COMPARISON OF INTERPLANETARY DISTURBANCES AT THE NEAR SPACECRAFT WITH CORONAL MASS EJECTIONS AT THE SUN

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ABSTRACT

We examined interplanetary magnetic field disturbances recorded at the NEAR-Shoemaker spacecraft when it was above either the east or west solar limb as seen from Earth, and then we identified the associated coronal mass ejections (CMEs) detected above the limbs by the SOHO/LASCO coronagraph. We found 10 cases where a non-recurring IP disturbance could be associated with a CME. Eight of the disturbances included a magnetic flux rope signature. Flux rope chirality and axis orientation were determined for each one and compared with chirality and axis orientation at the Sun, as inferred from flux-rope signatures – filaments and sigmoids – that could be associated with the CMEs. In most cases, the chirality and orientation inferred from these pre-eruption flux rope signatures agreed well with the flux rope signatures at NEAR. These results suggest, in agreement with Plunkett et al. (2000), that the flux ropes existed prior to eruption and that the flux ropes on the Sun become flux ropes in interplanetary space. Comparisons of the CME speeds to the time-of-flight (TOF) average speeds showed that flux ropes are less accelerated or decelerated by the solar wind than are the CME leading edges. These results imply that the faint features or loops that make up the CME leading edges are probably distinct from the flux ropes.

1. INTRODUCTION

This paper presents an attempt to identify the solar origins of interplanetary (IP) magnetic flux ropes; to follow their evolution in the corona and IP space; and to relate the structure of IP magnetic field disturbances to coronal mass ejection features, such as bright loops and knots.

Studies attempting to link CME features at the Sun with IP flux ropes have been hampered by the fact that CMEs ejected at ~ 90º from the Sun-Earth line are the ones best delineated in coronagrams, whereas they are the least likely to be sampled \textit{in situ}. Conversely, structures within Earth-directed “halo” CMEs are poorly delineated in coronagrams, but the fleet of near-Earth spacecraft records their IP signatures very well. Optimum IP and solar data are rarely available for CMEs and the corresponding IP events. During most of the Solar and Heliospheric Observatory (SOHO) mission (since 1995), there have been no IP spacecraft in quadrature with Earth, i.e., in positions ~ 90º off the Sun-Earth line. However, the Ulysses probe was occasionally in near-quadrature,
and it recorded some interplanetary CMEs that could be traced to SOHO CMEs and Yohkoh X-ray events (Funsten et al. 1999; Reisenfeld et al. 2003; Weiss et al. 1996).

Before the SOHO era, there were several in-quadrature studies linking magnetic clouds (MCs) (Klein & Burlaga 1982) and other IP disturbances with CMEs observed at lower resolution than that of SOHO’s Large Angle Spectrographic Coronagraph (LASCO). In the first convincing association (Burlaga et al. 1982), a CME was imaged by the Solwind coronagraph on the spacecraft P78-1, and a subsequent MC was detected on the Helios 1 spacecraft, which was nearly 90° west of the Sun-Earth line and directly in the path of the CME. With coronagraph data from Solwind and the Solar Maximum Mission and IP data from Helios and the Pioneer Venus Orbiter, further studies showed that fast CMEs tend to decelerate in the solar wind while slow ones accelerate. Lindsay et al. (1999) provide an overview of this work.

There has been much speculation about what CME bright features tell us about the magnetic fields that thread them, e.g. (Cremades & Bothmer 2004; Krall et al. 2001). Are the leading-edge loops parts of an expanding flux rope or are they separate field structures that comprise material and fields that were part of the background corona? Does the frequently seen bright knot that Illing and Hundhausen (1985) referred to as the core correspond to the center of a flux rope? Does the projected CME structure depend on the orientation of the flux rope in the plane of the sky?

Several comparisons of CME images with models of CME magnetic structure have been published. For example, Chen et al. (2000) inferred from LASCO images that the morphological features and dynamical properties of the 1997 September 9 CME were consistent with those of an erupting magnetic flux rope. Plunkett et al. (2000) concluded that a twisting prominence ejected with the CME of 1998 June 2 existed in the low corona prior to CME onset. They also concluded, on the basis of an MHD model (Wu & Guo 1997), that the bright front of the CME was the leading edge and the prominence the trailing edge of the flux rope.

MCs are associated statistically with CMEs and solar filament eruptions (Bothmer & Schwenn 1994; Gosling 1990; Marubashi 1986; Rust 1994; Wilson & Hildner 1984). Many CME/MC Earth-directed events have been studied with SOHO images and data from in-situ heliospheric magnetometers. For example, Webb et al. (2000) studied the filament eruption and CME of 1997 May 12 and the ensuing MC. They showed that the filament axis upon eruption and the axis of the associated magnetic cloud passing Earth several days later were both nearly parallel with the ecliptic plane. The magnetic flux in the MC was commensurate with the flux in magnetic regions whose fields were opened by the CME. Also, the chirality (handedness) of the flux rope magnetic fields in the MC matched the chirality inferred for the magnetic fields in the filament. Yurchyshyn et al. (2001) obtained similar results.

Coronal X-ray sigmoids, which display many of the characteristics expected of flux ropes (Low & Berger 2003; Rust & Kumar 1996), are frequent precursors of CMEs and MCs (Canfield, Hudson & McKenzie 1999). In an event studied by Van Driel-Gesztelyi et al. (2000), the inferred chirality of the sigmoidal flux rope agreed with the chirality of the associated MC. Although the chirality of erupting filaments is very well correlated with that of the corresponding MCs (Bothmer & Rust 1997), Leamon, Canfield & Pevtsov (2002) found that the chirality of sigmoids generally agrees only 70% of the time with the MC chirality. Filaments and sigmoids are both thought to be formed in magnetic flux ropes (Low & Berger 2003; Rust & Kumar 1994), but one must
rely on hard-to-verify models so the evidence for flux ropes in them is less conclusive than it is for MCs, where the fields are measured in situ and can frequently be fitted rather well with a simple flux rope model field.

To find the IP counterparts to CME features, we used data from the Near Earth Asteroid Rendezvous-Shoemaker spacecraft (NEAR). NEAR was launched in 1996 February, and it continued to operate until 2001 February 12. NEAR ranged between 1.0 and 1.8 AU from the Sun, and it was often in near-quadrature with Earth, which is ideal for in-situ sampling of the CMEs seen with LASCO and the Extreme-Ultraviolet Imaging Telescope (EIT) on SOHO.

