

## Source regions of solar wind disappearance events

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[1] During the period 1999–2002 there have been three instances, in May 1999, March 2002, and May 2002, respectively, when the solar wind densities at 1 AU dropped to abnormally low values ( $<0.1 \text{ cm}^{-3}$ ) for extended periods of time (12–24 h). These long-lasting low-density anomalies observed at 1 AU are referred to as “solar wind disappearance events” and in this paper, we locate the solar sources of the two disappearance events in March and May 2002 and show that like the well-studied disappearance event of 11 May 1999, these events too originate in active region complexes located at central meridian and are characterized by highly nonradial solar wind outflows. We also show that during disappearance events, the interplanetary magnetic field is stable and unipolar and the associated solar wind outflows have extended Alfvén radii. Using the fact that solar wind flows from active regions have higher ratios of  $\text{O}^{7+}/\text{O}^{6+}$  than wind from coronal holes, we try to pinpoint the solar sources of these very unusual and rare events and show that they represent the dynamic evolution of either active region open fields or small coronal hole boundaries embedded in or near large active region complexes located at or close to central meridian.

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### 1. Introduction

[2] The magnetic field in the heliosphere evolves in response to the solar photospheric field at its base. This evolution, together with the rotation of the Sun, drives space weather through the continually changing conditions of the solar wind and the magnetic field embedded within it. Given this broad framework, it appears that the solar sources of interplanetary disturbances that travel outward from the Sun could be due to many causes. Although the majority of them could be due to CMEs, there are many instances where they may have been caused by flare related events or coronal hole outflows. It is apparent that all these phenomena are linked to the underlying disturbances in the magnetic field and that they manifest in different ways depending on the local conditions on the Sun.

[3] The solar wind at 1 AU is known to be strongly supersonic and super Alfvénic with Mach and Alfvén numbers being on average 12 and 9, respectively. However, during these so called “solar wind disappearance events,” the Earth is engulfed by extremely low-density solar wind flows, which typically last between 12 and 24 h. As a

consequence, there is a dramatic expansion of the Earth’s magnetosphere and bow shock. In the case of the well-known disappearance event of 11 May 1999, the expanding bow shock, normally located at  $\sim 10$  Earth radii, reached an upstream distance of nearly 60 Earth radii. The extremely spectacular nature of the solar wind disappearance event of 11 May 1999 has caused it to be one of the most extensively studied and reported solar wind related events in recent times. Many studies have been reported using both space based and ground based instrumentation that have tried to understand the true nature of this unique and unusual solar wind outflow of 11 May 1999 [Crooker *et al.*, 2000; Farrugia *et al.*, 2000; Richardson *et al.*, 2000; Usmanov *et al.*, 2000; Vats *et al.*, 2001; Balasubramanian *et al.*, 2003; Janardhan *et al.*, 2005]. However, only one of these studies [Janardhan *et al.*, 2005] has led to any firm conclusions about the solar source of this disappearance event.

### 2. Solar Wind Disappearance Events

[4] Using the OMNI and ACE spacecraft data base from 1962 to 2002, Usmanov *et al.* [2003] looked for those events that had densities  $\leq 0.4 \text{ cm}^{-3}$  and found a total of 18 such events. Of the 18 events, seven were found to have minimum density values of  $\leq 0.2 \text{ cm}^{-3}$  and of the seven events, three took place in cycle 23. Table 1 lists these three events from Usmanov *et al.* [2003]. It can be seen from Table 1 that the Alfvén Mach numbers (last column) are all significantly less than 1.

[5] In the study by Janardhan *et al.* [2005], the authors have carried out the complicated process of tracing the solar wind outflows back to the Sun and showed that the solar source was possibly a small coronal hole located close to the

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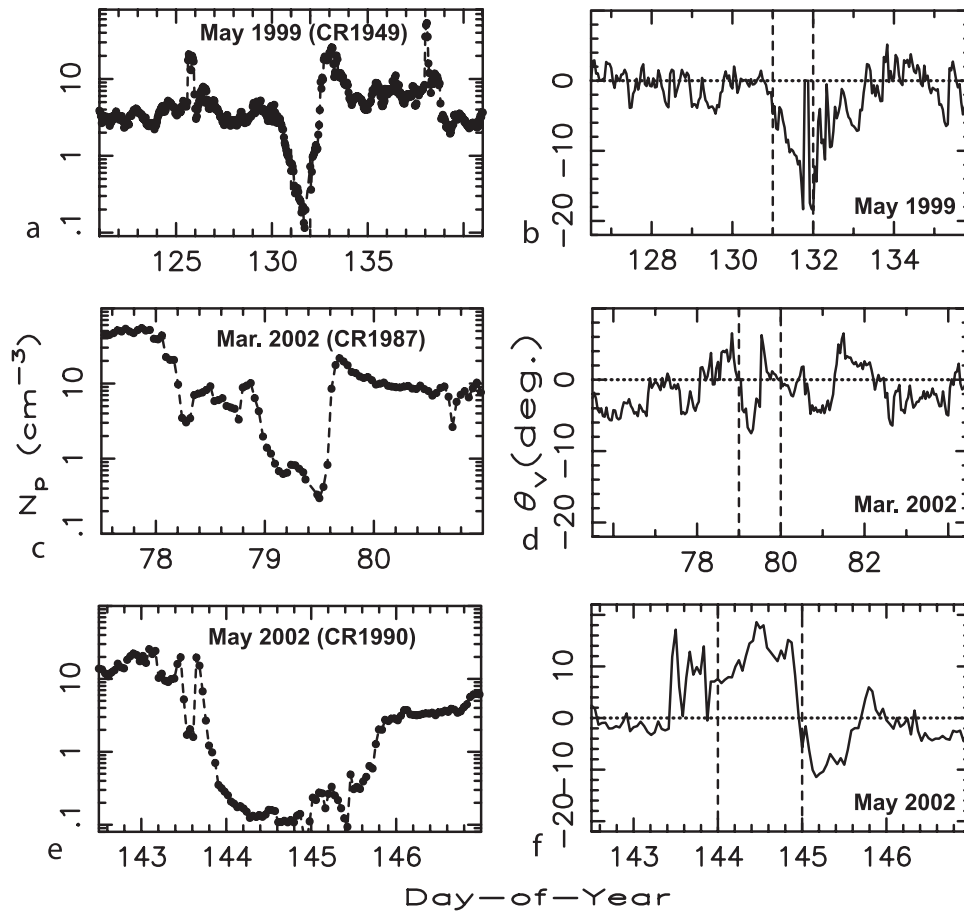
**Table 1.** Three Disappearance Events in Cycle 23 Which Had Minimum Densities Dropping Below  $0.2 \text{ cm}^{-3}$ <sup>a</sup>

