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An unusual current sheet in an ICME: Possible association with C/2006 P1 (McNaught)

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[1] On December 15, 2006, a strong ICME crossed the twin STEREO spacecraft while they were still close together in near-Earth space. In the midst of this traversal, a strong current sheet was observed in the magnetic records, whose properties are inconsistent with our present understanding of the magnetic structure of an interplanetary coronal mass ejection (ICME). A possible cause of this current sheet is the extended dust trail of C/2006 P1 (McNaught), whose orbital plane the ICME traversed close to the Sun. If this association is correct, then charged dust can produce twists in the interplanetary magnetic field that can persist for an AU or longer. Further, as a result of this electromagnetic interaction, small dust particles can be carried out of the solar system.
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1. Introduction

[2] Solar system dust is charged, and therefore interacts with the flowing magnetized plasmas of the solar system [*Zook et al.*, 1996; *Grün*, 2007]. This interaction may not be important for the dynamics of large dust particles with sizes greater than 1 micron, but can be important for submicron dust. An example of a dynamically important dust-plasma interaction is the phenomenon known as Interplanetary Field Enhancements, IFEs, first observed by the Pioneer Venus Orbiter magnetometer [*Russell et al.*, 1984a], of which a significant fraction of the IFEs were associated with the passage of asteroid 2201 Oljato between the Sun and Venus [*Russell et al.*, 1984b; *Russell*, 1987]. These disturbances are distinguished by a cusp-shaped rise in the interplanetary magnetic field and strong twists in the magnetic field direction near the peak field strength. Later, *Jones et al.* [2003] discovered the same phenomenon in Ulysses' magnetic field data, and also attributed these events to the pickup of charged dust, identifying some of the events with dust from comet 122P/DeVico.

[3] A completely independent set of observations of the interaction of dust with magnetized plasma has been made by the dust detectors on Ulysses, Galileo, and Cassini, that found dust streams near Jupiter and Saturn [*Grün et al.*, 1992a, 1992b; *Srama et al.*, 2004]. These streams are believed to be accelerated when the dust particles are picked up by the corotational electric field of the plasma circulating with the planet. When the gyroradius of the dust particles becomes sufficiently large due to their becoming quasi-neutral or entering a weak field region, they can escape the planet's gravitational field, because the corotational velocity, which they achieve during the pickup process, greatly exceeds the escape velocity [*Grün et al.*, 1993]. These particles are small, 10 nm-sized, and traveling at velocities of over 200 km/s [*Zook et al.*, 1996]. When they enter the solar wind, they are strongly affected by the direction and strength of the interplanetary magnetic field [*Grün et al.*, 1996].

[4] These two phenomena are examples of charged-dust-plasma interactions that we, at least partially, understand. Another common attribute of these two types of charged-dust interactions is that they are detected moderately close to their sources, so that we can recognize and identify the source. We expect that there are other interactions, but we have not yet recognized them, either because the phenomenon has been incorrectly attributed to solely a plasma effect, and/or that measurements of the causative dust particles have not been reported since the responsible particles are very small and sparse. In this letter, we report on a possible dust-solar wind interaction that is detected far from the source of dust, raising the question of the role of the solar wind in cleansing the innermost solar system of its dust population.

2. STEREO Alignment With Comet McNaught

[5] Shortly after STEREO's launch in late 2006, C/2006 P1 (McNaught) was approaching perihelion, soon to become a household word due to its spectacular dust trail. On December 15, STEREO A and B had just received their first gravity assists from by the Moon to start STEREO A on its drift ahead of the Earth. STEREO B was later to get a second lunar boost to insert it into its heliocentric orbit drifting behind the Earth. On this day, the two spacecraft and Earth were only 4° from alignment with the point of intersection of the orbit of comet McNaught and the ecliptic plane. At this time, comet McNaught was high above the ecliptic plane and heading toward its perihelion that would occur on January 13, 2007, at a heliocentric distance of 0.171 AU. This geometry was similar to that which led to the observation of multiple interplanetary field enhancements (IFEs) associated with asteroid 2201 Oljato, as it flew inside of Venus' orbit on three occasions during the Pioneer Venus mission [*Russell*, 1987]. The projection of the STEREO-Comet McNaught geometry is shown in the ecliptic plane in Figure 1. Measured from the point of observation, Comet McNaught's intersection with the ecliptic plane was over 100 million km away,

