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Solar wind : structure and dynamics

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Abstract. The interplanetary scintillation (IPS) observations can be used for the determination of structure and dynamics of the solar wind. The parameters of the plasma irregularities of the solar wind are usually derived by investigating the interplanetary scintillation observations in the light of scattering theories. Here we present a case study of parameter estimation using diffractive-refractive scattering approach. Solar wind speed at the point of closest approach of Sun to the radio source-observer line can be estimated using three station as well as single station IPS observations. Using the 'garden hose' model of solar plasma flow in the interplanetary medium, an improved scheme of back-projection of solar wind speed to its origin in the solar corona is proposed. The scheme provides estimation of solar plasma acceleration in the inner heliosphere. Here typical solar plasma acceleration results for 1987-88 are also presented and discussed. The solar plasma acceleration is found to vary from ~4 meters/sec^2 to 23 meters/sec^2.

1. Introduction

The phenomenon of interplanetary scintillation is caused by the scattering of radio waves (coming from compact radio sources) by the electron density irregularities present in the solar wind (Dennison and Hewish, 1967). The IPS observations have been used to investigate the properties e.g. their size, orientation, distribution, motion, etc. (Coles and Kaufman, 1978; Kojima and Kakinuma 1990; Manoharan and Ananthakrishnan 1990; Alurkar et al. 1993 and references therein). Here, some of these aspects will be presented and discussed with two essentially new features :

1. The IPS observations are analysed in the light of diffractive refractive scattering approach. This approach was developed by Booker and MajidiAhi 1981 and later applied to several cases of scattering of radio wave in the irregular ionospheric regions (Vats et al. 1981, Booker et al. 1986,

Booker and Tao 1987, Booker et al. 1987, etc.) The approach was also applied to laser scintillation in the irregular atmosphere (Booker and Vats 1985). Most of the applications of diffractive-refractive scattering approach were surveyed by Vats (1989). This approach have not been seriously applied to IPS observations, so far. In the next section (section 2) on the structure of solar wind plasma, this approach will be outlined briefly and applied to the observations of IPS at 103 MHz.

2. The solar wind speed measurements by the IPS method will be back projected with an improved model of solar wind variation in the IPM. The section on dynamics of solar wind (section 3) will describe the assumptions of this model. The model leads to the estimation of solar plasma acceleration in the inner heliosphere. That section will present the typical results of this analysis.

2. The structure of solar wind plasma

The scattering approach outlined by Booker and MajidiAhi (1981) distinguishes between refractive and diffractive scattering depending on whether the irregularities are greater or less than the Fresnel scale which depends on the observing wavelength and the distance between the irregular medium and observer. Another important quantity in the scattering process in the mean square fluctuation of phase which is given below :

$$<(\Delta\phi)^2> = 4r_e^2 \sec\chi \ \lambda^2 \, Lo \int <(\Delta N)^2> dz \qquad (1)$$

where r_e, χ, λ, Lo and $<(\Delta N)2>$ are classical size of the electron, zenith angle of the radio source, observing wavelength, outer scale of the irregularities and mean square fluctuation of ionization density in the medium.

The observed spectrum of intensity fluctuation of a compact radio source 3C 48 on 14 February 1996 is shown in Fig. 1. These observations were taken by an IPS array at Rajkot (Vats and Deshpande 1994). Lovelace et al. 1970 reported that under suitable conditions it may be possible to derive the speed of solar wind from the observed spectrum of intensity fluctuations. Vats (1986) used this method and derived solar wind speed for several observations. This method derives solar wind speed (v) by the following relations :

$$v = \upsilon \sqrt{\pi \lambda z} \qquad (2)$$

where υ is the observed upper roll off frequency in the spectrum. For the spectrum of Fig.1, the derived speed is ~ 277 km/sec. The observed roll off frequency ~0.13 Hz in the spectrum (Fig.1) can also be used to calculate spatial upper roll off frequency as $2\pi\upsilon/v$ which comes ~3×10^{-3} km^{-1}.

Oza et al. (1997) used a range of integrated mean square fluctuation of ionization density as 10^{25} to 10^{29} m^{-5} and calculated upper and lower roll off frequencies in the spectrum of interplanetary scintillation at 103 MHz. Using their theoretical investigations for the observations of interplanetary scintillation at 103 MHz, the observed value of spatial upper roll off frequency (~3×10^{-3} km^{-1})

