Triggering of magnetic reconnection in a magnetosheath current sheet due to compression against the magnetopause

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[1] We report in-situ measurements by three THEMIS spacecraft showing the evolution of reconnection in a solar wind current sheet as the current sheet transited from the solar wind across the bow shock and close to the magnetopause on July 11, 2008. The observations suggest that the solar wind reconnection exhaust within the current sheet was disrupted by its interaction with the bow shock, while the subsequent compression of the current sheet against the magnetopause significantly reduced both the current sheet thickness and the plasma β and initiated reconnection at a new X-line located within the magnetosheath. Furthermore, electrons were heated at the center of the magnetosheath exhaust, in contrast to the previously reported absence of electron heating in solar wind exhausts, but consistent with electron heating occasionally observed in association with magnetopause reconnection. This suggests that the level of electron heating in reconnection exhausts depends strongly on the boundary conditions. **Citation:** Phan, T. D., T. E. Love, J. T. Gosling, G. Paschmann, J. P. Eastwood, M. Oieroset, V. Angelopoulos, J. P. McFadden, D. Larson, and U. Auster (2011), Triggering of magnetic reconnection in a magnetosheath current sheet due to compression against the magnetopause, *Geophys. Res. Lett.*, *38*, L17101, doi:10.1029/2011GL048586.

1. Introduction

[2] Magnetic reconnection is a universal plasma process which converts magnetic energy into particle energy. While much is known about reconnection in space and laboratory plasmas the conditions necessary for the onset of reconnection are not yet well understood. Reconnection signatures are detected in only a fraction of the current sheets observed in the solar wind, in the magnetosheath, at the magnetopause, and in the magnetotail. In order to predict when and where reconnection will occur in space and laboratory plasmas, one needs to know what conditions trigger or suppress it.

[3] Observations in the magnetotail have revealed that a thin current sheet is required for collisionless reconnection, with the onset of reconnection occurring when the thickness of the magnetotail current sheet is of the order of an ion skin depth [e.g., *Sanny et al.*, 1994]. However, at the subsolar magnetopause, where the current sheet is usually thin (~ a few ion skin depths) [e.g., *Berchem and Russell*, 1982] due to the constant compression of the solar wind against the magnetosphere, reconnection flows are detected at only about 50% of all magnetopause crossings, even when the magnetic shear angle across the local magnetopause is large (>60°) [e.g., *Paschmann et al.*, 1986]. This indicates that a thin current sheet is a necessary, but not sufficient condition for reconnection. The magnetopause observations further suggest that the plasma β (the ratio of plasma to magnetic pressure) in the magnetosheath adjacent to the magnetopause may be a controlling factor, with reconnection less likely to occur when $\beta > 2$ [e.g., *Paschmann et al.*, 1986]. However, a recent study of solar wind reconnection events suggested that the occurrence of reconnection depends not on β alone, but on a combination of the magnetic field shear angle and the difference between the plasma β values on the two sides of the current sheet, $\Delta\beta$ [*Phan et al.*, 2010]. For low $\Delta\beta$ reconnection occurs for both low and high magnetic shear angles, whereas for high $\Delta\beta$ reconnection occurs only when the field shear angle is large. These findings confirm an earlier theoretical prediction by *Swisdak et al.* [2003, 2010] that reconnection is suppressed by the diamagnetic drift of the X-line associated with asymmetric reconnection. This suggests that changing the current sheet thickness, the ambient plasma β or the size of $\Delta\beta$ across the current sheet could all be ways to inhibit or trigger magnetic reconnection. However, to date, there has not been a study that examined how reconnection depends on the combined effect of current sheet thinning, $\Delta\beta$, and magnetic field shear angle.