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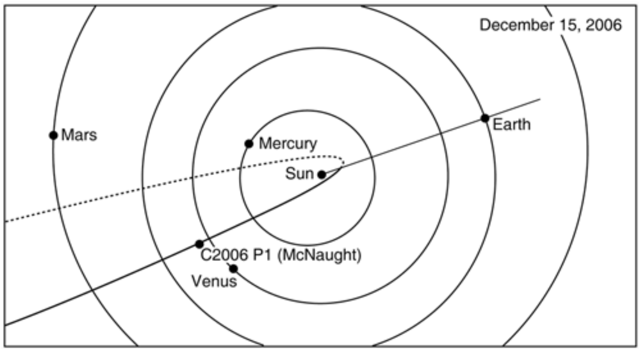

Figure 1. View from the north ecliptic plane of the orbits of the terrestrial planets and their positions on December 15, 2006, together with the trajectory of comet C/2006 P1 (McNaught). The comet's trajectory changes from solid to dashed as it moves from above the ecliptic plane to below. The thin line joining the Sun to the Earth is within 4° of the intersection of the McNaught orbit with the ecliptic plane. Dust in the orbit plane ahead of the comet could be carried outward to Earth at this time if the ICME were able to accelerate the charged cometary dust.

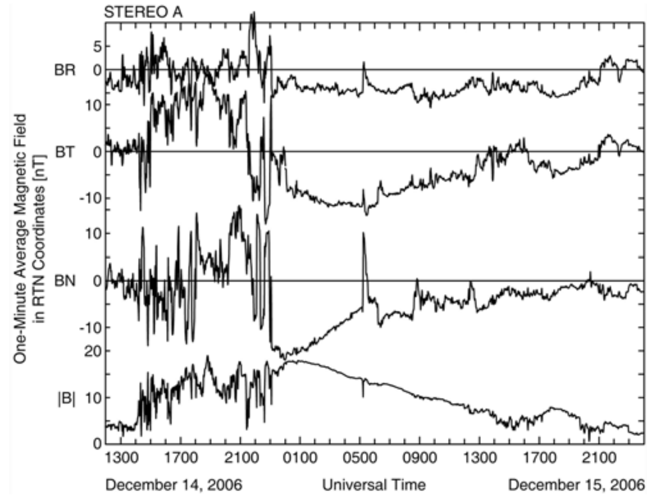

Figure 2. One-minute average magnetic field from STEREO A during the passage of the ICME on December 14–15, 2006. The coordinate system is RTN, with R radially outward from the Sun, and T perpendicular to the plane containing R and the Sun's rotation axis. N is in the latter plane and northward perpendicular to R.

and not just 5 million km, as Oljato's orbit had been during its "conjunction" with Pioneer Venus.

3. ICME of December 14

[6] The STEREO mission was still commissioning its instruments in December 2006, as the end of solar cycle 23 was coming to a close. The magnetometers were operating, and had been calibrated using the Earth's magnetic field, but the solar wind ion detector had not yet entered its operational mode. On December 14, at 1300 UT, the leading shock arrived in front of what was to be the last strong ICME to hit Earth in the old solar cycle. The magnetic field from this classic ICME as measured by the STEREO A magnetometer is shown in Figure 2. As expected, this fast ICME has a leading shock wave followed by a turbulent magnetosheath as shown by the turbulent magnetic field strength and components from 1400–2300 UT on December 14. Then the spacecraft entered a region of quiet magnetic field with elevated magnitude and slowly varying components where the field rotates principally in the T-N plane. This region is generally called the magnetic cloud and is the driving force that propels the ICME outward in the solar wind. The field magnitude gradually declines throughout the event and merges into the pre-existing field about 2300 UT on December 15, 2008. The magnetic profile of the ICME is unusual in only one aspect. In the middle of the ICME, the magnetic field nearly reverses its sense in the R, radial, and N, normal, directions, with very little change in magnitude, instead of following its earlier and later slow evolution in strength and direction. This same current sheet (not shown) is seen in Wind, ACE, and STEREO B magnetic field records. The J × B force exerted by this current is mainly orthogonal to the solar wind flow direction, since the magnetic field strength along the flow (R direction) is small. In contrast, we expect the stresses in the ICME to be mainly along the solar wind flow as it overtakes the solar wind plasma. Thus, there is no obvious relation of the current sheet structure to the physics of the magnetic flux rope that forms the core of the ICME. While no plasma measurements are available from STEREO at this time, solar wind data are available at Wind and ACE. The plasma before and after the current sheet are identical. During the current sheet passage, the direction of the flow changes abruptly by 7° in the direction opposite planetary motion. At the end of the passage of the current sheet, the plasma conditions abruptly return to their earlier conditions. There is no evidence for any change in the surrounding ICME at this time. We now examine more closely the structure of the double current sheets that bound the bent field lines.

