

Reply to comment by P. Riley and J. T. Gosling on “Are high-latitude forward-reverse shock pairs driven by overexpansion?”

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Received 16 January 2007; revised 11 March 2007; accepted 10 April 2007; published 7 July 2007.

Citation: Manchester, W. B., IV, and T. H. Zurbuchen (2007), Reply to comment by P. Riley and J. T. Gosling on “Are high-latitude forward-reverse shock pairs driven by overexpansion?,” *J. Geophys. Res.*, 112, A07103, doi:10.1029/2007JA012272.

[1] During its passage through the high-latitude heliosphere, Ulysses observed interplanetary coronal mass ejections (ICMEs) bounded by forward-reverse shock pairs. Gosling *et al.* [1995] originally proposed the shock pairs form as a result of CME overexpansion into the ambient solar wind. Manchester and Zurbuchen [2006] suggested an alternative explanation for forward-reverse shock pairs in which the reverse shock forms as a result of deflections of the solar wind caused by the passage of the CME. In this model, fast solar wind overtakes slower plasma forming a reverse shock at high-latitude poleward of the ejected flux rope. Apparent signatures of ICMEs such as enhanced magnetic field strength, low plasma beta, and field direction rotation are produced by the plasma flows outside of the flux rope. The salient difference between these two models is that in the case of Gosling *et al.* [1995], the shocks surround the ejecta while in the model of Manchester and Zurbuchen [2006], the shocks extend laterally beyond the ejecta.

[2] It is possible that both overexpansion and flow-deflection are responsible for forming high-latitude forward-reverse shock pairs in the solar wind. However, shock pairs formed in these two ways are expected to have different observational signatures particularly with respect to their plasma composition. In the case of overexpansion, Ulysses will have passed directly through the ejecta, while in the case of Manchester and Zurbuchen [2006], Ulysses will pass only through perturbed fast solar wind. The ambient solar wind and CME ejected plasma have different charge state composition for the following reasons. The ambient fast solar wind originates in open, coronal-hole associated field whereas CMEs originate from closed line regions in the corona where the temperatures are higher and the plasma is more highly ionized. Consequently, CMEs have elevated amounts of highly charged ions such as O⁷⁺ [Richardson and Cane, 2004; Zurbuchen and Richardson, 2006] Second, coronal hole and topologically closed regions are also associated with distinct differences with respect to

their elemental composition [von Steiger *et al.*, 2000]. This dichotomy in elemental and ionic composition and their relation to magnetic topology has also been found through spectroscopic analysis close to the Sun [Feldman *et al.*, 2005].

[3] Considering these compositional signatures, the high-latitude events under discussion by Gosling *et al.* [1995] fall in two categories. In some events, the composition of the high-latitude events look just like low-latitude CMEs, with all the signatures one would expect, and additional bounding shock pairs which are not found at low-latitudes, as pointed out by Gosling *et al.* [1995]. However, a portion of the so-called high-latitude events look indistinguishable from coronal hole associated wind with respect to their elemental and ionic composition [von Steiger and Richardson, 2006]. However, in this study, it was found that the ratio of He²⁺ to H⁺ is found to be much more erratic and less useful for identification as only half of CMEs show an elevation. He enhancements occur with strong correlation with ionic charge state enhancements, but not all ionic charge state enhancements lead to He enhancement [von Steiger *et al.*, 2006] These compositional signatures are complemented by observations of counter streaming electrons [Gosling *et al.*, 1988], which have been taken to indicate closed field lines and CME ejected plasma at high latitude. Events possessing both solar wind composition and counterstreaming electrons therefore present a contradiction with conclusions regarding the closed magnetic topology and plasma that originates on open field lines. In the work of Manchester and Zurbuchen [2006], we speculated that counterstreaming electrons might exist on open field lines associated with high-latitude forward-reverse shock pairs. In support of this view, we now point out that counterstreaming electrons are in fact observed leaking out of corotating interaction regions (CIRs) where they are energized at shocks bounding the CIR [Steinberg *et al.*, 2005]. These energized electrons stream sunward along open field lines opposite to the normal electron flux that streams away from the Sun. As pointed out by Steinberg *et al.* [2005], the properties of these counterstreaming electrons is quite similar to those observed on closed field lines associated with ICMEs. This counterstreaming mechanism can explain bidirectional electrons on the open field lines of our model of CME-driven high-latitude forward-reverse shock pairs

