Comment on "Jupiter: A fundamentally different magnetospheric interaction with the solar wind" by D. J. McComas and F. Bagenal

S. W. H. Cowley,[1] S. V. Badman,[1] S. M. Imber,[1] and S. E. Milan[1]

Received 12 November 2007; accepted 24 April 2008; published 24 May 2008.

Citation: Cowley, S. W. H., S. V. Badman, S. M. Imber, and S. E. Milan (2008), Comment on ''Jupiter: A fundamentally different magnetospheric interaction with the solar wind'' by D. J. McComas and F. Bagenal, *Geophys. Res. Lett.*, *35*, L10101, doi:10.1029/2007GL032645.

[1] *McComas and Bagenal* [2007] (hereinafter referred to as MB) have presented a discussion of the reconnection-mediated interaction of the Jovian magnetosphere with the interplanetary medium, which they suggest to be significantly different to that at Earth. In the latter case, it is well established that 'open' flux is produced at the magnetopause when the interplanetary magnetic field (IMF) is directed opposite to the equatorial planetary field, is transported to the tail by the solar wind, and returns as closed flux via plasma sheet reconnection preferentially during substorms, thus forming the Dungey cycle of flux transport [e.g., *Dungey*, 1961]. MB propose that the consequences of open flux production at Jupiter are different, however, due to a suggested difficulty of closed flux tube return from the tail against a substantial down-tail flow of iogenic plasma. They suggest instead that open flux is effectively removed by two-lobe reconnection when the IMF has the opposite polarity, such that the open flux in the system remains small. Two-lobe reconnection has been discussed theoretically for many years [e.g., *Dungey*, 1963; *Cowley*, 1981], though convincing evidence for its occurrence at Earth has only recently been found [e.g., *Imber et al.*, 2006, 2007]. Here, however, we question both aspects of MB's discussion.

[2] With regard to the return of tail flux by plasma sheet reconnection, MB characterise the process as requiring closed field contraction over distances of ~1500–2000 R_J at speeds of ~40 km s^{-1}, thus requiring ~30–40 days. They suggest this to be unlikely given the surrounding fast down-tail flow of iogenic plasma. However, we regard this scenario as being unduly pessimistic, first because the estimate of the distance to the tail reconnection site is unrealistically large, and second because the closed flux tube contraction speed is unrealistically small, both contributing to unrealistically large estimates of the transport time. MB's estimate of the distance to the tail reconnection site is essentially the length of the entire tail of open field lines, obtained by multiplying the solar wind speed by the residence time of open flux tubes in the lobe. This time is estimated to be 3–4 days on the basis that open field lines flow toward the plasma sheet at 10% of the solar wind speed (~40 km s^{-1}) for 10% reconnection efficiency with the IMF, leading to a tail length of ~1500–2000 R_J as indicated above. In fact, this significantly underestimates the length of the Jovian tail, since the lobe flow speed is slowed relative to MB's estimate by the ratio of the lobe and IMF field strengths, i.e. factors of two to three, while an overall magnetopause reconnection efficiency of ~10% seems optimistic. A more realistic residence time is ~10–20 days [*Nichols et al.*, 2006], leading to tail lengths of ~5000–10000 R_J in agreement with *Lepping et al.* [1983].

[3] The main point to emphasise, however, is not the inaccuracy of MB's tail length estimate, but that such estimates provide no information about the location of the tail reconnection sites, other than an upper limit. For Earth, for example, similar estimates produce tail lengths of ~1000 R_E [e.g., *Milan*, 2004], while substorm-related reconnection is typically initiated at down-tail distances of ~20–30 R_E [e.g., *Nagai and Machida*, 1998]. While flux return from the distant tail may be unlikely as MB suggest, a reasonable conclusion is that open flux will then accumulate until reconnection occurs substorm-like sufficiently close to the planet that the closed flux is indeed able to return. The return flow speeds are then expected to be comparable to the lobe Alfvén speed [e.g., *Badman and Cowley*, 2007], at least an order of magnitude faster than the return speeds employed in MB's estimate.

[4] Significant evidence indeed exists for sporadic reconnection in the Jovian nightside plasma sheet at distances of ~100 R_J, resulting in ion jets directed both toward and away from the planet [e.g., *Woch et al.*, 2002]. These dynamics are generally assumed to relate to pinch-off of distended closed field lines and the down-tail release of iogenic plasma occurring as part of the Vasyliunas cycle [*Vasyliunas*, 1983]. However, supposing that after plasmoid release the reconnection continues into the tail lobe, then closed flux is generated that will clearly flow back to the planet unencumbered by surrounding down-tail flow, whether the combined reconnection is envisaged as large-scale [*Cowley et al.*, 2003], or occurs more sporadically and multiply on smaller scales [*Kivelson and Southwood*, 2005]. While Dungey- and Vasyliunas-cycle tail reconnection need not be coherently related in this way, the argument is sufficient to show that open flux return from the Jovian tail by plasma sheet reconnection is not as problematic as MB suggest.