[4] With multi-spacecraft observations, one can sometimes track the evolution of current sheets and their boundary conditions as they convect from the solar wind across the bow shock and toward the magnetopause. *Phan et al.* [2007] reported observations of a thick (260 ion-skin-depth) tangential discontinuity (TD) that was apparently not reconnecting in the solar wind but that did reconnect after the related current sheet had crossed the bow shock and convected toward the magnetopause. Thus the combination of solar wind and magnetosheath observations provides a unique opportunity for studying the conditions necessary for the onset of reconnection. However, it could not be determined in that study whether it was the compression across the bow shock or the compression against the magnetopause that was more significant for triggering reconnection. Recent 2D and 3D global hybrid simulations suggest that while the

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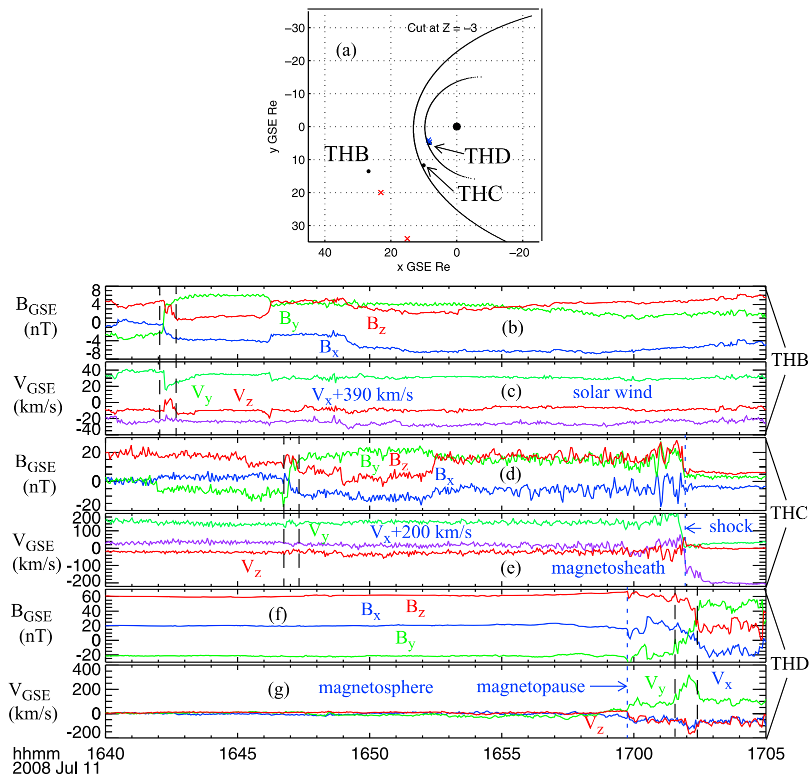

Figure 1. (a) The THB, THC, and THD spacecraft locations, together with the estimated X-line locations (assuming reconnection rates of 0.1 and 0.03) in the solar wind (red crosses) and in the magnetosheath (blue crosses). (b, c) The magnetic field and plasma velocity in the geocentric solar ecliptic (GSE) coordinates measured by THB in the solar wind. (d, e) The field and velocity measured by THC in the magnetosheath close to the bow shock. (f, g) The field and velocity measured by THD in the magnetosheath close to the magnetopause. In GSE, the +x direction points from the Earth to the Sun, the +z direction is perpendicular to the ecliptic plane and northward, and +y completes the right-handed orthogonal system. The edges of the current sheet under discussion are marked by pairs of vertical dashed lines.

bow shock does compress solar wind TDs, compression across the bow shock alone would be insufficient to initiate reconnection in originally thick solar wind TDs and additional compression against the magnetopause would be required [*Omidi et al.*, 2009; *Pang et al.*, 2010].

[5] In the present paper we use observations from 3 spacecraft to track the evolution of a current sheet, which originally contained a reconnection exhaust in the solar wind, as the current sheet crossed the bow shock and approached the magnetopause. One spacecraft was located in the solar wind, one was in the magnetosheath close to the bow shock and one was in the magnetosheath in the vicinity of the magnetopause. The presence of the two spacecraft in the magnetosheath allows us to distinguish the relative effect of compression at the bow shock versus compression against the magnetopause. Surprisingly, the observations indicate that the bow shock actually disrupted the solar wind reconnection exhaust, at least locally, while the compression against the magnetopause triggered reconnection at a new X-line that was unrelated to the original X-line in the solar wind.

2. Spacecraft Locations and Instrumentation

[6] Figure 1a shows the spacecraft locations for this event relative to *Farris et al.*'s [1991] model bow shock and magnetopause. All three spacecraft were located duskward of the Sun-Earth line. THEMIS B encountered the current sheet in the solar wind while THEMIS C and D detected it later in the magnetosheath. Note that the model magnetosphere slightly over-estimates the radius of the magnetopause at THEMIS D. This study uses 3s resolution plasma [*McFadden et al.*, 2008] and magnetic field [*Auster et al.*, 2008] data from the 3 spacecraft.

