Supporting Online Material

1. Open magnetic flux vs. latitude at solar minimum and maximum.

Figure S1 addresses two major issues: the dependence of the open flux, $B_T r^2$, on latitude and possible changes between solar minimum and maximum (1). At minimum, single polarities are present at high latitudes. The open flux is clearly independent of latitude with essentially the same means (right column) in the north and south hemispheres. At maximum, because the current sheet is highly inclined, both sectors are present at almost all latitudes (2). A gap appears in the north polar cap where only one polarity is observed. The means are more variable because of increased solar activity but are consistent with the open flux being independent of latitude in both phases of the solar cycle. Furthermore, the means are essentially the same at minimum and maximum in spite of the dramatic reconfiguration that takes place in the solar magnetic field.

The latitude independence of $B_T r^2$ during minimum is interpreted as indicating that excess magnetic pressure near the sun’s poles, because of the stronger fields there, forces the solar wind to lower latitudes (3, 4). Eventually, equilibrium is reached with the magnetic flux uniformly distributed and the elimination of the latitude gradient in the magnetic field strength. The field-induced non-radial flow is estimated to be complete within a few solar radii and outside this distance the solar wind flow is radial. The low latitudes reached by the fast solar wind, while the polar coronal holes are confined to high latitudes, is the result of this over-expansion.
The absence of a latitude dependence of flux at maximum indicates that the solar wind flow near the sun is also non-radial even though the sources are at low latitude and distributed over more of the solar disc (2). Excess magnetic pressure at the equivalent low latitude magnetic poles and the resulting over-expansion explains why low latitude field lines can reach high latitudes. The heliospheric current sheet separates field lines from near-equatorial magnetic poles having opposite polarities just as at solar minimum. Since the HCS is highly inclined, fields adjacent to the current sheet reach high latitudes including the polar caps.

The average values of \( B_r r^2 \) are approximately the same at minimum and maximum in spite of a large increase in the total solar flux that becomes an order of magnitude larger than the open flux. A recent theory proposes that the open flux is invariant or quasi-invariant (5). An important consequence of the absence of a latitude gradient is that the measurements at any latitude can be converted to the total open flux from the sun by simply multiplying \( B_r r^2 \) by \( 4\pi \) (3). Thus, the solar cycle variation in open flux can be studied using only in-ecliptic measurements of \( B_r \) dating back to 1965 (1, 6). These measurements show that the open flux varied by much less than a factor of two in two of the four recent sunspot cycles and varied only slightly during the solar maximum of 1970. Therefore, the invariance seen at Ulysses may be a feature of the present cycle. Alternatively, a time variation may still appear as the present cycle continues. The changes in two of the cycles tended to occur after the polar cap reversals and the open flux may subsequently be found to increase along with the polar cap field. Nevertheless, the relative constancy of the open flux is likely to be an
important constraint on the on-going redistribution of flux between low and high latitudes during the solar cycle as described below.

2. Properties of the heliospheric magnetic field source dipole.

Magnetic flux, $\Phi$, is equivalent to pole strength, $p$, the two being related by $\Phi = 4\pi p$. Since the open flux of one sign of the HMF is equal to $2\pi B_r r^2$, $p = B_r r^2 / 2$. A value of $B_r r^2 = 3 \text{nT} (\text{AU})^2$ (Fig.S1) is equivalent to $6.75 \times 10^{13} \text{Wb}$ and $p$ to $3.38 \times 10^{13} \text{Wb}$ (or $3.38 \times 10^{21} \text{Mx}$, the unit preferred by solar physicists). If the two poles lie on a “source surface” located at 2.5 solar radii, $r_S$, the dipole moment becomes $m = 5 r_S p = 1.18 \times 10^{23} \text{T m}^3$ (or $1.18 \times 10^{33} \text{gauss cm}^3$). This derivation leads to reasonable values of all the parameters, e.g., the photospheric field at the pole is $6.9 \times 10^{-4} \text{T}$ (6.9 gauss).

The latitude and longitude of the magnetic poles are obtained, in principle, from the shape of the heliospheric current sheet. The longitudes of the poles are obtainable from the sector structure, i.e., the longitudes at the midpoint of each sector. The latitudes of the poles are given by the inclination of the current sheet or, equivalently, by its maximum latitudinal extent. The inclination or maximum latitude can be derived from several sources: observations above or below the solar equator by spacecraft or Earth in its motion around the sun, extrapolation of observed photospheric magnetic fields to a “source surface” followed by determination of the neutral line separating inward and outward fields (7, 8), or correlation with another parameter such as sunspot number.
For any given solar rotation, it may not be possible to determine all three parameters of the source dipole accurately because of distortions in the shape of the current sheet caused by low latitude coronal holes or active regions. However, the above discussion illustrates how a simple source dipole can account for the basic properties of the observed heliospheric field.

3. Relation of HMF source dipole to the solar field.

The solar cycle change in the HMF can be construed as a gradual rotation of the source dipole from an axial to an equatorial orientation, continuing toward the opposite heliographic pole thereby accounting for the changed polarities in the polar caps. This simplistic model is referred to as a “rotating dipole” (9).