[5] We now turn to MB's second argument, that open flux can instead be effectively removed from the tail by two-lobe reconnection poleward of the cusp, such that the amount of open flux in the system remains small. This requires the open flux removal rate by two-lobe reconnection for southward-directed IMF, averaged over typical

[1]Department of Physics and Astronomy, University of Leicester, Leicester, UK.

0094-8276/08/2007GL032645

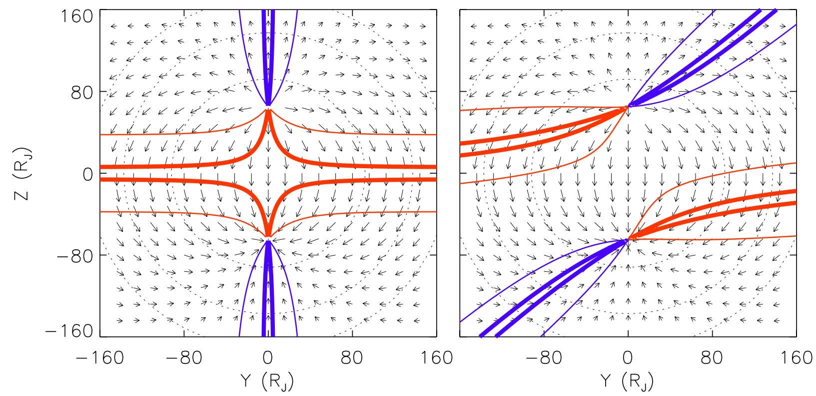

Figure 1. Plots of the Jovian magnetopause viewed from the Sun showing contours of the field shear angle across the boundary, where the heavy and light lines enclose regions where the fields are within 5° and 30° of anti-parallel, respectively, for northward (red) and southward (blue) IMF polarities. The IMF in the plane of the diagram is (left) directed exactly north and south (vertically) and (right) tilted clockwise by 45°. The modelling methodology follows *Cooling et al.* [2001], the magnetopause being described as a paraboloid of revolution about the planet-Sun (X) axis, with its focus located at half the nose standoff distance at R_{MP} = 65 R_J. Dotted circles indicate the magnetopause intersection with the planes X = 0, −80, and −160 R_J. The planetary field (black arrows) is everywhere tangential to the magnetopause and maps from the northern to the southern cusps, located at (X, Y, Z) = (R_{MP}/2, 0, ±R_{MP}). The magnetosheath field includes realistic draping over the magnetopause.

interplanetary conditions at Jupiter, to be at least equal to the averaged open flux production rate for northward-directed IMF. The difficulty with this suggestion is illustrated in Figure 1, where we view the Jovian magnetopause from the Sun. Details are contained in the figure caption, but briefly, the black arrows show the magnetospheric field just inside the magnetopause, similar to MB's Figure 3, while the red and blue lines show contours of the field shear angle across the magnetopause computed using the model of *Cooling et al.* [2001]. Figure 1 (left) shows results for exactly northward and southward IMF (red and blue contours respectively), where the thick and thin contours in each case show where the draped IMF is within 5° and 30°, respectively, of anti-parallel to the adjacent magnetospheric field. These delimit the magnetopause regions where reconnection is most likely, since the process is favoured by large magnetic shear. For northward IMF a wide swath of likely reconnection sites exists across the equatorial region where open flux production can take place. For southward IMF, however, the east-west band poleward of each cusp is relatively narrow, leading to smaller reconnection rates. The reconnection rate (flux per unit time equivalent to voltage) can be expressed as

$$V_{rec} = v_{SW} B_{\perp SW} L_{SW}, \quad (1)$$

where v_{SW} is the solar wind speed, $B_{\perp SW}$ the strength of the IMF component perpendicular to the solar wind velocity, and L_{SW} the width of the solar wind channel that reconnects with the magnetospheric field. Though not all of the interplanetary flux that impinges on the preferred regions will reconnect, such that L_{SW} will be less than the east-west extent of the regions shown, Figure 1 (left) nevertheless indicates that the open flux production rate for northward IMF will significantly exceed the single-hemisphere lobe reconnection rate for southward IMF. Since open flux closure in the latter case then requires two reconnections of the same interplanetary flux tube, one poleward of each cusp, the rate of this process will be reduced still further relative to open flux production.

[6] In the more general case where the IMF is tilted away from north-south, another issue arises illustrated in Figure 1 (right). Here the IMF is tilted clockwise by 45°, directed between top right and bottom left. The likely reconnection region for open flux production for the northward polarity is again significantly broader transverse to the IMF than for single lobe reconnection for the southward polarity. In addition, however, the spatial offset of the two cusp regions to either side of the IMF direction makes it increasingly difficult for individual interplanetary flux tubes to impinge on the reconnection regions in both hemispheres as required for two-lobe reconnection. While single-lobe reconnection may then continue at appreciable rates, two-lobe reconnection and open-flux closure becomes highly improbable. For Earth, *Imber et al.* [2006, 2007] estimate from auroral and ground-based studies that two-lobe reconnection at rates of practical relevance for the open flux budget ceases at IMF angles of ∼10°–15° from due north.