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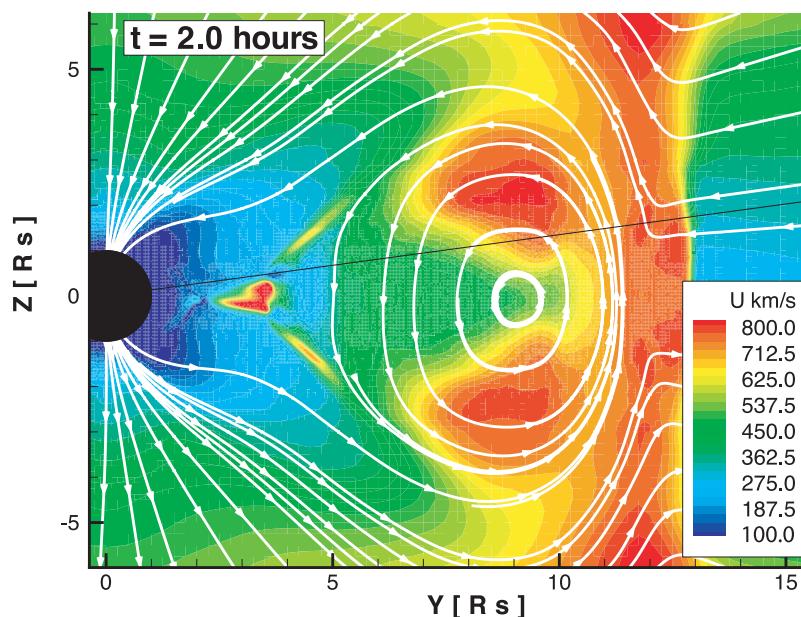


Figure 1. Meridional slice of the three-dimensional coronal mass ejection (CME) model showing velocity in color and magnetic streamlines (ignoring the component out of the plane). Circular lines show the central cross section of the flux rope. The radial line (colored black) is the location along which values are extracted for plots of pressure and radial velocity.

and resolves the apparent contradiction of solar wind composition found on field lines assumed to be closed.

[4] For the overexpansion mechanism to work, the CME near solar minimum presumably originates from a low-latitude active region then expands laterally into the fast wind and must not drive the reverse shock inside the sonic point where it would propagate back toward the Sun. These important characteristics are not adequately treated by Gosling and Riley [Gosling *et al.*, 1995; Riley *et al.*, 1997] as the inner boundary of their models is placed outside the sonic point. The simulation of Manchester and Zurbuchen [2006] models CME propagation from its physical starting point at the base of the corona with a magnetic flux rope rather than a high pressure density pulse introduced beyond the magnetosonic point in the solar wind. Figure 1 shows the magnetically driven CME two hours after initiation with the velocity shown in color and magnetic stream lines drawn white. A forward shock is seen ahead of the flux rope as a discontinuity in velocity.

