ULYSSES OBSERVATIONS OF A RECURRENT HIGH SPEED SOLAR WIND STREAM AND THE HELIOMAGNETIC STREAMER BELT

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Abstract. Near-ecliptic solar wind observations by Ulysses on its way to the polar regions of the Sun, compared with those from IMP 8 at 1 AU, showed that high-speed streams decay and broaden with heliocentric distance from IMP to Ulysses, as expected. In July 1992 while travelling south at -13°S and 5.3 AU, Ulysses encountered a recurrent high-sped stream, that may also have been observed at IMP 8. The stream has been observed a total of 14 times in each solar rotation through June 1993 at -34°S. The source of the high-speed stream is an equatorward extension of the south polar coronal hole. From July 1992 through June 1993, averages of solar wind peak speed increased while density decreased with heliographic latitude, A low-speed, high-density flow in the valleys between peaks of the high-speed stream, observed recurrently, is associated with the heliomagnetic (coronal) streamer belt encircling the heliomagnetic equator. Both the stream and the belt crossed Ulysses with the solar rotation period until April 1993 when the streamer belt disappeared at -29°S heliographic latitude as the spacecraft climbed beyond it to higher latitudes. At its maximum inclination, the streamer belt was tilted at -29° to the heliographic equatorial plane at this time in the solar cycle.

Introduction

A general understanding of 3-dimensional aspects of the heliosphere has developed following the discovery with Mariner 2 of high-speed solar wind streams separated by slower flows. However, there is still much to be learned about the solar wind very near to and far from the Sun and out of the ecliptic. Observations with Helios 1 and 2 in the inner heliosphere and with Pioneers 10 and 11 and Voyagers 1 and 2 in the outer heliosphere (see e.g. *Schwenn* [1986]; *Smith and Wolfe* [1979]; *Lazarus and Belcher* [1987]) have contributed greatly to our present understanding. To extend this understanding of the 3-dimensional evolution of the solar wind in the heliosphere, it was felt that a mission cover-ing large ranges of heliocentric distance and heliographic latitude with an improved generation of instruments was needed. This, was a prime motivation for the ESA/NASA Ulysses mission over the poles of the Sun, Below, we report observations from two Los Alamos National Laboratory solar wind plasma experiments: one on Ulysses [*Bame et* al., 1992], on its way to the polar regions of the Sun, and one on IMP 8, locked in Earth orbit since 1973, serving as a 1 AU in-ecliptic monitor.

Observations and Discussion

In this section, we present Ulysses and IMP 8 observations and discuss their relationship to heliospheric phenomenology. In subsections below. we examine (1) the near ecliptic evolution

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with heliocentric distance of streams between IMP 8 and Ulysses,(2) the latitudinal evolution of a single major recurrent stream observed by Ulysses, (3) the solar source of the major recurrent stream, and (4) streams and adjoining flows of the heliomagnetic streamer belt.

After launch on October 6,1990, Ulysses flew out to encounter Jupiter in February 1992 where it was deflected from the ecliptic reward the south polar regions. Six-hour averages of solar wind speed, V, from Ulysses, spanning January 1, 1991 through June 1993 are given in Figure 1. Heliocentric radial distances are shown in the 1991 panel and heliographic latitudes in the 1992 and 1993 panels. Carrington rotation intervals for the spacecraft, taking account of the longitude separation from Earth but not solar wind speed propagation times, are identified by the diamonds at the tops of the panels.

IMP 8 was launched in 1973 into a large, nearly circular orbit where it spends a substantial fraction of time outside the Earth's bow shock in the solar wind. Data from the IMP 8 3-plate electrostatic analyzer are presented in Figure 2, which displays hourly avenges of speed at 1 AU in the ecliptic during 1991-1992. Gaps in the data are times when tracking was not available, or IMP was in the magnetosphere.