Date	Day of Year (DOY)	$\rho_{\text{min}}, \text{cm}^{-3}$	Alfvén Mach Number
11-05-99	131	0.02	0.41
20-03-02	79	0.14	0.50
24-05-02	144	0.07	0.54

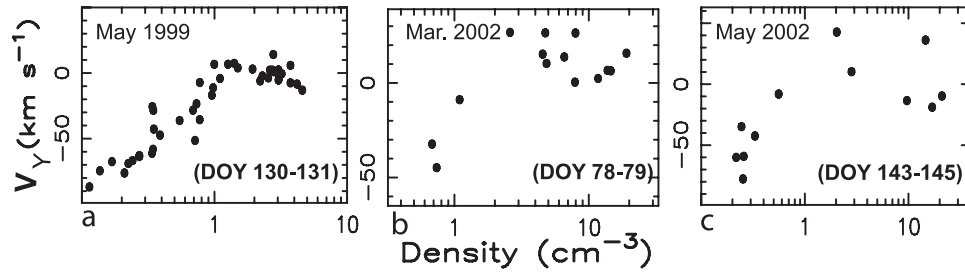
<sup>a</sup>Columns 1 through 4 are the date, day of year, minimum density values, and Alfvén Mach numbers, respectively.

large active region complex AR8525 in Carrington rotation 1949, that was located at central meridian when the flows began. Their work has also shown that the solar wind flows responsible for the 11 May 1999 event were highly non-radial and associated with stable and unipolar interplanetary magnetic fields. Furthermore, the Alfvén radius ( $R_A$ ), (the radial distance out to which the solar wind corotates with the Sun) which is a function of both the density and the magnetic field, was found to move outward significantly. It is therefore interesting to compare the 11 May 1999 event with the two events in March and May 2002, respectively. Figure 1 (left) shows, by filled circles joined by a dashed

line, hourly averages of ACE spacecraft measurements (at 1 AU) of proton density as a function of day-of-year (DOY) for the May 1999 (Figure 1a), March 2002 (Figure 1c), and the May 2002 event (Figure 1e), respectively. Figure 1 (right) shows, by a solid line, the deviation from the radial flow direction of the solar wind as a function of DOY for the May 1999 (Figure 1b), March 2002 (Figure 1d), and the May 2002 event (Figure 1f), respectively. The two dashed, vertically oriented parallel lines on the right demarcate the event days (see Table 1) DOY 131, in May 1999 (Figure 1b); DOY 79, in March 2002 (Figure 1d), and DOY 144, in May 2002 (Figure 1f), respectively. The dotted line at  $\theta_v = 0^\circ$  indicates the radial flow direction, with the negative sign indicating a westward deviation. It can be seen from Figure 1 (left) that for the event of May 1999 the densities continued to drop through the whole of DOY 131 and remained below  $1 \text{ particle cm}^{-3}$  for over 24 h. For the March 2002 event, the densities remained low for about half a day during DOY 79 before beginning to rise again while for the May 2002 event, the densities remained low for the whole of DOY 144. From Figure 1 (right) it is clear that for the entire duration that the densities remained low, the solar



**Figure 1.** Plots of proton density, measured by the ACE SWEPAM instrument at 1 AU as a function of DOY for the disappearance events of (a) May 1999, (c) March 2002, and (e) May 2002. The Carrington rotation in which the event occurred is also indicated. On the right is shown, by a solid line, the deviation from the radial flow direction of the solar wind as a function of DOY for the (b) May 1999, (d) March 2002, and (f) May 2002 event, respectively. The vertically oriented dashed parallel lines on the right demarcate the event dates, DOY 131 (Figure 1b), DOY 79 (Figure 1d), and DOY 144 (Figure 1f), while the dotted line at  $\theta_v = 0^\circ$  on the right indicate the radial flow direction.



**Figure 2.** Plots of hourly averages of the variation of proton density as a function of the azimuthal component of the solar wind velocity for the three disappearance events of (a) May 1999, (b) March 2002, and (c) May 2002. The negative values of  $V_y$  imply a westward flow direction in the azimuthal plane.