[5] These are scientifically important properties of CME models that seek to explain high-latitude events, in particular the ability to treat the expansion of the flux rope in the low corona where a reverse shock would propagate toward the Sun. In this regard, there were several significant characteristics of our model that were not accurately represented in the comment by Riley and Gosling [2007] or which had not been entirely explained by Manchester and Zurbuchen [2006]. These have been summarized in Figure 2, which represents the same calculation previously described by Manchester and Zurbuchen [2006]. First, the flux rope possesses an internal pressure that is much larger than the ambient solar wind as shown in Figure 2a. Here, the ratio of the total (magnetic + thermal) pressure for the CME state relative to the ambient state is plotted along a radial line at two hours after initiation. There is a pressure peak at $13 R_{\odot}$

associated with the shock and a second broader peak centered at $8 R_{\odot}$ that is produced by the magnetic pressure of the flux rope. This central pressure is 17 times greater than the ambient pressure and causes the flux rope to overexpand in the radial direction as seen in Figure 2b. The front of the flux rope is traveling outwards 400 km/s faster than the rear. By comparison, the velocity difference of the background wind at these same locations (shown as the dotted line) is only 175 km/s. Contrary to the claims of Riley and Gosling, the flux rope is rapidly overexpanding close to the Sun and does not drive a reverse shock by overexpansion. Furthermore, while the flux rope expands radially, its angular size remains nearly constant from the low coronal to 1 AU, which is consistent with observations of CMEs by LASCO [St. Cyr *et al.*, 2000]. In contrast, the overexpansion model requires that CMEs expand in angular size beyond the magnetosonic point to penetrate the fast solar wind and produce a reverse shock that will not travel toward the Sun. Such angular expansion of CMEs is contrary to what is observed.

[6] The initiation of the CME in the low corona allows for deflection of the wind close to the Sun that is not possible when the CME is introduced outside the magnetosonic point. In our model, it is the meridional deflection of the bimodal wind by the flux rope that leads to reverse shock formation rather than over expansion. The deflections of the solar wind are at the location of a steep meridional gradient in radial velocity causing the fast stream to be radially aligned with a slower moving wind ahead of it. The two streams collide poleward of the flux rope forming compressions that steepen into reverse shocks by $r = 50 R_{\odot}$. The high-latitude shocks are large in amplitude forming significant plasma compressions that should be observable by white light observations of the extended corona, as provided by STEREO [Lugaz *et al.*, 2005].

