Solar wind speed structure near the Sun at 3-12 $R_\odot$

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Abstract

Estimates of solar wind speed obtained by Armstrong et al. [1986] based on 1983 VLA multiple-station intensity scintillation measurements inside 12 R. nave been compared with source surface magnetic field maps and white light coronagraph measurements. The observed speed vari at ions are found to depend primarily on changes in heliographic latitude and longitude, which leads to the first results on speed structure in the acceleration region of the solar wind. Over an equatorial hole, solar wind speed is relatively high (-230 km/s) and stead y (-50 km/s peak-to-peak variations), similar to the fast wind observed recently by Ulysses over the south polar coronal hole but beyond 2.0 AU. Across the streamer belt, the near-Sun flow speed is not uniformly slow, but instead shows large-scale variations in the range of -100-300 km/s. The. minima, which correspond to the coronal source regions of the low-speed solar wind, most likely coincide with the stalks of coronal streamers observed in white-light measurements, and shown recently by Doppler scintillation measurements to have a filamentary structure. The detection of significant wind shear over the streamer belt is consistent with the result, based on *in situ* density and scintillation measurements, that density fluctuations are more fully developed in the slow wind near the heliospheric current sheet than in the fast wind associated with coronal holes.

Introduction

Mapping solar wind velocity near the Sun is fundamental to understanding the origin and expansion of the solar wind. In the absence of *in situ* measurements inside 0.3 AU, IPS (interplanetary scintillation) measurements using both natural radio sources and spacecraft radio signals have served as an important means for remotely probing solar wind flow [Dennison and Hewish, 1967; Coles, 1992]. In spite of their sparsity in the vicinity of the Sun, these measurements have led to general evidence for acceleration of the solar wind within 20 R_O [Ekers and Little, 1971; Armstrong and Woo, 1981; Tyler et al.,)981; Scott et al., 1983; Armstrong et al., 1986; Colts et al., 1991; Tokumaru et al., 1992; Rickett, 1992; Efimov, 1994], as well as the velocity profile of a fast moving interplanetary shock at 13 R_O [Woo and Armstrong, 1981].

Recent investigat ions near the Sun and based on Doppler scintilla ion measurements have found large variations in the magnitude of electron density fluctuations which appear to represent spatial structure organized by the large-scale coronal magnetic field [Woo and Gazis, 1993; Woo et al., 1994, 1995a, 1995 b]. In light of the prevalence of quasi-stationary structure near the Sun, revealed not only by radio propagation but also white-light measurements [Koutchmy and Livshits, 1992; Fisher and Guhathakurta, 1995], a closer examination of solar wind speeds obtained from IPS measurements and their relat ion ship to solar and coronal measurements would t ›e useful. '1 'he purpose of this paper is to carry out such a comparison using the multiple-stat ion intensit y scintillation measurements of 3C279 conducted at the VLA in 1983 [Armstrong et al., 1986]. Multiple-station (as man y as seven stations) intensity scintillation measurements provide the most rigorous estimates of solar wind speed, and the VLA measurements are particularly valuable because they not only probed close to the Sun in the range of 3 to 12 R. but also observed large and interesting variations.

Comparison of VLA, Solar, and Coronal Observations

Reproduced in Fig. 1 arc the mean solar wind flow speeds estimated by Armstrong et al. [1986] from the 1983 VLA scintillation measurements. Results from both ingress and egress phases of the 3C279 occultation are displayed. The measurements represent real changes in the solar wind since the scatter significantly exceeds the uncertainties of the measurements as characterized by the error bars. If the flow speed variations reflect radial variation, the scatter in the measurements makes it difficult to determine a meaningful trend from the measurements in the range of **4-12** R_O. On the other hand, the striking result of Fig. 1 is the abrupt change in speed in the range of 3-4 R_O in both ingress and egress cases, indicating the occurrence of strong acceleration.