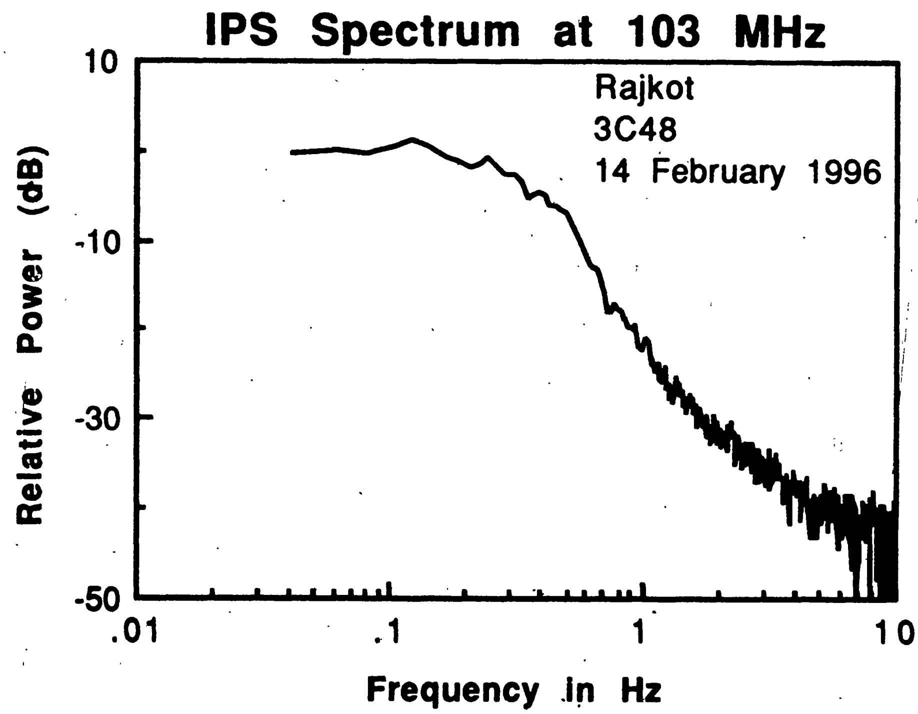

Figure 1. A typical interplanetary scintillation spectrum at 103 MHz.

seems to correspond to the integrated mean square ionization density (~3 × 10^{27} m^{-5}) in the interplanetary medium at the time of present observations. From this the following were calculated:

rms phase deviation	=	43 radians
focal scale	=	8.4 kms
peak scale	=	1223 kms
lens scale	=	1112 kms

The rms phase deviation of 43 radians as such appears to be large specially if one compares it with the diffraction theory. There are two reasons for this (1) the usage of Lo (outer scale of the irregularities) in eq. (1), this is assumed to be ten times Fresnel scale. So this will give ten times larger rms phase deviation (mathematically) and (2) real physical reason for large rms phase deviation is that practically in the interplanetary medium the waves will undergo multiple scattering (here because the line of sight is about 70° away from Sun, it will be weak multiple scattering). The approach used for the calculation substitutes thick screen of interplanetary medium by a thin screen for mathematical simplicity. This is quite a drastic substitution of one problem by another, but it greatly simplifies the problem (Booker and MajidiAhi, 1981). Thus a large weak scattering medium is approximated to a thin phase screen with large rms phase fluctuations.

It is planned to carry out similar analysis of the observations of various sources at different epoch and thereby derive the information regarding these parameters at different locations in the heliosphere. The results will provide a quantitative model of heliospheric plasma.

3. Solar plasma acceleration in the inner heliosphere

Interplanetary scintillation is the only ground based method of measuring solar wind speed outside the ecliptic plane. Manoharan et al. 1995 conducted a unique campaign of interplanetary scintillation in which, for the first time, scintillation enhancements were predicted in real time by observing solar events on 7-8 May 1992 and then detected by both Ooty and Cambridge telescopes the actual enhancement in scintillation. Good consistency was found between IPS observations from both observatories and in situ shocks detected by IMP-8, Yohkoh and soft X-ray images. This enhancement was due to coronal mass ejection. These observations provide direct relations of interplanetary observations and solar events. As outlined by Mehta et al. 1997, it is possible to backproject the observed solar wind speed to the point of its origin in the solar corona. The model assumes that the heliosphere can be divided in two parts (1) the inner heliosphere upto a distance of ~20 solar radii from Sun, where solar plasma is accelerated (for the simplicity of calculations we assumed constant acceleration in this region) and (2) the outer heliosphere where the solar wind speed does not change, it keeps flowing almost constantly. As the Sun rotates around its axis, the radially outward blowing wind will have the spiral shape.

With these simple assumptions solar wind speed measurements based on IPS at 327 MHz for 1987-88 were back projected and the solar plasma acceleration in the near heliosphere. Mehta et al. 1997 presented the results for Carrington rotation 1789 wherein the acceleration was reported to be least ~4-6 m/sec^2 in the solar equatorial region and increased to ~18-24 m/sec^2 in the higher latitude regions. Here the analysis for the years 1987 and 1988 is presented in the form of (i) solar plasma acceleration maps for 1987 and 1988 (Fig.2) and (ii) mean acceleration variation as a function of heliolatitude (Fig.3).