[7] These considerations indicate that for corresponding IMF tilt angles, open flux production for northward IMF will generally exceed open flux removal by two-lobe reconnection for southward IMF. If the IMF distribution is then essentially symmetric north-south, open flux production for northward IMF will be only partly (and perhaps only marginally) offset by two-lobe reconnection for southward IMF. However, if open flux removal is only partial then MB's scenario fails, and the net open flux must accumulate in the tail lobes until removed by other means, principally by plasma sheet reconnection according to our discussion above. Indeed, the planetary-modulated hot ion fluxes observed near the magnetopause during the recent New Horizons Jovian tail pass [*McComas et al.*, 2007] may themselves be a signature of plasma sheet reconnection in an extended twisted tail, as predicted by *Milan et al.* [2005].

References

Badman, S. V., and S. W. H. Cowley (2007), Significance of Dungey-cycle flows in Jupiter's and Saturn's magnetospheres, and their identification on closed equatorial field lines, *Ann. Geophys.*, *25*, 941–951.

Cooling, B. M. A., C. J. Owen, and S. J. Schwartz (2001), Role of the magnetosheath flow in determining the motion of open flux tubes, *J. Geophys. Res.*, *106*, 18,763–18,775.

Cowley, S. W. H. (1981), Magnetospheric and ionospheric flow and the interplanetary magnetic field, in *The Physical Basis of the Ionosphere in the Solar-Terrestrial System*, pp. (4–1)–(4–14), Advis. Group for Aerosp. Res. and Dev., Neuilly-Sur-Seine, France. (Available as ADA098119 from www.ntis.gov.)

Cowley, S. W. H., E. J. Bunce, T. S. Stallard, and S. Miller (2003), Jupiter's polar ionospheric flows: Theoretical interpretation, *Geophys. Res. Lett.*, *30*(5), 1220, doi:10.1029/2002GL016030.

Dungey, J. W. (1961), Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, *6*, 47–48.

Dungey, J. W. (1963), The structure of the exosphere, or adventures in velocity space, in *Geophysics: The Earth's Environment*, edited by C. DeWitt, J. Hieblot, and A. Lebeau, pp. 505–550, Gordon and Breach, New York.

Imber, S. M., S. E. Milan, and B. Hubert (2006), The auroral and ionospheric flow signatures of dual lobe reconnection, *Ann. Geophys.*, *24*, 3115–3129.

Imber, S. M., S. E. Milan, and B. Hubert (2007), Observations of significant flux closure by dual lobe reconnection, *Ann. Geophys.*, *25*, 1617–1627.

Kivelson, M. G., and D. J. Southwood (2005), Dynamical consequences of two modes of centrifugal instability in Jupiter's outer magnetosphere, *J. Geophys. Res.*, *110*, A12209, doi:10.1029/2005JA011176.

Lepping, R. P., M. D. Desch, E. C. Sittler Jr., K. W. Behannon, L. W. Klein, J. D. Sullivan, and W. S. Kurth (1983), Structure and other properties of Jupiter's distant magnetotail, *J. Geophys. Res.*, *88*, 8801–8815.

McComas, D. J., and F. Bagenal (2007), Jupiter: A fundamentally different magnetospheric interaction with the solar wind, *Geophys. Res. Lett.*, *34*, L20106, doi:10.1029/2007GL031078.

McComas, D. J., F. Allegrini, F. Bagenal, F. Crary, R. W. Ebert, H. Elliott, A. Stern, and P. Valek (2007), Diverse plasma populations and structures in Jupiter's magnetotail, *Science*, *318*, 217–220.

Milan, S. E. (2004), A simple model of the flux content of the distant magnetotail, *J. Geophys. Res.*, *109*, A07210, doi:10.1029/2004JA010397.

Milan, S. E., E. J. Bunce, S. W. H. Cowley, and C. M. Jackman (2005), Implications of rapid planetary rotation for the Dungey magnetotail of Saturn, *J. Geophys. Res.*, *110*, A03209, doi:10.1029/2004JA010716.

Nagai, T., and S. Machida (1998), Magnetic reconnection in the near-Earth magnetotail, in *New Perspectives on the Earth's Magnetotail*, *Geophys. Monogr. Ser.*, vol. 105, edited by A. Nishida, D. N. Baker and S. W. H. Cowley, pp. 211–224, AGU, Washington, D. C.

Nichols, J. D., S. W. H. Cowley, and D. J. McComas (2006), Magnetopause reconnection rate estimates for Jupiter's magnetosphere based on interplanetary measurements at ∼5 AU, *Ann. Geophys.*, *24*, 393–406.

Vasyliunas, V. M. (1983), Plasma distribution and flow, in *Physics of the Jovian Magnetosphere*, edited by A. J. Dessler, pp. 395–453, Cambridge Univ. Press, New York.

Woch, J., N. Krupp, and A. Lagg (2002), Particle bursts in the Jovian magnetosphere: Evidence for a near-Jupiter neutral line, *Geophys. Res. Lett.*, *29*(7), 1138, doi:10.1029/2001GL014080.

S. V. Badman, S. W. H. Cowley, S. M. Imber, and S. E. Milan, Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK. (swhc1@ion.le.ac.uk)