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CORONAL WHITE-LIGHT JETS NEAR SUNSPOT MAXIMUM

Y.-M. WANG AND N. R. SHEELEY, JR.
Code 7672, E. O. Hulburt Center for Space Research, Naval Research Laboratory, 4555 Overlook Avenue, SW, Washington, DC 20375-5352;
ywang@yucca.nrl.navy.mil, sheeley@spruce.nrl.navy.mil
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ABSTRACT

During the 1996–1997 activity minimum, the Large Angle and Spectrometric Coronagraph (LASCO) on the *Solar and Heliospheric Observatory* (*SOHO*) recorded numerous jetlike ejections above the Sun's polar regions. In a previous study, we showed that these white-light ejections were the outward extensions of extreme-ultraviolet (EUV) jets, which in turn originated from flaring bright points inside the polar coronal holes. Here we investigate a number of jetlike events observed with LASCO during the current sunspot maximum. To identify the solar surface counterparts of these events, we again use Fe XII $\lambda195$ images obtained by the EUV Imaging Telescope on *SOHO*. The white-light jets in our sample have angular widths of $\sim3°–7°$ and velocities typically of order 600 km s^{-1}; they tend to be brighter and wider than the polar jets observed near sunspot minimum and are distributed over a much greater range of latitudes. Many of the ejections are recurrent in nature and originate from active regions located inside or near the boundaries of nonpolar coronal holes. We deduce that the jet-producing regions consist of systems of closed magnetic loops partially surrounded by open fields; perturbations in the closed fields caused them to reconnect with the overlying open flux, releasing the trapped energy in the form of jetlike ejections. In some events, the core of the active region erupts, producing fast, collimated ejections with widths of up to $\sim15°$.

Subject headings: Sun: activity — Sun: corona — Sun: coronal mass ejections (CMEs) — Sun: filaments — Sun: magnetic fields — Sun: prominences

1. INTRODUCTION

During the 1996–1997 sunspot minimum, time-lapse movies made with the Large Angle and Spectrometric Coronagraph (LASCO) on the *Solar and Heliospheric Observatory* (*SOHO*) revealed the intermittent presence of long, linear structures propagating outward from the Sun's polar regions (St. Cyr et al. 1997; Wang et al. 1998; Wood et al. 1999). An average of $\sim$3–4 of these faint white-light jets, whose angular widths ranged from $\sim1°$ to $\sim4°$, were observed daily at sky-plane–projected heliocentric distances of $r \sim 2$–$6\ R_\odot$. Their leading edges propagated at velocities of 400–1100 km s^{-1}, while the bulk of their material traveled at lower speeds of order 250 km s^{-1}. The ejections have also been detected in O VI and Lyα with the Ultraviolet Coronagraph Spectrometer on *SOHO*, at heights of $r \sim 2\ R_\odot$ (Dobrzycka et al. 2000, 2002). From Fe XII $\lambda195$ images recorded with the EUV Imaging Telescope (EIT) on *SOHO*, Wang et al. (1998) identified low-corona counterparts to 27 LASCO jet events during 1997–1998. In all cases, the corresponding EIT jets were found to originate near extreme-ultraviolet (EUV) bright points located inside the large polar coronal holes.

As the Sun's high-latitude magnetic fields reverse their polarity and the polar holes shrink and disappear toward sunspot maximum, the occurrence rate of white-light jets over the polar regions might be expected to decrease markedly. These relatively faint events should also tend to be increasingly masked by streamers and ordinary coronal mass ejections (CMEs). Indeed, the jetlike ejections detected by LASCO during 1999–2001 have generally been brighter and more widely distributed in latitude than those seen during 1996–1998. This study explores the nature and origin of the solar maximum jets.

2. OBSERVATIONS

As in Wang et al. (1998), our basic procedure is to identify jetlike events in *SOHO*/LASCO images and then to search for possible solar-surface counterparts in *SOHO*/EIT images. We have not attempted a systematic survey of all narrow, impulsive ejections recorded by LASCO during the 1999–2001 activity maximum, which would run to many hundreds of cases. To limit the range of the investigation, we have selected a number of well-observed events that are clearly associated with coronal holes and/or have narrow, jetlike Fe XII $\lambda195$ counterparts.

The LASCO instrument (Brueckner et al. 1995) comprises three coronagraphs with overlapping fields of view: C1 ($1.1\ R_\odot \lesssim r \lesssim 3\ R_\odot$), C2 ($2\ R_\odot \lesssim r \lesssim 6\ R_\odot$), and C3 ($4\ R_\odot \lesssim r \lesssim 30\ R_\odot$). Both C2 and C3 are externally occulted, white-light coronagraphs; C1 was designed for spectrometric purposes but has been out of operation since 1998 June. Each component is equipped with its own 1024×1024 pixel CCD camera, which records images with an effective 2 pixel resolution of 11″ (C1), 24″ (C2), and 112″ (C3). Except for a 4 month interruption during 1998, when contact with the *SOHO* spacecraft was lost, C2 and C3 have been monitoring the corona continuously from the vicinity of the L1 point since early 1996.

The EIT instrument (Delaboudinière et al. 1995) employs normal-incidence, multilayer-coated optics and a 1024×1024 pixel CCD to record full-disk images in the four emission lines Fe IX $\lambda171$, Fe XII $\lambda195$, Fe XV $\lambda284$, and He II $\lambda304$. The images extend out to $r \sim 1.5\ R_\odot$ and have a 2 pixel resolution of 5″. High-cadence observations are made routinely only in Fe XII $\lambda195$, whose emission peaks at a temperature of 1.6×10^6 K.

Typically, C2, C3, and $\lambda195$ images are recorded once every $\sim$20, $\sim$30, and $\sim$12 minutes, respectively. Both

LASCO and EIT ejective events are most easily identified by subtracting pairs of images taken at successive times. In such difference frames, white (black) indicates that the local coronal brightness or density has increased (decreased) during the lapsed interval.

In the following subsections, we describe our selected sample of jetlike events observed near sunspot maximum.

2.1. *Recurrent Jet Activity during 1999 August 21–25*

During the latter half of 1999 August, LASCO recorded an unusual number of jetlike ejections over the southeast polar region of the Sun. Five of these events, from the period August 21–25, had clearly identifiable EIT counterparts. The corresponding white-light and Fe XII λ195 jets are displayed in the left and right columns of Figure 1. The event of August 21 (*top row*) consists of two closely spaced jets, visible in both the LASCO C2 and EIT difference images. The source of the August 21–25 jets is seen to be a small active region located inside the southeast limb at a latitude of $\sim$35°–40°. As the source region, which lies at the poleward edge of a much larger activity complex, rotates westward, the position angle (P.A.) of the white-light jets increases progressively from $\sim$158° to $\sim$176°. The directions of the EIT and LASCO jets are shifted significantly with respect to each other, suggesting that the ejected plasma bends sharply eastward as it propagates from the low corona to $r \sim 2\ R_\odot$. The angular widths of the white-light jets (some of which may consist of multiple ejections) range from $\sim$3° to $\sim$7°. Five fainter jets, having widths of only $\sim$1°–3°, were also detected in the same region during August 20, 22, 23, and 27.

Figure 2 shows the jet-emitting region as it appears in daily He I λ10830 spectroheliograms (*left*) and Fe I λ8688 magnetograms (*right*) obtained at the National Solar Observatory (NSO/Kitt Peak) during August 21–23. The small active region lies at the eastern end of a coronal hole (white area in the He I λ10830 images) centered near latitude S35°. This negative-polarity hole forks and terminates just to the north and south of the active region, surrounding it on three sides (although the southern arm shrinks significantly after August 22). In the magnetograms, the active region has the form of a small bipolar magnetic region (BMR), with its leading, negative pole located equatorward of its trailing, positive pole (the normal polarity orientation for a southern hemisphere bipole during solar cycle 23).