Two types of solar observat ion have been useful for interpreting Doppler/phase scintillation measurements near the Sun, and are used for comparison with the VLA results: surface magnetograph and white-light coronagraph data. Simultaneous white-light coronagraph measurements arc especially important; like the VLA observations, they are path-integrated measurements, and observe the. same corona off the limbs of the Sun. Equally important is the fact that near the Sun large variations in solar wind properties deduced from radio propagation measurements are often observed. Since white-light measurements provide measurements in the plane of the sky (as opposed to point in the plane of the sky by radio propagation measurements), the availability y of simultaneous white-light coronagraph measurements makes it possible to distinguish temporal and spatial variations in the radio observations.

Shown in Fig. 2 is the contour map of the source surface magnetic field strength produced by the Wilcox Solar Observatory for Barrington Rotation (CR) 1740 [Hoeksema and Scherrer, 1986], the period during which the VLA measurements were made. Superimposed are eight white dots labelled by DOY (day of year). These represent the points of closest approach of the 3C279 radio path mapped back to the surface of the Sun at 0000 UT. If the solar wind is assumed to bc sphericall y symmetric, most of the contribution to the path-integrated VLA measurement is from the solar wind near the closest approach point. Although data were taken on only six days -- three during ingress and three during egress --- fortuitously, the ingress observations probed the region overlying the neutral line and streamer belt, where the solar wind is general] y dense (confirmed by white-light measurements discussed below) and slow, and enhanced density fluctuations are observed, whi le the egress observations probed the open field region where the solar wind is generally fast, density is low (again confirmed by white-light measurements discussed below), and density fluctuation enhancements are absent [Woo et al., 1994].

During CR 1740, measurements of the lower corona were available from the HAO Mauna Loa Solar Observatory Mk 111 and the Solwind coronagraphs. Significantly, the HAO [Fisher et al., 1985] and Solwind (N, Sheeley, private communication) observations showed that there was no coronal mass ejection (CME) activity in the vicinity of the solar wind regions probed by the VLA measurements. Thus, the observed variations in solar wind speed deduced from the VLA measurements are due to spatial variation alone. Shown on the left in Fig. 3 are two Mk 111 K-coronameter synoptic contour maps of polarized brightness pB at a height of 1.7 R. published by Fisher et al. [1985]. The upper and lower maps are constructed from data off the east and west limbs, respectively. As in Fig. 2, superimposed white dots represent the closest approach points of the 2C379 radio path. Only those corresponding to the VLA ingress measurements are shown on the upper map, since ingress took place above the east limb. Similarly, the white dots on the lower map correspond to the egress measurements.

The upper and lower panels on the right in Fig. 3 represent the time series of the VLA solar wind speeds for ingress (east) and egress (west), respectively. The time axes are reversed in order to facilitate comparison with the corona graph maps on the left, and corresponding closest approach distances are indicated on the upper ordinates. Estimates of solar wind speed were obtained at an approximate rate of one per hour. Assuming that the VLA flow speed variations are due primarily to changes in longitude and latitude, the results in Figs. 2 and 3 show dramatic differences between the solar wind over the streamer belt and equatorial coronal hole. Over the streamer belt, where IPS [Kojima and Kakinuma, 1987; Rickett and Colts, 1991] and *in situ* plasma [Gosling et al., 1981; Schwenn, 1990] measurements beyond 0.3 AU indicate that the solar wind is generally slow, the VLA solar wind speed measurements show substantial large-scale variations inside 12 R_O, with gradients that are approximately 50 km/s per degree of angle along the closest approach point path. The variations are systematic enough that even though continuous data arc not available, at least two minima within the longitudinal range of about 35° can be inferred. These minima, which correspond to the coronal source regions of the slow solar wind, most likely coincide with the 'stalks' of coronal streamers that are observed at many solar radii in coronal eclipse [Koutchmy and Livshits, 1992] and white-light coronagraph measurements [Fisher and Guhathakurta, 1995]. Doppler scintillation studies indicate that these stalks arc manifested as scintillation enhancements representing filamentary structure, and have a similar occurence rate as the observed velocity minima — one or several over the width of the streamer belt [Woo and Gazis, 1993; Woo et al., 1994, 1995b]. That the streamers have evolved into faint stalks is further supported by the Solwind white-light coronagraph measurements off the east limb showing that the bright streamers seen at 1.7 R_0 by the HAO coronagraph have faded and essentially disappeared at the higher altitude of 3.6 R. (N. Sheeley, private communication). That velocity minima probably occur at these stalks is also supported by recent studies based on Doppler scintillation measurements that tracked the evolution of coronal streamers from near the Sun out to 1 AU [Woo et al., 1995b] where actual velocity minima have been measured at the heliospheric current sheet [Gosling et al., 1981; Borrini et al., 1981; Huddleston et al., 1995].