4. Central Current Sheet

[7] The central current sheet in Figure 2 consists principally of two antiparallel currents that first rapidly twist the

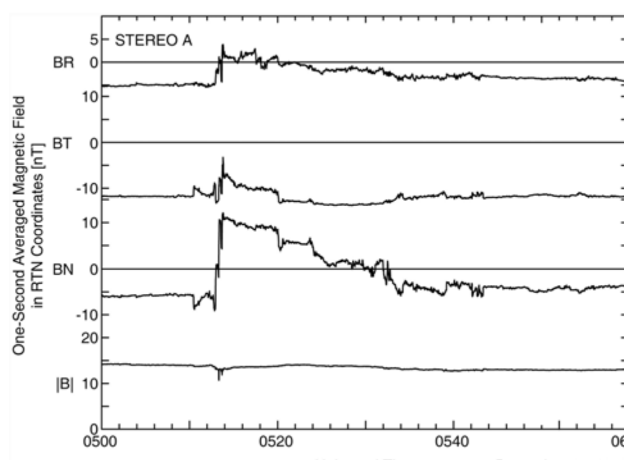

Figure 3. One-second resolution magnetic field measurements from STEREO A across the thin and thick current sheets in RTN coordinates.

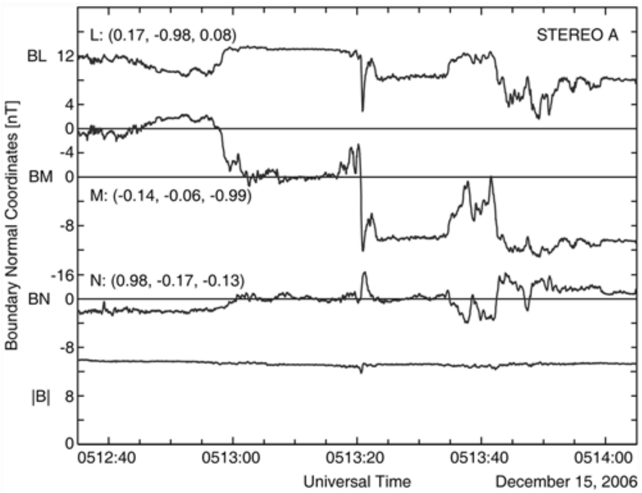

Figure 4. Thirty-two Hertz magnetic field measurements from STEREO A cross the thin central current sheet in boundary normal coordinates (L, M, N). This coordinate system is chosen so that L is along the quiet magnetic field before the current sheet at 0513:20 UT. N is along the cross product of L and the field in the quiet period after the current sheet. M is along the cross product of N and L. This assumes that the boundary on which the current sheet flows is a tangential discontinuity where the measurements are made. The direction cosines of the coordinate axes in heliocentric RTN coordinates are given in the figure. We note that the N-direction is nearly along R, and the L-direction, anti-parallel to T.

field away from the direction of the ICME's main rope structure and then slowly return the field to its original direction. This is shown in Figure 3. The thin current crosses STEREO in one minute, from 0513–0514 UT; the thick current lasts about 20 minutes, from 0514–0534 UT. Since the solar wind is flowing at nearly 800 km/s, as measured by the Wind and ACE spacecraft, these sheets are approximately 4.5×10^4 km, and 9×10^5 km thick, respectively. There are fluctuating fields ahead of the thin sheet and after the thick sheet. These currents resemble the current sheets at IFEs in which thin and thick current sheets also occur [*Russell et al.*, 1984a]. What is missing here that distinguishes this structure from an IFE is a cusp-shaped magnetic field strength enhancement.

[8] The standard sample rate of the STEREO magnetometers is 8 Hz. In addition to these data, a burst mode snapshot of the field at 32 Hz was captured across the first current sheet. Figure 4 shows this time series of the magnetic field across the thin current sheet. The magnetic field evolves in steps with thin current sheets separated by quiescent intermediate field directions. We have chosen to display the time series here in a coordinate system ordered by the steady field before and after the central current sheet. This assumes that the structure is principally a tangential discontinuity with zero field along the normal to the boundary, defined by the cross product of the magnetic fields in the two quiet regions. This normal (0.98, −0.17, −0.13) in RTN coordinates is nearly parallel to the expected solar wind direction. STEREO A and STEREO B see almost identical structure.