Of course, the changes in the solar magnetic field are actually more complicated than a simple rotating dipole. Taken seriously, the model implies that the magnetic poles rotate from the polar caps along the sun’s surface toward the equator and then into the opposite hemisphere. In fact, the polar cap fields disappear and then reappear with the opposite signs. Furthermore, the low latitude magnetic poles have a separate origin and evolution.

The strong magnetic fields associated with sunspots develop into “unipolar magnetic regions”, equivalent to magnetic poles, having opposite polarities. The unipolar regions from the trailing or following sunspots have a polarity that is opposite to the polar cap fields. They gradually drift pole ward and, because they have the opposite polarity, erode the polar cap fields causing them to disappear. As more unipolar regions continue to arrive, they reestablish the polar caps but with the reversed polarity. During the descending phase of solar activity, unipolar regions continue to arrive
strengthening the polar cap fields while the sunspots and active regions at low latitudes are decaying. This evolution leads to the dominance of the polar cap fields and axial dipole at solar minimum. This phenomenological description is referred to as the Babcock-Leighton model (10). Wang and Sheeley (11) have recently simulated essential features of the model.

The correspondence between the “rotating dipole” and the solar field is undoubtedly due to the sun having a significant dipole component at all times. At minimum, this component is associated with the strong polar cap fields. At maximum, the dipole component is the resultant of several low latitude magnetic poles (unipolar regions) containing open fields. At the onset of solar maximum, the strong equatorial fields cause an increasingly large equatorial dipole just as the axial dipole begins to decay. The resultant dipole that produces the HMF then begins its rotation away from the sun’s poles toward the equator as observed.

4. Solar cycle variation of interstellar dust.

Interstellar dust was detected first by Ulysses (12, 13). The dust enters the heliosphere with the same velocity as neutral interstellar gas. The incoming flux is expected to remain constant but, inside the heliosphere, the sun’s gravitational field, solar radiation pressure and, since the dust is electrically charged, the HMF exert forces on the dust. The more massive grains are affected by gravity and radiation pressure but the motion of the low mass interstellar dust is dominated by the magnetic force.

Theory indicates that changes in the HMF causes a solar cycle variation in the dust distribution (14). The dust is deflected toward higher latitudes (defocused) when the polar cap field is outward in the north hemisphere and the dust is deflected equator-ward (focused), when the north
polarity is inward. The modulation also depends on the inclination of the HCS. Ulysses measurements address the questions: Is the dust flux modulated by the solar cycle? What changes in the HMF are important?

The flux does change significantly with the solar cycle (Fig. S2). In 1996, near minimum, the interstellar grains began a slow decrease that continued until near maximum (2000) when the flux leveled off and began to increase. A model that includes changes in the field polarity and the inclination of the solar dipole reproduces the observations qualitatively. The model predictions for several different size grains are shown.

An important factor relating the observations to the model is the speed of the dust, which is much smaller than the solar wind speed. Field changes at the sun reach the dust in the outer heliosphere in a year or less but the dust does not reach the inner heliosphere until much later. The decrease near minimum in 1995-1996 is consistent with the polarity reversal (to defocusing) in 1990. The subsequent recovery near 2000 coincides with the minimum current sheet inclination in 1995. Thus, the decrease and recovery sun are delayed by 5 to 6 years.

The model does not explain the recent recovery of the flux to a high level. Improvements to the model are apparently needed such as a more realistic magnetic field model and alterations to the size and electrical charge of the dust. However, the Ulysses results are an important contribution to understanding the distribution of dust inside the Heliosphere and its time variations.


Coronal Mass Ejections are best imaged when they occur near the limb of the sun because the corona is optically “thin” and structures at
essentially all longitudes can contribute to a coronal image. In May 2001, Ulysses was positioned off the west limb of the sun, 90° away from the Sun-Earth line, an ideal location in which to compare in-situ observations with coronal images of a CME. Fortunately, a large mass ejection occurred on Day 127 (May 7) headed in the direction of Ulysses. Images of the event obtained by the Solar Heliospheric Observatory (SOHO) are shown in the top four panels of Figure S2. The two left panels show the corona before the eruption with many streamers located at a variety latitudes (or position angles). The contrasting two right-hand panels show the CME as it leaves the Sun’s limb at about “three o’clock”. It is brighter near the Sun (panel 3) because it expands rapidly as it travels outward.

The bottom five panels show how various heliospheric constituents react to the event. The upper panel contains electric fields measured over a broad range of frequencies between 1 kHz (in the plasma wave regime) and 1 MHz (radio frequency regime) (15). Field strength is color coded with red corresponding to the strongest signals. Among the many burst-like signals, four are related to the CME. Shortly after the CME was imaged near noon on Day 127, two strong descending tones occurred. These signals, classified by radio astronomers as type III bursts, are attributed to waves emitted by energetic electrons traveling outward along the HMF at much higher speeds than the CME. The radio waves propagate directly to the spacecraft and are seen soon after the event at the sun. The upper quarter panel shows another (green-yellow, Type II) burst that begins shortly after the Type IIIIs and whose frequency declines gradually until the CME and its shock arrive at Ulysses (beginning of Day 130). Type II bursts are radio waves emitted by electrons in the immediate vicinity of the shock as they travel along with it. Their observation allows shocks to be tracked from the sun to the spacecraft.
and provide a measure of the shock speed. The fourth set of signals is observed when the shock and CME arrive. The upper band contains locally-generated Electron Plasma Emissions whose time dependence mimics the variations in the solar wind density in the panel just below it. The strong fields extending down to the lowest frequencies are also produced by the shock and are electrostatic Ion Plasma Oscillations and electromagnetic Whistler Mode Waves.