wind flows at 1 AU were highly nonradial. Figure 2 shows the variation of the azimuthal component of the solar wind velocity ( $V_y$ ), as a function of density for the disappearance events of May 1999 (Figure 2a), March 2002 (Figure 2b), and May 2002 (Figure 2c), respectively. The densities and velocities are hourly averages measured by the SWEPAM instrument on board the ACE spacecraft, with the negative values of  $V_y$  implying a westward flow deviation in the azimuthal plane. It is clear from Figure 2 that as the density decreases, the azimuthal or westward flow deviation of the solar wind increases. This anticorrelation is most apparent in the data of 11 May 1999. Given the fact that the magnetic field is constant, the Alfvén radius, normally a function of both the density and the magnetic field, would be a strong function of the density during the disappearance events. It is also clear from Figure 2 that the azimuthal component of the solar wind velocity went as high as  $\sim 100 \text{ km s}^{-1}$  for the disappearance event of May 1999 and it went to  $\sim 50 \text{ km s}^{-1}$  and  $\sim 80 \text{ km s}^{-1}$  for the two events of March 2002 and May 2002, respectively. If we therefore assume that this azimuthal velocity component ( $V_a$ ) was due to corotation of the solar wind out to a distance corresponding to the Alfvén radius, then  $R_A$  can be computed since  $R_A \Omega_\odot = V_a$  where,  $\Omega_\odot = 1.642 \times 10^{-4} \text{ deg s}^{-1}$  is the angular speed of the Sun. Thus  $R_A$  could extend outward from its normal location of  $\sim 0.05 \text{ AU}$  to as much as  $0.23 \text{ AU}$  for the May 1999 event and out to  $0.12 \text{ AU}$  and  $0.19 \text{ AU}$  for the events of March and May 2002, respectively. Thus  $R_A$  can extend outward by a factor of 2–5 during a disappearance event.

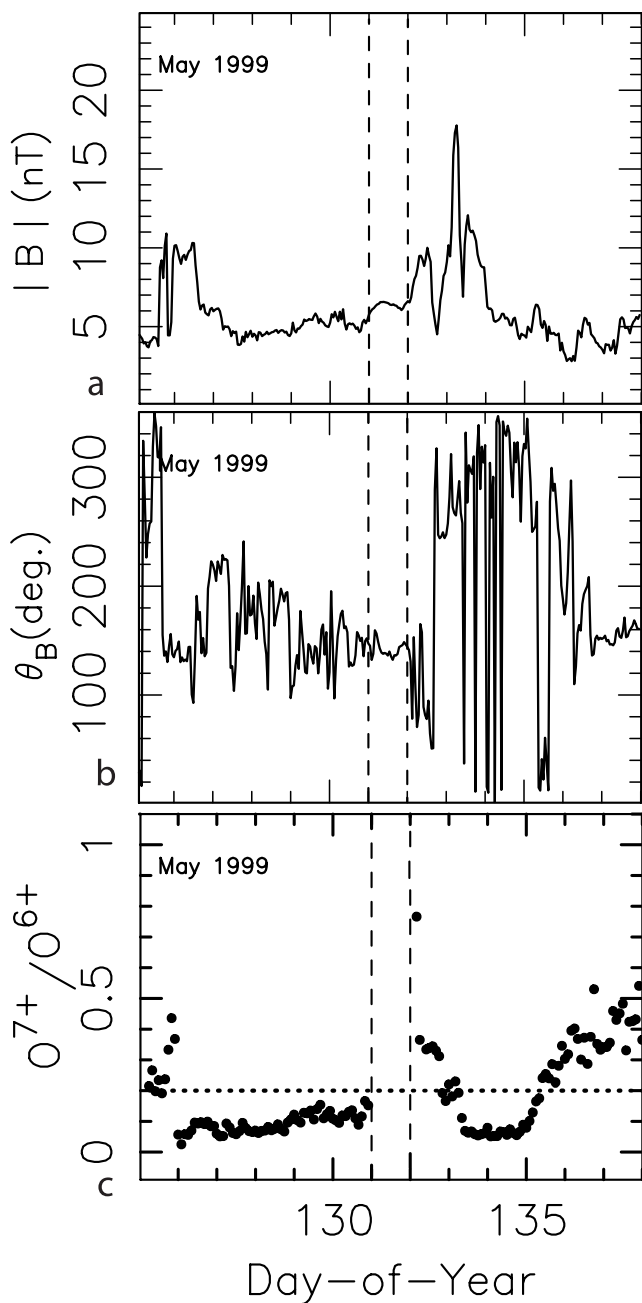
### 3. Disappearance Event of May 1999 Revisited

[6] Figure 3 shows as a function of DOY, the absolute magnitude of the magnetic field in nT (Figure 3a), the actual direction of the magnetic field in the ecliptic plane (Figure 3b), and the charge state ratio  $O^{7+}/O^{6+}$  (Figure 3c) for the event of 11 May 1999. The vertically oriented dashed parallel lines demarcate the event DOY, and the horizontal dotted line in Figure 3c is marked at  $O^{7+}/O^{6+} = 0.2$ . One can see that the field shows hardly any fluctuation during DOY 131 and remains constant. The direction of the magnetic field also remains unchanged, in contrast to other days when the direction of the field shows large and rapid changes. It must be noted here that in addition to the clear anticorrelation seen between azimuthal velocity and density (Figure 2), the magnetic field remaining constant and unchanged during DOY 131 provides additional support

for the fact that the Alfvén radius became strongly influenced by the density alone. Finally, the charge state ratio  $O^{7+}/O^{6+}$  is seen to remain well below 0.2 on all days between 5 and 10 May 1999. The lack of data points on 11 May 1999 probably imply that the extremely low densities do not produce a sufficient number of counts for reliable  $O^{7+}/O^{6+}$  measurements. A detailed study of solar wind outflows from active region sources and coronal holes has shown that solar wind from active regions have higher ratios of  $O^{7+}/O^{6+}$  than wind from coronal hole sources [Liewer *et al.*, 2004]. Wind from active region sources typically had the ratio  $O^{7+}/O^{6+} = 0.1\text{--}0.6$  while coronal hole wind typically had  $O^{7+}/O^{6+} < 0.2$ . As stated earlier, Janardhan *et al.* [2005] have traced the solar source of the 11 May 1999 event to an active region complex AR8525 and identified a small appropriately located coronal hole as the possible source of this event. From Figure 3 it is apparent that the low variance in the magnitude of the magnetic field (Figure 3a), the lack of change in the actual direction of the magnetic field (Figure 3b), and the  $O^{7+}/O^{6+}$  ratios  $< 0.2$  (Figure 3c) strongly support a coronal hole origin of the solar wind outflows responsible for the flows of 11 May 1999. However, it is important to bear in mind that earlier work by Kojima *et al.* [1999], Luhmann *et al.* [2002], and Arge *et al.* [2003] has shown that apart from coronal hole open fields, there is also solar wind coming from open flux in or near active regions. It has also been shown [Schrijver and Derosa, 2003] that at solar maximum  $\sim 40\%$  of the heliospheric open flux comes from active regions.

