THE ASTROPHYSICAL JOURNAL, 668: L79–L82, 2007 October 10

FIRST DIRECT OBSERVATION OF THE INTERACTION BETWEEN A COMET AND A CORONAL MASS EJECTION LEADING TO A COMPLETE PLASMA TAIL DISCONNECTION

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Received 2007 July 5; accepted 2007 August 17; published 2007 October 1

ABSTRACT

This a discovery report of the first direct imaging of the interaction a comet with a coronal mass ejection (CME) in the inner heliosphere with high temporal and spatial resolution. The observations were obtained by the Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI) Heliospheric Imager-1 (HI-1) aboard the *STEREO* mission. They reveal the extent of the plasma tail of comet 2P/Encke to unprecedented lengths and allow us to examine the mechanism behind a spectacular tail disconnection event. Our preliminary analysis suggests that the disconnection is driven by magnetic reconnection between the magnetic field entrained in the CME and the interplanetary field draped around the comet and not by pressure effects. Further analysis is required before we can conclude whether the reconnection occurs on the day side or on the tail side of the comet. However, the observations offer strong support to the idea that large-scale tail disconnections are magnetic in origin. The online movie reveals a wealth of interactions between solar wind structures and the plasma tail beyond the collision with the CME. Future analyses of this data set should provide critical insights on the structure of the inner heliosphere.

Subject headings: comets: individual (2P/Encke) — Sun: coronal mass ejections (CMEs)

Online material: mpeg animation

1. INTRODUCTION

Comets are unique probes of the heliosphere. Observations of cometary tails have been our first indication of the existence of a solar wind (Biermann 1951). The tail forms when the cometary ionosphere is channeled radially away from the Sun by the interplanetary magnetic field (IMF) draping around the cometary ionosphere. The continuous interaction between the solar wind and the comet can occasionally result in a spectacular phenomenon: the disconnection of the entire plasma tail of the comet. The conditions that lead to these so-called disconnection events (DEs) are not universally accepted (see Voelzke 2005 for a review). Two mechanisms are being considered for the onset of DEs: (1) increases in the ambient solar wind pressure can give rise to plasma instabilities in the tail and could also lead to a DE, albeit a partial one; or (2) magnetic reconnection, either sunward when the comet crosses an IMF boundary (e.g., Niedner & Brandt 1978) or at the tail side when the comet encounters a shock or an area with varying Alfvén Mach number (Russell et al. 1986). Recent observations (Voelzke 2005 and references therein) and theoretical modeling (Ying-Dong et al. 2007) support the idea that the majority of DEs are caused by sector boundary crossings. However, a significant number of them, ranging between 25% and 50%, appear to occur away from sector boundaries and must have a different origin (Delva et al. 1991; Wegmann 1995). It is thought that comet encounters with coronal mass ejections (CMEs) could be responsible for DEs. On few occasions, DEs may have been observed around the time of the predicted passage of the CME over the comet location (e.g., see Figs. 2 and 3 in Jones & Brandt 2004). In all cases, the comet-CME interaction has not been observed directly, leaving open the question of how the CME plasma interacts with the comet tail. There are several reasons for the lack of observations: CMEs occur intermittently, comets occupy a very small area in the heliosphere, and synoptic remote imaging of the inner heliosphere was unavailable until recently. But the *STEREO* mission (Kaiser et al. 2007) is changing all that.

In this Letter, we report the first direct imaging of a CME-induced tail disconnection using the SECCHI telescopes (Howard et al. 2007) aboard the *STEREO-A* spacecraft. The high spatial and temporal resolution of the SECCHI HI (Socker et al. 2000) allowed us to follow the interaction between the CME and the comet in detail and infer the disconnection trigger. In addition, we detected the cometary plasma tail to previously unprecedented distances. The time series of the SECCHI observations show the response of the tail to solar wind structures and provide fascinating insights into the structure of the inner heliosphere (see online movie version of Fig. 3).

2. OBSERVATIONS

The observations of comet 2P/Encke were acquired by the SECCHI HI-1 instrument on the *STEREO-A* spacecraft. The HI-1 passband is 630–730 nm. Encke has an orbital period of 3.3 yr with aphelion at 4.1 AU and perihelion at 0.33 AU. It is a relatively faint comet with a maximum apparent visual magnitude of 6.5.[3] The comet was in the HI-1 field of view from 2007 April 16 to 26 and the DE was recorded on April 20 at about 18:50

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[3] See http://en.wikipedia.org/wiki/Comet_Encke.