(l). *Evolution of solar wind streams with heliocentric distance.* During 1991, as shown in Figure 1, the speed at Ulysses displayed an unremarkable, irregular series of small solar wind streams and transient disturbances driven by coronal mass ejections (CMEs), with one exception in March. Peak speeds rarely exceeded 650 km s^{-1} and the total spread of V, from stream peaks to minimums in the valleys generally did not exceed -250 km s^{-1} except for the March event, when V reached -1000 km s^{-1} from a hose near 450 km s^{-1} during a time of CME flows and transient shock disturbances. These peak and total spread values of V at Ulysses can be compared with those at IMP at 1 AU (see Figure 2) where large, well-defined, and narrow streams were observed with speeds reaching above 700 kms-^{1} and with total spreads of ~400 km s^{-1}. Two or more streams were commonly observed in single solar rotations at IMP throughout 1991-92.

Comparing the average characteristics of the solar wind flows at both spacecraft in the first half of 1992, while streams at IMP remained well-defined, those at Ulysses became even more irregular and confined within an even narrower total spread of ~100 km s^{-1}. Contrasting Figures 1 and 2, it is apparent that streams and transient disturbances in and near the ecliptic are strongly damped as they propagate outward [e.g. *Gosling et al.*, 1976]. Minimum speeds rise and maximum speeds fall as momentum is transferred from fast to slow wind, and narrow streams broaden in longitude as fast plasma pulls away from slower plasma behind, creating rarefactions.

(2). *Latitudinal evolution of a major high-speed stream.* Ulysses first observed a long-term recurrent high-speed solar wind stream in early July 1992, when irregular small streams in the first half of 1992 were replaced by a major high-speed stream. The stream has appeared during 14 solar rotations from July 1992 through June 1993. Stream peaks are numbered in Figure 1 for easy reference. Small-scale structures around the major peaks may be smaller streams or substreams merging with the dominant stream; they are not considered here. It is of interest to note that the first appearance of this major stream occurred during a time of major change in the heliospheric magnetic sector structure [see *Balogh et* al., 1993].

Interestingly, a succession of stream peaks at IMP, starting with a strong peak in early June, appeared through the remainder of 1992 with a period of 27.33 days. Dots with this period are above the peaks in Figure 2 at the 900 km s^{-1} level. Because of a data gap, no peak could be detected on day 232 when it was due. There is evidence that these IMP stream peaks were from the same stream observed at Ulysses starting in early July. The delay between appearances at IMP and Ulysses can be accounted for by the longitudinal separation of Earth and Ulysses, plus the solar wind propagation time from 1 AU to 5.3 AU, and plus possible delays associated with the latitudinal shape of the front of the stream, since Ulysses was 13.4°S below the ecliptic. The magnetic polarity of two of the stream peaks at IMP was inward (R. P. Lepping, personal communication); polarity for the other peaks is presently unavailable. As reported later, polarity of the stream at Ulysses is also inward, and polarity of the polar coronal hole to which the stream maps from both spacecraft. is inward as well. This circumstantial evidence that the same stream was observed with two spacecraft. IMP 8 at 1 AU and Ulysses at 5.3 AU, is compelling, but because this association is not essential to the remainder of this report, it is not persued further.

Figure 3. shows several solar wind parameters from Ulysses as it travelled south: maximum and minimum speeds observed as the stream peaks and valleys passed in each solar rotation, and average solar wind densities. The stream appeared and developed over two solar rotations with peak 1 having a speedof611 km s^{-1} at a latitude of 13.4°S and heliocentric distance of 5.3 AU, and peak 2 having a speed of 730 km s^{-1} at 14.5°S and a slightly smaller distance. A latitudinal gradient of -100 km s^{-1} deg^{-1} is inferred from these data, but this value should be viewed with caution because of possible temporal changes in the stream between observations. It can be compared to a value of 30-100 km s^{-1} determined for a stream at 0.31 AU [*Schwenn et al.*. 1978].

As Ulysses travelled to 33.6"S and 4.6 AU, the stream continued to appear with speeds between 730 and 830 km s^{-1}, except for peak 6 in November when a very fast CME-driven disturbance drove the peak speed to971 km s^{-1}. Figure 3 shows two points for this solar rotation, one at the peak of the disturbance, and one estimated for the peak if it had been undisturbed.