3. Observations

3.1. Overview of the Observations

[7] Figures 1b–1g show that the properties of the current sheet at the three THEMIS spacecraft were quite different. THEMIS B (THB), located in the solar wind at GSE [26.9, 13.6, −8.0] R_E, detected a current sheet, as evidenced by the sudden changes in the magnetic field components (Figure 1b), with embedded reconnection outflow (Figure 1c) at 06:42:09–06:42:37 UT. The total magnetic field rotation (or magnetic shear angle) across the current sheet was ~100°. The reconnection exhaust was identified by the presence of accelerated flow within the region where the field rotated, with jet speed of ~25 km/s relative to the ambient solar wind, or ~80% of the predicted Alfvenic outflow speed of 31 km/s based on a 4nT anti-parallel field and a density of 8 cm^{-3} in the inflow region [*Cassak and Shay*, 2007].

[8] Figure 1d shows that about five minutes after the solar wind current sheet passed THB, it was detected by the THC

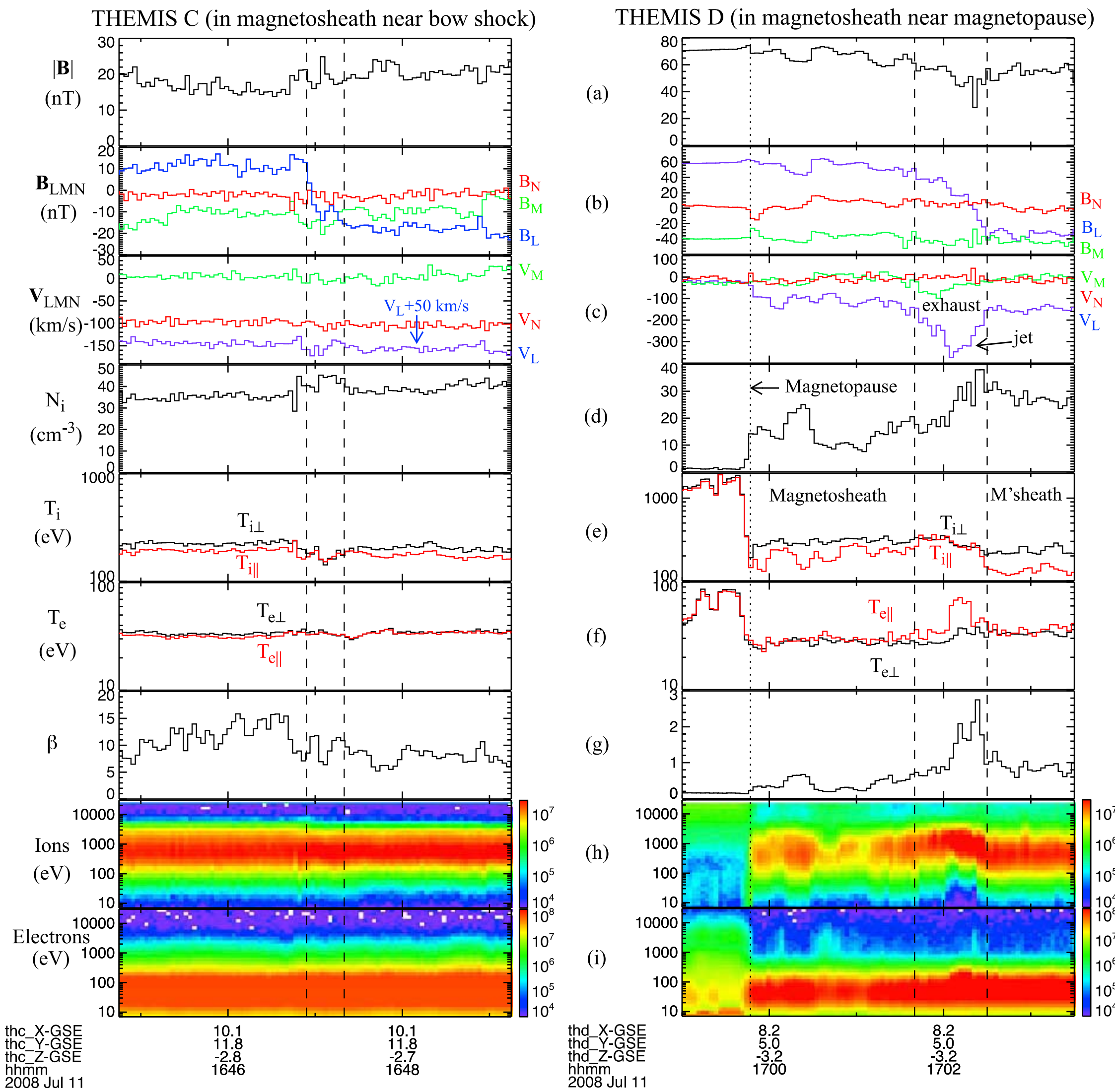

Figure 2. Detailed observations by (left) THC and (right) THD illustrating the absence and presence, respectively, of a reconnection exhaust within the current sheet. (a) The magnetic field magnitude, (b) the magnetic field in LMN coordinates obtained by the minimum variance analysis of the magnetic field, (c) ion velocity in LMN, (d) ion density, (e) ion temperature, (f) electron temperature, (g) plasma β, (h) ion energy spectrogram in units of eV s^{-1} cm^{-2} $ster^{-1}$ eV^{-1}, and (i) electron energy spectrogram in eV s^{-1} cm^{-2} $ster^{-1}$ eV^{-1}. The left and right vertical dashed lines denote the leading and trailing edges of the current sheet, respectively.

spacecraft (located at GSE [10.1, 11.8, −2.7] R_E) in the magnetosheath immediately downstream of the bow shock. There the magnetic shear angle was 97°, nearly the same as upstream in the solar wind. However, there was no evidence for a reconnection jet (Figure 1e) in the current sheet at THC (see Section 3.2 for more details).