Figure 3 focuses on the EIT jet of August 23. Here the formation and evolution of the jet are illustrated by the sequence of undifferenced Fe XII λ195 images taken at 12 minute intervals between 21:24 and 22:12 UT. The location of the nearby coronal hole is indicated by the He II λ304 image recorded at 19:18 UT (Fig. 3, *second panel at right*), while the distribution of the photospheric field at 20:47 and 22:23 UT is shown by the pair of Ni I λ6768 magnetograms taken with the Michelson Doppler Imager (MDI) on *SOHO* (lower right panels of Fig. 3). The jet is directed from the positive-polarity sector of the BMR into the region of weak, negative-polarity background field to the south. At the start of the event, a small brightening appears in the Fe XII λ195 image at 21:36 UT, in the vicinity of the polarity inversion line of the BMR. At 21:48 UT, the incipient jet is observed as a southward pointing, cusplike structure with one leg originating near the compact brightening; at the same time, an ejection or pattern of brightenings propagates northeastward from the latter point. By 22:00 UT, a long, narrow jet has developed, with its base shifted just eastward of the original cusp structure. An inspection of the MDI magnetograms suggests that some flux cancellation occurs between 20:47 and 22:23 UT near the location of the compact Fe XII λ195 brightening, although the lack of higher cadence magnetic data makes the relationship to the EIT event unclear.

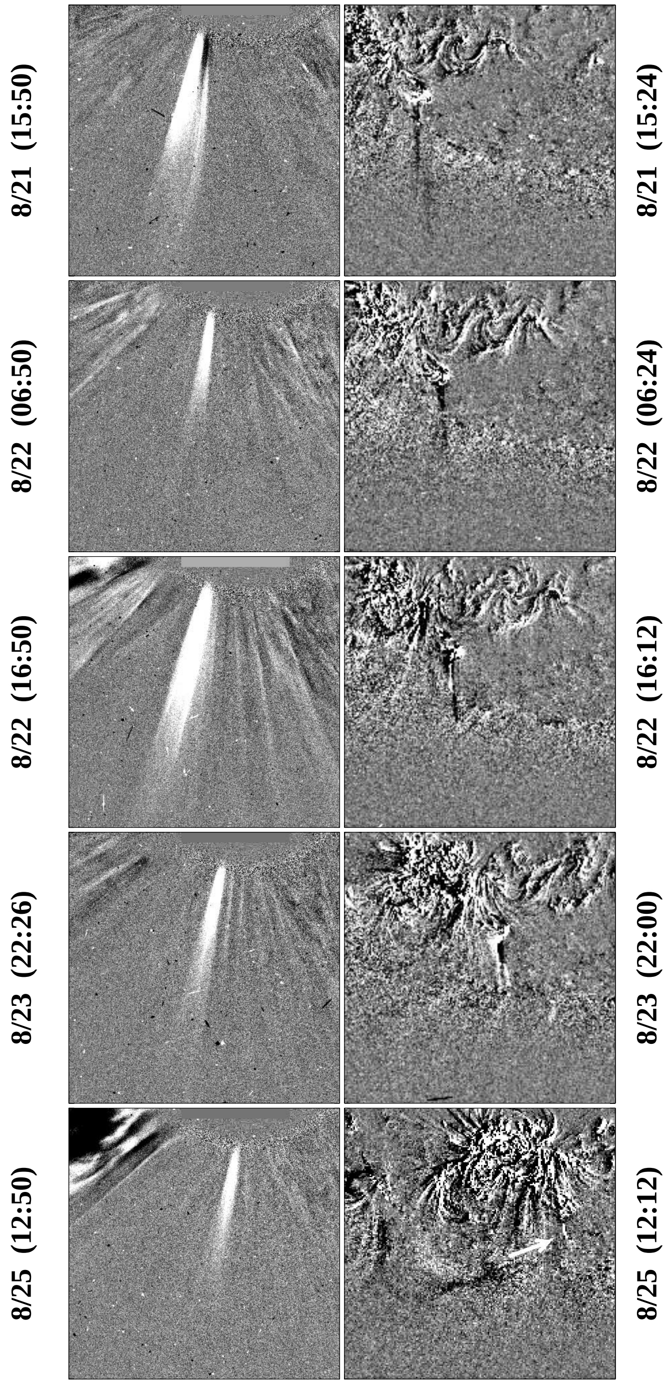

FIG. 1.—Correlated LASCO/EIT jets during 1999 August 21–25. *Left:* Five white-light jet events; each frame represents the difference between two LASCO C2 images taken 24–60 minutes apart. *Right:* EUV counterparts of the white-light jets; each frame represents the difference between two Fe XII λ195 images taken 12 minutes apart. Arrow in the bottom right panel indicates the location of the August 25 EIT ejection.

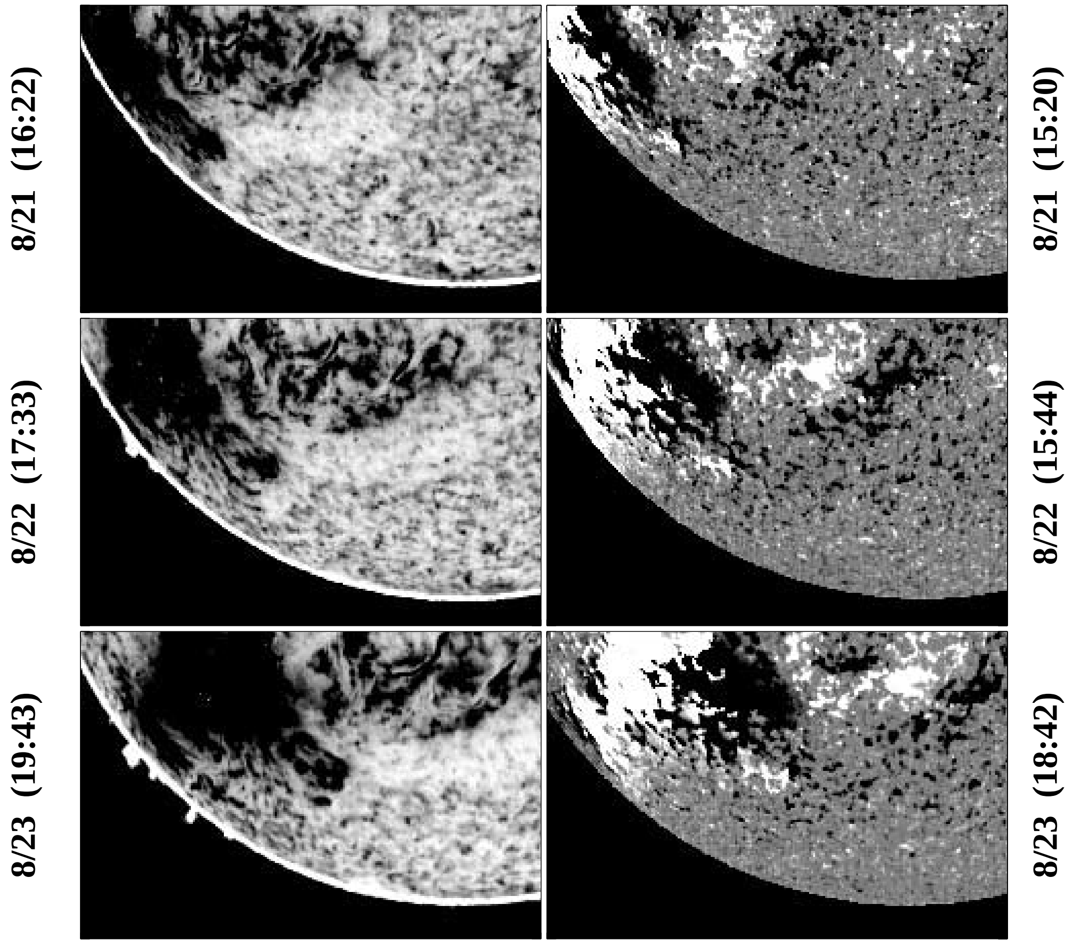

FIG. 2.—He I λ10830 spectroheliograms (*left*) and Fe I λ8688 magnetograms (*right*) from NSO/Kitt Peak, showing the jet-emitting region as it rotates from the east limb toward central meridian during 1999 August 21–23. The LASCO/EIT jets originated from the small active region at the eastern edge of the midlatitude coronal hole (*whitish area* in the He I λ10830 images); a corresponding BMR may be seen in the magnetograms.