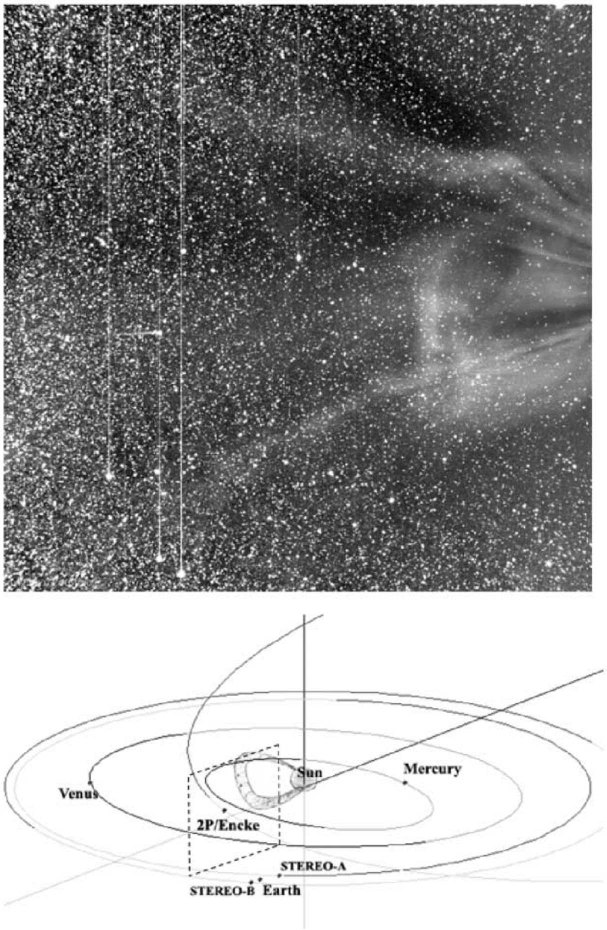

FIG. 1.—*Top*: SECCHI HI-1 observation (2007 April 20, 2:50 UT) of the encounter of a CME with comet 2P/Encke. The comet is 0.76 AU away from *STEREO-A*. The field of view is 20° (corresponding to ~42×10^6 km at the comet distance) and the pixel size is 70″ (~41×10^3 km). The right-hand edge of the image is 15 $R_\odot$ above the eastern solar limb. *Bottom*: View of the heliosphere on April 20. The comet is 0.34 AU away from the Sun and its tail is pointed at ~45° away from the Sun-Earth line. The cartoon flux rope CME represents our concept for the shape and orientation of the CME based on current analysis. The flank of the CME is more likely to interact with the comet. The dotted rectangle shows the HI-1 field of view and is approximately to scale.

UT. Figure 1 provides the context for this event. The large diffuse feature on the right side is the CME. It formed as a faint and slow ejection over the eastern solar limb on April 19 according to the LASCO (Brueckner et al. 1995) observations. Because of the very gradual initiation of this event, we could find no coronal or surface signatures to locate its source region. To understand the CME-comet interaction we examine the status of the heliosphere around the comet as derived by the ENLIL model (Odstrcil et al. 2002). The model is routinely run by the Community Coordinated Modeling Center (CCMC) in support of the *STEREO* mission.[4] We plot the derived radial solar wind speed around the location of the comet with the radial magnetic field vectors superimposed (Fig. 2). The comet is situated in relatively fast solar wind (~420 km s^{-1}) and the IMF is directed radially outward.

3. RESULTS

The HI instruments are very sensitive telescopes as they were designed to detect the extremely faint signal from interplanetary CMEs. The increased sensitivity is beneficial for cometary observations and enabled us to detect the plasma tail to unprecedented distances from the coma. The comet is located at 0.76 AU from the spacecraft. The HI-1 images reveal a plasma tail extending at least 6° (corresponding to ~12.6×10^6 km at the distance of the comet) in Figure 1. At later times the tail extends to ≥20° (≥42×10^6 km), beyond the HI-1 field of view (see online movie).

