SOLAR CYCLE EVOLUTION OF THE SOLAR WIND IN THREE DIMENSIONS

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ABSTRACT

Measurements of the solar wind speed both in and out of the ecliptic are presented for 1971-82. The speed estimates, which were made with the interplanetary scintillation system at UC San Diego, have been compared to _in situ_ spacecraft measurements for ecliptic radio sources. Good agreement is found for large, slowly evolving structures, and thus such structures can be studied up to 60 degrees north and south heliographic latitude. Annual average wind speeds are presented versus latitude for an entire solar cycle. Fast wind streams from the poles persisted through declining and low solar activity, but were closed off during four years of high activity. This evolution follows that of the polar coronal holes, as displayed by comparing averaged speed and coronal density over latitude and longitude. The most recent data (1982) show the reestablishment of large tilted polar holes and associated fast streams. Coronal magnetic field data show that the neutral sheet is confined to low latitudes at solar minimum and extends to high latitudes at solar maximum; thus the slow solar wind comes from the same latitude range as that of the neutral sheet.

We have investigated the three-dimensional structure of the solar wind during the last eleven years using the technique of interplanetary scintillation (IPS). Three radio antennas at 74 MHz are used to measure the velocity of the scintillation pattern, which is caused when waves from a small-diameter radio source travel through inhomogeneities in the solar wind plasma and are detected at the earth (Armstrong and Coles 1972). Figure 1 illustrates the geometry, showing as a heavy line the region on the line of sight to the source which contributes most of the scintillation. The velocity of the pattern is an average of the velocities weighted by the level of "micro-turbulence" (on scales of 50-300km). In this paper we present results on the simple assumption that the IPS velocity estimates the solar wind velocity at the point P where the line of sight passes closest to the sun. The unique aspect of the IPS method is that the point P is not confined to the ecliptic and reaches 60 degrees north and south latitudes. Results from 1972-79 were described by Coles et al, 1980.

The "point interpretation" of IPS data has been checked by comparison of velocities from an ecliptic radio source with estimates of the solar wind velocity at the point P made by spirally mapping _in situ_ measurements from earth-orbiting spacecraft. There is generally good agreement, as is shown in Figure 1 of Coles et al. (1978) for 1973. Similar agreement to within 50 km/s was also found during 1974 and 1975 (Harmon, 1975); these were periods when the solar wind was dominated by stable recurrent fast streams. We are in the process of extending the comparison through solar maximum when there are more transient variations; here we find a somewhat worse agreement. In particular, the IPS data underestimate the speed during brief increases due to either narrow streams or transient disturbances. Nevertheless, it is clear that a reliable first-order

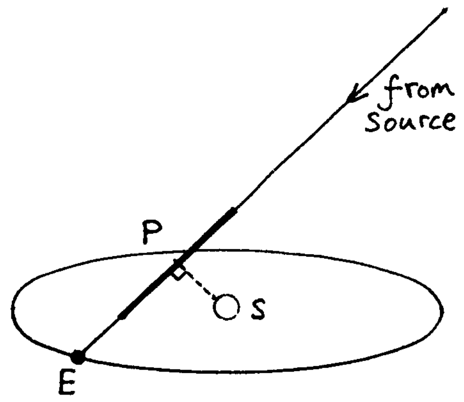

Figure 1. Geometry of IPS observation.

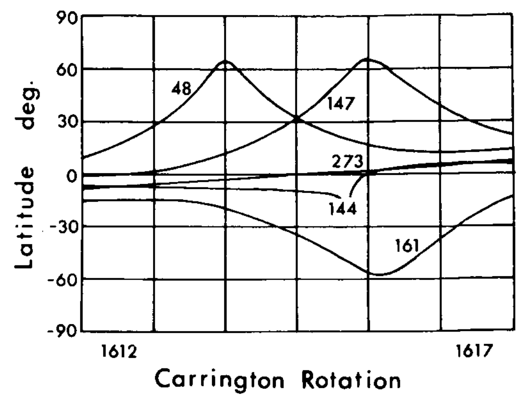

Figure 2. The latitude-longitude tracks of the point P during six rotations in 1974.

description of the large-scale slowly varying wind structure in three dimensions is available from our observations, covering 1972 to 1982.