The initiation of the August 21 and 22 jets followed a similar pattern to that of August 23. In each case, the development of the narrow EUV jet was preceded by an eruption that appeared to originate near the neutral line of the BMR, and in which a pattern of Fe XII λ195 brightenings was observed extending toward the northeast. Although we are unable to determine the nature of the eruptions, it is possible that they represent ejections of filament material, which is more easily detected when the event occurs at the solar limb (see the following subsections).

The white-light jets in Figure 1 were significantly brighter than those seen over the polar coronal holes during 1996–1998; unlike the latter, they could be tracked well into the LASCO C3 field of view beyond $r \sim 6\ R_\odot$. The height-time trajectories of these jets can be displayed using a technique developed by J. H. Walters and described in Sheeley et al. (1999). The procedure is to extract, from each of a succession of LASCO running-difference images, a radial strip centered on the given event; the strips are then oriented vertically and arranged in a time-ordered sequence. Figure 4 shows a height-time map constructed from both C2 and C3 data over the interval 1999 August 21–24; here the vertical axis extends to $r = 20\ R_\odot$, while the viewing slit is centered at P.A. $= 163°$. Each ejection produces a black and white track, in which (for a density enhancement) white leads black in the direction of motion. The three longest tracks correspond to the jet events in the top, third, and fourth rows of Figure 1. From the average slopes of their trajectories, we deduce that these jets travel at roughly constant velocities of order 600 km s^{-1}. When the detailed structure of the tracks is taken into account, however, the leading edges of the jets (as defined by the outer boundary of the white region) are found to propagate outward at $\sim$700–1000 km s^{-1}, whereas their "centroids" (as defined by the black-white boundary) travel at only $\sim$300–500 km s^{-1}. This wide range of speeds, which may reflect the nonsimultaneous, multicomponent nature of the ejections, causes the jets to elongate as they propagate away from the Sun (see also Wang et al. 1998).

2.2. *Jet Event of 1999 April 10*

In Figure 5 (*top panel*), a 3° wide jet is seen entering the LASCO C2 field of view at 04:31 UT on 1999 April 10; the velocity of the ejection is of order 600 km s^{-1}. The lower panels of Figure 5 show the evolution of the source region as it appears in Fe XII λ195 difference images. At 03:24 UT, two loop systems begin to erupt simultaneously at the Sun's southwest limb, one of which is associated with an active region, the other of which overlies a small high-latitude fila-

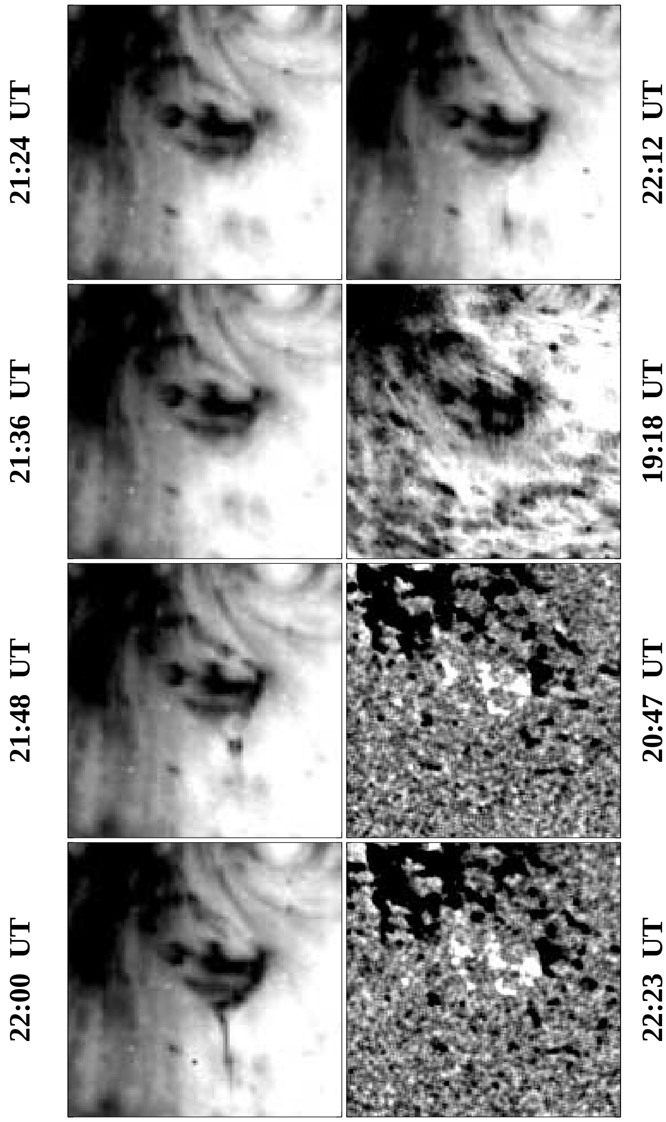

FIG. 3.—*Left, top right:* Sequence of undifferenced Fe XII $\lambda195$ images taken at 12 minute intervals, showing the formation and evolution of the EIT jet of August 23. Gray scale has been reversed so that bright EUV emission appears dark. *Second panel at right:* He II $\lambda304$ image recorded before the event; gray scale has been reversed so that strong plage appears black and coronal hole areas are white. *Lower right panels:* MDI Ni I $\lambda6768$ magnetograms recorded before and after the jet event. Gray scale for the line-of-sight photospheric field ranges from $B_{\rm los} \leq -20$ G (*black*) to $B_{\rm los} \geq +20$ G (*white*).

ment. The latter eruption subsequently develops into the spiked structure visible at 04:03 and 04:36 UT. The spike or cusp overlies a pair of abutting loop arcades; its P.A. ($\sim$219°) corresponds roughly to that of the LASCO C2 jet ($\sim$216°).

2.3. *Jet Event of 1999 May 7*

At 22:26 UT on 1999 May 7 (one rotation after the event described in § 2.2), a white-light jet was observed over the southwest polar region at P.A. $\sim$ 207° (Fig. 6, *top panel*). As indicated by the sequence of undifferenced Fe XII $\lambda195$ images in the bottom three panels of Figure 6, the probable source of this jet was an ephemeral region centered at P.A. $\sim$ 202° inside the remnant of the south polar hole. At 22:00 UT, this mini active region ejected a small filament (visible as a whitish feature in the reversed gray-scale images); subsequently, an arcade of miniature postflare loops appears to form. (Subtraction of the images taken at 22:00 and 21:48 UT reveals the presence of a very faint, jetlike depletion above the erupting filament.) The LASCO jets observed during the solar minimum period were similarly triggered by flaring bright points or small ephemeral regions inside the polar coronal holes (see Wang et al. 1998).

2.4. *Jet Event of 1999 September 18*

Figure 7 (*top panel*) shows a bright, $\sim$7° wide jet entering the C2 field of view (P.A. $\sim$ 66°) at 19:31 UT on 1999 September 18. A corresponding jet structure can be seen at P.A. $\sim$ 71° in the difference of Fe XII $\lambda195$ images taken at 19:13 and 18:48 UT (Fig. 7, *second panel*). The ejection originates from a small active region located toward the northern end of a low-latitude corona hole, which is rotating past the east limb and is represented by the dark area in the undifferenced $\lambda195$ frame at 18:48 UT (Fig. 7, *third panel*); the arrow in this frame points to a small filament that is also ejected during the event (with the subsequent formation of miniature postflare loops). The location of the active region relative to the coronal hole is seen more clearly in the Fe XV $\lambda284$ image recorded 3 days later (Fig. 7, *bottom panel*). The same active region–coronal hole system produced several other jetlike LASCO/EIT events earlier on September 18. The basic configuration is reminiscent of the source region of the August 21–25 jets.