From the last eight peaks, a latitudinal gradient of ≤ 10 km s^{-1} deg^{-1} can be derived for the core of the stream over the latitudinal range of these measurements. Again, the accuracy of this determination should be viewed with caution, but an extrapolation from the last point suggests that the average speed should reach ~900 km s^{-1} by -38°S and continue to rise thereafter. However, 'it will not be suprising to find that this assumption of a continued linear progression is unrealistic.

For stream appearances 3-12, the average stream peak speed is 782 km s^{-1}, and that for minimums following peaks 1-11, is 418 km s^{-1} (see Figures 1 and 3). This gives an average peak-to-valley ratio of 1.87, A significantly smaller peak-to-valley ratio of 1.45 is found for appearances 12 and 13 at heliographic latitudes of 28.9°S and 30.4°S. These peaks have speeds of 803 and 828 km s^{-1}, followed by 556 and 569 kms $^{-1}$ in the valleys. Importantly, as discussed in subsection 4, this sharp step up in minimum speed accompanied by a step down in maximum density (not shown here), shows that Ulysses crossed from onc regime in which it sampled the heliomagnetic streamer belt to another in which the belt was no longer present.

A negative gradient of average proton density with heliographic latitude is demonstrated by Ulysses data shown in Figure 3. Normalized proton density, nR^2, where n is the measured density and R is the heliocentric distance, binned by solar rotation and plotted against heliographic latitude, shows a decrease in mean density by a factor of -2.5 over a 24° *range*, or an average gradient of -(). 1 cm^{-3} deg^{-1}. It is expected that a future analysis in which heliomagnetic latitude is employed will provide a more physically meaningful, steeper gradient in the vicinity of the heliospheric current sheet.

(3). *Solar source of the major recurrent high-speed stream.* *Synoptic* maps of the chromospheric 1083 nm helium line strength observed at the National Solar Observatory on Kitt Peak for odd Barrington rotations, CR 1857-1869 are shown in Figure 4. The maps have been processed to enhance areas of weak line strength to show coronal holes as large dark patches. These patches, such as the large extended ones at the poles, are the bases of coronal holes. Smaller patches are filament channels and areas of slightly weaker than normal helium absorption in quiet regions.Thesouth polar hole evident in all the maps is notably strong during this year.

To identify the source of the persistent stream at Ulysses, the stream was mapped back to the Sun for comparison with features in the synoptic maps, using the constant velocity approximation. Profiles of the mapped-back stream, identified by Barrington rotations, are shown in Figure 5. Because speeds on the rising portion of the stream are significantly altered by momentum transfer between the stream and slower solar wind ahead, mapping for that portion is not used. Instead the longitudinal positions of the very sharp stream edges for the trailing portions were transferred to Figure 4 where they are shown by vertical bars in the panels for CR 1859-1869. These lines, falling near the eastern edge of the dark equatorward extension of the polar coronal hole, show that as the extension migrates eastward, the profiles of the stream at Ulysses also migrate eastward. Considering all of these factors, we identify this equatorward extension as the source of the stream, (The stream at IMP, discussed earlier, also traces to this extension.) A similar eastward migration of the magnetic sector structure in the heliosphere during this period is discussed by *Balogh et al.*, [1993]. Additional reinforcement of this source identification is furnished by the measured magnetic polarity of the *stream* [*Smith et al.*, 1993] and polar hole, both inward,

(4). Streams and heliomagnetic streamer belt flows. The succession of peaks and valleys of solar wind speed exhibited in Figure 1 arises from a conceptually simple heliospheric system. Single peaks in the speed are due to passage across Ulysses of the high-speed stream emanating from the equatorward extension of the south polar coronal hole, and valleys between stream peaks are due to crossings of the heliomagnetic streamer belt, commonly thought to encircle the heliomagnetic equator and extend outward surrounding the embedded heliospheric current sheet [e.g. *Gosling et al.*, 1981; *Feldman et al.*, 1981]. Both the stream and belt appearances have the period of solar rotation. Until April 1993, solar wind flows from the heliomagnetic streamer belt reached relatively constant lowest speeds and highest densities. Because the heliomagnetic equator is tilted from the heliographic equator, this flow with lowest speed and highest density alternates with the high-speed stream.