[9] Fifteen minutes after THC's encounter with the current sheet, THD was located in the magnetosheath (at GSE [8.2, 5.0, −3.2] R_E) close to the magnetopause. There it detected the same current sheet (with similar magnetic field profile as well as similar magnetic shear ~93°, Figure 1f) with an embedded plasma jet (Figure 1g). However, the plasma jet at THD was directed nearly opposite to the jet observed by THB in the solar wind. The jet speed of ~200 km/s at THD was almost a factor of 10 higher than the jet speed at THB. The 15 minute delay is longer than would be expected from simple gas dynamic models of the magnetosheath, but might be explained by more sophisticated models that include the effect of compression of the magnetic field against the low-magnetic-shear magnetopause observed in this event (discussed below).

3.2. Contrasting Current Sheet Structure and Boundary Conditions Immediately Downstream From the Bow Shock and Immediately Upstream From the Magnetopause

[10] To investigate why a reconnection exhaust was not observed in the current sheet immediately downstream from the bow shock and what triggered reconnection in the current sheet close to the magnetopause, we examine the data from THC and THD in more detail. Figure 2 (left) shows the observations by THC and Figure 2 (right) shows those by THD. The THD data also shows the contrast between the magnetopause crossing at ~17:00 UT and the magnetosheath

current sheet crossing at ~17:02 UT, with the latter being flanked by the magnetosheath on both sides.

3.2.1. Presence or Absence of Plasma Jetting

[11] Figures 2b and 2c show the THC and THD magnetic field and ion velocity in the local current sheet (LMN) coordinate system determined by minimum variance analysis [*Sonnerup and Cahill*, 1967], with N along the overall current sheet normal, L aligned with the anti-parallel (i.e., reconnecting) field component, and M along the guide field direction. It is clear in this coordinate system that there was no reconnection jet in the current sheet at THC. In contrast, a reconnection jet was clearly evident at THD (Figure 2c, right), with the V_L jet speed of ~215 km/s being comparable to the predicted reconnection outflow speed of ~208 km/s for the observed inflow densities of 20 cm^{-3} and 30 cm^{-3}, and B_L of 55 nT and −40 nT on the leading and trailing edge of the exhaust, respectively [*Cassak and Shay*, 2007].