Our study was somewhat hampered because NEAR carried no heliospheric plasma or energetic particle detectors, but it did have a magnetometer (Lohr et al. 1997) to measure the remanent magnetization of asteroid 433 Eros. As it turns out, Eros has no remanent magnetization (Acuña et al. 2002). Moreover, the magnetic field near the asteroid showed no evidence of any asteroid-solar wind interaction (Anderson et al., 2003), so the magnetometer always measured the IP magnetic field.

The NEAR magnetometer provided nearly continuous observations with an accuracy of 1 nT, which is sufficient to characterize flux ropes and other magnetic signatures in the solar wind (Anderson & Acuña 2003). But, lacking solar wind proton temperature and density data, we cannot be sure that the flux ropes we found in the NEAR magnetometer data were the low beta, low temperature structures expected for MCs. From now on we will refer to events that showed elevated IP fields with slow directional rotation as flux ropes instead of MCs. Nevertheless, we believe there is substantial overlap of our flux ropes with MCs. For example, Mulligan et al. (2001a; 1999) analyzed magnetometer measurements obtained by both NEAR and Wind. When NEAR and Wind were closely aligned, the flux rope signatures recorded by NEAR agreed very well with those for MCs recorded by Wind. Of course, Wind has documented many MCs (Wu & Lepping 2002).

The NEAR/LASCO combination allowed us to identify structures, such as CME bright knots, or “cores,” and leading-edge, or “frontal,” loops, as discussed by Illing and Hundhausen (1985), for example, and attempt to match them with corresponding structures in the IP magnetometer data.

In the next section we discuss the NEAR and SOHO data selection and analysis techniques and provide a statistical survey of our results. In Sec. 3 we discuss four example events and show in detail how we inferred the chirality and magnetic axis orientation from the available solar images and IP magnetometer data. Sec. 4 includes results on how flux ropes might be discerned from CME leading-edge loops based on how their speeds are influenced by the solar wind. Sec. 5 presents our conclusions.

2. DATA ANALYSIS

2.1 IP Event Identification

We searched for disturbances in the NEAR magnetometer records, starting with the criterion that NEAR had to be within 45° of the plane of the sky as seen from Earth. The eligible intervals were 1997 Day 225 to Day 245; 1998 Day 223 to Day 361; 1999 Day 190 to Day 365; and 2000 Day 1 to Day 120. We then required that the total disturbed magnetic field strength had to be above 10 nT for at least 3 h. In the 453 days
of NEAR magnetometer data that we examined, we found 31 interplanetary disturbances meeting this criterion.

We eliminated from further consideration all events identifiable as recurrent disturbances, such as co-rotating interaction regions (CIRs) and heliospheric current sheet crossings (HCSs). CIRs and HCSs were identified by their 27-day recurrences and/or an abrupt magnetic field direction change. A total of 15 events were disqualified based on these criteria. It is possible that some CME-associated events were eliminated because they coincided with CIRs or HCSs. The remaining 16 disturbances are candidates for CME-associated events.

2.2 Identification of Associated CMEs

To compare CMEs with our 16 IP disturbances, we first searched the full-resolution, partial-frame LASCO coronagraph movies for CMEs in a window of time corresponding to average disturbance propagation speeds between 300 and 800 km s\(^{-1}\). According to Gosling (1997), very few CMEs near the ecliptic plane have speeds at \(\sim1\) AU outside this range. Higher speeds are occasionally associated with X flares (Watanabe, Kojima & Tokumaru 2000), but only one of our events occurred within a week of an X flare – the 1999 November 27 eruption at 1205 UT, and it did not produce a CME with speed \(>800\ \text{km s}^{-1}\).

To be sure not to miss any possibly associated CMEs, we extended the nominal time windows opened by the 300 – 800 km s\(^{-1}\) average speed criterion to include full 24-h periods. This resulted in windows 4 to 6 days wide 3 to 10 days prior to the IP disturbance, depending on the distance to NEAR. CME loops and bright knots were tracked in height vs. time at the sub-solar latitude of the NEAR spacecraft, i.e., in the radial direction to NEAR as corrected for the 7° tilt of the heliographic coordinate system. We included only CMEs that appeared to originate in the octant centered on the sub-solar position of NEAR, i.e., the CMEs must not only appear to leave the Sun from the right quadrant and appear to be headed directly for NEAR, they must also be associated with frontside or backside activity when NEAR was in front of or behind the limb, respectively. How we made the associations with inner corona activity will be clarified by the examples given in Sec. 3.

In addition to requiring that the CMEs appeared to be following a Sun-NEAR line, we also required them to be bright enough to be tracked in the LASCO C3 coronagraph images. Our assumption was that if a CME were detected at NEAR it could not have been a minor event as seen by LASCO. This assumption is consistent with the rate of events at NEAR, about one per month, which is about the same as the rate of geomagnetic-storm-producing full halo (Earth-directed) CMEs (Zhao & Webb 2003), and it is consistent with the rate of magnetic cloud detections at the WIND spacecraft, as reported on the web site: http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1.html.

There was usually only one candidate CME in the correct solar octant and temporal acceptance window. Where several CMEs might qualify, we chose the one whose speed, as measured from the LASCO image sequences, was closest to the time-of-flight (TOF) speed, as calculated by dividing the distance from the Sun to NEAR by the time between CME onset and IP event onset. For a further check on our CME identifications, we examined the lists of CMEs and speeds compiled by the Catholic University of America (CUA) at http://cdaw.gsfc.nasa.gov/CME_list/index.html. We did
not find any new candidates from the CUA lists. For several of our events, the CUA catalog lists CME onset times and speeds that differ from ours. It is important to note that precise determination of CME onset time is not necessary because the time-of-flight average speed is calculated over an interval of 4 – 6 days. And our measured CME speeds usually differ from the CUA speeds because we tracked features in the apparent radial direction toward NEAR whereas the CUA speeds are those of the most prominent leading-edge CME features.

