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LETTER TO THE EDITOR

The solar wind disappearance event of 11 May 1999: source region evolution[*]

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ABSTRACT

Context. A recent, detailed study of the well-known "*solar wind disappearance event*" of 11 May 1999 traced its origin to a coronal hole (CH) lying adjacent to a large active region (AR), AR8525 in Carrington rotation 1949. The AR was located at central meridian on 05 May 1999 when the flows responsible for this event began. We examine the evolution of the AR-CH complex during 5−6 May 1999 to study the changes that apparently played a key role in causing this disappearance event.
Aims. To study the evolution of the solar source region of the disappearance event of 11 May 1999.
Methods. Using images from the Soft X-ray Telescope (SXT), the Extreme-ultraviolet Imaging Telescope (EIT) and the Michelson Doppler Imager (MDI) to examine the evolution of the CH and AR complex at the source region of the disappearance event.
Results. We find a dynamic evolution taking place in the CH-AR boundary at the source region of the disappearance event of 11 May 1999. This evolution, which is found to reduce the area of the CH, is accompanied by the formation of new loops in EUV images that are spatially-and-temporally correlated with emerging flux regions as seen in MDI data.
Conclusions. In the period leading up to the disappearance event of 11 May 1999, our observations, during quiet solar conditions and in the absence of CMEs, provide the first clear evidence for Sun-Earth connection originating from an evolving AR-CH region located at central meridian. With the exception of corotating interacting regions (CIR), these observations provide the first link between the Sun and space weather effects at 1 AU, arising from non-explosive solar events.

Key words. Sun: activity – Sun: corona – Sun: magnetic fields – Sun: solar-terrestrial relations – Sun: solar wind

1. Introduction

During the period 11−12 May 1999 solar wind densities, as observed by the Advanced Composition Explorer spacecraft (ACE; Stone et al. 1998) located upstream of the Earth at the Lagrangian point L1, dropped to unusually low values (<1 cm^{-3}) for extended periods of time (>24 h). This unusual and extended density depletion was also accompanied by very low-velocity solar wind flows (<300 km s^{-1}) and caused a dramatic expansion of the Earth's magnetosphere and bow shock (Le et al. 2000). It has been estimated that the expanding bow shock moved outwards to a distance of ~60 Earth radii, the lunar orbit, from its normal location of ~10 Earth radii. The extremely spectacular nature of this event has caused it to be referred to as the "*day the solar wind nearly died*" (Lockwood 2001).

In a recent study of this event, Janardhan et al. (2005) traced the solar wind outflows, observed at 1 AU, back to the Sun and showed that the flows responsible for the event began on 05 May 1999 from an active region-coronal hole (AR-CH) complex located at central meridian. They suggested that a continuously evolving CH boundary could cause a pinch-off, leading in turn to a separation of the CH outflow. The expansion of this detached solar wind flow, by a factor of 6−7, could then give the desired low densities at 1 AU. Given that the travel time between the Sun and the Earth, at the low velocities observed, was

~5−6 days, it was argued that a pinch-off taking place ~24−48 h after the start of the coronal hole outflow would cause typical particle densities of 20−25 particles cm^{-3} at ~0.5 AU (the approximate distance the CH outflow would have moved outwards in 48 h) to be reduced to 0.1 particle cm^{-3} at 1 AU. Thus, the expansion of a large, detached, low-velocity flow region from a small CH (as it propagated out to 1 AU) could give rise to an extremely large, low-density cloud that engulfed the Earth on 11 May 1999, as seen from interplanetary scintillation (IPS) observations (Balasubramanian et al. 2003).

Isotopic ratios of O^{7+}/O^{6+} are known to be good proxies for associating solar wind outflows to either AR or CH (Liewer et al. 2004). In a recent study it was shown that the solar source of this event could not be pinned down to either an AR or a CH (Janardhan et al. 2008), as the O^{7+}/O^{6+} ratios were sometimes indicative of a CH origin and at other times indicative of an AR origin. Such a fluctuating O^{7+}/O^{6+} signature was attributed by Janardhan et al. (2008) to a dynamic and rapid evolution taking place at the AR-CH boundary region, which was at the solar source of the event.