Each observation provides a wind speed estimate characteristic of the point P whose heliographic coordinates vary as the earth moves round the sun and the sun rotates. For a given radio source the latitude changes systematically through the calendar year. The distribution of good scintillators in the sky gives our best latitude coverage in the north and south during March to August each year, as shown in Figure 2 for 1974. Here the latitude and longitude of point P mapped to the sun at 400km/s are displayed for six Carrington rotations. In order to study the shape of solar wind structures we have mapped each observation from P to the sun along a spiral assuming constant radial velocity equal to the observed value. Thus each observation gives an estimate of the wind speed at a point on the effective source surface beyond which the plasma flow is radial. See Sime and Rickett (1978) for a discussion of the limitations of such mapping. Since for a single rotation the coverage in latitude and longitude is rather sparse, we average the data for periods of six or twelve months.

The general picture that has emerged from our observations is that the polar regions of the sun are the source of long-lived fast streams through much of the solar cycle. This is seen in plots of the average wind speed against solar latitude both to the north and south (see Figure 1 of Coles et al. 1980). In Figure 3 we show such plots for the years from 1972 to 1982. These show the fast polar streams as elevated average speeds at high latitudes and a U-shaped dip to lower speeds in the ecliptic. Throughout declining solar activity (1972-75) the fast polar streams were a persistent feature, but were sometimes tilted from the poles and intercepted the ecliptic; this is seen as a wider U-shape and elevated speeds in the ecliptic. At solar minimum (1976) the fast polar streams were centered on the rotation axis and were wide, extending down to latitudes of 30 deg N and S. Through solar maximum (1978-81) they disappeared and only with current decline of solar activity (1982) have they started to reappear.

It is clear that this pattern of evolution matches that of the polar coronal holes, which persist through most of the cycle but close off during solar maximum while the dipolar fields reverse. We can examine the structure of

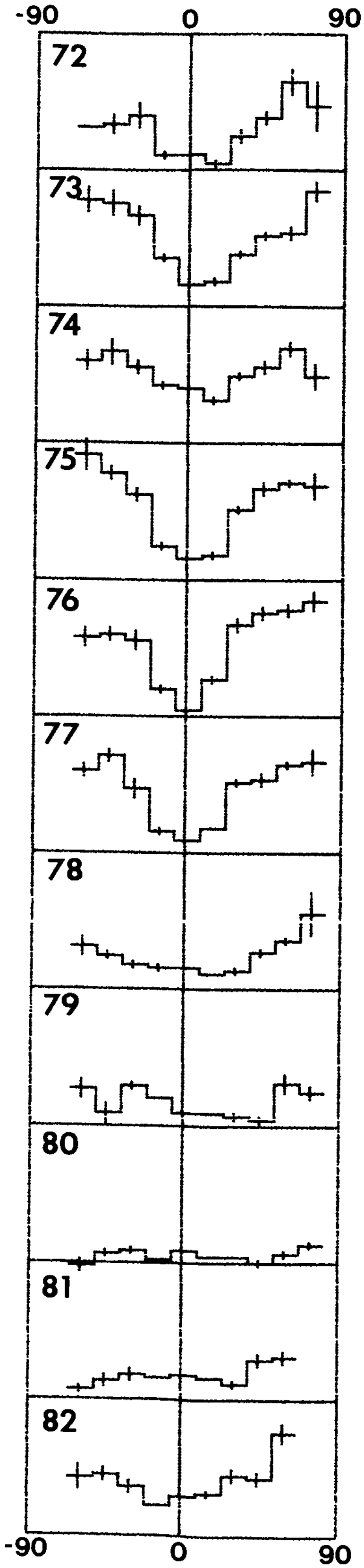

Figure 3. Annual averages of solar wind speed versus latitude in 15 degrees bins. The horizontal lines are at 300 km/s and 600 km/s. Vertical bars are $\pm 2\sigma$ in the mean.