Five of the 16 IP events could not be associated with a CME, because of LASCO data gaps. We found 10 events with CMEs that met our criteria for association. There was only one case with no candidate CME where one could have been identified. We list the 11 events in Table 1, where columns 1 and 2 give the IP and CME onset times to within a tenth of a day. Columns 3 and 4 give the distance of NEAR from the Sun and its position relative to the Earth-Sun line. In all cases NEAR was west of the Sun except for the CME of 1998 November 9, when the spacecraft was 13.5° behind the east limb. The data in columns 1 – 3 were used to calculate the TOF average speed of the leading edge of the disturbances for comparison with the measured CME leading-edge bright loop speeds. The latter were corrected for projection effects under the assumption that the tracked feature was headed directly for NEAR. We corrected the speeds of the bright knots in the same manner to compare them with the TOF average speeds of the flux ropes. We made this comparison to see if the speeds correlate, and we found a correlation of 0.6 between bright knot speeds and the TOF average speeds of the centers of the corresponding IP flux ropes. This implies that the data are consistent with the common assumption that the bright knot or core corresponds to the center of a flux rope. The accelerations listed in columns 7 and 10 were calculated under the assumption of constant acceleration from the Sun to NEAR.

2.3 IP and CME Properties

Among the 11 IP events in Table 1, eight included an interval ranging from 4 to 32 h during which the magnetic field exhibited a pattern of smooth rotation. We called those intervals flux ropes, but since we lack particle and plasma data, our flux ropes may not all be MCs, as defined by Klein and Burlaga (1982). Assuming that MC diameters cluster around some mean value, we would expect that, if we are indeed looking at MC-like flux ropes, the faster moving ones would have briefer signatures at NEAR. There is, in fact, a negative correlation (-0.64) between the durations and TOF speeds of the flux-rope signatures. To carry this one step further, we estimated the diameters of the eight flux ropes by calculating duration × TOF speed. The diameters clustered about 0.2 AU for six events and 0.05 AU for two events. The small flux ropes may correspond to filaments similar to those found by Ruzmaikin, Martin & Hu (2003). We will discuss this further in Sec. 3.4. The other flux ropes’ average diameter is about the same as those reported by Lepping et al. (1997). This adds support to the features’ identifications as MC-like flux ropes.

To characterize the flux ropes, we defined them by eye according to the pattern of field variation along the east-west and north-south axes. We looked for intervals of smooth and large variation in at least one axis. We assumed the start and stop times of passage through the flux rope occurred when the variation either flattened out or was interrupted by a sharp discontinuity. When the field was east pointing, then north, then
west, we followed Bothmer and Rust (1997) in labeling it ENW, which corresponds to passage through a cloud with a left-handed helical field with its central axis pointing north. Similarly, when the field direction rotated from north to east to south, we called that an NES pattern, which corresponds to a right-handed field with an east-pointing axis. From the sense of rotation deduced in this manner, the chirality turned out to be right-handed in five flux ropes and left-handed in three (see Table 2).

To determine the orientation of the flux rope axes more precisely, we performed a minimum variance analysis (Bothmer & Schwenn 1998) on the field measurements. The method gives the axis orientation and chirality of the flux rope fields. We identified minimum variance with the radial component of the flux rope fields, maximum variance with the azimuthal component, and intermediate variance with the axial direction. The results agree with the visual classifications. They are given in Table 2. In addition, in each case, we were able to fit the field measurements with a noncylindrically symmetric helical model field (Mulligan & Russell 2001). The flux rope axis orientation is described by the clock angle, which is the projection of the axis on the plane perpendicular to the vector from NEAR to the Sun. The clock angle scale has north = $0^\circ$ and east = $90^\circ$. The two approaches to determining the axis direction differed, but they always put the clock angle in the same octant. Clock angle was similarly sensitive to our somewhat arbitrary choices of start and stop times for the flux rope passage.

To determine the chirality of each flux rope before eruption and, if possible, the axis orientation for comparison with the IP flux ropes, we examined chromospheric and coronal images for filaments and sigmoids that could be associated with the CMEs. Previous work (Martin & McAllister 1997; Rust 1999a) provides a guide to interpretation of these solar flux rope signatures. Our technique is described in the example events, below.

Five of the eight flux ropes could be associated with eruptions from solar regions with clear flux rope signatures, i.e., dextral or sinistral filaments or forward or reverse sigmoids. In all but one case, the chirality inferred from the solar flux rope signatures agreed with the IP flux rope chirality. In four out of six cases where we inferred a clock angle from the orientation of the filaments or sigmoids, it agreed to within $36^\circ$ with the IP flux rope clock angle. This correlation of solar and IP chirality and field direction implies that the flux ropes on the Sun become flux ropes in IP space.

3. EXAMPLE EVENTS

3.1. Interplanetary Event of 1998 November 13 - 15

We found only one CME candidate (Figure 1) to associate with the magnetic field in this IP disturbance, which varied wildly at its leading edge and was followed, 24 h later, by the relatively smoothly rotating field of a left-handed flux rope. The CME was a large, bright, structured loop that lifted off the east limb on November 9. Close examination of the LASCO C2 movie shows that the CME started slowly at 0725 UT.
More material is visible after 0918, and at 1154 the CME seemed to accelerate. These events are counted as separate CMEs in the CUA catalog, but running the C2 movie back and forth certainly gave us the impression that a single CME left the east limb that morning. In our examination of this event and others, we found that the CUA catalog is a useful aid, but it cannot replace direct examination of the LASCO data for CME structure and correlation with IP events.

Two features, the leading edge of the loop and a bright knot (Figure 1), were tracked to heights of 25 R\(_0\) and 17 R\(_0\), respectively. Their speeds as they left the LASCO field of view were 800 and 500 km s\(^{-1}\), respectively, compared with the TOF speeds of 680 km s\(^{-1}\) for the leading edge of the disturbance and ~505 km s\(^{-1}\) for the center of the flux rope. In Figure 1, double-tipped arrows mark the beginning and ending times of NEAR’s passage through the flux rope. Figure 1 illustrates the correspondence between the NEAR magnetic disturbance signal, labeled with the projected TOF speeds, and CME structure as shown by the LASCO coronagraph. We infer that the CME bright knot corresponded to the 1998 November 13 — 15 flux rope, which had TOF speeds of 480 — 570 km s\(^{-1}\). The highly disturbed field in front of the flux rope is probably ambient solar wind fields swept up and folded into a rampart or “sheath” by the CME loop, which evidently slowed from 800 km s\(^{-1}\) to an average speed of ~ 650 km s\(^{-1}\).