2.5. *Jetlike Events of 1999 November 12 and 14*

From 06:54 to 07:54 UT on 1999 November 12, a bright ejection with an angular width of order 10° traversed the LASCO C2 field of view at P.A. $\sim$ 277° (Fig. 8, *left panels*). Here as in most of the white-light events described in this paper, the ejection widens with time and drifts systematically in direction and P.A., since it consists of multiple components emitted at slightly different times and locations. From its track in a height-time map constructed from C2 and C3 running-difference images (not displayed here), we deduce that the velocity of the ejection was of order 900 km s^{-1}, with a small amount of deceleration occurring in the C3 field of view. The Fe XII $\lambda195$ difference images in the right-hand column of Figure 8 show an active region undergoing an eruption directly underneath the white-light event. No well-defined EUV jet is seen; instead, the active region loops appear to open up during the eruption, forming a relatively wide, vertical structure. As is evident from the Fe XV $\lambda284$ image in the bottom right panel, the active region is located inside a low-latitude coronal hole, where it emerged 3 days earlier.

As shown in Figure 9, the same active region erupted 2 days later during its west limb passage. The white-light ejection propagates at a nearly constant speed of order 1000 km s^{-1}; in LASCO C3 images, it appears as an elongated, looplike structure with an angular width of $\sim$15°. A series of jetlike events was also observed on October 17–18, during the previous west-limb transit of the same positive-polarity coronal hole. The source of the ejections was again an active region inside the hole.

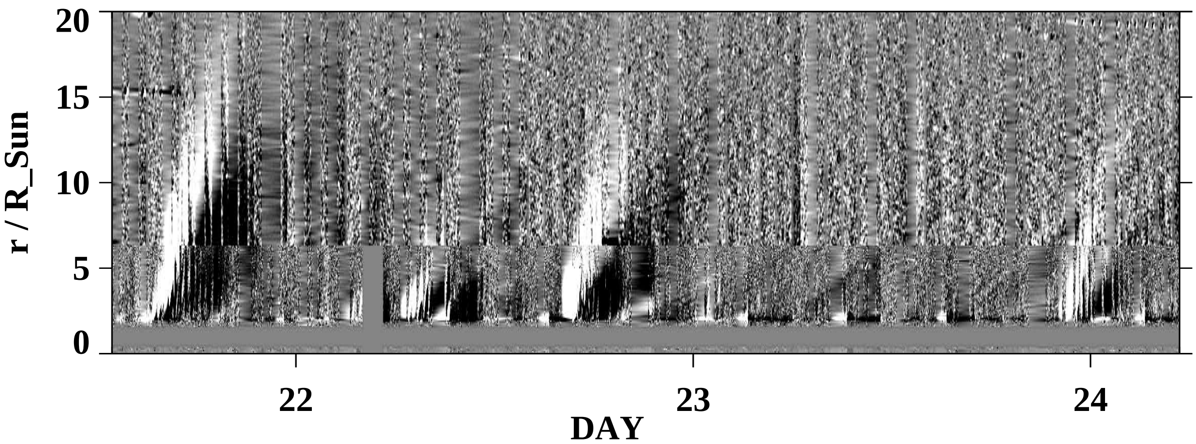

FIG. 4.—Height-time trajectories for the white-light jets of 1999 August 21–23. Radial strips centered at P.A. = 163° were extracted from successive LASCO C2 and C3 running-difference images and arranged in a time-ordered sequence. The resulting r-t map, which has been truncated at $r = 20\ R_{\odot}$, consists of a series of tracks in which white leads black in the direction of motion.

2.6. *Recurrent Jets of 2000 June 21*

Figure 10 shows two "homologous" LASCO/EIT jet events recorded on 2000 June 21. Although the white-light jets emerged into the LASCO C2 field of view above the north polar region, the source was a small active region located inside a negative-polarity, on-disk coronal hole near latitude N30°. From an inspection of NSO/Kitt Peak and MDI magnetograms taken during June 18–23 (not reproduced here), we deduce that the associated BMR was undergoing rapid diffusive decay and flux cancellation at the time of the eruptions.

2.7. *Recurrent Jets of 2000 September 22–23*

The Fe XV λ284 image in Figure 11 shows an activity complex along the western boundary of a transequatorial coronal hole that persisted near Carrington longitude 180° from September through December of 2000. (The rotation-by-rotation evolution of this negative-polarity coronal hole is displayed in Fig. 2 of Sheeley & Wang 2001.) When the active region reached the west limb on 2000 September 22–23, it emitted three Fe XII λ195 jets at P.A. ~ 288°–290°; corresponding white-light ejections, having angular widths of ~3°–7°, were recorded at P.A. ~ 290°–295° (see Fig. 12, where the LASCO and EIT events are displayed in the left and right columns, respectively). As is evident from the tapered appearance of the white-light jets (with their relatively narrow leading edges), the ejections broadened with time during each event.

2.8. *Recurrent Jetlike Events of 2000 November 3–5*

The transequatorial coronal hole in Figure 11 appeared two rotations later with an active region now present along its southeastern boundary. A series of correlated LASCO/EIT events were observed as this active region rotated into view at the east limb during 2000 November 3–5 (Fig. 13). The white-light ejections (shown here in instantaneous C2 images rather than difference frames) were centered at P.A. ~ 108°–114°, directly above the erupting active region, and had widths ranging from ~3° to ~15°. In the case of the November 5 event, a filament eruption was observed in Fe XII λ195 and the white-light ejection contained a loop-shaped structure with a central cavity (see Fig. 13, *bottom left panel*). Height-time maps indicate that the ejections of November 3 and 5 each consisted of two or more components with speeds ranging from ~800 to ~500 km s^{-1}; the tracks showed noticeable deceleration (downward curvature) in the C3 field of view.

3. RELATION TO THE CORONAL MAGNETIC FIELD

In Wang et al. (1998), we suggested that the LASCO/EIT jets observed near solar minimum were triggered by field line reconnection between small bipoles inside the polar coronal holes and the surrounding open flux. An obvious question is whether the relatively bright jets and jetlike ejections described in § 2 originated in a similar manner, except that the coronal holes are now located at lower latitudes and the bright points are replaced by larger bipoles or active regions, which sometimes straddle the hole boundaries or lie between two holes of like polarity. To address this question, we examine the coronal field configuration in the vicinity of the 1999 August 21–25 and April 10 events, as deduced by applying a potential-field source-surface (PFSS) extrapolation to the observed photospheric field. In the PFSS model (Schatten, Wilcox, & Ness 1969), the corona is assumed to remain current free out to a spherical "source surface" at $r = 2.5\ R_{\odot}$, where the tangential field components are set to zero; at the inner boundary, the radial component B_r of the potential field is matched to the photospheric field, which is assumed to be radially oriented at the depth where it is measured (Wang & Sheeley 1992). All field lines that extend from the photosphere to the source surface are defined to be "open," and their footpoint areas are taken to represent coronal holes. It should be emphasized that the PFSS model is not intended to describe the detailed magnetic topology of the source region at the time of the eruption but only the global, time-averaged distribution of the coronal field.

Figure 14 shows the field line configuration over the southeast quadrant of the solar disk on 1999 August 23, obtained by extrapolating the NSO/Kitt Peak photospheric field map for Carrington rotation (CR) 1953. Open field lines (*color coded green*) are rooted to the north and west of the small, jet-producing bipole, which lies at the southwest corner of a much larger active region. The negative-polarity footpoint areas of this open flux correspond approximately