### 4. Disappearance Events of March and May 2002

[7] Figure 4 (top) shows, at 1 AU, the absolute magnitude of the interplanetary magnetic field (IMF) in nT as a function of DOY for the events of March 2002 (Figure 4a) and May 2002 (Figure 4b), respectively. Figure 4 (bottom) shows the actual direction of the magnetic field in the ecliptic plane ( $\theta_B$ ), as a function of DOY for the events of March 2002 (Figure 4c) and May 2002 (Figure 4d), respectively. The vertically oriented dashed parallel lines demarcate DOY 79 (Figure 4, left) and DOY 144 (Figure 4, right) for the disappearance events of March 2002 and May 2002, respectively. It can be seen from Figure 4 that the magnetic field shows a low variance, is stable through the first half of DOY 79 and drops gradually during the second half of DOY 79 for the event of March



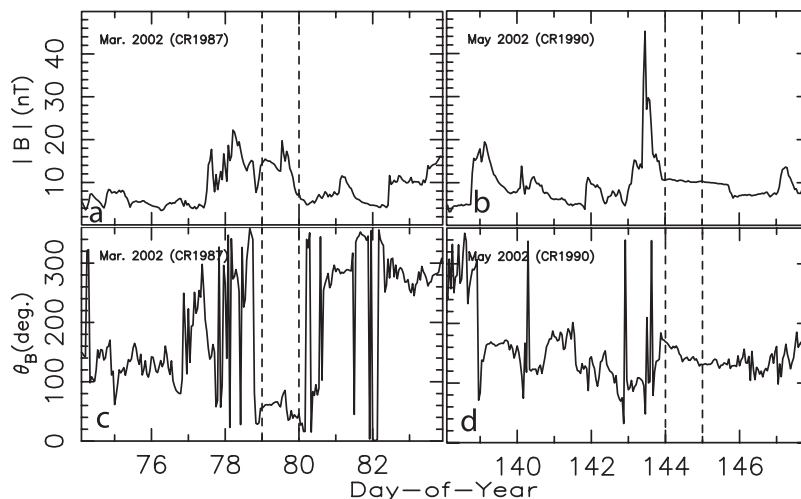
**Figure 3.** As a function of DOY, (a) the absolute magnitude of the magnetic field, (b) the actual direction of the magnetic field in the ecliptic plane, and (c) the charge state ratio  $O^{7+}/O^{6+}$  for the event of May 1999. The vertically oriented dashed parallel line demarcates the event date, DOY 131 and the finely dotted horizontal line in the Figure 3c is drawn at  $O^{7+}/O^{6+} = 0.2$ .

2002. The magnetic field however, remained unipolar throughout DOY 79. It may be noted that correspondingly, the densities remained low for about half a day during DOY 79 (Figure 1) before beginning to rise again for the event of March 2002. For the event of May 2002, the magnetic field remained stable and unipolar throughout DOY 144. Correspondingly, for the May 2002 event, the densities remained low for the whole of DOY 144.

[8] For the 11 May 1999 event, the work by *Janardhan et al.* [2005] has shown that when the Alfvén radius extends outward during a disappearance event, source locations determined by a traceback technique using constant velocities along Archimedean spirals do not have significant errors in spite of the solar wind flow being nonradial. Thus for the two events in March and May 2002, we have traced the observed ACE velocities back along Archimedean spirals to the source surface at  $2.5 R_{\odot}$  to determine their source locations. Figure 5 (top) shows hourly averages of solar wind velocities as observed by the SWEPAM instrument on board the ACE spacecraft as a function of DOY for the events of March 2002 (Figure 5a) and the same velocities traced back to the source surface at  $2.5 R_{\odot}$  (Figure 5b). Figure 5 (bottom) shows the ACE velocities for the May 2002 event (Figure 5c) and the velocities traced back to the source surface at  $2.5 R_{\odot}$  (Figure 5d). The vertically oriented dashed parallel lines demarcate the event DOY (Figure 5, left) and the corresponding traceback DOY (Figure 5, right).