On November 9, at CME onset, NEAR was 13.5° behind the east limb, 1.78 AU from the Sun, and at a projected solar latitude of 6.6° N. We examined H\(\alpha\) and EUV images to determine where the CME originated. The CME was followed at 1500 UT by post-flare loops rising over the SE limb, so we focused on active regions that rotated around the east limb in the following days. Figure 2 shows the H\(\alpha\) features in and around AR 8384 at S 30° E 14° five days after the CME. The filament would have been just behind the limb on the day of the CME. Since filaments usually reform after eruption, we suggest that an earlier manifestation of this filament could be identified with this event. Because the “barbs” of the filament (Martin, Marquette & Bilimoria 1992) are oriented like right-hand exits on a highway, the filament must have been formed in a left-handed flux rope, according to the interpretation method of Rust and Kumar (1994). According to this interpretation, the dark H\(\alpha\)-absorbing material is supported against gravity in the concave upward coils of the magnetic flux rope threading the filament. Thus, a filament threaded by a left-handed flux rope would appear to have threads turning toward the right. Such filaments are sometimes called “dextral.” For some detailed comparisons of actual filaments with flux rope models supporting H\(\alpha\)-absorbing material, see Aulanier, Srivastava & Martin (2000).

Another clue to the chirality of the magnetic fields in the active region can be found in the large sunspot, labeled “CCW spot” in Figure 2. By CCW we mean that the fibril pattern around the sunspot makes it appear that the sunspot had been rotating counter-clockwise. As Nakagawa et al. (1971) showed, such a fibril pattern fits nicely with a left-handed axially symmetric force-free field. Incidentally, Rust & Martin (1994) showed that dextral filaments in active regions are invariably connected to CCW spots, which supports the interpretation that dextral filaments are threaded by left-handed helical fields.

Having inferred the chirality of the filament, we tried to infer its axial field direction. From analysis of Figure 2, we concluded that the axial field was directed into the small negative polarity spot, just to the left of the large CCW spot. If this inference is correct, then the magnetic axis of the filament would have had a clock angle of about
210°, i.e. pointing SW. This is in good agreement with the minimum variance and model analyses of the IP flux rope, which gave a clock angle of 222° and 208° for the axis orientation, resp.

3.2. Interplanetary Event of 2000 January 7-9

On January 7, NEAR was 1.37 AU from the Sun and just 12° behind the west limb at a sub-solar latitude of 16° S. The CME (Figure 3) most likely associated with this event left the west limb at ~25° S at 0530 UT on January 2. The leading edge was a loop whose measured speed at the Sun was 500 km s⁻¹. If it had continued unchecked, it would have arrived at NEAR about half a day earlier, as indicated by the long white arrow. The bright knot inside the loop had a speed at the Sun of 360 km s⁻¹, which corresponds to passage of the peak field intensity, recorded at 1800 UT on January 8. In Figure 3 the inset graph of total field intensity shows that the speeds of the tracked features are in close agreement with the TOF speeds, which ran from ~440 km s⁻¹ for the leading edge to ~310 km s⁻¹ for the trailing edge. The detailed comparison of features shown in Figure 3 suggests that the leading edge of the CME decelerated to solar wind speed (~450 km s⁻¹) while the center of the flux rope maintained a speed of ~360 km s⁻¹. Although there are no plasma data available, the magnetometer trace suggests the presence of a forward shock and a sheath at the leading edge and one or possibly two reverse shocks at the following edge of the cloud. These results are consistent with Ulysses observations of magnetic clouds associated with limb events (Funsten et al. 1999).

During most of 2000 January 8, NEAR sampled a right-handed flux rope with axial field directed northward at a clock angle of 12° according to a model fit (see Figure 4). On the Sun on December 27, there was a large Hα filament at about S 15° W 40°. On the same day Yohkoh recorded an S-shaped sigmoid there, which is the signature of a right-handed flux rope. The orientation of the filament and the sigmoid both implied a clock angle of ~150° for the axial field direction, following the technique of Bothmer and Rust (1997). The flux rope, whose presence we infer from the filament and sigmoid, would have been about 30° over the west limb on January 2 when the CME occurred. At that time NEAR was 12° behind the limb, so it would have had a high probability of intercepting any flux rope ejected from the region. However, the orientation of the flux rope axis at 1.37 AU differs from the orientation inferred from solar observations by ~130°.

3.3. Interplanetary Event of 1999 August 24

On August 24 NEAR was 1.16 AU from the Sun and 38° behind the west limb when its magnetometer recorded the event shown in Figure 5. The vertical dashed lines in the top panel of the figure mark the interval that we identify as passage through a flux rope. The middle panel of the figure shows the projections of the field on the axes of minimum, intermediate, and maximum variance during passage through the flux rope only. The bottom panel gives the hodogram, which shows the track of the field vector in the plane perpendicular to the flux rope axis. This hodogram is typical of the events we studied, and in this case, it shows a consistent clockwise rotation of the field direction, indicative
of a right-handed flux rope. For the Figure 5 event and for most of the others, we tried a few different start and end points to see if it changed the chirality. Chirality proved to be robust but clock and cone angles were sensitive to our choices of start and stop times.

The candidate CME for this event started on August 18 at 1130 UT. The LASCO movie shows that it had a speed of 370 km s\(^{-1}\), in fair agreement with the projected TOF speed of 287 km s\(^{-1}\) for the leading edge of the disturbance at NEAR. The CME originated near AR 8662, which was on the SW limb. \(\text{H}\alpha\) images show that a sinistral filament (Figure 6a) erupted and that it was associated with a forward sigmoid (Figure 6b), as seen in a SOHO/EIT image at Fe XV 284 Å. Both signatures are indicative of right-handed helical magnetic fields. The IP flux rope also had right-handed helicity. Because the filament ran roughly 45° to the equator with positive fields to the W, we deduce that the axial field direction would have a clock angle of about 135°. The IP flux rope had a clock angle between 40° (flux rope model) to 4° (minimum variance analysis).

3.4. Interplanetary Event of 1997 August 20

A disturbance in the IP magnetic field when NEAR was 1.8 AU from the Sun and 37° Earthward of the west limb started late on August 19 and continued for about 30 h. At 0600 on August 20, in the midst of the disturbance, the field rotated quite rapidly from west to east. As shown by the hodogram on the bottom of Figure 7, the field then had the characteristic signature of a flux rope: a relatively strong total field with low variance and a characteristic rotation about one axis. The 3.5 h duration was unusually short, and except in the flux rope, the field vector direction showed no overall rotation.