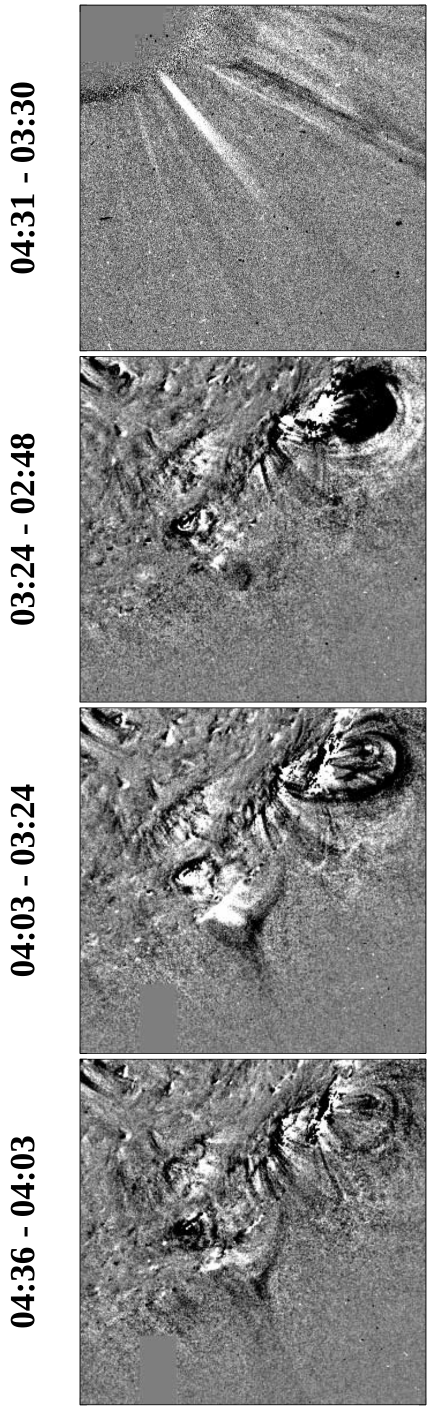

FIG. 5.—Jet event of 1999 April 10. *Top panel:* Difference of LASCO C2 images taken at 04:31 and 03:30 UT, showing the white-light jet. *Bottom three panels:* Fe XII λ195 difference images, showing the evolution of the source region at the southwest limb between 03:24 and 04:36 UT.

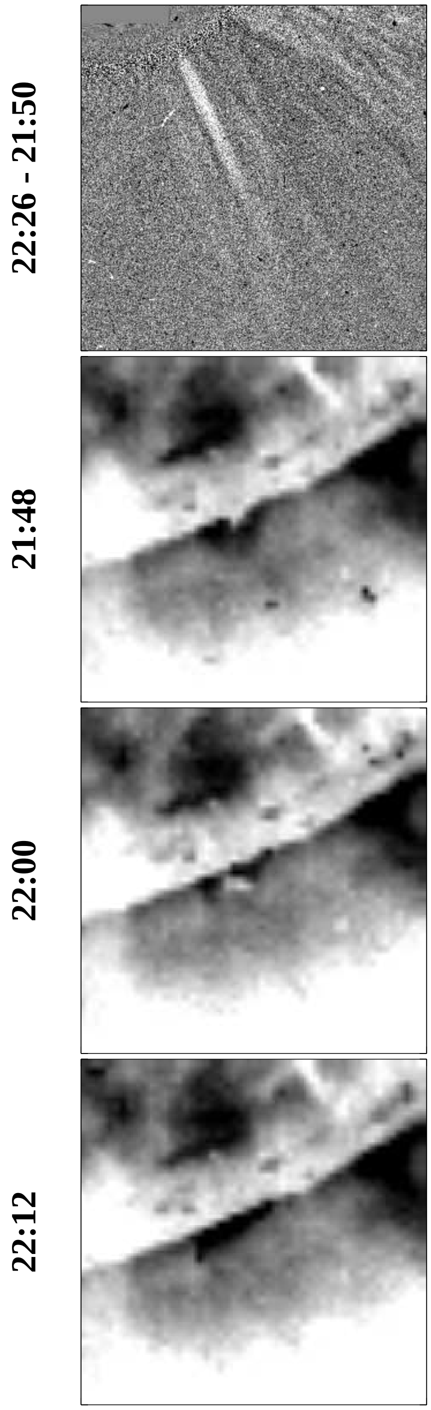

FIG. 6.—Polar-hole jet event of 1999 May 7. *Top panel:* Difference of LASCO C2 images taken at 22:26 and 21:50 UT, showing the white-light jet. *Bottom three panels:* Undifferenced Fe XII λ195 images recorded at 21:48, 22:00, and 22:12 UT, showing the ejection of a small filament from an ephemeral region inside the south polar hole. Here the gray scale has been reversed so that bright EUV emission appears dark and the filament is visible as a small white feature.

to the location of the midlatitude coronal hole in Figures 2 (*bottom left panel*) and 3 (*second panel at right*). The open field lines originating just northward of the positive-polarity sector of the small bipole are highly nonradial, curving first westward as they cross above the BMR, then eastward as they approach the source surface at $r = 2.5\ R_{\odot}$. If we associate the jets of August 21–25 with these field lines, we can then understand why the direction of the ejections appears to swing from southwestward in the Fe XII λ195 images to southeastward when traversing the LASCO C2 field of view (see Fig. 1). The jets were presumably triggered when the closed loops connecting the poles of the BMR reconnected with the overlying open flux. The footpoints of the latter would then have been transferred from the region north of the BMR to its negative-polarity sector.

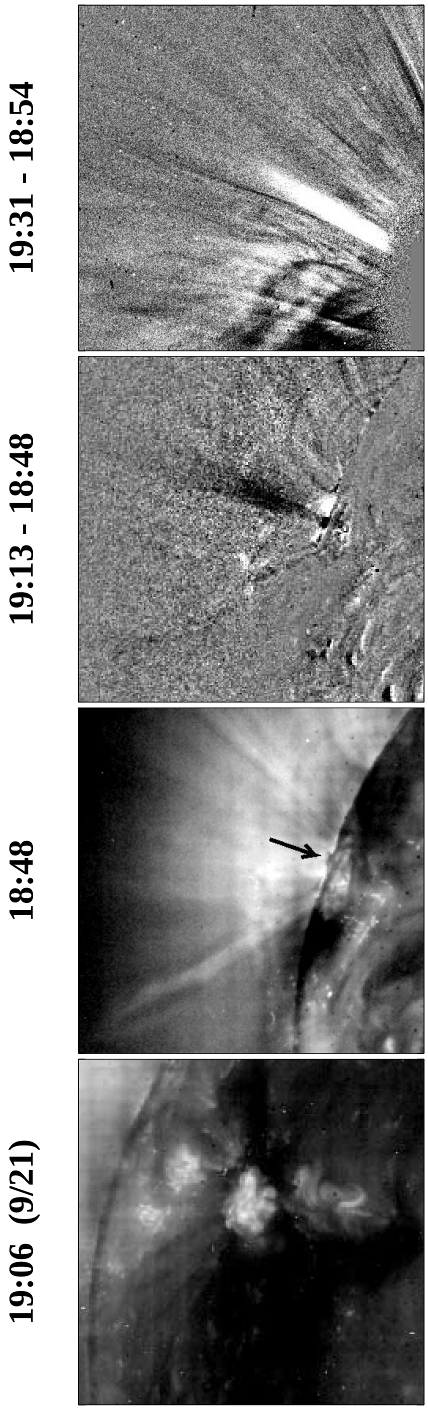

FIG. 7.—Jet event of 1999 September 18. *Top panel:* Difference of LASCO C2 images taken at 19:31 and 18:54 UT. *Second panel:* Difference of Fe XII λ195 images taken at 19:13 and 18:48 UT. *Third panel:* Undifferenced Fe XII λ195 image at 18:48 UT; arrow indicates a small filament that is ejected during the event. *Bottom panel:* Undifferenced Fe XV λ284 image recorded at 19:06 UT on September 21. The jet-emitting active region lies inside a low-latitude coronal hole, represented by the black areas in the lower two panels.