In April 1993, at --29°S heliographic latitude, there was a sharp step change in the flows between stream peaks in one solar rotation; lowest speeds stepped up to a higher level and highest densities (not shown) stepped down to a lower level, signaling that Ulysses had risen above the maximum latitude reached by the tilted heliomagnetic streamer belt, inclined to the heliographic equatorial plane. Possible warps in the configuration of the belt are unknown at present, but this measurement gives the maximum tilt of the sheet whether it is warped or not. We note that this step change was coincident with changes in magnetic field conditions at Ulysses, reported by *Smith et al., [1993],* showing the disappearance of magnetic sector structure and appearance of a prevalent unipolar field geometry.

The timing from the last appearance of the lowest speed solar wind flow to the next time when it could have been *seen,* but was missing, determines a -29° maximum tilt of of the heliomagnetic streamer belt from the heliographic equatorial plane, for this time in the solar cycle. Because it is known that the heliomagnetic current sheet is embedded in the streamer belt, our results imply a tilt of -29° for the current sheet as well, which is confirmed by the Ulysses magnetometer data [Smith et al., 1993]. This crossing of the current sheet was earlier than predicted by *Suess et al.*, [1993] on the basis of measurements made during solar cycle 21. We note that it is possible that the location of the streamer belt might change in the near future so it may be observed again before the Ulysses south polar passage in 1994; data are being monitored for this.

Clearly, the Ulysses probe of heliocentric distance and heliographic latitude is providing important new information on solar wind stream dynamics and the heliomagnetic streamer belt in the heliosphere. It has already provided some interesting observations and undoubtedly it will provide us with some surprises as higher latitudes are explored.

Acknowledgements , We thank N. R. Sheeley, Jr. for helpful discussions and R. P. Lepping for providing magnetic polarity of the stream at IMP. The JPL and ESTEC Project Offices and the Project Scientists are thanked for their cooperation and continued support. The work at Los Alamos was performed under the auspices of the U. S. Department of Energy with financial support from the National Aeronautics and Space Administration; that at the Jet Propulsion Laboratory of the California Institute of Technology has been carried out under contract to NASA; the National Solar Observatory is a division of the National Optical Astronomy Observatories operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation. NSO/Kitt Peak data used here are produced cooperatively by NSF/NOAO, NASA/GSFC, and NOAA/SEL.