The arrival of the shock is apparent in the solar wind density, velocity and magnetic field magnitude as an abrupt jump. This event is strong with a large increase in velocity of several hundred km/sec and an unusually high density ($\approx 100 \, \text{cm}^{-3}$) and field strength ($\approx 30 \, \text{nT}$) behind the shock. The decline from very high to very low density and the accompanying monotonic decrease in speed identify the CME material or ejecta. It has expanded from a structure comparable in size to the sun (upper panels) to one lasting several days and extending over a large fraction of an astronomical unit. The average shock speed from the sun to Ulysses is 940 km/sec while the speed at arrival (derived from B and V upstream and downstream) is close to 700 km/sec. A deceleration of the CME and shock as they propagate through the slower-moving solar wind is commonly observed.

The flux of energetic particles (protons with energies $< 7 \, \text{MeV}$) accelerated by the shock is in the bottom panel. It is customary for energetic particles to be seen well upstream and downstream of the shock (which they can outrun because of their high speeds). The particles are kept in the vicinity of the CME by irregularities in the magnetic field that scatter them back and forth across the shock as it propagates outward. A maximum in intensity is often seen at the shock rather than the decrease as seen here.
Since the field lines behind the shock intersect it further upstream, more efficient acceleration must be occurring at other locations rather than locally.


For Solar Energetic Particles (SEPs) accelerated in very large events, there is typically a very high correlation between particles observed near the equator and by Ulysses over the poles. Simultaneous measurements in the ecliptic plane and at Ulysses reveal events that they are remarkably similar at both observing points, particularly during their decay phases when the intensities are declining. Figure S4 shows examples for 175-315 keV SEP electrons when Ulysses was in both the north and south polar caps. Very similar behavior is observed for protons at energies from a few MeV up to about 100 MeV. In spite of large separations in latitude, longitude and radial distance the intensities during the decay become almost equal at Ulysses and near Earth. This absence of spatial gradients implies that these particles fill the inner heliosphere to form a large “reservoir” from which they slowly escape.

The existence of particles at high latitudes and the disappearance of spatial gradients may be attributable to a combination of effects, the pole-ward spreading of field lines from the low latitude coronal holes and active regions, the efficient diffusion of particles across field lines from low to high latitudes and in longitude, and the extension of CMEs across wide ranges of latitude and longitude. However a full explanation has not been achieved.

REFERENCES

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FIGURE CAPTIONS

Figure S1. Open magnetic flux.

The data are values of $B_r r^2$ in outward (positive) and inward (negative) sectors averaged over successive solar rotations. Vertical bars show the standard error associated with each average. The means and standard deviations of the averages appear in the right-hand column. The solid lines are means over the four transits between equator and pole.

Figure S2. Solar cycle variation in interstellar dust compared with a model.

The temporal variation of the interstellar dust flux at the location of Ulysses is compared with a computer simulation (red: 0.2 micrometer dust grains; green: 0.3 micrometer grains; crosses: Ulysses measurements). The decrease in flux after 1996 is the result of a defocusing that began in 1990. The recovery is correlated with the low inclination of the HCS in 1995 and not, as might be supposed, with the current solar maximum.

Figure S3. A large solar eruption and Coronal Mass Ejection.

The four solar images were taken by SOHO before and during a large Coronal Mass Ejection. A dynamic spectrum (frequency and amplitude versus time) of radio and plasma waves between 1 and 103 kHz is the next lower panel followed by solar wind density, speed, magnetic field strength and the intensity of energetic particles. The CME causes characteristic changes in the plasma and magnetic field and is accompanied by radio waves and a shock wave that accelerates the energetic particles.
Figure S4. Solar Energetic Particles: the Reservoir

The left (right) panel contains electron fluxes in the south (north) polar cap. One set of data (gray) was recorded in the ecliptic at 1 AU by the ACE spacecraft (located in the ecliptic plane upstream of Earth) and the other set (black) is Ulysses data. The position of Ulysses in radial distance, longitude and latitude appears just below the horizontal (time) axis. There is a close correspondence between events at the two spacecraft in spite of large differences in the latitudes and longitudes. The largest events rise rapidly but decay very slowly over tens of days when the intensities at the two spacecraft are almost identical.
SOLAR MAXIMUM

- INWARD Mean -3.48 St Dev 0.75
- OUTWARD Mean 3.27 St Dev 0.91

SOLAR MINIMUM

- INWARD Mean -3.30 St Dev 0.32
- OUTWARD Mean 3.03 St Dev 0.27