#### 4.1. Active Region Locations

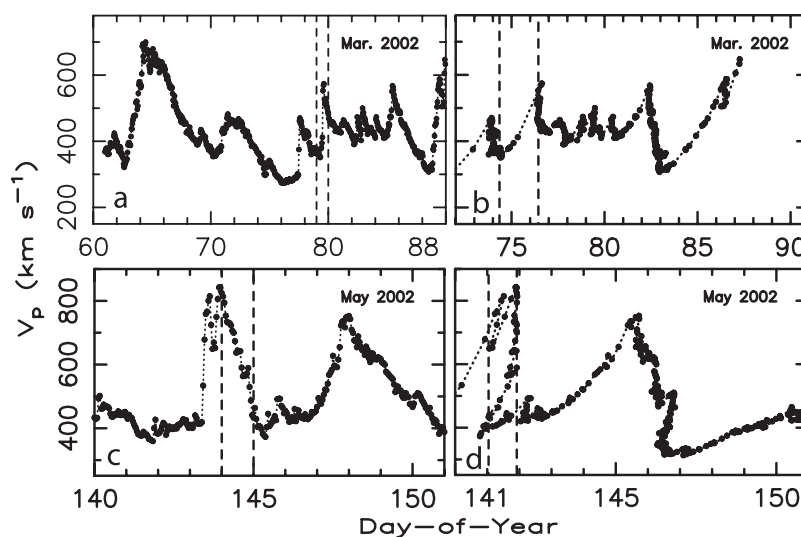
[9] Active regions on the Sun are often ignored as a source for the IMF at 1 AU. However, it has been shown in a detailed theoretical study, complemented with a potential-field-source-surface model for the coronal and inner-heliospheric magnetic fields, that solar wind outflows from active regions comprise  $\leq 10\%$  during solar minimum and up to 30–50% during solar maximum [*Schrijver and Derosa, 2003*]. This finding is in spite of the simplification that the authors made of a uniform, steady solar wind from the source surface outward into the heliosphere. The three disappearance events described here were traced back to the Sun using constant velocities along Archimedean spirals, and Figure 6 (left) shows maps of the solar photosphere corresponding to the traceback dates of the three events, namely, 5 May 1999 (DOY 125, Figure 6a); 15 March 2002 (DOY 74, Figure 6c); and 21 May 2002 (DOY 141, Figure 6e). Figure 6 (right) shows maps of the solar photosphere on the event days, namely, 11 May 1999 (DOY 131, Figure 6b); 20 March 2002 (DOY 79, Figure 6d); and 24 May 2002 (DOY 144, Figure 6f). The locations of the large active regions to the vicinity of which the solar wind flows were traced back are shown and AR8525, AR9866, and AR9957 have been emphasized and marked with an arrow in Figures 6a, 6c, and 6e, respectively. The same active regions are indicated on the event days in Figure 6 (right) and again emphasized and marked with an arrow. It is clear from Figure 6 that the back projected regions of the solar wind flows at 1 AU all originate in or near large active regions that are located close to central meridian when the solar wind flows began. It is instructive to note here, the correlation between the location of the active region at central meridian and the duration of the low velocities at 1 AU. From a comparison between Figure 1 (left) and Figure 6 we can see that for the May 2002 event, on DOY 141, when the low-density solar wind flows began, AR9957 was located  $\sim 12^{\circ}$  east of the central meridian. Thus Earth-directed flows from this region would continue for a longer duration as AR9957 would have been located east of the central meridian on DOY 141, almost exactly at central meridian on DOY 142 and  $\sim 12^{\circ}$  to



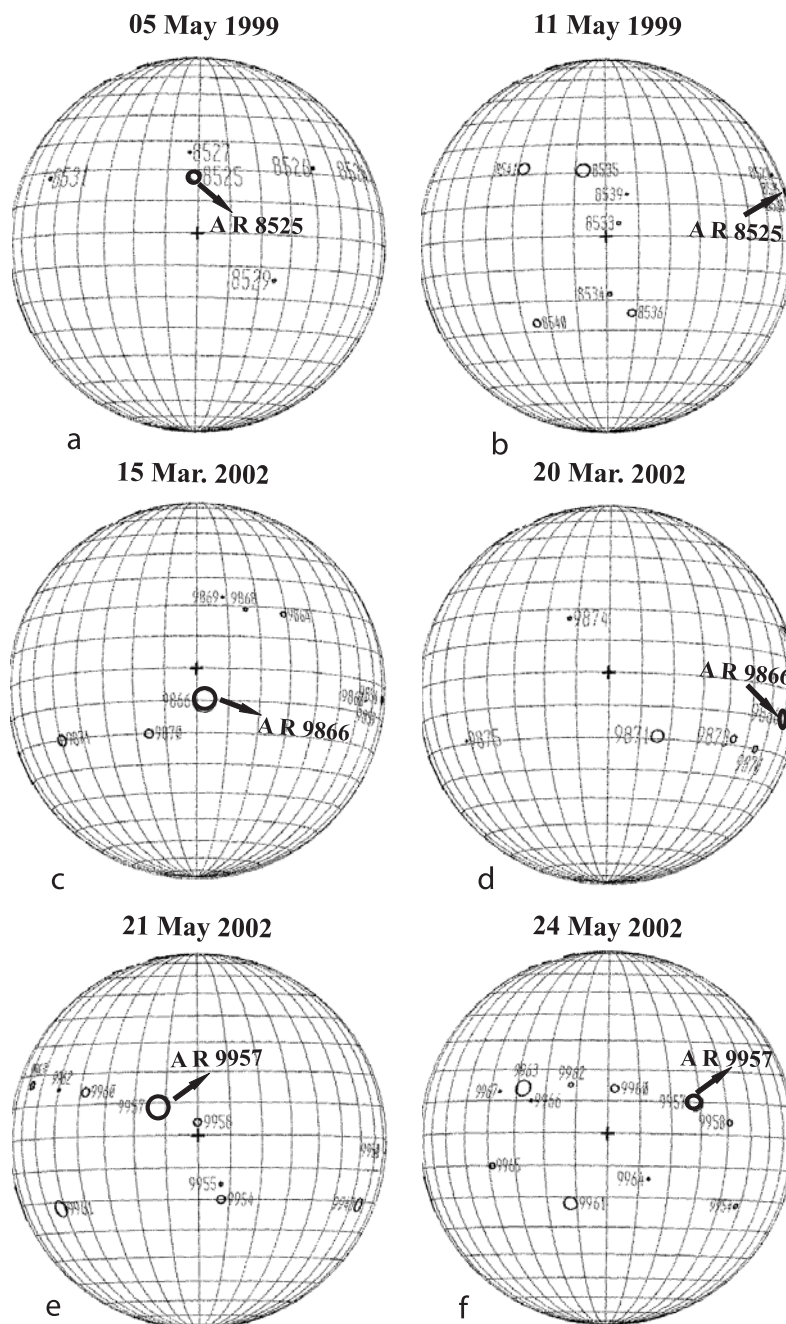
**Figure 4.** As a function of DOY, the absolute magnitude of the IMF in nT for the events of (a) March 2002 and (b) May 2002, respectively. The actual direction of the magnetic field in the ecliptic plane,  $\theta_B$ , is shown for the events of (c) March 2002 and (d) May 2002, respectively. The vertically oriented dashed parallel lines demarcate DOY 79 (left) and DOY 144 (right).

the west of central meridian on DOY 143. Thus AR9957 would have been close to central meridian, or in other words, ideally located for producing Earth directed flows, for a much longer period as compared to the other two events of May 1999 and March 2002. It is clear from Figures 1 and 6 that this is indeed the case with the low densities persisting for over 24 h for the event of May 2002 as compared to the March 2002 event for which the low densities last only for about half a day. For the March 2002 event, the source region is in the vicinity of AR9866 which is located a few degrees to the west of central meridian on DOY 75 when the low-density flows began.