the polar streams in more detail by studying the velocities averaged over several rotations into a longitude and latitude map. Figure 4 shows averages over seven Carrington rotations centered on the March to August interval for each of the even years from 1972 to 1982. The average wind speed in 15x15 degree bins is displayed in the left hand panel by five shades of grey (250-349km/s as light shading, up to over 650 km/s as black, with white indicating no data). The middle panel shows the coronal electron density in similar format estimated from the HAO white light coronameter (Mark II data supplied by D. Sime 1972-78 and Mark III data supplied by R. Fisher 1980-82 (they come from $1.5R_o$ and $1.7R_o$ from solar center, respectively). Regions of low density are white ($<1.510^{-8}$ pB) and represent the large coronal holes; particularly clear are those over the poles which correspond to the regions of fast solar wind (polar streams). For 1976-80 the right hand panels show the coronal magnetic field for a single rotation at the center of each seven rotation average. These data are the magnitude of the radial magnetic field at a source surface assumed to be at $2.2R_o$, derived from a potential field model fitted to the line-of-sight surface field measured at the Stanford solar observatory and supplied by J. Wilcox. Darker shading corresponds to stronger radial fields; the light band marks the neutral sheet separating positive and negative fields.

The polar streams can be seen as generally faster wind speeds at the top and bottom of each map. In 1974, however, they were centered about 30 degrees from the poles and so were seen as two fast streams per rotation by ecliptic spacecraft. Note also how the band of slow wind corresponds well with the band of high density, which separated coronal magnetic fields of opposite polarities. The data for 1973 are similar in form though the streams were at different longitudes and in 1973 the