Although many studies have attempted to understand the disappearance event of 11 May 1999 (Crooker et al. 2000; Farrugia et al. 2000; Richardson et al. 2000; Usmanov et al. 2000; Balasubramanian et al. 2003; Janardhan et al. 2005, 2008), none have examined the source region of this event. We study the source region of the 11 May 1999 disappearance event to understand the evolution and dynamics of this AR-CH complex and to
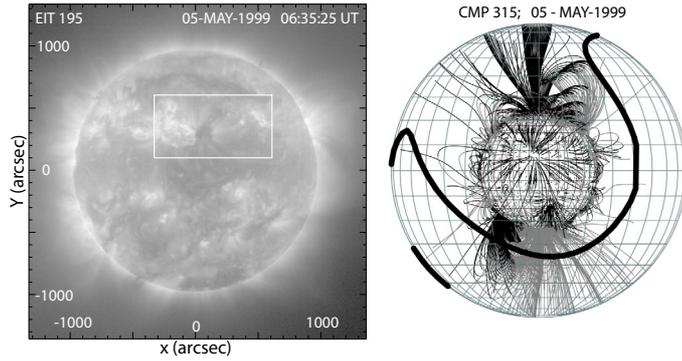

Fig. 1. *Left*: full-disk EIT 195 Å image on 05 May 1999. The boxed region contains AR8525 and the small CH lying against its westernmost boundary. *Right*: three-dimensional structure of the coronal magnetic field on 05 May 1999, with the field lines projected on to a source surface at 2.5 $R_\odot$. The thick wavy line is the magnetic neutral line. See text for details.

try and pin-point its implications to solar-terrestrial relationships in the absence of explosive solar events.

2. Observations

The EIT (Delaboudinière et al. 1995) provides observation of the Sun at four different wavelengths viz. 171 Å (Fe IX/X; 1.0 MK), 195 Å (Fe XII; 1.5 MK), 284 Å (Fe XV; 1.8 MK), and 304 Å (He II; 0.05 MK). The images recorded at 171 Å, 195 Å, and 284 Å are mainly dominated by iron lines and probe systematically higher heights and temperature regions in the corona. However, the images recorded at 195 Å are contaminated with the Fe VIII line as well as the Fe XXIV line, with the former being dominant in CH regions and later in flaring ARs (Del Zanna et al. 2003; Tripathi et al. 2006). Therefore, these images can be used to study the evolution of the both ARs and CHs.

In addition to EIT images, SXT images with the Al/Mg filter (Tsuneta et al. 1991) were used to study the higher temperature (3−5 MK) responses and MDI line-of-sight magnetograms (Scherrer et al. 1995), from the Solar and Heliospheric Observatory (Domingo et al. 1995), were used to study the evolution of photospheric magnetic fields around 05 May 1999, the approximate launch time of the disappearance event of 11−12 May 1999. The images were processed using the standard IDL based solar-soft software tree.

3. Data analysis and results

Figure 1 (left) shows a full disk EIT 195 Å image on 05 May 1999. The white box on the solar disk encloses the AR-CH complex, which is the region of interest in this study. The small CH can be clearly seen butting up against the western most boundary of AR8525, which is located at central meridian. Figure 1 (right) shows the three-dimensional structure of the coronal magnetic field on 05 May 1999 as viewed from a Carrington longitude of 315°, the central meridian passage longitude for 05 May 1999. The fields were computed using a potential field source surface (PFSS) model (Hakamada & Kojima 1999). The differently-shaded magnetic field lines distinguish the two polarities (black: positive and grey: negative) and are shown projected onto a source surface at 2.5 $R_\odot$, beyond which the potential field lines are assumed to be radial. Only fields between 5−250 G on the photosphere are plotted. The thick

wavy line is the solar magnetic neutral line. The black, outward pointed open fields lines at central meridian and slightly north of the equator are clearly visible and correspond to the location of AR8525 and the CH. Based on the PFSS model it is clear that the target region shows open field lines emanating from the AR-CH complex.