The west limb coronagraph map in Fig. 3 shows that the egress measurements took place over an equatorial coronal hole formed by the equatorward extension of the north polar coronal hole. This equatorial hole is newly formed, as it is not present on the coronagraph map based on east limb measurements conducted half a solar rotation earlier. This hole is also clearly observed in the Solwind coronagraph data as an even larger clearing in the streamer belt at 3.6 R_0 (N. Sheeley, private communication). While solar wind speed varies between 100-300 km/s over the streamer belt, egress measurements over the equatorial coronal hole show a fast but steady solar wind --- mean speed of about 230 km/s with a peak-to-peak variation of about 50 km/s. The steady nature of the fast wind is similar to that of the polar fast wind observed by Ulysses beyond 2 AU [Phillips et al., 1994]. This result may not be surprising since, like the near-Sun low-latitude fast solar wind, the distant Ulysses fast wind undergoes less evolution due to interaction with low-speed wind by virtue of its high latitude. The degree of steadiness of the wind observed near and far from the Sun appears similar, as Ulysses observed peak-to-peak variations of -200 km/s in its 1 -hr speed averages out of an average of -750 km/s over the south polar coronal hole (private communicant ion M. Neugebauer). While the measurements of DOY 282-283 arc not continuous, the egress measurements convey the impression that the transition from slow wind over the streamer belt to fast wind over the coronal hole is abrupt. This abruptness is consistent with the observation by Helios velocity measurements beyond 0.3 AU that leading edges of high-speed streams tend to steepen closer to the Sun [Schwenn, 1990]. Although not necessarily significant because of only one data point, it is nevertheless interesting that the highest speed occurs not in the center of the hole but at the edge of the coronal hole, as some studies have predicted [Sheeley et al., 1991; Wang et al., 1994].

As we have seen, when viewed as stemming from changes in latitude and longitude, the VLA speed measurements have led to new results that arc both reasonable and consistent with solar, coronal, and *in situ* plasma measurements. Acceleration can only be discerned in Fig. 1 in the range of 3.5-4 Ro, and yet these measurements all took place over the high density streamer belt rather than the equatorial coronal hole. Clearly, the VLA speed variations arc caused primarily by variations in longitude and latitude rather than by heliocentric distance, and acceleration is best studied using radially aligned intensity scintillation measurements [Colts et al., 1991].

Conclusions and Discussion

Although conducted over only six days, the 1983 VLA measurements were frequent enough to show substantial variations in solar wind speed inside 12 R_O. Moreover, these measurements remarkably took place over both the streamer belt and an equatorial coronal hole, and at a time when simultaneous white-light measurements of the corona were available. Vastly different results have been observed depending on proximity of the c1oscs1 approach point to the neutral line. Over the equatorial coronal hole, the wind is fast (230 km/s) and steady (peak-to-peak variation of 50 km/s), similar to the behavior of fast wind observed by Ul ysses *in situ* measurements over the south polar coronal hole but beyond 2 AU.

The origin of the slow wind is one of the outstanding questions in solar wind research [Schwenn, 1990; Kopp, 1994]. This study reveals that across the streamer belt, flow speed is not uniformly slow, but instead exhibits large-scale variations in the range of -100-300 km/s. The minima, which correspond to the coronal source regions of the slow solar wind, most likely coincide with the stalks of coronal streamers that have been observed in whit e-light measurements and observed as enhanced density fluctuations in Doppler stint illation measurements. The latter have. shown that the structure of the stalks is filamentary. The presence of substantial wind shears over the streamer belt and near the Sun is consistent with the result, based on *in situ* measurements beyond 0.3 AU and Doppler scintillation measurements inside 0.3 AU, that density fluctuations in the slow wind are more fully developed than those in the fast wind [Marsch and Tu, 1990; Roberts et al.> 1991, 1992; Woo et al., 1995].