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Figure Captions

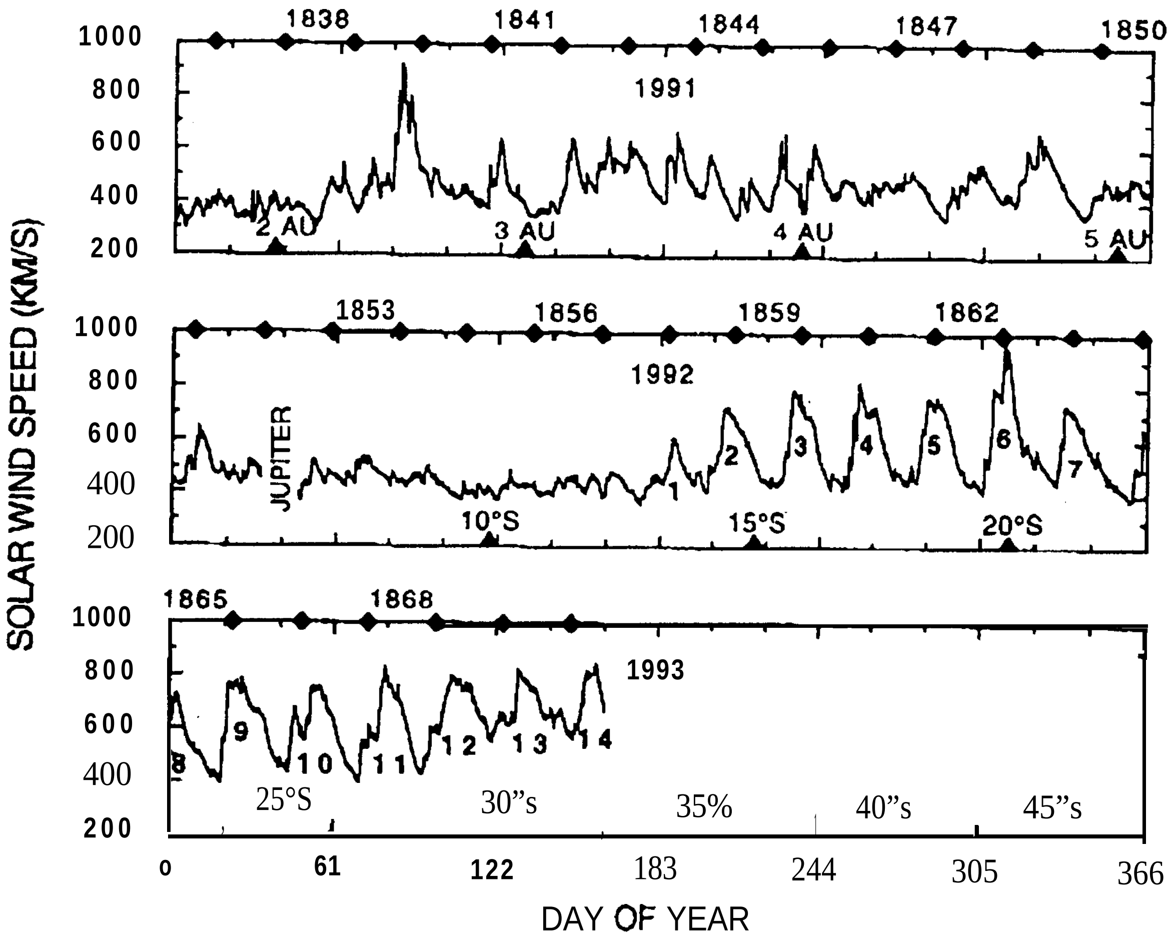
Fig. 1. Six-hour averages of solar wind speed measured at Ulysses from January 1991 to mid-year 1993.

Fig. 2. Hourly averages of solar wind speed from IMP 8 at 1 AU in the ecliptic in 1991-1992.

Fig. 3. Data showing (1) the heliographic gradient with latitude of mean proton density normalized by R^2 for varying heliocentic distance, (2) minimum proton bulk speeds between peaks of the persistent solar wind stream, and (3) maximum speeds at the peaks.

Fig. 4. Synoptic maps of chromospheric 1083 nm helium line strength observed at the National Solar Observatory on Kitt Peak. Ordinates are sine of the heliospheric latitude spanning from -1 (90°S) at the bottom of each panel to +1 (90°N) at the top. In this format, time runs from right to left within each panel.

Fig.5. Superposed plots of Ulysses speed mapped back to Barrington longitude at the Sun. In this format, time runs from right to left.



