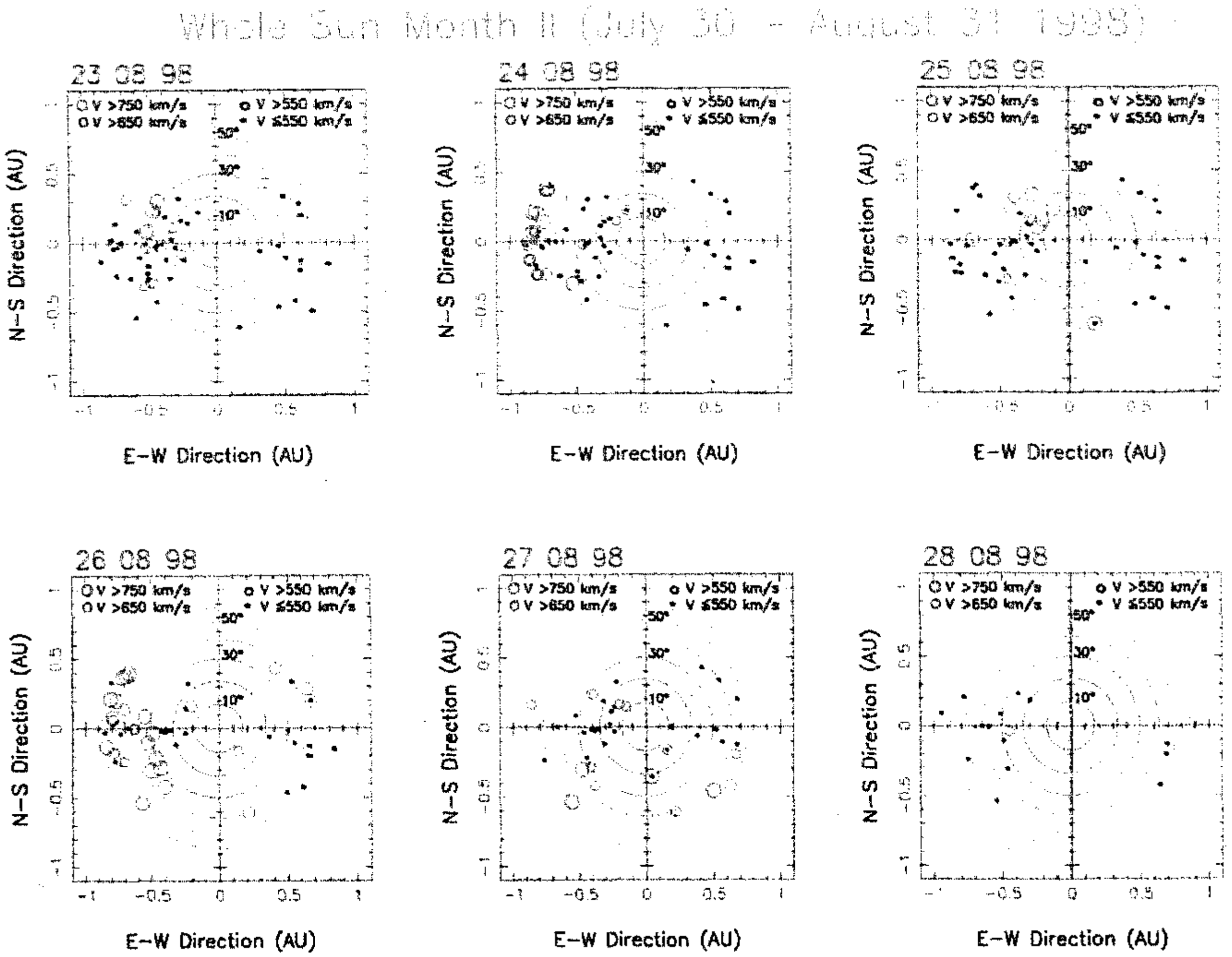

Figure 2. Plots show the velocity distribution in a polar plot for six days during August 23-28, 1998, as a function of distance from the Sun in AU. The inside elongation circles are in the interval of 10°. The diameters of the small circles are in proportion to the estimated velocity, as shown in the inset. During August 23-24 and August 25-26, one can clearly see the propagation of high velocity transients from close to the Sun towards 1 AU.

(STOA) model and knowing the flare position and flaring time, it is possible to predict the general direction of propagation and look for enhancement in the turbulence of scintillating sources. It has also been possible to track the disturbances and find that the initial high velocities at close radial distances from the Sun decelerate in a predictable way, as they propagate (Ananthakrishnan *et al.* 1999, Ananthakrishnan *et al.* 2000). While the STOA model has not been fully vindicated due to the smallness of the available event samples, Smith *et al.* (2000) have recently shown that 'the percentage of successful predictions to within an accuracy of 12 hours of shocks for the STOA is 53%'. Reliable use of the STOA model for the purpose of predicting IPD propagation on a routine basis requires many such studies.