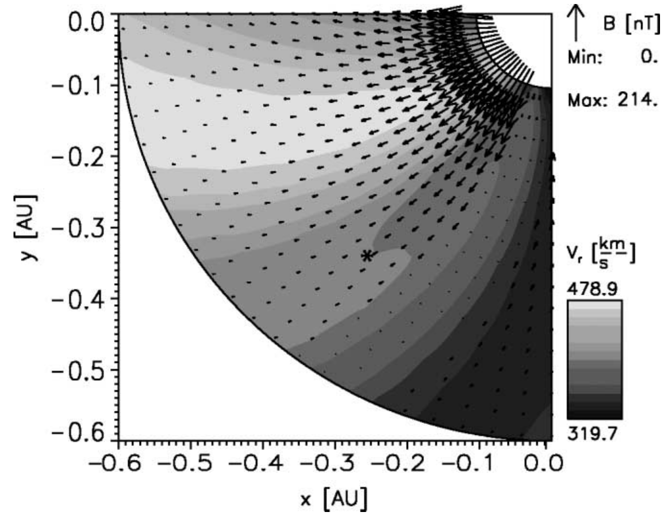

FIG. 2.—Status of the heliosphere around comet Encke on 2007 April 20 based on the ENLIL MHD model. The gray scale shows the radial solar wind speed and the arrows mark the direction of the radial component of the IMF. The length of the arrows is proportional to the magnetic field strength. The location of the comet is shown by the star symbol.

3.1. *The CME-driven Tail Disconnection*

The plasma tail of the comet responds very dynamically to its environment. This interaction, and more importantly, the comet-CME interaction, can be best appreciated in the running difference movie available in the online version of this Letter. To examine the details of the CME-comet interaction, we concentrate on just four instances of the event (Fig. 3). The first frame shows the preevent situation. The CME-comet interaction apparently starts at 15:30 UT. It is not clear yet whether this is a superposition due to a projection effect or whether the two bodies occupy the same region of space. No evidence of disconnection is evident until the image taken at 18:50 UT. The tail, however, is becoming progressively brighter as the CME sweeps by. Finally, a gap develops in the tail at a distance of ~0.5° (10^5 km) behind the coma. By 20:50 UT the tail is clearly disconnected and is carried off by the CME front. A new tail, about 1° long (2.1×10^6 km), has already formed by that time demonstrating the continuous nature of tail formation is very efficient. It seems that the CME encounter was the reason for the tail disconnection, but what is the mechanism behind the DE? Is the pressure pulse at the front or the magnetic fields entrained in the CME responsible for the disconnection?

3.1.1. *What Triggers the Tail Disconnection?*

First, we examine whether the dynamic pressure exerted by the CME can be responsible for the DE. The observations in the LASCO coronagraphs (2–30 $R_\odot$), in the SECCHI COR2 coronagraphs (2.5–15 $R_\odot$), and in Figure 1 show that the CME is a typical example of a flux-rope-type event (Vourlidas et al. 2000). In other words, the CME contains a large-scale magnetic structure. The CME is ejected very slowly from the Sun, reaching a speed of only 370 km s^{-1} at 16 $R_\odot$. This speed is similar to the expected

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[4] See http://ccmc.gsfc.nasa.gov/stereo_support.php.