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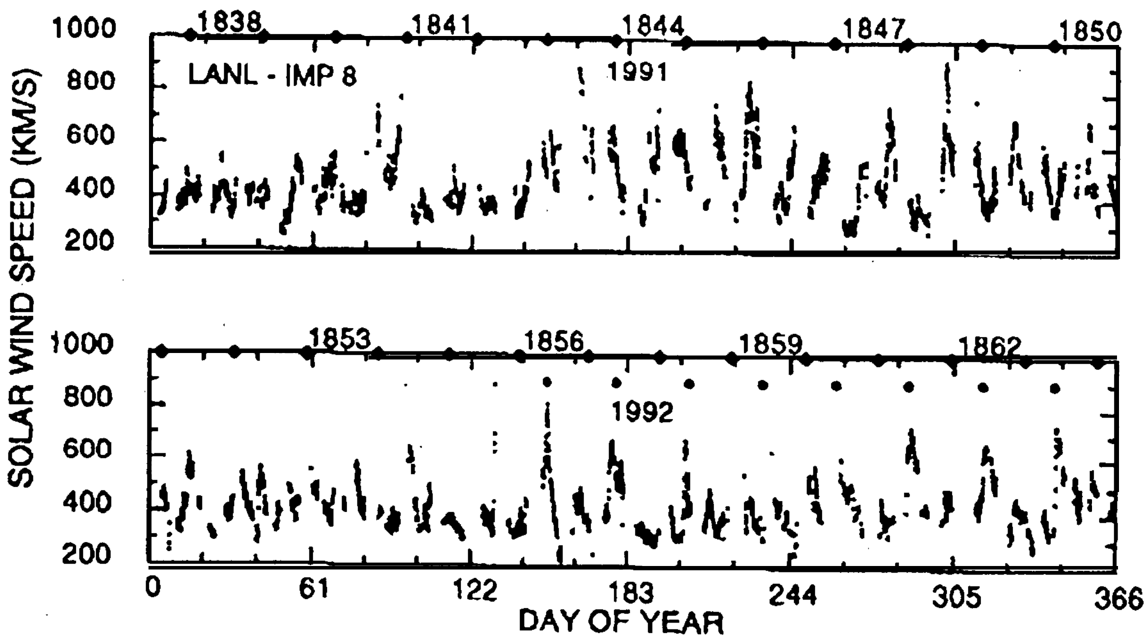

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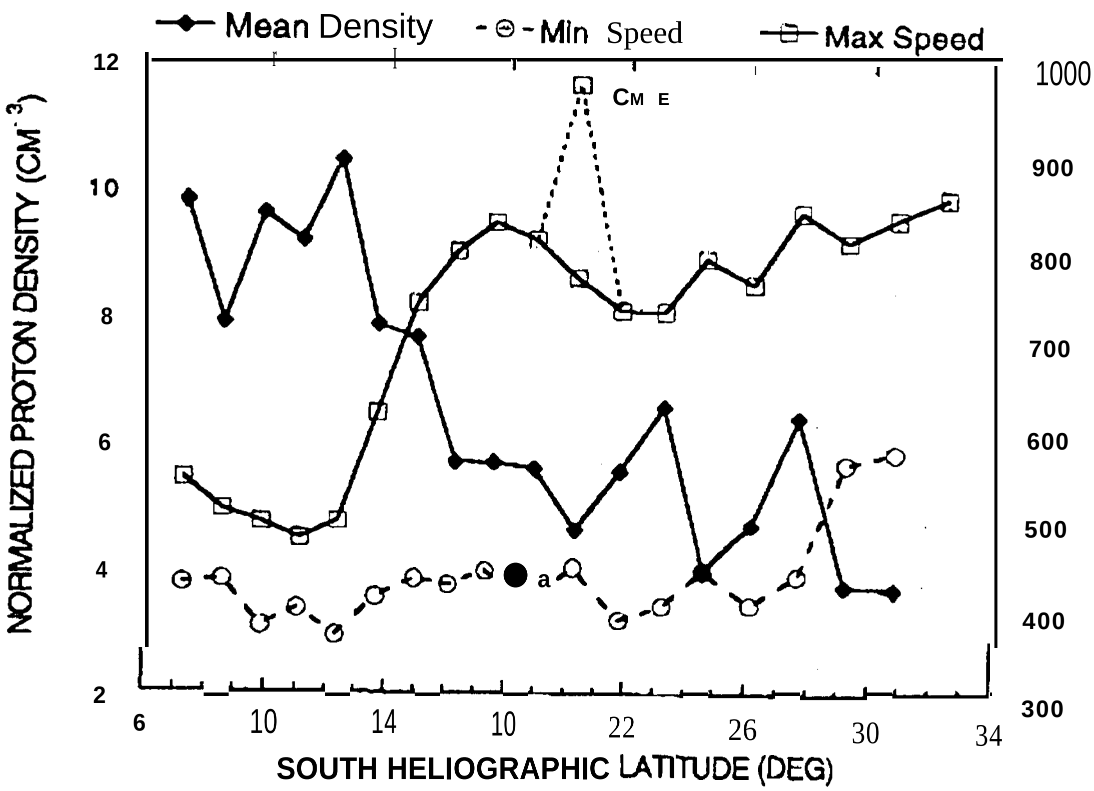