5. Discussion and Conclusions

[9] The observation of the plasma tail of a comet by an interplanetary spacecraft far from the comet is a rare but not unexpected event. Ulysses, in fact, has crossed the tails of three comets: Hyakutake in 1996 [*Jones et al.*, 2000]; McNaught-Hartley [*Gloeckler et al.*, 2008]; and C/2006 P1 (McNaught) in February 2007 [*Neugebauer et al.*, 2007]. The possibility of the dust trail of a comet interacting with an ICME has been discussed by *Ragot and Kahler* [2003], but only from the standpoint of the effect of the ICME on the dust and not as here, where we are concerned with the signature of the pickup in the magnetized plasma. We have considered other possible explanations for the current sheet and have not found other likely explanations. While there are reports of interacting ICMEs in the literature [e.g., *Rees and Forsyth*, 2004], the current sheet seen here is not seen in any of these examples. Often, a "shock" is seen propagating through the leading ICME [e.g., *Rees and Forsyth*, 2004, Figure 2] when a collision takes place. Further, there are distinct changes in the field and plasma at the point of contact. Here, the field and plasma conditions return to their original state of the current sheet passes. We note that our putative dust pickup occurred 29 days before the comet itself crossed the ecliptic plane. However, in the events detected in association with the apparitions of 2201 Oljato, similar lead and lag times were found for the dust events [*Russell*, 1987].

[10] The relative geometry of the Earth and the intersection of the orbit comet McNaught with the ecliptic plane on December 15 ensures that the ICME seen at the Earth has passed through the comet's dust trail. However, since we do not know the exact path of the ICME plasma, we do not know for certain that the plasma reaching STEREO went through the dust trail. Furthermore, the similarity of the current structure to that of an IFE is striking. The simplest explanation for the existence of the mid-ICME current sheet is that the ICME has picked up charged dust as it crossed the dust trail, and that dust has been accelerated perpendicular to the solar wind flow by the $V \times B$ electric field of the convecting ICME. Conservation of momentum in this direction requires that the field bend in the direction across the flow. Thus, the current sheet is a natural outcome of the dust pick up. We emphasize that dust particles have a lot of inertia compared to the surrounding solar wind plasma, so the best physical picture to describe this interaction is that the dust particle does not move across the solar wind flow direction, but rather, the solar wind plasma is deflected by the dust particle. This threads the magnetic field across existing streamlines and gathers momentum over a larger area. While we do not know that the dust particles have been held inside the ICME for the entire trip from the comet, this could have occurred, given the observations of dust streams at Jupiter with velocities of over 200 km/s. The presence of the current sheet in the ICME may be serendipity, for had the current sheet occurred elsewhere in the normal "turbulent" solar wind, we would not have recognized it as a special feature. However, close to the Sun, the interplanetary magnetic field is nearly radial, aligned with the flow, and the electric field in the frame of the dust will be small. In contrast, the magnetic

structure of a CME and its high velocity produces a strong electric field (about 10 mV/m) that will more rapidly accelerate charged dust particles than the normal solar wind magnetic field of 1.4 mV/m. Thus, ICMEs may have a special role in removing dust from near the Sun. It is significant that this current sheet structure resembles the magnetic structure of the magnetopause which undergoes reconnection. The stretched magnetic field produced by the accelerating charged dust stores energy in the magnetic field in a manner analogous to that in the Earth's magnetotail. Reconnection would relieve the stretched field and lead to dissipation of the energy stored in it.

[11] In summary, we believe that the most probable explanation for the signature in the center of the December 15, 2006 ICME is the pickup of dust from the dust trail of comet McNaught. There is nothing in the observations reported herein that allows us to estimate the size of the picked up dust particles, but electromagnetic forces are expected to be most important at the smallest scales, $\sim$10 nm, and below the scale size affected by light pressure, the beta meteoroids [*Grün*, 2007]. These meteoroids have been observed on hyperbolic orbits leaving the solar system [*Wehry et al.*, 2004]. We believe the electromagnetic process described here could help clear the inner solar system of its very smallest dust particles.

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