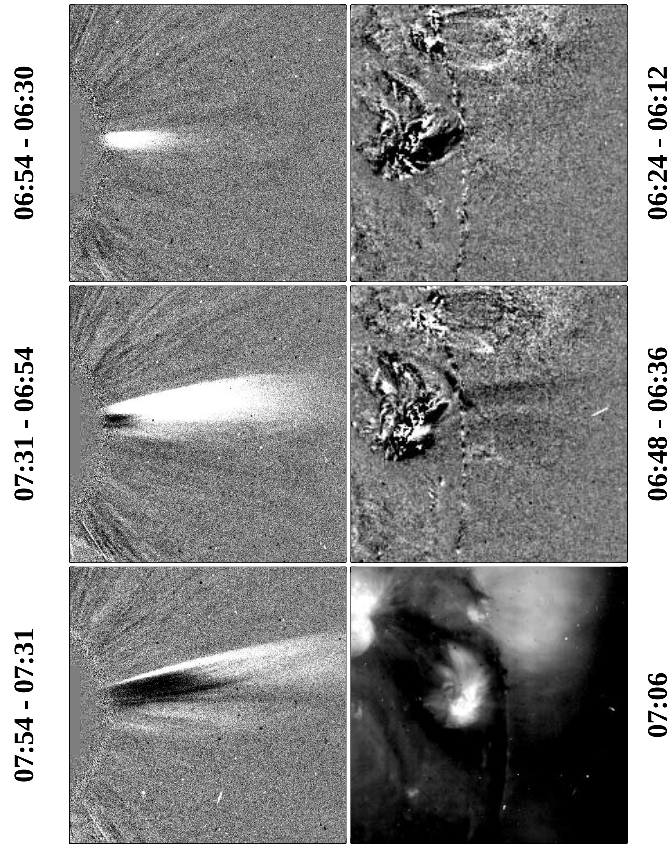

FIG. 8.—Jetlike event of 1999 November 12. *Left:* LASCO C2 running-difference images, showing the white-light ejection traversing the 2–6 $R_\odot$ field of view between 06:54 and 07:54 UT. *Top two panels at right:* Fe XII λ195 difference images, in which the underlying active region is seen undergoing an eruption between 06:24 and 06:48 UT. *Bottom right:* Undifferenced Fe XV λ284 image recorded at 07:06 UT, showing that the active region lies inside a low-latitude coronal hole.

In attributing the formation of the jets to magnetic reconnection between the BMR and the adjacent coronal-hole fields, we implicitly assume the presence of some perturbation to drive the footpoint exchange. Fe XII λ195 observations like those shown in Figure 3 suggest that the small active region underwent a series of miniflares or filament eruptions during August 21–25 and that the jets developed in association with these disruptions of the closed field region.

Figure 15 displays the field line configuration at the southwest limb on 1999 April 10, as derived from the Wilcox Solar Observatory (WSO) photospheric field map for CR 1948. The LASCO/EIT jet (Fig. 5) originates from the region of north-south–oriented loops near the limb. These closed field lines (*coded red*) are surrounded on their poleward and limbward sides by open field lines (*green*), which are rooted in the remnant of the old-cycle, negative-polarity polar hole and in its detached equatorward extension. (Although not shown in this paper, the corresponding coronal holes may be seen in NSO/Kitt Peak He I λ10830 observations during CR 1948.) As in the case of the August events, we deduce that the April 10 jet was triggered by reconnection between the closed loops and the adjacent open flux. This inference is also supported by the morphological appearance of the EIT event, in which the spike representing the jet overlies a pair of closed loop systems (see Fig. 5, *bottom two panels*). The observed structure is suggestive of field line reconnection between a bipole and a monopole, as portrayed in Figure 5 of Shibata et al. (1992) or Figure 3 of Wang (1998). In this model, the jet occurs along the interface between two open flux systems of the

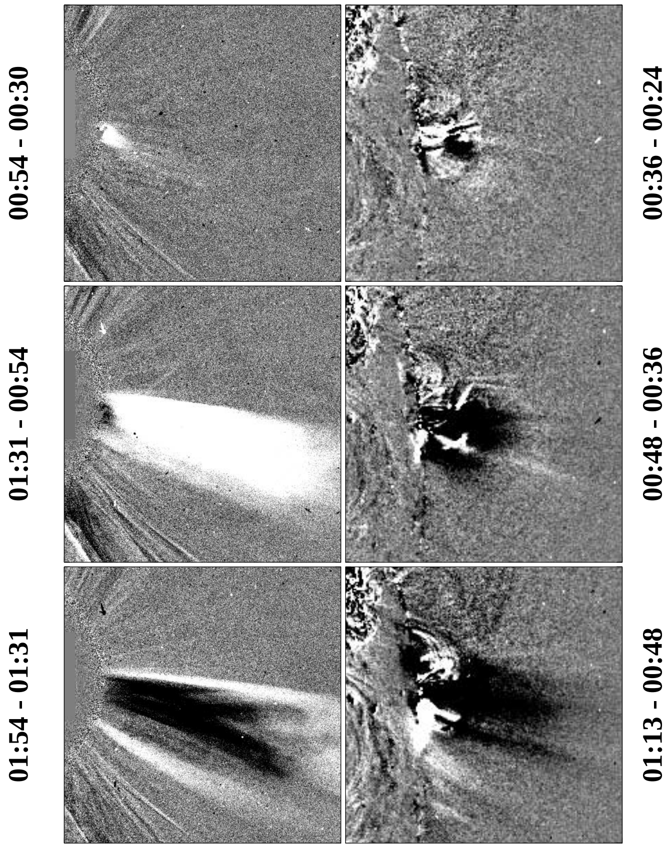

FIG. 9.—Impulsive ejection of 1999 November 14, originating from the same active region–coronal hole system as in Fig. 8. *Left:* Sequence of LASCO C2 running-difference images. *Right:* Sequence of Fe XII λ195 running-difference images.

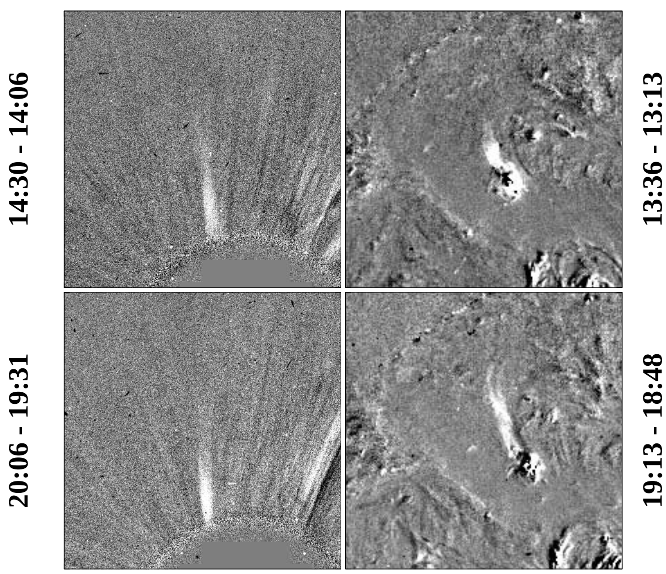

FIG. 10.—Two LASCO/EIT jet events 2000 June 21. *Left:* LASCO C2 difference images showing the white-light jets over the north polar region. *Right:* Fe XII λ195 difference images showing the corresponding EUV ejections. The source of the jets is a small active region located on the disk inside a midlatitude, negative-polarity coronal hole.

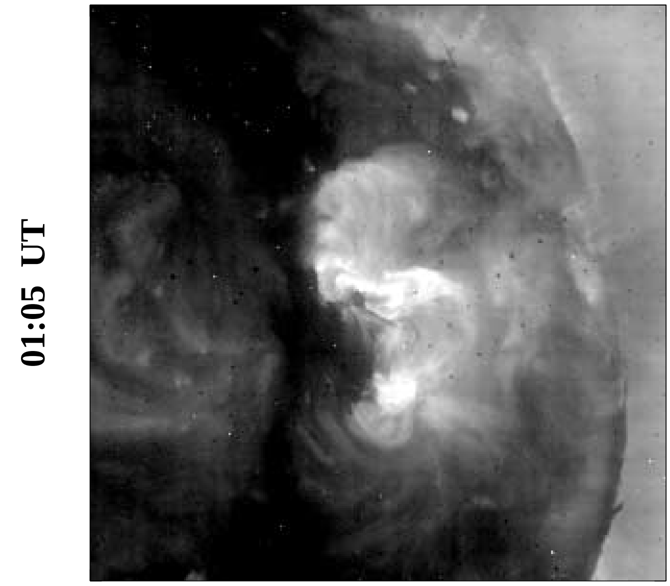

FIG. 11.—Fe XV λ284 image recorded on 2000 September 19, showing a narrow transequatorial coronal hole with an active region lying along its western boundary. The active region was the source of the jets in Fig. 12.