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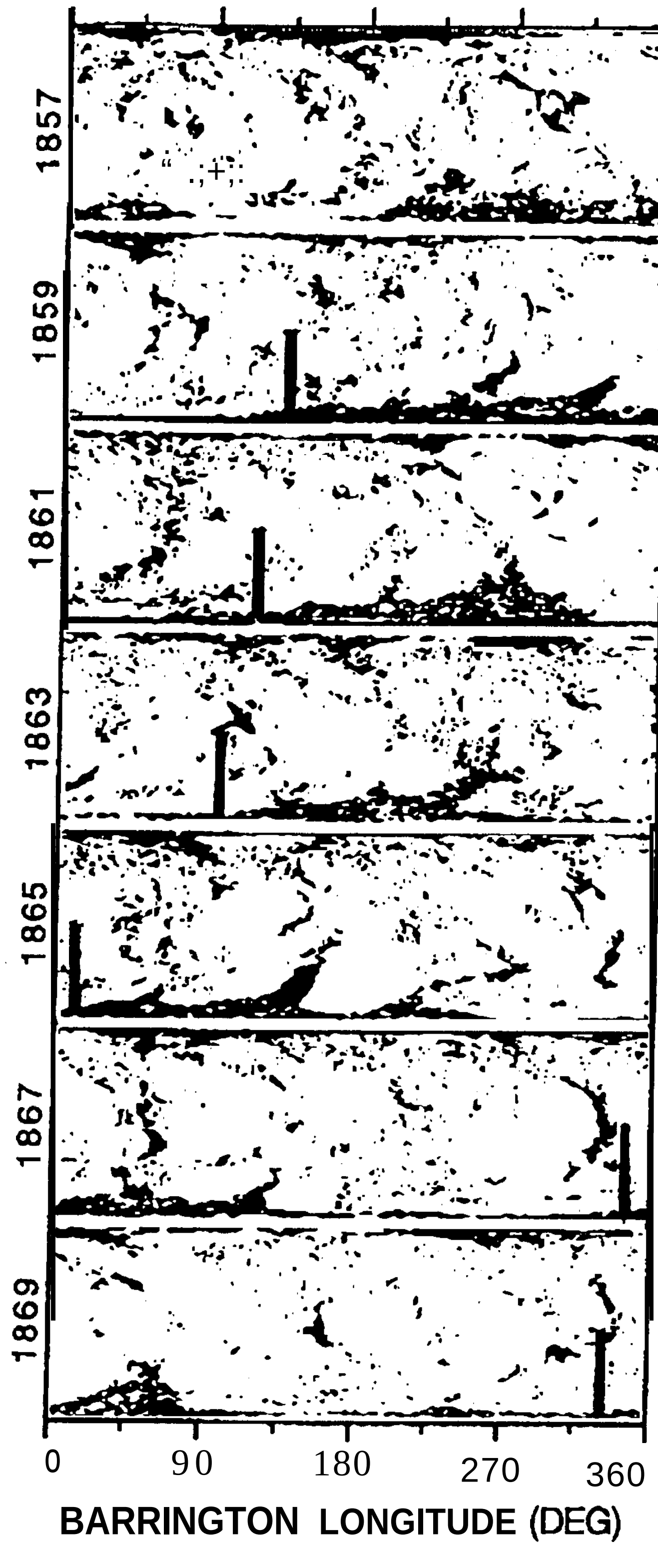