[10] Since there are a large number of active regions on the solar disk around solar maximum, and since the trace-back errors are  $\sim 30^\circ$  [Janardhan *et al.*, 2005], the question arises as to whether the association of the back projected locations of the solar wind flows to large active regions at central meridian is a chance occurrence. This would be the case if, for example, there was a large active region located roughly every  $30^\circ$  on the solar disk. To rule out this possibility, we have rotated the solar disk by an additional  $\sim 30^\circ$  or, in other words, examined active region maps two days prior to each of the trace back dates and found no large active region complexes within  $30^\circ$  of central meridian. By rotating the Sun by  $\sim 30^\circ$ , we would in effect be having a



**Figure 5.** Hourly averages of solar wind velocities as observed by the SWEPAM instrument on board the ACE spacecraft, as a function of DOY for the events of (a) March 2002 and (c) May 2002. The observed ACE velocities have been traced back to the source surface at  $2.5 R_\odot$  and are shown for (b) March 2002 event and (d) May 2002. The vertically oriented dashed parallel lines demarcate the event DOY (left) and the corresponding traceback DOY (right).



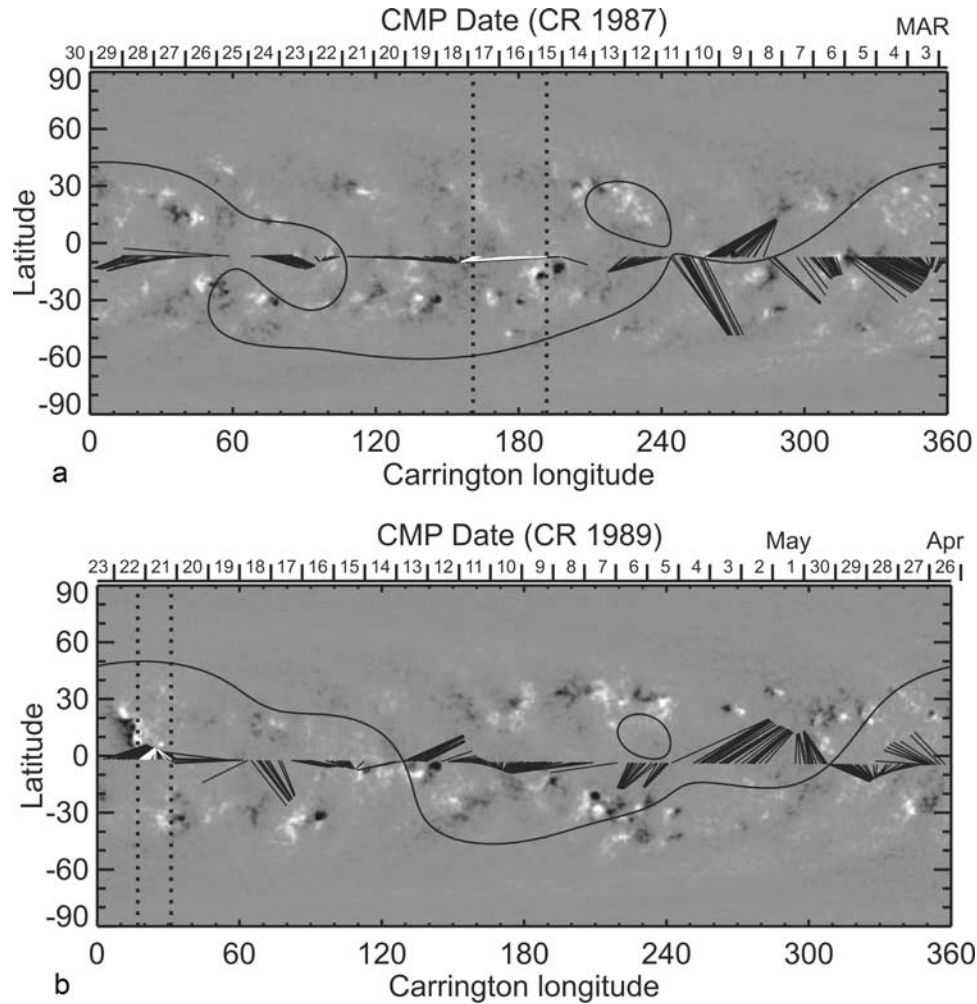
**Figure 6.** Maps of the solar photosphere (left) on the traceback dates and (right) on the event days. The locations of the large active regions to the vicinity of which the solar wind flows were traced back are shown and the active regions AR8525, AR9866, and AR9957 are emphasized and marked by an arrow for the events of (a,b) May 1999, (c,d) March 2002, and (e,f) May 2002, respectively.

“false” Sun, but with the same random distribution of active regions, and a chance association would give a positive result even after the rotation. A careful examination of active region maps before the traceback dates has ruled out such a chance association.