Figure 2 shows images of the solar disk corresponding to the boxed region from the left-hand panel of Fig. 1. Each image is approximately centered on the AR-CH complex AR8525 on 05 May 1999 (left-hand panels) and 06 May 1999 (right-hand panels). Starting from the top, the panels show respectively, EIT 171 Å; EIT 195 Å; EIT 284 Å, and SXT images with the Al/Mg filter on 05 May 1999 (left) and 06 May 1999 (right). The small CH lying ∼300 arcsec north and immediately adjacent to AR8525, whose western-most boundary is located almost exactly at central meridian, can be easily identified in the images. New bright features at the center can be seen to be producing a discernible change in the CH region on 06 May 1999, as compared with the previous day. These changes, perceived as a constriction developing across the CH, are indicated by white arrows in two of the right-hand panels. The two SXT images (lower most panels) also show a change in the emission on 06 May as compared to 05 May. It may be noted that images taken on 05 May and 06 May in Fig. 2 are normalized to the same intensity scaling.

To further substantiate the occurrence of this constriction or pinch-off taking place in the CH, we show EIT base difference images of the region in Fig. 3. The images were obtained by subtracting a reference EIT image on 05 May 1999 at 06:35:25 UT from EIT images obtained at intervals of ∼9 h ahead of the reference image. Note that the images were differentially rotated to the time of the reference image. The black regions in the difference images represent original features from the reference image, while the white regions show changes that have occurred from the time of the reference image. The three panels clearly show the changes that can be seen to produce a constriction or narrowing of the CH in the ∼24 h interval between the first panel on the left and the third panel on the right. The evolution of the CH, as observed by the EIT at 195 Å, can be unambiguously seen in the base-difference movie Movie1.gif[1], wherein the new bright features within the CH can be seen to be producing a progressive reduction in its area by causing a clear constriction or "*pinch-off*" across the CH.

Figure 4 shows MDI magnetograms, displayed between ±300 G, of the boxed region of the solar disk from the left-hand panel of Fig. 1. The left-hand panel is at 06:24:03 UT on 05 May 1999 while the right-hand panel is on 06 May, a little over 24 h ahead of this time. Note that the image in the right-hand panel has been rotated to the time of the panel on the left. The black and white regions in each panel correspond to negative and positive polarities respectively. The small, white, circular region of strong magnetic field lying slightly north and almost exactly at central meridian corresponds to the location of a small sunspot. The negative polarities surrounding the strong sunspot field on 05 May are moving magnetic features that appear around spots during their decay phase (Harvey & Harvey 1973). On 06 May, a new negative polarity (shown by arrow numbered 1), whose corresponding positive polarity is not identifiable unambiguously, is seen to appear to the northwest of the sunspot field. Also seen are two bipolar regions to the far west (arrows numbered 2 and 3), with the westernmost being clearly seen from 04 May and the one to its east beginning to emerge and evolve