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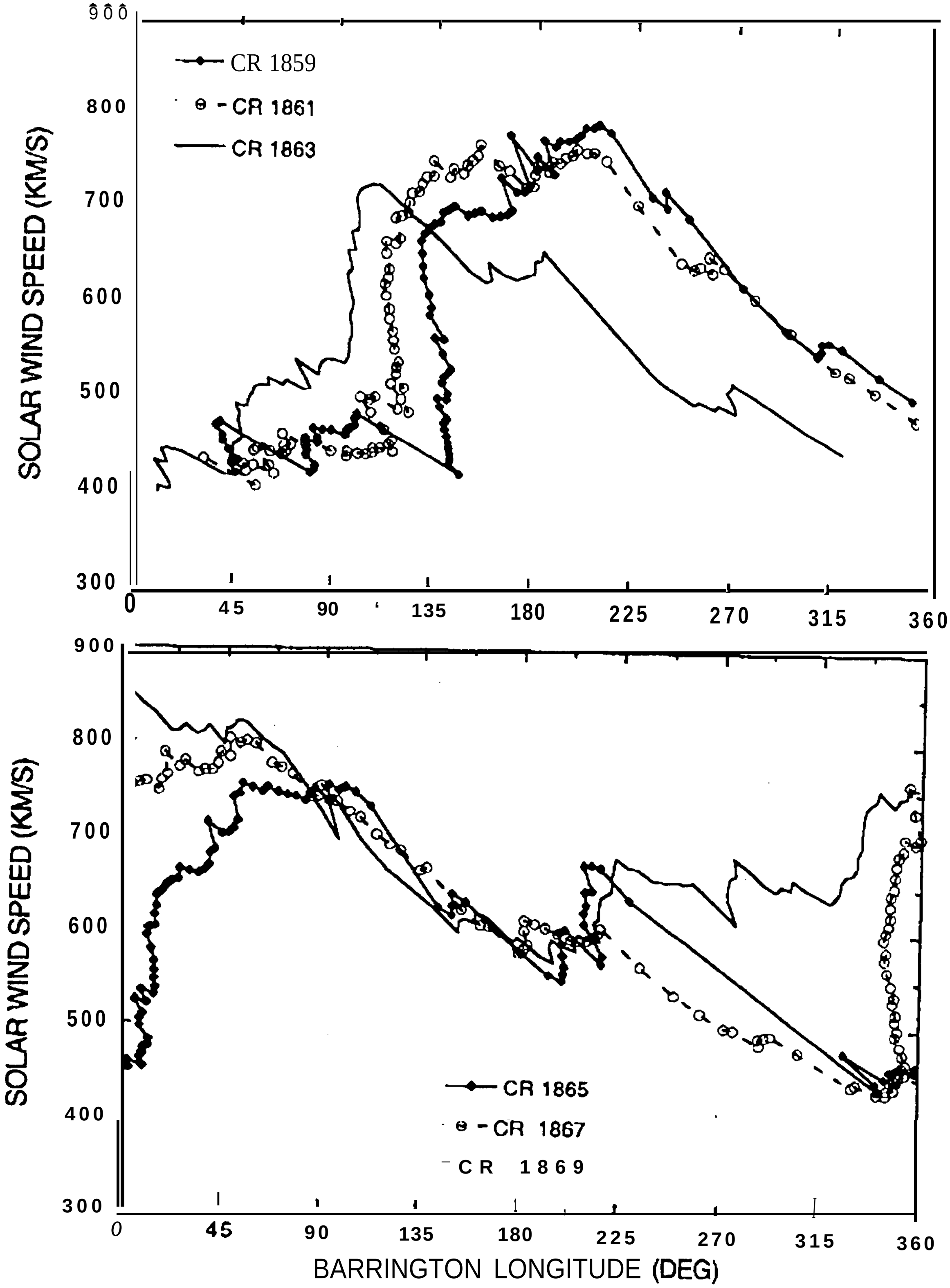

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