There was only one bright, west limb CME candidate in the 1997 August 9 – 15 acceptance window. It was a streamer blowout with two faint loop segments followed by a bright knot (Andrews & Howard 1999). The first loop appeared in the LASCO C2 field of view at ~0800 UT on August 13. From ~1100 UT until 2400 UT, the two loop segments had accelerations of 9 m s\(^{-2}\) and 2 m s\(^{-2}\) and average speeds of 320 km s\(^{-1}\) and 220 km s\(^{-1}\), respectively. Assuming that the CME was headed directly for NEAR, these speeds become 401 km s\(^{-1}\) for the leading edge of the first loop segment and 276 km s\(^{-1}\) for the second loop segment.

The TOF speeds inferred from the IP data are 479 km s\(^{-1}\) for the leading edge and 445 km s\(^{-1}\) for the center of the flux rope. Since the TOF speed is comparable with the average solar wind speed, it is plausible that the CME continued to accelerate beyond the coronagraph’s field of view. The highly structured character of the CME seen in the LASCO movie is consistent with the IP disturbance, which displayed a complex internal magnetic structure.

Between 0407 UT and 0619 UT on August 13, SOHO/EIT 195 Å images showed coronal dimming and filament brightening, the characteristic signatures of a filament eruption, in AR 8070, at S20° W48°. Synoptic \(\text{H}\alpha\) images confirm that a filament disappeared there between 0730 UT on August 12 and 0730 UT on August 13. The LASCO C2 coronal images show a bright circular knot (Figure 8) that followed the two earlier loop segments. It moved so slowly through the inner corona that it seemed to hang almost motionless between 0927 and 1440 UT. Afterwards, it accelerated at 1.6 m s\(^{-2}\) and by the time it reached the outer edge of the C3 field of view it had a speed of 320 km s\(^{-1}\). We identify this knot with the erupted filament, especially since it was bright in the Ly\(\alpha\) line (Strachan et al. 1999).
The 1997 August 13 CME is similar to the 1997 October 19 one studied by Dere et al. (1999), where a circular feature accelerated slowly and took 8 h to pass through the C2 FOV. Only with running difference images or with edge enhancement, as in Figure 8, does the circular profile of the flux rope stand out.

Hα images and the magnetogram on August 11 show that the filament had a right-handed helical field, according to the Rust and Kumar (1994) interpretation of filament features. From the filament’s position relative to the underlying magnetic fields, we can also conclude that its axial field clock angle was ~315°. This orientation agrees with the noncylindrically symmetric best-fit model, which assigned a clock angle of 303° to the axial field at NEAR. Mulligan et al. (2001b) give details of this flux rope model. Minimum variance analysis of this event gives a clock angle of 351°.

The flux rope at NEAR was right-handed, according to the model fits, the same as the inferred chirality of the flux rope of the filament. Although it is tempting now to identify the thin flux rope directly with the erupted filament, we must be cautious because the bright knot itself (Figure 8) was ejected at a ~ 30° angle to the Sun-to-NEAR direction (Strachan et al. 1999). Nevertheless, assuming that the bright knot of filament material was entrained in just a limited segment of a large, erupting flux rope, we identify the IP flux rope with the filament’s flux rope. This conclusion is consistent with the results of Ruzmaikin, Martin & Hu (2003), who studied three CME/MC-associated events. They found in each case that the magnetic fields of the MC and of an entrained high-density filament knot were flux ropes, and in each case the two flux ropes shared the same chirality. Our 1997 August event lasted about 4 h at a distance of 1.78 AU, whereas the filaments Ruzmaikin, Martin & Hu interpreted lasted about 3 h at a distance of 1 AU. At a solar wind speed of 450 km s\(^{-1}\), we calculate the diameter of the August flux rope to be 0.043 AU compared with diameters of 0.01 - 0.07 AU for the Ruzmaikin, Martin & Hu events.

4. EFFECT OF THE SOLAR WIND ON CME SPEED

We performed an analysis similar to those by Lindsay et al. (1999) and Gopalswamy et al. (2001) in which the speeds at which CME features leave the Sun are compared with the TOF speeds to determine the average acceleration between the Sun and the spacecraft. Our measurements of the LASCO images gave the apparent speed of each tracked CME feature – leading edge or bright knot – as projected on the plane of the sky. We then corrected these projected speeds by assuming the CME features were headed directly for NEAR. Next we compared the resulting speeds with the TOF speeds, calculated by dividing the distance to NEAR by the time difference between CME onset and magnetic feature arrival at NEAR. The objective was to determine how the inferred TOF speeds of magnetic features in the IP disturbances compared with the candidate CME feature speeds near the Sun.

The comparison of CME and TOF speeds is subject to large uncertainties. The worst is in not knowing the true trajectory of the tracked CME features. In the absence of polarization data, one cannot uniquely infer the true trajectory from the trajectory in the plane of the sky. Actual trajectories may be as much as 60° from the assumed one, so the tracked features may not be vectored to NEAR at all. Hence, the results of our comparisons depend on the assumption that we have correctly identified features that were directed at NEAR. And it is unclear where to draw the line between fields
corresponding to a CME’s leading edge and the rampart of swept-up solar wind fields, as seen in several of the example events.

We focused on the CME leading edge velocities and IP disturbance onsets. In a similar analysis, Gopalswamy et al. (2001) found that CME acceleration \( a \) (m s\(^{-2}\)) = 2.193 – 0.0054\( u \), where \( u \) is the initial speed of the CME in km s\(^{-1}\). The equation suggests that fast CMEs tend to slow toward 406 km s\(^{-1}\) while the slow ones accelerate toward that speed, which is approximately the average solar wind speed. From a similar analysis of our data, we find \( a = 1.32 – 0.003u \). In this case the imputed solar wind speed was 440 km s\(^{-1}\).