#### 4.2. Magnetic Fields

[11] Figure 7 shows synoptic maps during CR1987 (Figure 7a) and CR1989 (Figure 7b) made using Kitt Peak magnetograms. The Carrington longitude is marked at the

bottom of the map while dates of central meridian passage (CMP) are marked at the top. Regions of strong magnetic field, corresponding to active region locations are shown as black and white patches that distinguish the two magnetic polarities. The curved black line on both the maps is the source surface magnetic neutral line. The groups of converging black lines on each map join potential field computations of the magnetic field on the source surface at  $2.5 R_{\odot}$  with their corresponding counterparts on the photosphere. The fields were computed using a potential



**Figure 7.** Synoptic Kitt Peak magnetograms during (a) CR1987 and (b) CR1989. Active region locations are shown as black and white patches that distinguish the two magnetic polarities. The solid curved lines on both Figures 7a and 7b are the source surface magnetic neutral lines. The groups of converging black lines on each map join potential field computations of the magnetic field on the source surface at  $2.5 R_{\odot}$  with their corresponding counterparts on the photosphere. The potential field lines that are marked in white and demarcated by vertically oriented dotted parallel lines, correspond to fields with CMP date of 15–16 March 2002 (Figure 7a) and 21–22 May 2002 (Figure 7b).

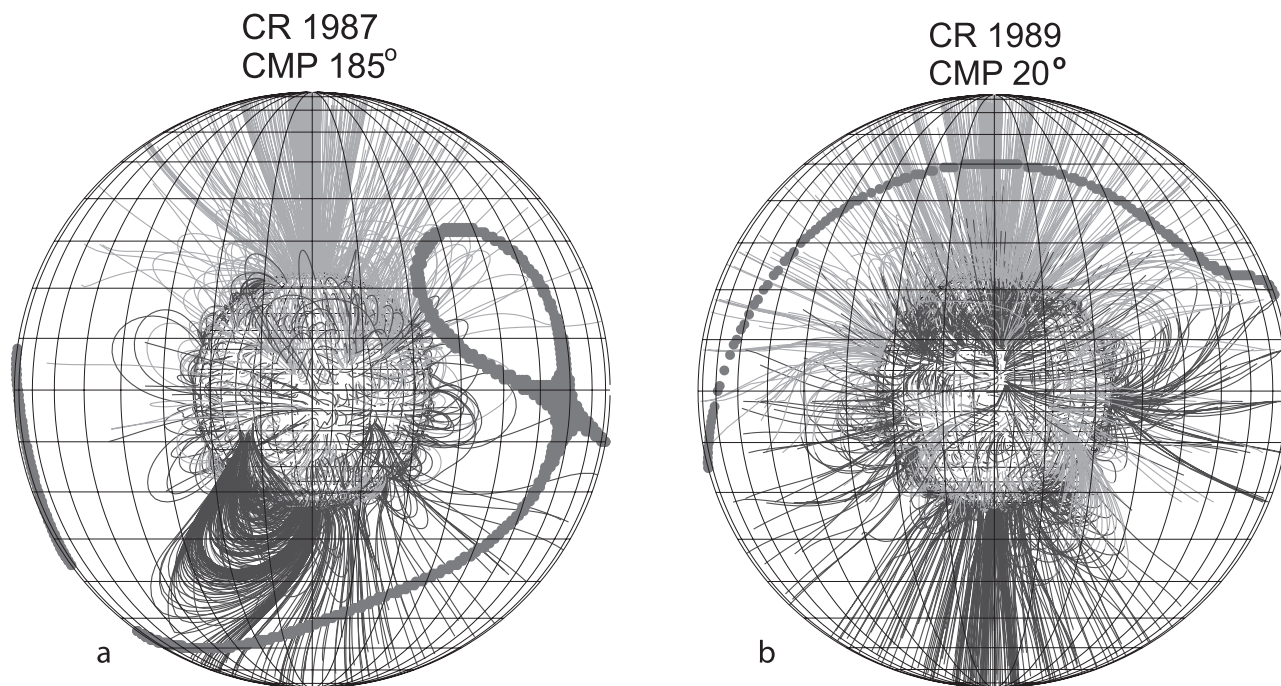
field model developed by *Hakamada and Kojima* [1999]. The source surface magnetic fields from the potential field computations lie in an equally spaced grid along the equator while their photospheric foot points lie in tightly bunched regions associated with active regions north and south of the equator. The potential field lines that are marked in white in both the maps indicate fields corresponding to the traceback dates at  $2.5 R_{\odot}$  and lie within the two dotted, vertically oriented, parallel lines that bracket the traceback locations of DOY 79 (Figure 7a) and DOY 144 (Figure 7b).

[12] Figure 8 show the three-dimensional structure of the coronal magnetic field corresponding to the traceback dates 15 March 2002 in CR1987 (Figure 8a) and 21 May 2002 in CR1989 (Figure 8b). Figures 8a and 8b are shown as viewed from a Carrington longitudes of  $185^{\circ}$  and  $20^{\circ}$ , respectively. These longitudes correspond to the traceback CMP dates. The differently shaded magnetic field lines distinguish the two polarities and are shown projected on to a source surface at  $2.5 R_{\odot}$  beyond which the potential

field lines are assumed to be radial. The black field lines are the outward or positive polarity lines while the grey field lines correspond to inward or negative polarity. Only fields between 5 G and 250 G on the photosphere are plotted. The thick wavy line in each panels is the magnetic neutral line. The black, outward pointed open fields lines around the central meridian are clearly visible in both Figures 8a and 8b. A similar plot for CR1949 during the disappearance event of 11 May 1999 can be seen in the paper by *Janardhan et al.* [2005] and clearly shows the open field region at central meridian on 05 May 1999.