3.2.2. Presence or Absence of Plasma Heating

[12] THC, immediately downstream from the bow shock, did not detect an electron temperature enhancement within the current sheet (Figure 2f, left) and actually detected a slight decrease in the ion temperature (Figure 2e, left) there. The lack of any temperature enhancements in the current sheet at THC is also evident in the ion (Figure 2h, left) and electron (Figure 2i, left) energy spectrograms. In contrast, close to the magnetopause THD detected a slightly enhanced parallel ion temperature (Figure 2e, right) within the current sheet and a factor of 2 increase in electron parallel temperature (Figure 2f, right) near the current sheet center.

3.2.3. Evolution of Current Sheet Boundary Conditions Across the Magnetosheath

[13] The plasma β immediately adjacent to the current sheet at THC (Figure 2g, left) was ~8. In contrast, β adjacent to the exhaust at THD (Figure 2g, right) was ~0.5 on the leading edge side and ~1 on the trailing edge. The large reduction in β on approach to the magnetopause was due to the fact that the magnetic field strength at THD (Figure 1f) was nearly a factor of three higher than at THC, while the density dropped by more than 30% going from THC to THD. The asymmetry in the plasma β on the two sides of the THD exhaust was likely associated with the presence of a plasma depletion layer [*Zwan and Wolf*, 1976] at the exhaust leading edge caused by magnetic field pileup against the low-shear, non-reconnecting magnetopause [e.g., *Paschmann et al.*, 1993].

3.3. Evolution of the Current Sheet Thickness Across the Bow Shock and the Magnetosheath

[14] The current sheet in the solar wind at THB was convecting at a normal velocity (V_N) of ~−370 km/s (not shown). With a current sheet crossing duration of 28 s, the width of the solar wind exhaust was 10360 km, or 130 ion skin depths based on a density of 8 cm^{-3}. At THC, the magnetosheath current sheet convected at a normal velocity of ~−100 km/s (Figure 2c, left). Thus, the crossing duration of 26 s translates to a width of 2600 km, or 72 ion skin depths based on a density of 40 cm^{-3}. Closer to the magnetopause, the current sheet V_N at THD was ~11 km/s (Figure 2c, right). With an exhaust crossing duration of 50 s, the estimated thickness of the exhaust at THD was ~550 km, which corresponds to ~10–12 ion skin depths based on the ambient magnetosheath densities of ~20–30 cm^{-3} at the leading and trailing edge of the exhaust, respectively. Since the exhaust width expands with increasing distance from the X-line, the current sheet thickness at the reconnection site must have been substantially less than 550 km.

3.4. Estimated Locations of the X-Lines in the Solar Wind and in the Magnetosheath

[15] With knowledge of the reconnection exhaust thickness and its orientation we can estimate the location of the associated X-line in the solar wind and in the magnetosheath. This estimate depends on the exhaust opening angle, which is related to the reconnection rate, but which is difficult to measure experimentally. If we assume a dimensionless reconnection rate of 0.1, then the distance to the X-line would be 10 times the half width of the exhaust. With knowledge of the THB position, the exhaust half-width, as well as the solar wind exhaust outflow (L) direction (GSE [0.35, −0.86, 0.35]), the X-line would be ~5×10^4 km away from the spacecraft and be located at GSE [23, 20, −11] R_E. If we assume a reconnection rate of 0.03 [e.g., *Phan et al.*, 2006], the X-line would be three times further away from the spacecraft and be located at GSE [15, 34, −17] R_E. With either assumption it seems likely that the solar wind X-line encountered the Earth's bow shock at some point as it convected past the Earth (see Figure 1a).

[16] As for the X-line at THD, the outflow (L) direction was GSE [−0.33, 0.76, −0.56]. With an exhaust half-width of 275 km and an assumed reconnection rate of 0.1 or 0.03, respectively, the distance to the X-line from the spacecraft would be either 2750 km or 9200 km and the magnetosheath X-line would be located at either GSE [8.3, 4.7, −3.0] or GSE [8.7, 3.9, −2.4], respectively. Thus with either assumption, the estimated X-line location was very close to the spacecraft and well within the magnetosheath (see Figure 1a).