If, instead, we focus on the CME bright knot velocities and the time of flight of the center of the corresponding flux ropes at NEAR, we get \( a = 0.24 – 0.0007u \) for the average flux rope acceleration and 390 km s\(^{-1}\) for the imputed solar wind speed. Another way to express this result is to note that the average of the absolute accelerations for CME leading edges was 0.47 m s\(^{-2}\), while it was 0.12 m s\(^{-2}\) for the CME bright knots. Assuming that the bright knots are entrained in the flux ropes, we conclude that flux ropes are less affected by the force of solar wind by a factor of ~ 4 than are CME leading edges. These results suggest that the faint features or loops that make up the CME leading edges are distinct from the flux ropes.

5. CONCLUSIONS

In the NEAR magnetometer data set, we found 16 non-recurring IP disturbances and found a plausible CME association for 10 of them. Eight of the disturbances with CMEs included a flux rope signature. In most cases it was possible to identify the solar origins of the flux ropes, track their passage through the corona, and infer their acceleration or deceleration in IP space. In 4 cases out of 5, the chirality of the flux ropes, as indicated by their characteristic signatures before eruption, was the same as it was in interplanetary space. This is consistent with statistical studies that find that the inferred chirality of sigmoidal elements agrees 70% of the time with the MC chirality (Leamon et al. 2002).

Despite the less-than-perfect correlation, these results suggest, in agreement with Plunkett et al. (2000), that the flux ropes existed prior to eruption. It implies that flux ropes on the Sun become flux ropes in space. Alternative models suggesting that flux ropes are formed by reconnections during eruption would have to explain where the helicity of the IP flux rope comes from and why its chirality happens to agree with that of the flux rope on the Sun. However, reconnections inside flux ropes, a process that would conserve magnetic helicity and chirality, are likely to take place as the flux rope expands.

An initial objective of our study was to identify CME features, such as loops and bright knots, with IP features. Because definitive coverage of filament eruptions is sparse, we could not identify the bright knots with erupting filaments with certainty. However, the fact that the chirality of the IP flux ropes agreed with the inferred solar

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5 An anonymous referee has pointed out that “constant acceleration to 1 AU is, most likely, a fiction. If, for example, acceleration/deceleration takes place close to the Sun (well within 1 AU), then the "average acceleration" calculated will simply reflect the travel time/distance to the observing spacecraft. Since NEAR is approximately twice as far from the Sun as the Earth, then transit times will be ~twice those to 1 AU. Hence, average accelerations inferred from NEAR observations will be ~ half those inferred from 1 AU transit times. This is essentially what the formulae in the Gopalswamy et al. and present papers give. Thus, one could conclude from these formulae that acceleration does take place close to the Sun and that the CME speed is then relatively constant out to at least the location of NEAR Sun.”
feature chirality in 4 cases out of 5 strongly suggests that the bright knots we tracked were erupting filaments. In addition, we found a correlation of 0.6 between bright knot speeds and the TOF average speeds of the centers of the corresponding IP flux ropes.

Another result, summarized in Sec. 4 and exemplified in Figures 1 and 3, is that flux ropes speed up or slow down in the solar wind between \( \sim 30 \, R_\odot \) and \( \sim 300 \, R_\odot \), less than CME leading edges (loops) do. Our comparisons of the CME speeds with the time-of-flight (TOF) average speeds showed that flux ropes are less accelerated or decelerated by the solar wind than are the CME leading edges. These results imply that the faint features or loops that make up the CME leading edges are probably distinct from the flux rope fields. Perhaps they are fields and mass swept up from the background corona, forming a kind of rampart ahead of the flux rope, as postulated by Illing and Hundhausen (1985).

As implied above, at least some of the strong but variable fields that precede the IP flux rope signatures might be identified with the CME leading-edge loops. An alternative possibility is that all of the disturbed fields in front of the IP flux ropes are swept-up solar wind. Although it may be possible to discriminate between these two possibilities in events with complete particle, plasma and field data available, results to date are indecisive. Lepri et al. (2001) emphasize that even with the complete data sets provided by instruments on the Advanced Composition Explorer (ACE), they could not define necessary and sufficient conditions for identifying IP CMEs (or “ICMEs,” which have magnetic signatures like the IP events we studied). In at least one event, they found that the proton temperature in the disturbed fields in front of the IP flux rope was higher than the proton temperature in the flux rope, but lower than in the solar wind. This may indicate that these disturbed fields are at least in part distinct from the swept-up solar wind fields.

Lepri et al. also found that intervals of 20 h or more of high Fe charge states occurred in 50% of ICMEs. They inferred that those ICMEs must have been heated to temperatures as high as 6 MK. That is much hotter than the normal corona. As Kumar and Rust (1996) showed, an expanding coronal or solar filament flux rope loses magnetic energy, since its magnetic helicity is conserved, and they calculated that if that energy is dissipated as heat in small-scale current sheets, for example, then the plasma temperature may increase ten-fold. The fact that sigmoids brighten in X-ray images in the initial stages of CMEs is consistent with the picture drawn here of intense flux rope heating.

That eight of the 10 CME-associated IP disturbances included a flux rope may be interpreted from two points of view. One might infer that most IP disturbances due to CMEs have embedded flux ropes. On the other hand, the requirement for an elevated field lasting at least 3 h will bias our sample towards events with strong fields, such as magnetic clouds/flux ropes. Gosling (1990) found that only one-third of non-recurring IP disturbances have embedded magnetic clouds, as defined by Burlaga et al. (1982).

As Table 2 shows, in the six cases where we could compare flux rope orientation by its clock angle at the Sun with the clock angle at NEAR, we found agreement to within \( \sim 36^\circ \) in four cases, but disagreements of \( \sim 130^\circ \) in two cases. A possible explanation for the disagreements could be that the flux rope was writhing – changing orientation by \( \sim 180^\circ \) – during eruption, but not during passage through the LASCO field of view – 2.5 to 30 \( R_\odot \) – where we would have detected it. A striking example of a CME flux rope writhing through \( \sim 180^\circ \) was recorded at the Mauna Loa Observatory on 2003 February 18 with the Mark IV K-coronameter, whose field of view is 1.08 to 2.5 \( R_\odot \) (Y.
Fan, 2004, pvt. comm.). Writhing filaments are recorded occasionally in Hα and in EIT images.

We saw no writhing in the LASCO images: all CME features seemed to follow radial trajectories from the Sun. Without complimentary Hα, EIT or K-coronameter images, it will be difficult to interpret CME images in terms of flux rope orientation and structure, because writhing, when it happens, seems to occur below 2.5 R☉.