Both the figures (Figs2 and 3) show that solar plasma acceleration is low in the equatorial region and high at higher latitudes. It is also clear from Fig.2 that along the Carrington longitude there is not much variation in acceleration of solar plasma. The increase in solar plasma acceleration toward the polar regions may be due to the presence of coronal holes in the polar region. The open field lines of coronal holes provide easier plasma flow outward. The gradient of acceleration with heliolatitude is sharper for 1987 than that for 1988 (Fig.3). This difference is attributable to the solar activity variation. It is possible that in the high solar activity period there may not be a significant latitudinal variation in solar plasma acceleration. In this analysis the estimated acceleration is inversely proportional to the distance of acceleration - ceasing point (which is assumed to be 20 $R_\odot$. Thus, if the acceleration - ceasing point is moved toward Sun (at 15 $R_\odot$), the values of acceleration will increase by ~33% and on the other hand if this point is moved away from Sun (at 25 $R_\odot$), the values of acceleration will reduce by ~20%. The similar analysis for other years is being done and more quantitative results will be obtained. There is a plan to compare the results during different solar activity periods.

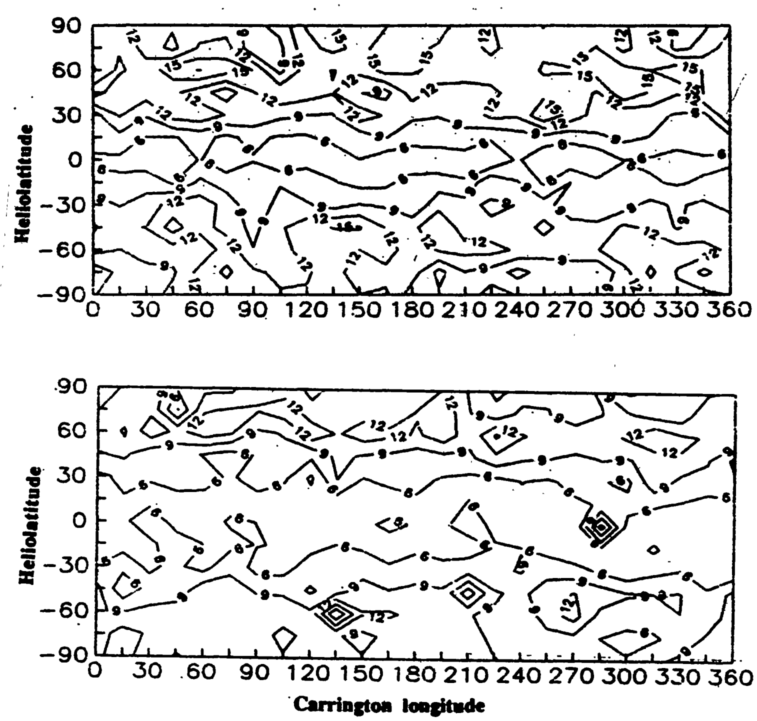

Figure 2. Maps of solar plasma acceleration for 1987 (top) and 1988 (bottom).

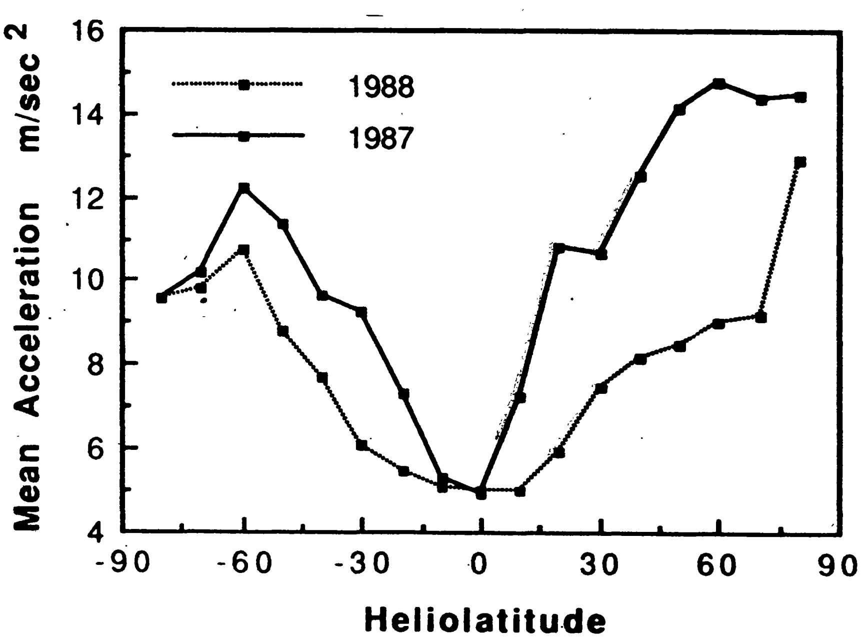

Figure 3 . Variation of mean solar plasma acceleration as a function of heliolatitude for 1987 and 1988.

Acknowledgments

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