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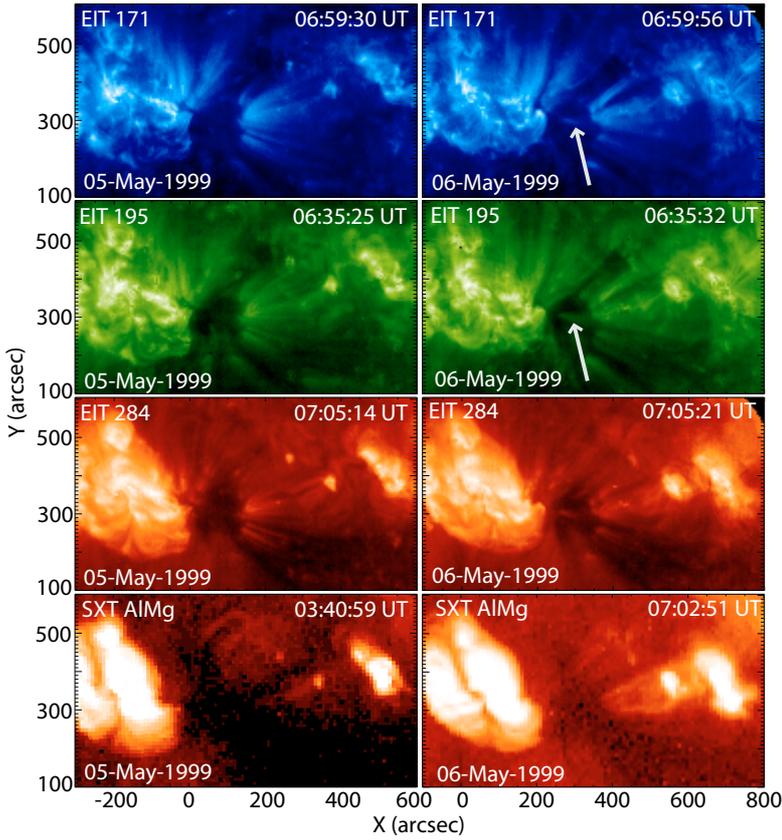
[1] Movies are available in electronic form.

Fig. 2. The boxed region of the solar disk from Fig. 1 on 05 May 1999 (*left column*) and 06 May 1999 (*right column*). *From the top* down are shown respectively, EIT 171 Å; EIT 195 Å; 284 Å; and an SXT image. The white arrows in two of *the right-hand panels* point to new bright features in the CH.
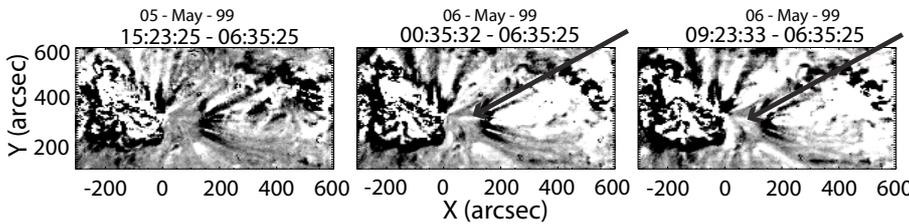

Fig. 3. Base difference images obtained at intervals of ~9 h. In *the middle and right-hand panels*, the reference image at *the left* at 06:35:25 UT on 05 May 1999 has been subtracted from images ~9 h ahead of it. The arrows in *the middle and right-hand panels* indicate the changes taking place in the CH.

from 04 May. The brightness observed in EIT and SXT images at these locations indicates the presence of hot closed loops.

The constriction taking place in the CH and seen as new bright features in its central region (see Fig. 2) can take place by a process of interchange reconnection (Baker et al. 2007) wherein the open CH field lines reconnect with the closed field lines to the west. This process will reduce the number of open field lines in the CH, thereby reducing the earth-directed solar wind outflows, produce the observed brightness at its center and shift the open field lines to a new location. The new locations of these shifted open fields need not be ideally located to produce earth directed outflows and would therefore not contribute to the subsequent events at 1 AU. The interchange reconnection process could also occur between the open CH fields and the closed field lines anchored at one end at the new negative polarity seen to emerge on 06 May (marked by arrow numbered 1 in Fig. 4) or between the open CH fields and the closed loops at the two bipoles to the west. A number of small new positive and negative polarities are also seen to appear around the CH location on 06 May. It is therefore possible that the interchange reconnection process could initially start between the CH open fields and these new closed loops to initiate the constriction process and then lead up to interchange reconnection with closed loops at the bipole locations to the west, in a gradual and stepwise

reconnection process (Attrill et al. 2007; Mandrini et al. 2007). For a detailed view of the evolution sequence in the AR-CH complex see the movie, Movie2.gif[1].

4. Discussion and conclusions

Using both spacecraft observations and tomographic IPS observations Janardhan et al. (2005) located the solar source region of the disappearance event of 11 May 1999 and showed that the flows responsible for the event originated around 05 May 1999 from a small CH lying adjacent to AR8525. We examined the AR-CH complex at the source region of this event using EIT, SXT, and MDI observations. The observations have clearly shown the rapid evolution and changes taking place in the CH lying adjacent to AR8525. The changes are seen to take place in a ~24 h interval starting from 05 May 1999, the approximate launch time of the disappearance event.