[17] The locations of the X-lines deduced from THB and THD (shown in Figure 1), together with the fact that the jets at THB and THD were directed toward each other and had different jet speeds, indicate that the reconnection jets observed by THB and THD must have originated from different X-lines. This is consistent with the exhaust at THD originating at an X-line within the magnetosheath and being independent of, and separate from, the X-line in the solar wind.

4. Summary and Discussions

[18] On July 11, 2008 the three THEMIS spacecraft tracked the propagation of a solar wind current sheet across the bow shock and to a position close to the magnetopause. The THB detection of a roughly Alfvenic jet embedded in the current sheet in the solar wind indicates that reconnection had occurred or was occurring in the solar wind current sheet. Shortly thereafter, the current sheet crossed the bow shock and was detected by THC immediately downstream in the magnetosheath, but without the reconnection accelerated flow signature. But as the current sheet convected further toward the magnetopause, reconnection flows reappeared when the current sheet encountered THD immediately upstream from the magnetopause. The magnetic field strength increased by a factor of 3 across the bow shock and increased further by another factor of 3, next to the magnetopause. Compared to the magnetosheath conditions near the bow shock, the compression against the magnetopause led to

a factor of 5 reduction of the current sheet thickness as well as a factor of 8–16 decrease of the ambient plasma β value, which also resulted in a small $\Delta\beta$ of ~0.5 across the current sheet. Both of these changes are favorable for the onset of reconnection. The observations thus suggest that reconnection was initiated near the magnetopause as the result of strong compression of the magnetosheath current sheet against the low-shear magnetopause, in agreement with the simulation results of *Pang et al.* [2010].

[19] The fact that no reconnection exhaust was observed immediately downstream of the bow shock is perhaps not surprising. THC was located duskward of the Sun-Earth line where the 80 km/s magnetosheath flow in the y direction resulting from bow shock deflection of the solar wind flow was much faster and was directed roughly opposite to the solar wind reconnection jet. This would have the effect of choking the reconnection outflow. However, it is not clear if reconnection was still active at the X-line when THC encountered the current sheet and, if still active, the X-line may not have yet encountered the bow shock. The interaction of reconnection exhausts with the bow shock is an unexplored topic that can be best addressed by simulations.

[20] With respect to the $\Delta\beta$-magnetic shear dependence of reconnection, the difference in β on the 2 sides of the current sheet was <1 at THC and ~0.5 at THD. With a magnetic shear of ~95°, the conditions at both spacecraft were well within the regime in which reconnection would not be suppressed by diagmagnetic drift of the X-line [*Swisdak et al.*, 2010]. Thus diamagnetic drift cannot account for the lack of a reconnection jet at THC. On the other hand, if the occurrence of reconnection depends on the ambient β instead of $\Delta\beta$, then a $\beta \sim 8$ at THC would not be favorable for reconnection [*Paschmann et al.*, 1986].

[21] This event is similar to that of a previously studied [*Phan et al.*, 2007] event observed by Cluster in that the magnetic field at the leading edge of the current sheet pointed roughly parallel to the dayside magnetospheric field. This may not be a coincidence since the compression against the magnetopause, and the concurrent reduction in current sheet width and β, would be strongest against a non-reconnecting, low-magnetic-shear magnetopause [e.g., *Phan et al.*, 1994].

[22] Finally, significant parallel electron heating was observed near the center of the magnetosheath reconnection exhaust. The fact that the electron heating was confined to the central region of the exhaust, where THD may have sampled plasma that had recently been within the diffusion region, suggests that the heating was associated with processes in or near the diffusion region, as opposed to heating across plasma discontinuities at the edges of the exhaust. Electron heating in this magnetosheath exhaust is in contrast to observations of solar wind exhausts, which so far have found no evidence for electron heating [e.g., *Gosling et al.*, 2005, 2007], but is consistent with electron heating that has been occasionally observed in association with magnetopause reconnection [e.g., *Gosling et al.*, 1986], suggesting that the level of electron heating in reconnection exhausts could depend strongly on the boundary conditions.

[23] The interaction of current sheets with the bow shock and the magnetopause may have applications beyond the near-Earth space as well. It has been suggested that similar interactions could also occur across the termination shock and/or at the heliopause of our solar system producing anomalous cosmic rays [*Drake et al.*, 2010] or in striped wind compression across termination shocks in pulsar wind nebulae [*Lyubarsky*, 2003].

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