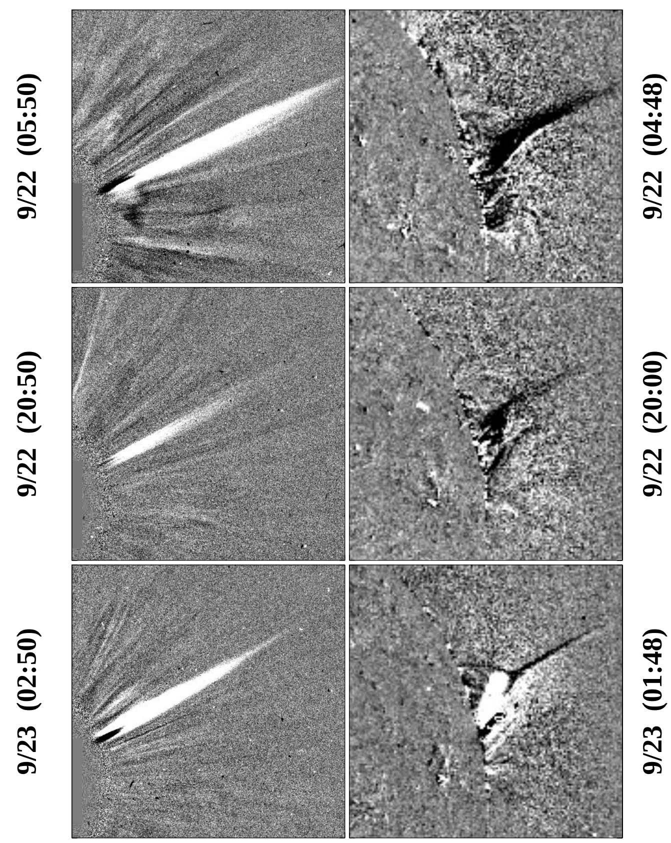

FIG. 12.—Recurrent LASCO/EIT jets 2000 September 22–23. *Left:* LASCO C2 difference images, showing three white-light jet events. *Right:* Fe XII λ195 difference images, showing the corresponding EUV jets. The ejections were observed as the active region–coronal hole system in Fig. 11 rotated past the west limb.

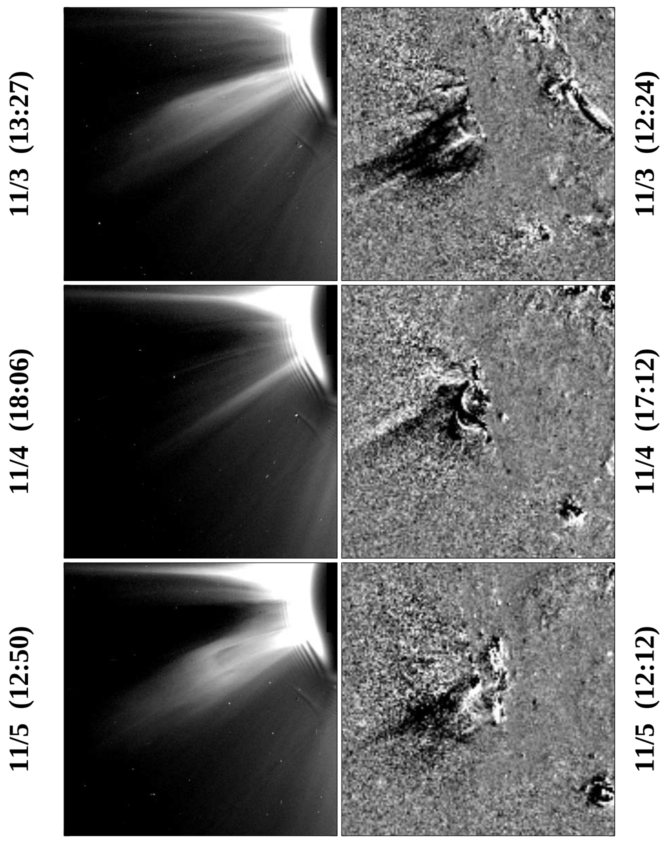

FIG. 13.—Three ejections from an active region–coronal hole system at the east limb 2000 November 3–5. *Left:* Instantaneous LASCO C2 images, showing the white-light events; here a background intensity distribution has been subtracted from each frame to remove the contributions of the F corona and instrumental stray light. *Right:* Fe XII λ195 difference images, showing the corresponding EUV eruptions. The coronal hole (which is the same as that in Fig. 11) is located near the east limb and extends to the north and south of the erupting active region.

same polarity, whose footpoint areas lie on opposite sides of a pair of loop arcades (or magnetic quadrupole). The reconnection process transfers open flux from one side of the separatrix to the other while at the same time transferring closed flux in the opposite direction. In the case of the April 10 event, Figures 5 and 15 suggest that an exchange of open flux took place between the remnant polar hole and its equatorward extension, mediated by the intervening closed field region.

The EIT events of 1999 April 10, May 7 (Fig. 6), September 18 (Fig. 7), November 14 (Fig. 9), and 2000 November 5 (Fig. 13) all showed evidence for the ejection of filament material, which was presumably initially trapped along closed field lines. The flux exchange process would have acted to release the trapped material while simultaneously being driven by the destabilization and outward motion of the filament (cf. the "magnetic breakout" scenario of Antiochos, DeVore, & Klimchuk 1999).

4. DISCUSSION

In this study, we have extended our previous results for the solar minimum period (Wang et al. 1998) by establishing that coronal holes continue to be sources of white-light jets at solar maximum. The jets can be interpreted quite generally as signatures of reconnection between closed magnetic structures and the open coronal-hole flux (as has been suggested by Shibata et al. 1992 for one class of *Yohkoh* X-ray jets). In the process, plasma is transferred from closed to open field lines and escapes into the heliosphere in the form of long, linear ejections.

During 1996–1998, the LASCO/EIT jets originated from bright points or ephemeral regions inside the polar coronal holes (Wang et al. 1998). These small bipoles presumably reconnected with the surrounding open fields as they emerged from below, underwent chance encounters with unipolar flux concentrations, or were otherwise perturbed. Figure 6 shows a polar hole jet in 1999 that was accompanied by a small filament eruption. It is evident that such "small-scale" events should also occur inside nonpolar coronal holes near sunspot maximum; however, the relatively faint jets thus generated are likely to be masked by streamer structures and CME activity. The expected number of such events is also limited by the factor-of-4 decrease in the total surface area occupied by coronal holes between solar minimum and maximum (see Wang, Lean, & Sheeley 2000). Most of the LASCO jets in our present sample originated not from bright points but from larger BMRs located inside or at the boundaries of coronal holes. The events were often accompanied by miniflares or filament eruptions, which in turn may have been induced by photospheric flux cancellation or emergence. Typically, a series of jets were emitted by the same active region over a period of up to several days, with each event consisting of a succession of narrower subejections. The jets were apparently triggered when the perturbed loop systems reconnected with the overlying open flux.

As demonstrated by the examples in Figures 8, 9, and 13, where the white-light structures have latitudinal extents $\gtrsim 10^\circ$, the ejections from a coronal hole need not take the form of thin jets. In these events, the core of the active region appears to erupt, creating new open flux and driving a fast, relatively wide but collimated outflow. In general, we note that the presence of a coronal hole facilitates the escape of plasma into the heliosphere by reducing the energy required for the erupting system to attain a fully open state. (The energy requirement is reduced because the initial configuration is already partially open.) The opening up of the active region fields proceeds in two stages: first, the rising loops reconnect with the overlying open flux of the coronal hole, producing narrow jets; following this footpoint exchange process, the core of the active region opens up and the ejection widens.

We emphasize that the events described in this study represent only a very small fraction of the narrow, impulsive ejections recorded by LASCO during 1999–2001; without having systematically examined the entire LASCO/EIT database, we have searched for cases that are clearly associated with coronal holes or in which the EUV counterpart has a jetlike appearance. On a rough statistical basis (and allowing for the difficulty in identifying hole boundaries near the solar limb), we estimate that at least one-half of the fast, linear white-light ejections with widths $\lesssim 10^\circ$ may have originated inside or near coronal holes.