Does a loop-cavity-knot structure mean we are viewing the flux rope end on, or at an angle, say 45º, as suggested by Chen et al. (2000)? Unfortunately, we cannot yet answer this question. It might be useful to try this again with STEREO mission (Rust 1999b) data, when they become available.

The kind of work described here could eventually lead to accurate predictions of the field configuration in IP disturbances on the basis of signature features in photospheric, chromospheric and coronal images. Learning how to interpret CME images in terms of the embedded magnetic fields would be especially useful for space weather forecasts when the two STEREO spacecraft, with their LASCO-like coronagraphs aboard, are in quadrature with Earth.

We are grateful to be able to check our measurements against the CME catalog generated and maintained by NASA and The Catholic University of America and the Naval Research Laboratory. We used data from SOHO, which is a joint ESA/NASA project. We are also grateful to the Japanese Institute of Space and Astronautical Science for use of the Yohkoh data and to the Big Bear Solar Observatory for Hα images. We thank Ron Lepping for modeling one of the events. We thank an anonymous referee for many helpful suggestions. NASA supported part of this work under grant NAG5-11584. The work of P. W. S. was supported by the Office of Naval Research.
REFERENCES

---. 1998, AnGeo, 16, 1
Burlaga, L. F., et al. 1982, GRL, 9, 1317
Canfield, R. C., Hudson, H. S., & McKenzie, D. E. 1999, GRL, 26, 627
Illing, R. M. E., & Hundhausen, A. J. 1985, JGR, 90, 275
Klein, L. W., & Burlaga, L. F. 1982, JGR, 87, 613
Kumar, A., & Rust, D. M. 1996, JGR, 101, 15667
Leamon, R. J., Canfield, R. C., & Pevtsov, A. A. 2002, JGR, 107, SSH 1
Lepping, R. P., Szabo, A., DeForest, C. E., & Thompson, B. J. 1997, SP-415, Correlated Phenomena at the Sun, in the Heliosphere, and in Geospace (ESA SP-415, Paris), 163
Lindsay, G. M., Luhmann, J. G., Russell, C. T., & Gosling, J. T. 1999, JGR, 104, 12515
Marubashi, K. 1986, AdSpR, 6, 335
Nakagawa, Y., Raadu, M. A., Billings, D. E., & McNamara, D. 1971, SoPh, 19, 72
Plunkett, S. P., et al. 2000, SoPh, 194, 371
Rust, D. M. 1994, GRL, 21, 241
Rust, D. M., & Kumar, A. 1994, SoPh, 155, 69
Wilson, R. M., & Hildner, E. 1984, SoPh, 91, 169
Wu, C.-C., & Lepping, R. P. 2002, JGRSpace, 107, SMP 19
Zhao, X. P., & Webb, D. F. 2003, JGRSpace, 108, SSH 4
Fig. 1. LASCO coronagraph image of the 1998 November 9 CME associated with the interplanetary disturbance of November 13 – 16 (day-of-year DOY 320 = November 16). The inset shows the variation in time of the total field strength at NEAR. The disturbance has a rippled “sheath” or rampart, followed by a smoothly rotating field, which passed by NEAR in the interval bounded by the double-tipped arrows. Time-of-flight speeds are shown on the lower horizontal axis, computed from the time difference between the onset of the associated CME and the time at NEAR. Compare the leading edge (800 km s$^{-1}$ upon leaving the Sun) with the rampart at TOF speed 650 km s$^{-1}$ and compare the bright knot (500 km s$^{-1}$ upon leaving the Sun) with the center of the flux rope’s TOF speed of 505 km s$^{-1}$. Solar north is up and west is to the right. (SOHO/LASCO coronagram)
Fig. 2. Hα features in and around solar AR 8384 at S30° E14° five days after the CME of 1998 November 9. From the counter-clockwise rotation of the spot and the pattern of barbs on the filament, we infer that the flux ropes in the region were left-handed. The filament would have been just over the east limb on the day of the CME, which NEAR detected from 13° over the limb. (Hα image from the Big Bear Solar Observatory)
Fig. 3. CME associated with the IP disturbance of 2000 January 7 recorded by NEAR at 1.37 AU. The long arrows show the correspondence between the measured CME speeds and the TOF speeds. We identify the bright knot with the IP flux rope, which passed by NEAR in the interval bounded by the double-tipped arrows. The measured bright knot speed of 360 km s\(^{-1}\) is close to the average flux-rope speed derived from the time of flight to NEAR. In the image, solar north is up and west is to the right, and we have reversed the time axis of the NEAR magnetometer record to facilitate comparison of the time profile of the magnetic field with the CME image. (SOHO/LASCO coronagram)
Fig. 4. Model showing orientation and size (~ 0.13 AU) of the flux rope at NEAR on 2000 January 7, based on the method of Mulligan et al. (2001b), which does not presume that the flux rope is force-free. The flux rope, indicated by the reticulated cylinder, had right-handed helical fields. The axial field, indicated by the blue line, was mostly northward at NEAR. (The X-axis is along the NEAR-Sun line and the Z-axis is perpendicular to the ecliptic plane.)
Fig. 5. (top) NEAR magnetometer data for the $B_{\text{total}}$ (black), $B_x$ (positive = sunward, red), $B_y$ (positive = eastward, green), $B_z$ (positive = northward, blue) and $B_{\text{total}}$ fields on 1999 August 24 - 25. Vertical dashed lines denote the beginning and end of the flux rope. (middle) Field components in the flux rope, in the minimum variance coordinate system ($B_{\text{total}}$, black; $B_{\text{min}}$, blue; $B_{\text{intermediate}}$, green; $B_{\text{max}}$, red). Note the rotation of the field in the maximum variance direction, which is nearly coincident with the east-west direction. (bottom) A hodogram showing the variation of the field in the $B_{\text{max}} - B_{\text{intermediate}}$ plane during passage through the flux rope.
Fig. 6a. (left) 1999 August 14 H\(\alpha\) image of AR8662 at 1658 UT and the long, dark sinistral filament (at arrowhead) that erupted at the onset of the CME of August 18. Fig. 6b (right) the associated sigmoid (S-shaped feature at arrowhead) as seen in the EIT 286 Å image on 1999 August 14 at 1906 UT. The filament and the sigmoid are both signatures of a right-handed magnetic flux rope. (BBSO and SOHO/EIT images)
Fig. 7. NEAR magnetometer results for the flux rope of 1997 August 20. The format is the same as in Figure 5.
Fig. 8. Edge-enhanced image showing the bright, elliptical knot in the CME of 1997 August 13. The material in the knot may outline part of the flux rope intersected by NEAR on August 20. The magnetometer data on the flux rope are shown in Figure 7.
TABLE 1.