### 4.3. Charge State Ratios of $O^{7+}/O^{6+}$

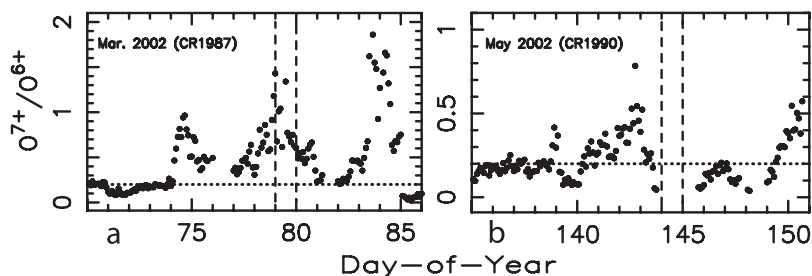
[13] Figures 9a and 9b show the charge state ratio  $O^{7+}/O^{6+}$  for the events of March 2002 and May 2002, respectively. The finely dotted horizontal lines in both Figures 9a and 9b are marked at  $O^{7+}/O^{6+} = 0.2$ , while the vertically oriented parallel lines demarcate DOY 79, in March 2002 (Figure 9a) and DOY 144, in May 2002 (Figure 9b). Unlike



**Figure 8.** Three-dimensional structure of the coronal magnetic field corresponding to the traceback dates for (a) 15 March 2002 in CR1987 and (b) 21 May 2002 in CR1989. Plotted in Figures 8a and 8b are the field lines having values in the range 5–250 G. The plots are shown as viewed from a longitude of 185° (Figure 8a) and 20° (Figure 8b), respectively. These longitudes correspond to the traceback CMP longitudes. The black and grey magnetic field lines distinguish the two polarities with the black field lines being the outward pointed or positive fields and the grey field lines being the inward pointed or negative field lines. The field lines are shown projected on to a source surface at  $2.5 R_{\odot}$ . The thick wavy lines in both Figures 8a and 8b are the magnetic neutral lines.

the May 1999 event the  $O^{7+}/O^{6+}$  ratio is above 0.2 when the low-density flows began for the two events, suggesting that the solar source was an active region open field [Schrijver and Derosa, 2003]. In each of the three cases, if one took  $O^{7+}/O^{6+} = 0.2$  as a rigid cutoff between a coronal hole (CH) source and an active region (AR) source, the May 1999 signature (see Figure 3) is clearly a CH-to-AR transition, while the May 2002 period is almost as clearly the reverse AR-to-CH transition. The March 2002 event is more complicated, but the oscillating CH-AR-CH-AR type of signature implies that there is a constantly evolving and dynamic boundary interface. The charge state ratio  $O^{7+}/O^{6+}$  thus provides evidence that these flow periods at 1 AU

represent the dynamic evolution of an open-closed field coronal hole to active region boundary. Support for this can also be seen in Figure 5 wherein the source-surface velocities are also seen to show these types of boundary signatures. For example, March 2002 is a weaker 400-to-600  $\text{km s}^{-1}$  transition during the disappearance event, and May 2002 shows a very strong 800-to-400  $\text{km s}^{-1}$  transition, although when projected onto the source surface, the same source-region time interval appears to have contributions from both high and low speed wind. Finally, the lack of data points for the duration of both the May 1999 and May 2002 events (see Figure 3 and Figure 9) probably imply that the extremely low densities do not produce a sufficient number



**Figure 9.** As a function of DOY, the charge state ratio  $O^{7+}/O^{6+}$  for (a) the March 2002 event and for (b) the May 2002 event. The finely dotted horizontal lines in both Figures 9a and 9b are marked at  $O^{7+}/O^{6+} = 0.2$  while the vertically oriented parallel lines demarcate DOY 79, in March 2002 (Figure 9a) and DOY 144, in May 2002 (Figure 9b).



of counts for reliable  $O^{7+}/O^{6+}$  measurements during these intervals.

## 5. Discussion and Conclusions

[14] From an analysis of the three disappearance events carried out it is apparent that the interplanetary magnetic field during disappearance events is stable and unipolar and the solar source locations are close to a large active regions located at central meridian. In cases when coronal holes could be identified in 10830 Å coronal hole maps or in EUV or soft X-ray images, as in the case of the 11 May 1999 event, there is apparently no ambiguity about the solar source as it is clear when there is a coronal hole. However, very often small X-ray/EUV coronal holes, may or may not be seen in 10830 Å coronal hole maps due to projection and line-of-sight effects. In an extensive study using 9 years of data from the YOHKOH soft X-ray telescope, *Kahler and Hudson* [2001] showed that small transient coronal holes, first discovered in Skylab data [*Rust*, 1983], occur in magnetic unipolar regions trailing large active regions and typically have lifetimes of  $\sim 48$  h. So solar source locations in active regions need not necessarily rule out a coronal hole origin. It must be noted here that though it has generally been assumed that coronal holes are unipolar regions, there have been several studies that have shown that there is solar wind coming from open flux in or near active regions [*Kojima et al.*, 1999; *Luhmann et al.*, 2002; *Arge et al.*, 2003; *Schrijver and Derosa*, 2003]. In fact it has been shown that solar wind outflows from active regions comprise  $\leq 10\%$  during solar minimum and up to 30–50% during solar maximum [*Schrijver and Derosa*, 2003].

[15] Another very interesting aspect is that the Alfvén radius is seen to extend outward by a factor of 2–5 from its normal location of  $\sim 0.05$  AU during a disappearance event. The duration of the low-density flows is also seen to be related to the location of the source region near central meridian, with source locations, slightly east of central meridian, at the start of the event, giving rise to longer duration low-density anomalies.

[16] In conclusion we can say that this work has highlighted the role of stable and unipolar outflows from the Sun, that are caused either by the dynamic evolution of active region open fields or the evolution of small coronal hole boundaries located at central meridian, in causing long lasting low-density anomalies at 1 AU. The work has also highlighted the need for systematic studies of the dynamics and evolution of active region open fields and CH boundaries. Studies of coronal hole boundaries could help define coronal hole boundary structure and thereby help in understanding boundary field connectivities. Regular and systematic observations by both ground and space based platforms can contribute in identifying many more such events in future studies.

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