Gilbert et al. (2001) have investigated a sample of 15 "narrow CMEs" with angular widths $\lesssim 15^\circ$, which were observed with the LASCO coronagraph between March and December of 1999. They found that 14 of their

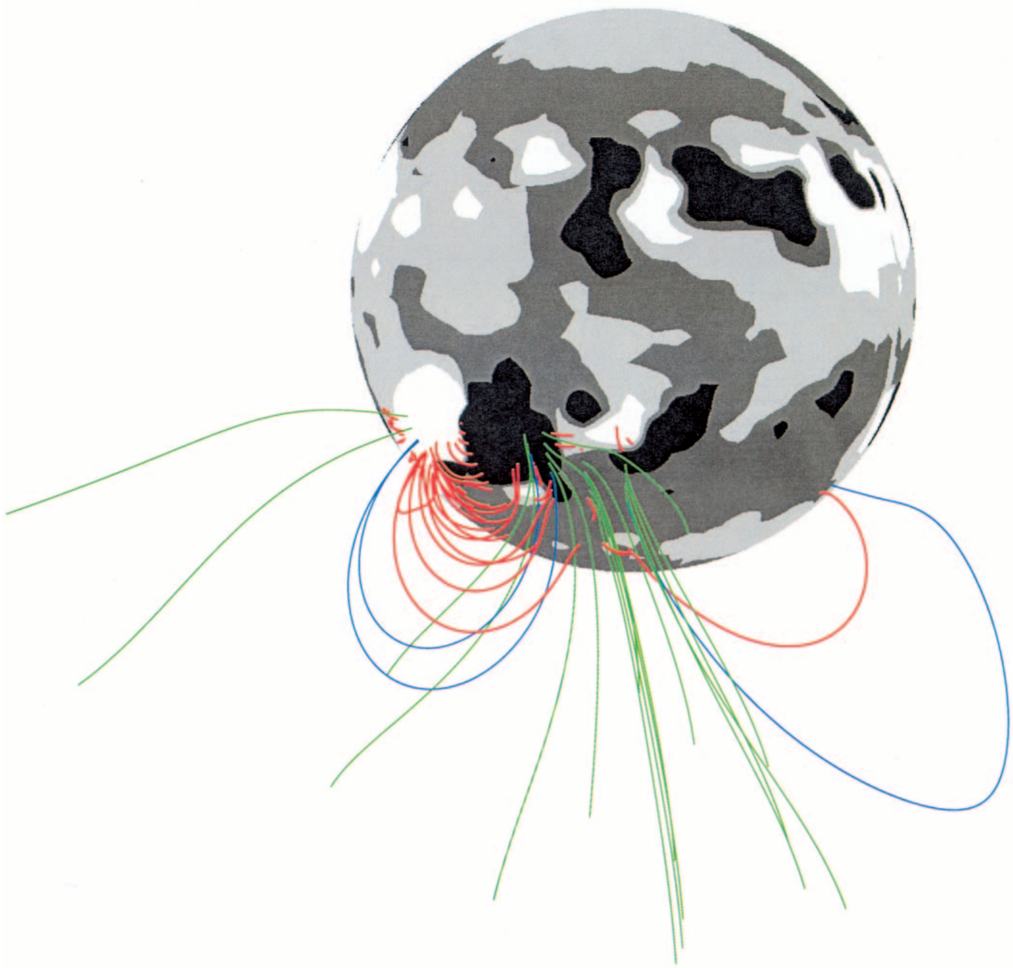

FIG. 14.—Magnetic field line configuration in the vicinity of the 1999 August 23 jet event. The coronal field was derived from a PFSS extrapolation of the NSO photospheric field map for CR 1953 (August 18 to September 14). Open field lines are shown as green; field lines that close below (above) $r = 1.5\ R_{\odot}$ are coded red (blue). Black, dark gray, light gray, and white shadings indicate areas of the solar surface where $B_r < -10$ G, $-10\ \mathrm{G} < B_r < 0$, $0 < B_r < 10$ G, and $B_r > 10$ G, respectively.

events were associated with filaments or flares and that 11 originated near sharp bends in the photospheric neutral line; they did not specifically look for spatial correlations with coronal holes, although some of their sources were located near hole boundaries. While they included the August 23 (22:26 UT) LASCO jet in their study, they associated it (incorrectly, we believe) with an Hα filament located near latitude S60° rather than with the EIT jet event displayed in our Figures 1 and 3. Otherwise, the sample of Gilbert et al. (some of whose events appear to represent continuous, nonimpulsive outflows) does not overlap ours.

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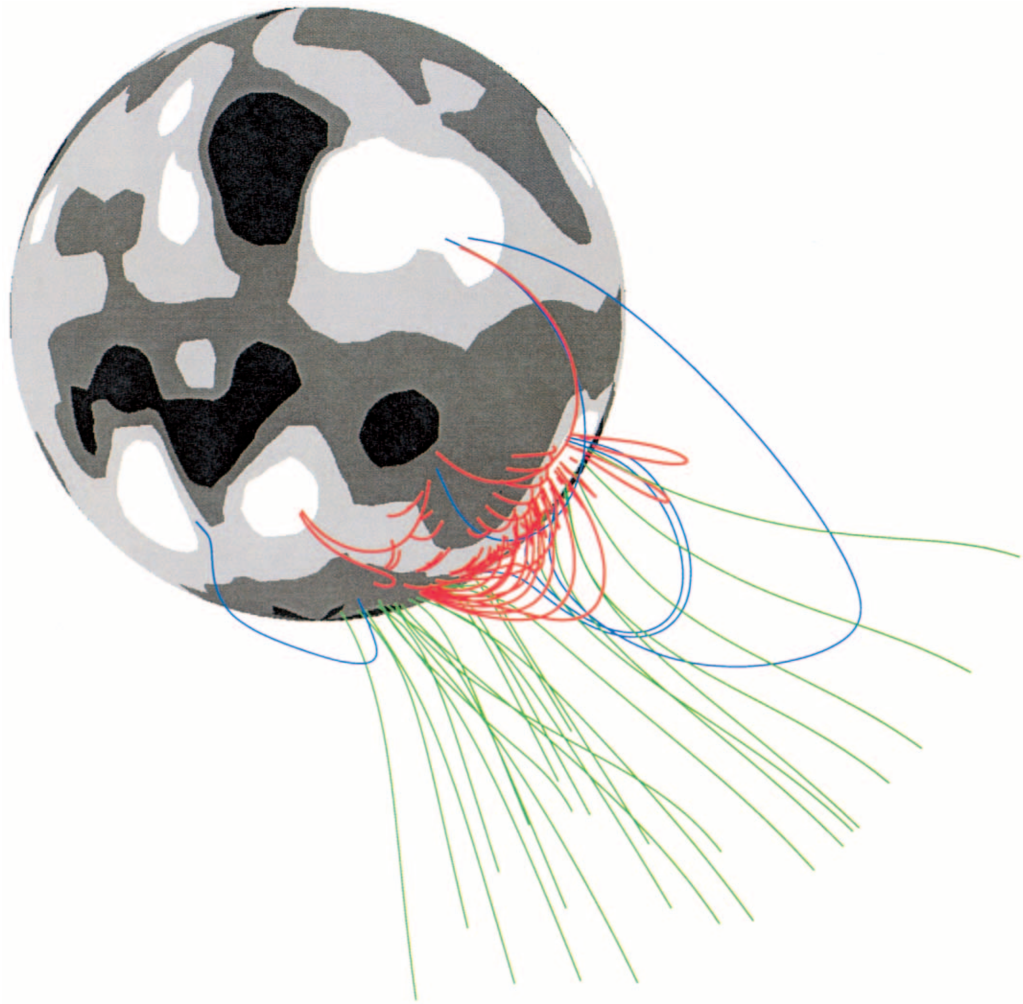

Fig. 15.—Field line configuration in the vicinity of the 1999 April 10 jet event. Here a PFSS extrapolation was applied to the WSO photospheric field map for CR 1948 (April 4 to May 1). Color coding and gray scale are as in Fig. 14.

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