SPEEDS AND ACCELERATIONS OF NON-RECURRING INTERPLANETARY DISTURBANCES AND ASSOCIATED CMES

<table>
<thead>
<tr>
<th>Disturbance Onset Date</th>
<th>CME Onset Date</th>
<th>NEAR Dist. (AU)</th>
<th>NEAR Longitude (Degrees)</th>
<th>Leading Edge TOF Speed (km s(^{-1}))</th>
<th>Corrected Leading Edge CME Speed (km s(^{-1}))</th>
<th>Leading Edge Acceleration (m s(^{-2}))</th>
<th>Corrected Knot Speed (km s(^{-1}))</th>
<th>Flux Rope TOF Speed (km s(^{-1}))</th>
<th>Flux Rope Acceleration (m s(^{-2}))</th>
</tr>
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<tbody>
<tr>
<td>1997 Aug 19.8</td>
<td>1997 Aug 13.3</td>
<td>1.8</td>
<td>52.95</td>
<td>479</td>
<td>401</td>
<td>0.140</td>
<td>276</td>
<td>445</td>
<td>0.280</td>
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<tr>
<td>1998 Nov 13.8</td>
<td>1998 Nov 9.4</td>
<td>1.78</td>
<td>-103.5</td>
<td>700</td>
<td>823</td>
<td>-0.322</td>
<td>514</td>
<td>505</td>
<td>-0.017</td>
</tr>
<tr>
<td>1999 Jul 28.5</td>
<td>1999 Jul 25.6</td>
<td>1.21</td>
<td>131.6</td>
<td>722</td>
<td>1230</td>
<td>-2.027</td>
<td>622</td>
<td>616</td>
<td>-0.019</td>
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<tr>
<td>1999 Aug 24.0</td>
<td>1999 Aug 18.5</td>
<td>1.16</td>
<td>128.2</td>
<td>365</td>
<td>585</td>
<td>-0.463</td>
<td>471</td>
<td>309</td>
<td>-0.288</td>
</tr>
<tr>
<td>1999 Oct 12.4</td>
<td>no CME</td>
<td>1.15</td>
<td>123.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1999 Oct 30.0</td>
<td>1999 Oct 26.9</td>
<td>1.18</td>
<td>121.09</td>
<td>655</td>
<td>385</td>
<td>1.000</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>1999 Nov 3.8</td>
<td>1999 Oct 29.9</td>
<td>1.19</td>
<td>120.27</td>
<td>420</td>
<td>428</td>
<td>-0.019</td>
<td>428</td>
<td>338</td>
<td>-0.172</td>
</tr>
<tr>
<td>1999 Nov 8.3</td>
<td>1999 Nov 4.9</td>
<td>1.2</td>
<td>119.54</td>
<td>611</td>
<td>552</td>
<td>0.202</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>1999 Dec 3.3</td>
<td>1999 Nov 26.3</td>
<td>1.26</td>
<td>113.9</td>
<td>312</td>
<td>345</td>
<td>-0.054</td>
<td>383</td>
<td>295</td>
<td>-0.138</td>
</tr>
<tr>
<td>2000 Jan 7.5</td>
<td>2000 Jan 2.2</td>
<td>1.37</td>
<td>102.1</td>
<td>451</td>
<td>542</td>
<td>-0.200</td>
<td>368</td>
<td>373</td>
<td>0.009</td>
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<tr>
<td>2000 Mar 21.1</td>
<td>2000 Mar 16.3</td>
<td>1.6</td>
<td>67.7</td>
<td>577</td>
<td>465</td>
<td>0.271</td>
<td>519</td>
<td>486</td>
<td>-0.067</td>
</tr>
</tbody>
</table>

Projected CME speeds were corrected by assuming they were headed directly for NEAR.
TOF speed = time-of-flight average speed
* No knot identified in CME images
### TABLE 2
COMPARISON OF IP AND SOLAR FLUX ROPE CHIRALITY

<table>
<thead>
<tr>
<th>Disturbance Date</th>
<th>IP Class</th>
<th>Bothmer Chirality</th>
<th>Inferred Chirality</th>
<th>Solar Origin</th>
<th>Flux Rope Clock Angle (Degrees)</th>
<th>Solar Origin Clock Angle (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997 Aug 19</td>
<td>WNE</td>
<td>RH</td>
<td>RH</td>
<td></td>
<td>351 - 303</td>
<td>315</td>
</tr>
<tr>
<td>1998 Nov 13</td>
<td>WSE</td>
<td>LH</td>
<td>LH</td>
<td></td>
<td>222 - 208</td>
<td>210</td>
</tr>
<tr>
<td>1999 Jul 28</td>
<td>NES</td>
<td>RH</td>
<td>a</td>
<td></td>
<td>72 - 44</td>
<td>45</td>
</tr>
<tr>
<td>1999 Aug 24</td>
<td>WNE</td>
<td>RH</td>
<td>RH</td>
<td></td>
<td>4 - 40</td>
<td>135</td>
</tr>
<tr>
<td>1999 Oct 12</td>
<td>b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1999 Oct 30</td>
<td>b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1999 Nov 3</td>
<td>WNE</td>
<td>RH</td>
<td>a</td>
<td></td>
<td>10 - 5</td>
<td>a</td>
</tr>
<tr>
<td>1999 Nov 8</td>
<td>b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1999 Dec 2</td>
<td>ENW</td>
<td>LH</td>
<td>RH</td>
<td></td>
<td>314 - 345</td>
<td>335</td>
</tr>
<tr>
<td>2000 Jan 7</td>
<td>WNE</td>
<td>RH</td>
<td>RH</td>
<td></td>
<td>12 - 26</td>
<td>150</td>
</tr>
<tr>
<td>2000 Mar 21</td>
<td>WSE</td>
<td>LH</td>
<td>a</td>
<td></td>
<td>186 - 209</td>
<td>a</td>
</tr>
</tbody>
</table>

*a* Could not determine from solar observations

*b* Not a flux rope

*c* First value from multivariant analysis: second value from model field fit