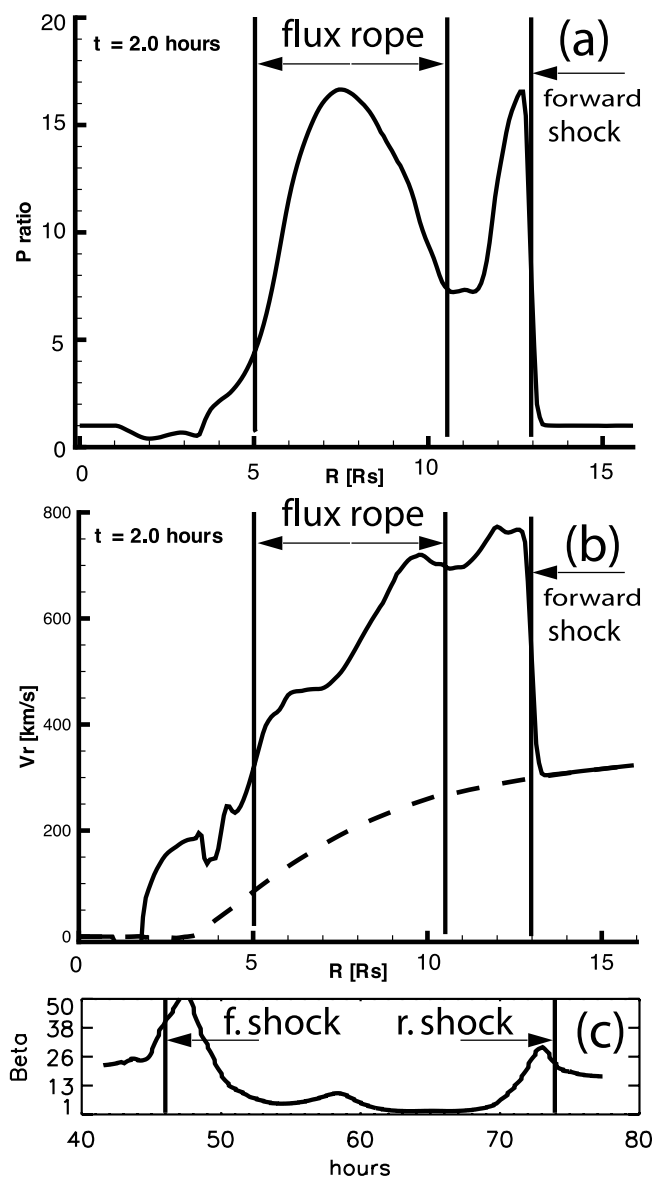


Figure 2. Line plots showing the structure of the CME close to the Sun and Earth, showing (a) the total pressure ratio of the CME relative to the ambient solar wind plotted as a function of distance from the solar center and (b) the radial velocity of the CME and ambient solar wind, shown by solid and dashed lines, respectively. The CME shows strong radial over-expansion driven by magnetic pressure. Also shown is (c) the plasma beta plotted as a function of time at a high-latitude point (34 degrees) at 1 AU. The plasma beta is depressed between the forward and reverse shocks to one twentieth the value found in the ambient wind.

[7] Our model does in fact reproduce observational characteristics of high-latitude CMEs bounded by forward-reverse shock pairs. The most notable features are magnetic fields with increased strength and rope like rotation, containing low pressure/density plasma found between nearly symmetric pressure/density enhancements created by the forward and reverse shocks. The stream deflections natu-

rally produce an expanding velocity profile imbedded in the fast wind. In particular, our model produces a low-beta disturbance contrary to claims of Riley and Gosling. Figure 2c shows a line plot of the plasma beta as a function of time at 1 AU at 34.0 degree heliographic latitude. At this location, the center of the reverse shock passes by, but this point at 1 AU is poleward of the flux rope. The plasma beta first increases at the forward shock and then decreases to 1/20 the ambient value in the center of the disturbance. Downstream of the reverse shock, the flow is deflected poleward in our model (not equatorward as stated by Riley and Gosling), which acts to bend open field lines of the fast wind into loop like structures that mimic the curvature of a flux rope poleward of the ejected rope. The magnitude of these meridional flows falls off with distance from the Sun. While we find velocities of 20 km/s at 1 AU we expect meridional flows of only a few km/s at 3 to 5 AU, which is consistent with observations from Ulysses. Our model produces a pattern of poleward deflection of the wind at both shocks, which is the meridional flow pattern also found in the overexpansion model shown by Riley *et al.* [1997]. Observations of meridional flows found with forward-reverse shocks do not show a consistent pattern of poleward deflection. Indentations in a shock front will result in equatorward flow deflections [Manchester *et al.*, 2005]. Greater variation in solar wind speed than found in our idealized model could produce indentations or corrugations on forward and reverse shocks that would explain the observed variation in meridional flow direction.

[8] Our model offers a different explanation of these events in which the forward-reverse shock pair is a direct consequence of dynamic interactions, which result from large-scale meridional deflections of the solar wind. This explanation naturally addresses some events inconsistent with over-expansion that have compositional signatures of coronal holes, suggesting that they are composed of coronal-hole associated fast streams. Also, our mechanism is clearly a high-latitude effect that relies on the overall heliospheric structure modeled here. It is therefore not expected that the same should happen at low latitudes. Our model's dependence on global solar wind structure also explains why CMEs with forward-reverse shock pairs are not found during solar maximum when the solar wind is highly structured and largely lacking a fast component.

[9] **Acknowledgments.** The simulation reported here was carried out on an Origin3800 supercomputer at NASA Ames. Ward Manchester was supported by Department of Defense MURI grant F49620-01-1-0359, NSF ITR grant 0325332, and NASA LWS grant NNX06AC36G at the University of Michigan. W.M. was also supported by LWS grant LWS03-0130-0149 in a subcontract from GMU.

[10] Amitava Bhattacharjee thanks the reviewer for his assistance in evaluating this paper.

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