Multiple stat ion intensit y scintillation measurements are path-integrated measurements and solar wind speeds deduced from them can be improved with detailed modeling [Grail et al., 1994]. While such modeling may lead to some improvement in the estimates in Fig. 1, it is not expected to affect the general conclusions of th is paper. Mult iple-station intensity scintillation measurements have indicated a possible turbulent envelope surrounding the Sun [Ekers and Little, 1971; Armstrong and Woo, 1981; Scott, 1983]. These deduced random velocity fluctuations may represent the spatial variations over the streamer belt found in this study, and the disappearance of the velocity fluctuations beyond ~20 $R_\odot$ a mere reflect ion of the evolution of these spatial variations to the mom uniform low-speed solar wind observed near the heliospheric current sheet at 0.3 AU and beyond [e.g., Marsch and Tu, 1990].

The results of this paper, along with recent gains in understanding of near-Sun solar wind morphology from Doppler scintillation measurements [Woo, 1995], reinforce the value of careful 1 y conducted multiple-station intensit y scintillation measurements such as the 1983 VLA measurements. Coordinated measurements of Doppler stint illation, multiple-station intensity scintillation, and white-light (e.g., SOHO) would be particularly useful in providing more details on the structure of coronal streamers and its relationship to the source of the slow solar wind.

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FIGURE CAPTIONS

Fig. 1 Estimates of solar wind speeds obtained by Armstrong et al. [1986] from VLA measurements during the ingress and egress phases of the 3C279 occultation in 1983.

Fig. 2 Source surface magnetic field map produced by the Wilcox Solar Observatory for Barrington Rot at ion 1740 from 1 locksema and Scherrer [1986]. The superimposed white dots arc the closest approach points of the radio path of 3C279 that have been mapped to the solar surface on the labelled day of year DOY at 00001 JT.

Fig. 3 Plots on the left are the HAO Mauna Loa Solar Observatory Mk III K-coronameter synoptic cent our maps of polarized brightness pB at a 1 height of 1.7 Ro from Fisher et al. [1984] based on cast (upper plot) and west (lower plot) limb measurements. Plots on the right arc VLA wind speeds obtained during the ingress (cast limb) and egress (west limb) phases of the 3C279 occultation, Time axes are shown in reverse and closest approach distances arc given on the upper ordinates. The white dots on the K-coronameter maps indicate the closest approach points mapped back to the Sun for the corresponding limb.