Based on the combined observations, it appears that the rapid evolution seen in the CH is due to a process of interchange reconnection taking place between the open CH fields and the closed fields from either the bipolar regions to their west or other small closed field regions as described above. The exact magnetic topology of the AR-CH region is however, complicated and would require a much more detailed study to isolate and pinpoint
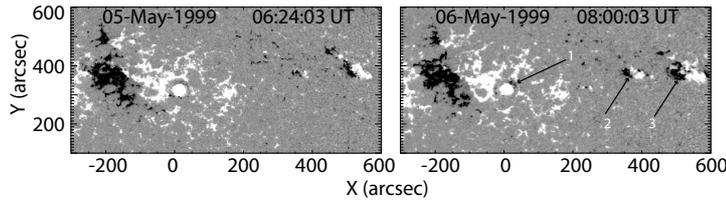
Fig. 4. MDI magnetograms of the boxed region of the solar disk from Fig. 1. The panels differ in time by a little over 24 h. Arrow 1 shows a small region of newly emerging negative flux while arrows 2 and 3 show two evolving bipolar regions.

the reconnection sites and locations of the opposing polarities involved. What is clear however, is that the interchange reconnection process causes the formation of new bright loops within the CH that can be perceived as a progressive constriction taking place across the CH. Since there is a a high degree of correlation between solar wind speed and size of the CH from which it emanates (Nolte et al. 1976; Neugebauer 1994; Wang 1994; Neugebauer et al. 1998; Kojima et al. 1999), we believe that, in this event, the formation of the new EUV loops would cause a reduction in the CH area and lead to a suppression of CH outflow. This would then give rise to slower velocity flows form regions that earlier produced faster flows, as has been observed in this event.

As stated above, the rapid changes taking place can be seen to be producing a progressive reduction in the area of the CH by causing a clear constriction or pinch-off across it. The observations thus provide support for the mechanism suggested by Janardhan et al. (2005) for causing the long lasting low density anomaly or "*disappearance event*" at 1 AU. Since this disappearance event was known to have had significant space weather effects (Rostoker 2000; Papitashvili et al. 2000), these observations clearly link the observed effects at 1 AU to a sequence of discernible changes taking place in an AR-CH complex on the Sun. Not considering CIRs, these observations thus provide, to the best of our knowledge, the first evidence for the so-called Sun-Earth "transmission-line" arising from non-explosive solar events.

Whether or not AR open fields connect to the interplanetary medium to produce solar wind outflows has been debated for some years now (Kojima et al. 1999; Luhmann et al. 2002; Arge et al. 2003; Schrijver & DeRosa 2003). However, the first actual observations of solar wind outflows from AR open fields located at central meridian and lying at the boundary of an AR and a CH have recently been reported (Sakao et al. 2007). These authors have shown that the observed solar wind outflows came from regions that showed large flux expansion factors and low-velocity solar wind, as identified by tomographic IPS observations. It must be noted here that the work by Janardhan et al. (2005) has reported both large flux expansion factors and low velocities from the source region of the 11 May 1999 disappearance event.

As opposed to the well-known drivers of space weather phenomena like CME's or large flares, disappearance events are not associated with explosive solar phenomena. However, they do produce other observable effects that are not fully understood. For example, Balasubramanian et al. (2003) have reported very unusual IPS power spectra attributed to high-energy Strahl electrons. The study of such events is therefore important in establishing and understanding solar terrestrial relationships in absence of explosive solar events. With the exception of CIR's our observations, as stated earlier, provide the first evidence for solar terrestrial connection caused by a non-explosive solar event.

Solar wind disappearance events constitute extreme deviations from the average conditions expected in the solar wind at 1 AU. It would therefore be important to continue such studies using both ground and space-based data to gain a better understanding of the dynamics and evolution of AR-CH boundary fields.

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