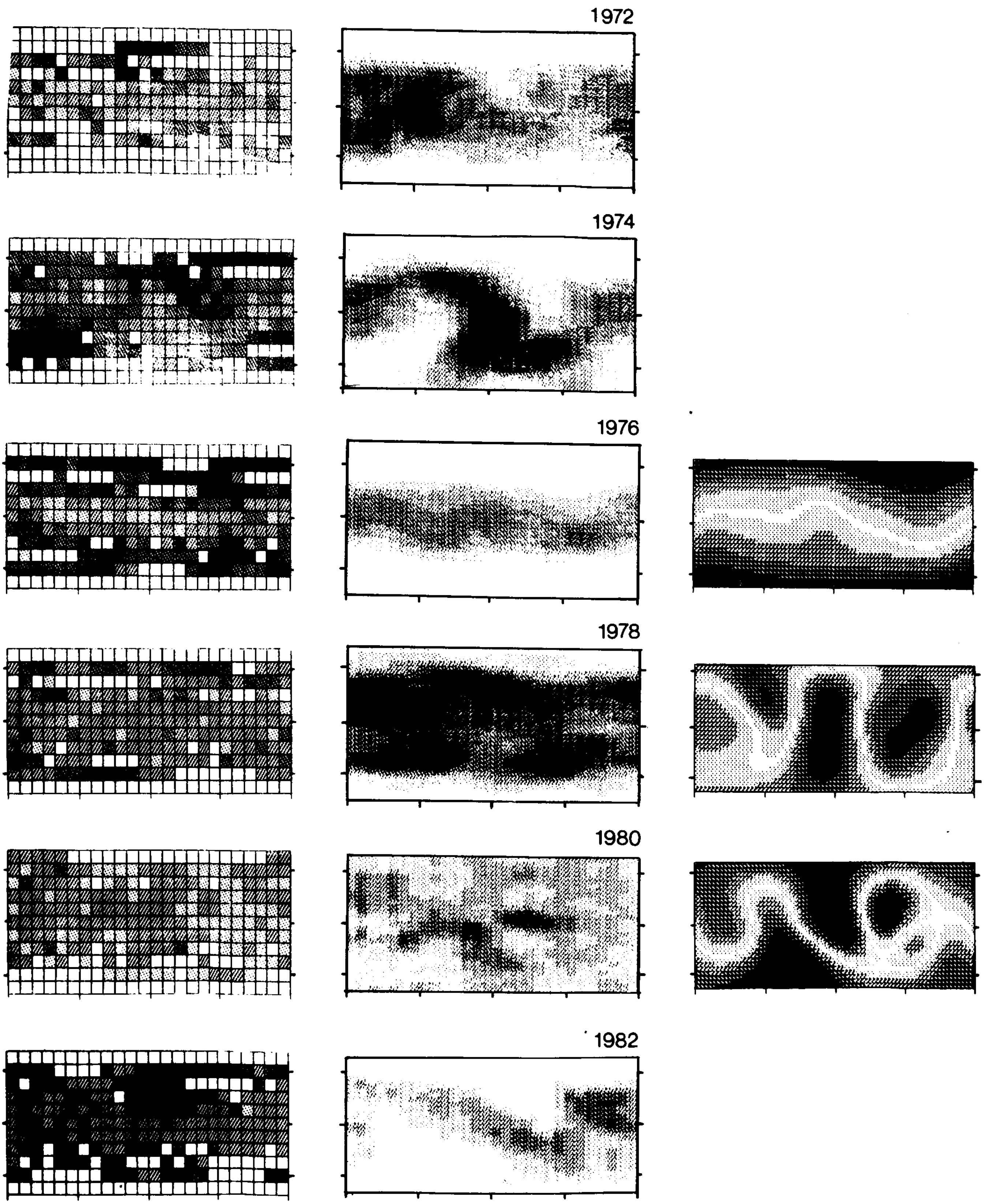
1972
1974
1976
1978
1980
1982

Figure 4. Left panels show solar wind speed as synoptic maps. Ticks on the vertical scale are at 60 degree intervals of latitude, on the horizontal scale are at 90 degree intervals of longitude. IPS data are averaged over six rotations. Fast is dark, slow is light, no data is blank. Middle panels show coronal electron density; dense is dark, holes are white. Right panels show coronal radial magnetic field magnitude; strong fields are dark, neutral sheet is white. Details are in the text.

southern stream was much wider than the northern one. The map for 1975 showed almost no change from 1974. In 1976 (solar minimum) the data show a narrow straight band of slow speeds along the solar equator, corresponding to wide fast streams which were well centered on the poles. For 1976 the small undulations in the current sheet match those in the locus of maximum density and would correspond to four magnetic sectors at the equator.

The first sunspots of the new cycle were seen at the end of 1977, and at the same time our IPS observations showed the north polar stream started to contract. The 1978 maps show that north and south polar streams had both contracted; slow wind extended to at least 60 degrees and also dense corona and