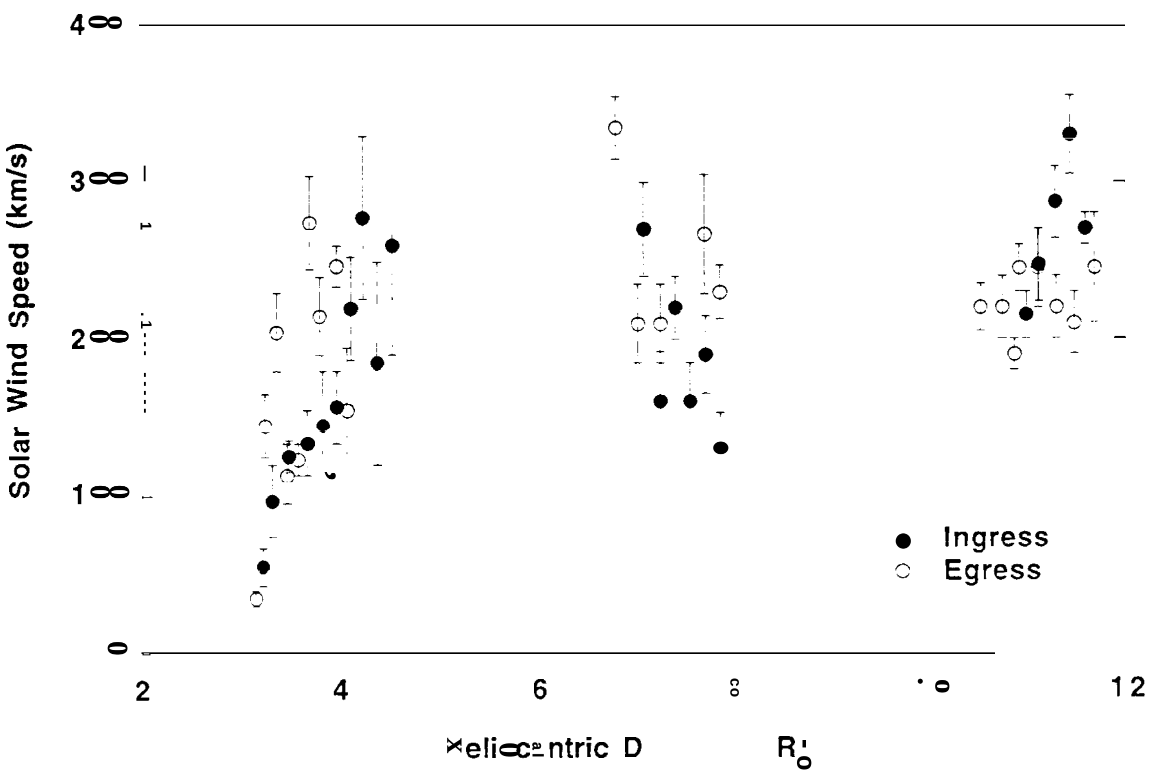


Fig 1

SOURCE SURFACE MAGNETIC FIELD

0, ±1, 2, 5, 10, 20 MICROTESLA

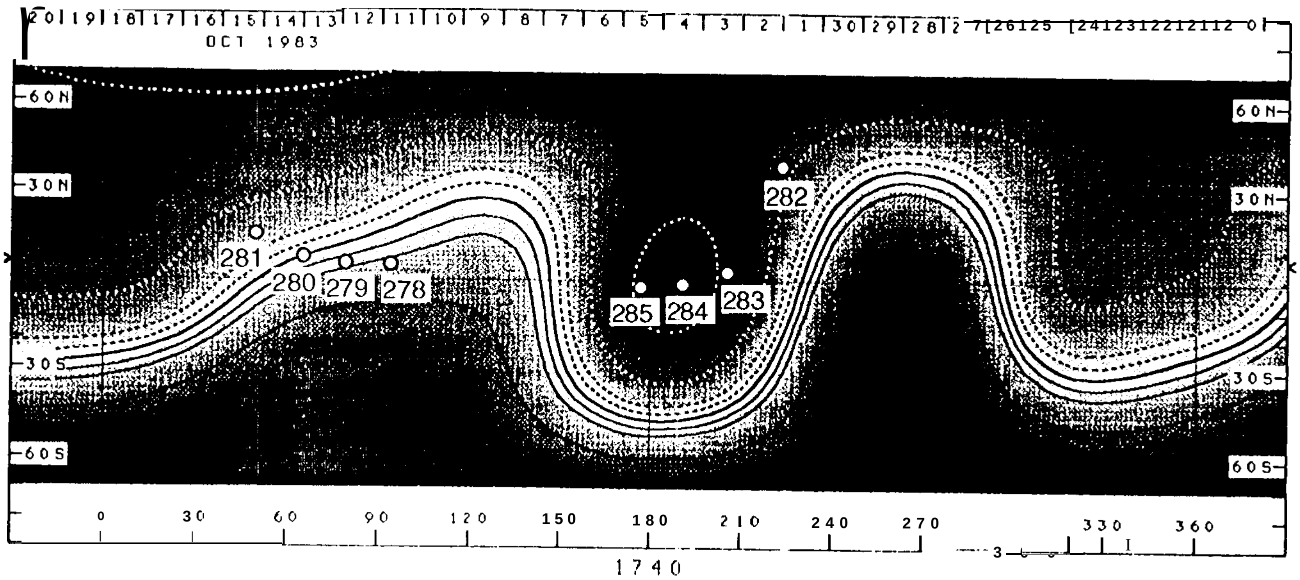
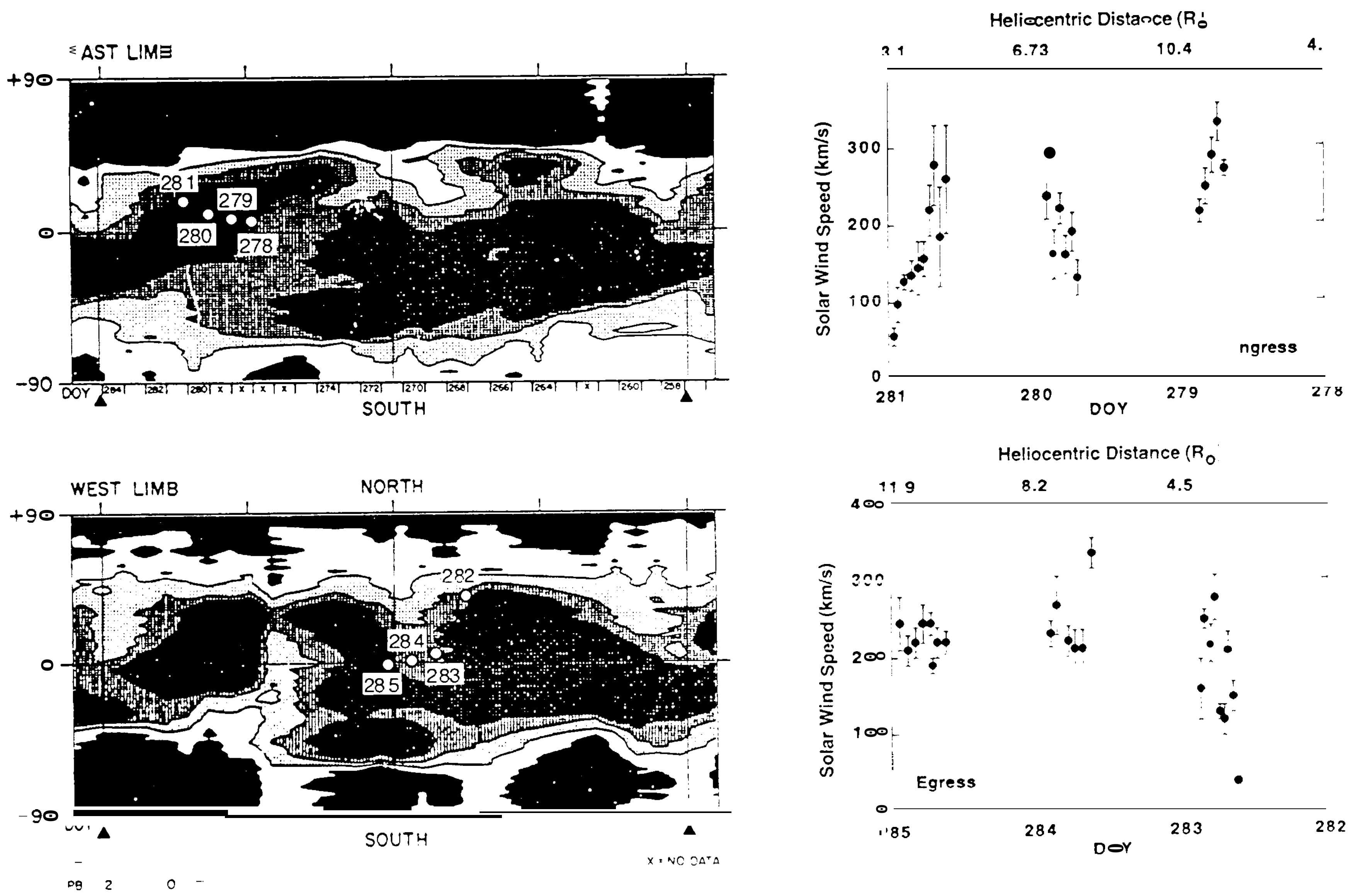


Fig. 2



EAST LIMB
+90
0
-90
DOY
SOUTH
281
279
280
278
WEST LIMB
NORTH
282
284
283
285
X = NO DATA
Heliocentric Distance (R
6.73
10.4
Solar Wind Speed (km/s)
300
200
100
0
281
280
279
DOY
ngress
Heliocentric Distance (R
8.2
4.5
Egress
284
283
282

Fig. 3