However, in order to be make more reliable predictions, it is valuable to do 3D MHD modelling. At present these models do not cover the full range of heliocentric distances from Sun to Earth. Detman *et al.* (2000) are currently developing a hybrid heliospheric modeling system (HHMS), which uses the potential field source surface model of Wang & Sheeley (1990) and produces a model for the solar corona to a surface that is at a distance of 2.5 solar radii. Empirical models are being developed that extrapolate the solar wind parameters from 2.5 to 21 $R_\odot$. An interplanetary global model 3D has been developed (Detman *et al.* 2000), which is a full 3D time

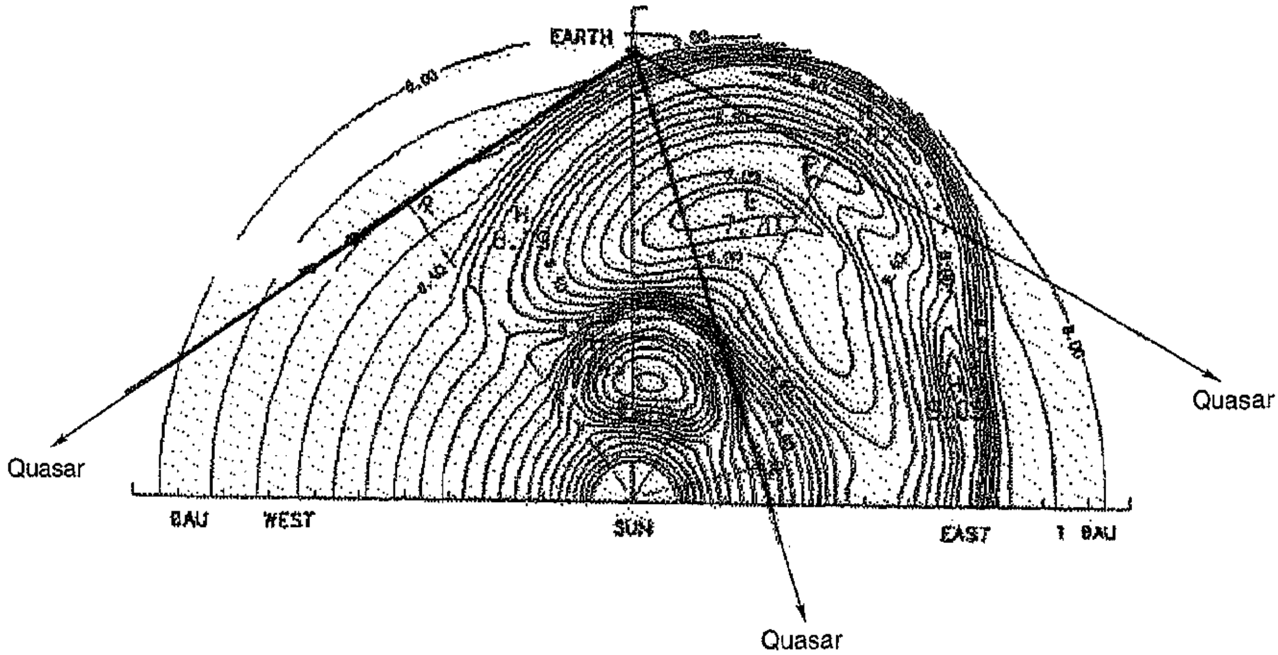

Figure 3. 3D MHD simulation showing the outward propagation of a disturbance. The straight lines are towards three quasars observed from the Earth by IPS, data from which could be used to constrain the model.

dependent MHD solar wind model for extrapolating the solar wind parameters from 21 $R_\odot$ to 214 $R_\odot$. The time series of solar wind parameters thus developed are to be constrained by the IPS time series observations principally using Ooty and Nagoya data. As shown in Fig. 3, IPS observations can be made in many different directions and the estimated model parameters in those directions can be compared with the observations. Such modeling is currently underway.

4. Conclusion

Based on a recent IPS observing campaign during August 1998 as well as on observations over the past several years using Ooty and Nagoya radio telescopes it is shown that propagating interplanetary disturbances which appear to originate from solar events like flares, CME's and transient coronal holes can be studied in the heliospheric distance range of 0.2 to 1.0 AU, by the simple, yet powerful method of IPS. This is of considerable value for space weather predictions. While the initial observing predictions used a simple shock-time-of-arrival model, preliminary work has been done to make 3D MHD model simulations which are constrained by parameters derived from IPS observations.

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