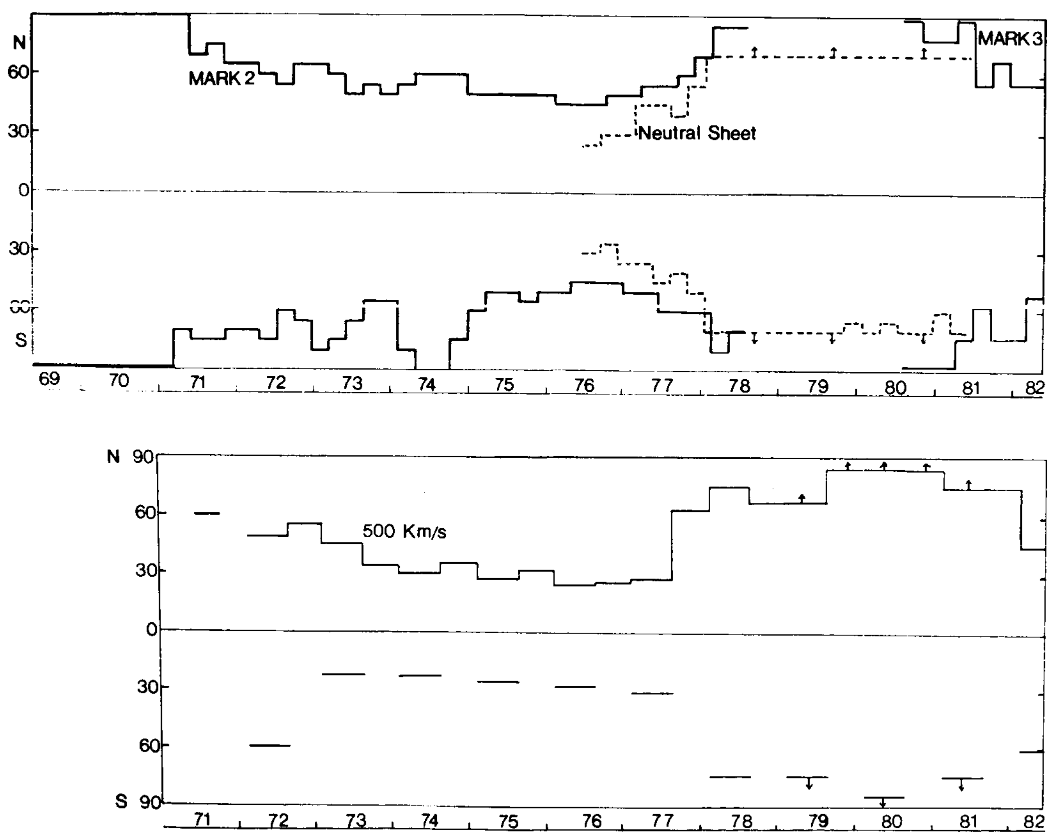

Figure 5. Upper panel shows six-month average boundary in latitude of the polar coronal holes from Mark II and III coronagraph data. Also shown are the extreme latitudes of the neutral sheet in an average magnetic field map over the same intervals. Lower panel shows the 500 km/s contour of six-month average speed, denoting the boundaries of the fast polar streams. Data from the south were only available once per year.

the neutral sheet extended to similar latitudes. Such (solar maximum) conditions persisted from 1978 to 1981, as typified by the 1980 maps. These show low velocities and high density at all latitudes and a complex neutral sheet with extensions to all latitudes. However the details of the neutral sheet are not easily traced in the density or velocity plots. The velocity map also shows a large region of slow wind (average speed less than 350 km/s at longitudes 250-330). This covered north and south latitudes and must have persisted over many rotations. There is no obvious corresponding feature in density but the neutral sheet shows an unusual tube structure separated from the main band of the sheet. It seems that the average wind speed from this complex magnetic topology is slower than from the rest of the sun.

The speed map for 1982 shows clear-cut regions of the fast polar streams and indeed, faster average speeds at all latitudes. The polar streams are again tilted away from the axis by more than 30 degrees at a longitude close to that of 1974. The density data also reveal a substantial change from 1980-81, showing large north and south polar coronal holes with equatorial extensions at the same longitudes as the polar streams. Spacecraft observations near the earth will presumably show two streams per rotation in this period.

Figure 5 summarizes the results for a solar cycle by displaying the 500 km/s contour of six-month average speed in latitude versus year. This represents the typical boundary of the polar streams and should be compared with the density contour chosen to represent the typical boundary of the polar holes, which is shown together with the highest latitude reached by the neutral sheet determined from the Stanford solar fields.

In summary, we note that in contrast to the equatorial solar wind the polar wind shows a very clear variation with solar cycle; it is slow when solar activity is high, and fast as activity declines or is low. The polar conditions are seen in the ecliptic when the fast polar stream becomes tilted from the axis, as tends to happen in the declining phase. The solar maximum observations show no large coronal holes and uniformly low velocities all over the sun. This clearly contradicts the view that all of the solar wind originates from large coronal holes (e.g., Hundhausen, 1977, page 295). The source of the wind must include open field regions which are not part of large coronal holes. At solar maximum we identified a persistent slow speed stream originating above a closed tube in the neutral sheet. Our conclusions affirm the close relation between the large coronal hole structures and high-speed solar wind, and inversely, between dense closed-field regions and slow speed solar wind.

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