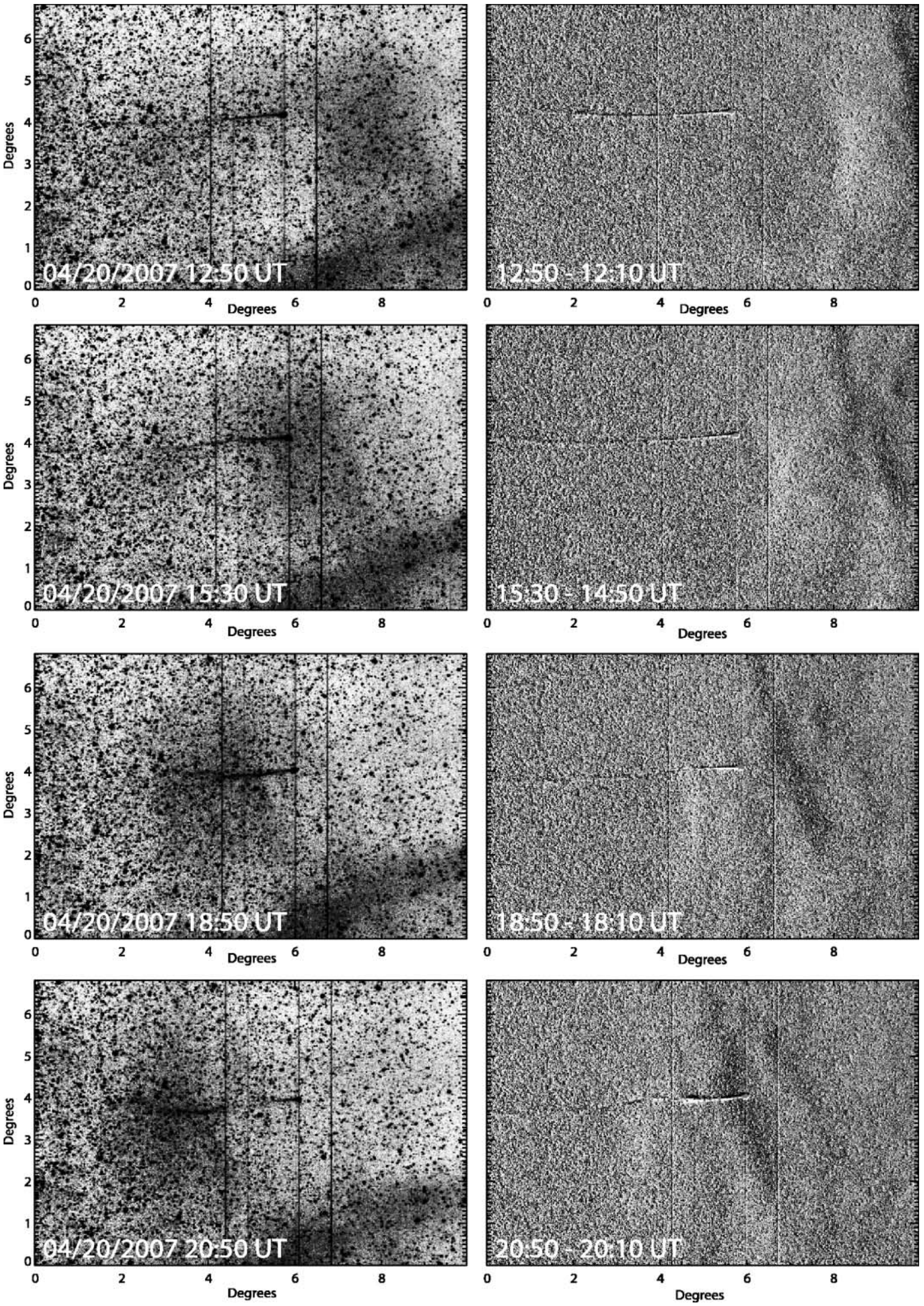

FIG. 3.—*Left panels*: SECCHI HI-1 observations of the tail disconnection of comet Encke. The images are shown in reverse color and are histogram-equalized to emphasize faint structures. *Right panels*: Running difference images. The vertical streaks are light from bright stars due to the shutterless operation of the HI cameras. The faint cloud approaching the comet is part of the CME front. The interaction starts at approximately 15:30 UT but the first evidence of disconnection is recorded at 18:50 UT. The tail is carried off by the CME front and a new tail has formed by 20:50 UT. [*This figure is available as an mpeg animation in the electronic edition of the Journal.*]

solar wind speed at these heights. When the CME encounters the comet, its projected speed is about 500 km s^{-1}. The solar wind speed is 424 km s^{-1} according to the simulations (Fig. 2). These speeds suggest that the CME is carried away by the solar wind and is unlikely to have developed a shock wave. The CME front is probably in pressure equilibrium. The instrument in-orbit calibration is still underway, but we can estimate the density jump at the CME front by measuring the brightness increase at the front relative to the background. The change is only 0.1%–0.2%. Using the CME and solar wind velocities given above, we estimate that the dynamic pressure increases by only ~20% due to the CME. Consequently, we can rule out the plasma pressure as a candidate for the disconnection. The existence of a detectable front indicates, however, that some plasma pileup occurs despite the absence of a shock. The plasma must accumulate then, on the surface of the flux-rope structure seen in the coronagraph images. In this case, the front of the CME and the front of the flux rope are the same structure and an intervening sheath region does not exist.

It is more likely that the disconnection trigger is magnetic in origin. An obvious candidate would be a sector boundary crossing. According to the ENLIL model, the comet crossed a sector boundary on April 19. On April 20, the comet is embedded in a radially outward IMF. Given the uncertainties of the model and the proximity of the comet to a sector boundary, we cannot completely discard this possibility. We believe, however, that it is an unlikely scenario because the observed DE is more impulsive than DEs associated with boundary crossings and the tail clearly interacts with the CME front (e.g., it brightens simultaneously with the CME passage, and it is carried away at the CME front). The only remaining possibility is that the DE is triggered by reconnection with the magnetic field of the CME. The reconnection could proceed in two possible ways:

1. *On the day side just as if the CME were a sector boundary*.—In this case, we would expect the formation of rays before the tail disconnection (Fig. 4, Ying-Dong et al. 2007), which we did not observe. The simulations also suggest that the angle between the CME and the IMF fields should be larger than 90°, which is certainly plausible. The delay between the arrival of the CME and the first evidence of disconnection could be a projection effect or could be an effect of the solar wind deceleration through the comet's coma due to mass-loading. As far as we can tell, however, both simulations and observations show that DEs associated with sector boundaries evolve slower than our event and never appear to result in a complete cutoff of the tail; a narrow tail seems to remain even while the bulk of the tail is drifting way. We note, however, that HI-1 has low spatial resolution (70″) compared to the telescopes used for cometary research. It is possible that the absence of ray formation or of the narrow leftover tail are caused by resolution effects and a more thorough analysis is needed before sunward reconnection could be dismissed.

2. *On the tail side in a manner similar to terrestrial substorms*.—The reconnection agent could be either the change in the magnetic field direction or the change in the Alfvén velocity, or both (Fig. 3, Russell et al. 1986). This theory predicts brightening of the tail, tail thinning, and downward acceleration of the disconnected tail. To look for brightening changes we increase the contrast by taking the difference between successive images. The results are shown in the right panels of Figure 3, where the CME front and the extent of the comet tail are now more visible. The tail starts to brighten at 15:30 UT when the front of the CME appears to first impinge on the comet. After removing the CME signal, the tail brightens by 17 UT to a maximum of 0.3% relative to its preevent level. The location of the maximum also drifts slowly away from the coma, leaving a thinner tail behind. The actual disconnection occurs between 18:20 and 18:50 UT. As can be seen in Figure 3, this occurs after the CME front crossed over the comet, which might be a projection effect. Since the CME source region could be close or behind the east limb, the CME is likely propagating along the sky plane and only its flanks interact with the comet. In the last panel, at 20:50 UT, the tail is clearly detached from the coma. The tail appears to drape around the front but this could be an indication that the tail has not accelerated yet to the ambient solar wind velocity. These observations are consistent with the DE being a result of tail-side reconnection between the IMF draped around the coma and the magnetic field at the front of the CME flux rope. If this interpretation holds after further analysis, then we are faced with a truly "comet tail substorm," as suggested by Jockers (1985).

4. CONCLUSIONS

We present a recent discovery from the SECCHI HI-1 instrument aboard the *STEREO-A* spacecraft: the first direct imaging of the interaction of a CME with the comet which led to a spectacular tail disconnection event. The temporal and spatial resolution of the observations allow us to infer the mechanism for the DE. It is likely magnetic reconnection between the magnetic field at the CME front and the IMF draped around the comet. It is likely that the reconnection occurs on the tail side of the comet but we cannot exclude the possibility of sunward reconnection at this stage. A modeling effort is currently underway and we will report the results in a more detailed paper in the near future. In the meantime, we want to make the community aware of the richness of the comet Encke observations. As the online movie shows, the full set of SECCHI observations reveals many more DEs and comet tail–solar wind interactions. The data set contains a wealth of information about the inner heliosphere which should be the subject of future, more detailed analyses. The *STEREO* mission follows an open data policy and all SECCHI observations are available from the *STEREO* and SECCHI Web sites.[5]

We thank the referee for the very useful suggestions and constructive comments that improved the manuscript. We are grateful to G. Stenborg for compiling the online movie and to K. Battams and A. Watson for bringing this event to our attention. The SECCHI data used here are produced by an international consortium of the Naval Research Laboratory, Lockheed Martin Solar and Astrophysics Laboratory, and NASA Goddard Space Flight Center (USA), Rutherford Appleton Laboratory and University of Birmingham (UK), Max-Planck-Institut für Sonnensystemforschung (Germany), Centre Spatiale de Liege (Belgium), Institut d'Optique Théorique et Appliqueé, and Institut d'Astrophysique Spatiale (France). The USA institutions were funded by NASA; the UK institutions by Particle Physics and Astronomy Research Council; the German institutions by Deutsches Zentrum für Luft- und Raumfahrt e.V.; the Belgian institutions by Belgian Science Policy Office; the French institutions by Centre National d'Etudes Spatiales and the Centre National de la Recherche Scientifique. The NRL effort was also supported by the USAF Space Test Program and the Office of Naval Research.

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[5] See http://stereo.gsfc.nasa.gov and http://secchi.nrl.navy.mil.

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