GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L07204, doi:10.1029/2010GL042618, 2010

Interplanetary field enhancements travel at the solar wind speed

C. T. Russell,[1,2] D. R. Weimer,[3] N. Omidi,[4] L. K. Jian,[2] J. G. Luhmann,[5] and R. J. Strangeway[2]

Received 20 January 2010; revised 9 March 2010; accepted 15 March 2010; published 10 April 2010.

[1] Interplanetary Field Enhancements (IFEs) are cusp-shaped increases and decreases in the interplanetary field, accompanied by a thin current sheet. They can last many hours and even the strongest have no leading or trailing shocks. These rare structures are of possible significance because their occurrence has been associated with potential sources of charged dust. On December 24, 2006, four well-separated spacecraft observed an IFE close to the Earth. From these four spacecraft measurements, we find that this IFE was traveling at the solar wind speed. This observation is consistent with previous encounters with fewer multiple satellites but is the first definitive measure of the speed of an IFE. This high speed is consistent with the lack of observation of shocks in association with these structures. At least on this occasion, the IFE was a pressure-balanced structure in which the thermal plasma pressure gradients balanced the magnetic pressure gradients. **Citation:** Russell, C. T., D. R. Weimer, N. Omidi, L. K. Jian, J. G. Luhmann, and R. J. Strangeway (2010), Interplanetary field enhancements travel at the solar wind speed, *Geophys. Res. Lett.*, *37*, L07204, doi:10.1029/2010GL042618.

1. Introduction

[2] Pioneer Venus magnetic field observations provided the first evidence for the phenomenon that has been called an interplanetary field enhancement. These structures generally consist of a steadily increasing, then decreasing, magnetic field, often coming to a cusp in the center and always containing a thin central current sheet [*Russell et al.*, 1984a]. These features are observed at all ecliptic longitudes at both 0.72 AU [*Russell et al.*, 1984a] and at 1.0 AU [*Arghavani et al.*, 1985]. At some longitudes there are more events than would be expected at random. In the Pioneer Venus data, one of these groupings occurred downstream of the point where the asteroid 2201 Oljato cut through the Venus orbital plane. The asteroid passed through the inner solar system three times when the mission was active, and each time the asteroid passed through perihelion and Pioneer Venus was nearby, even if not aligned with the asteroid, IFEs were seen [*Russell et al.*, 1984b; *Russell*, 1987]. Later *Jones et al.* [2003] associated IFEs with the dust trail of comet 122P/DeVico.

[3] If we accept this association, then an obvious possible mechanism is the pick-up of charged dust by the magnetized solar wind plasma. However, then we are faced with the question of how small, possibly submicron particles can create a disturbance that often is as large as the one the planet Venus creates through the interaction of the solar wind with its ionosphere. If there is coherent behavior of many dust particles that leads to this large extent, this coherency is also surprising.

[4] If we accept the possibility that these structures contain charged dust particles, then it is of some interest to determine how fast they are traveling. The absence of shocks suggests that the disturbance may be traveling close to the solar wind velocity. Solar-wind-speed dust particles have been inferred from the impacts on the STEREO spacecraft as recorded by the plasma wave instrument [*Meyer-Vernet et al.*, 2009]. However, these particles are very small, close to a nanometer in scale, and very numerous when they are present. Furthermore, in examining the magnetic records during these events, we have found no magnetic signatures and certainly nothing approaching the size of an IFE. So we are left with the impression that if charged dust particles are to be found in IFEs, they are possibly the more rare micron-sized particles than nanoparticles. We cannot contribute further to the question of the mass of these particles from the evidence we currently have, but we can study the speed of the disturbance even without knowing what is at the center of it. To do this we will examine multiple spacecraft observations of IFEs. First we review previously published examples that were ambiguous because they did not have the critical four-spaced measurements [*Russell et al.*, 1983] needed to determine the orientation of the phase front of the disturbance and to determine its speed.

2. Prior Multispacecraft Measurements of IFEs

[5] The ISEE mission provided only two-point measurements on the scale size of IFEs even though there were three spacecraft, because ISEE 1 and 2 were too close to each other to separate the time of arrival of the slowly changing magnetic field. *Arghavani et al.* [1985] were able to time two IFEs using the co-orbiting ISEE 1 and 2 spacecraft together with ISEE 3. The time delay found was consistent with convection at the solar wind speed. However, since the orientation of the structure could not be determined, this could not be proven. Another multispacecraft measurement occurred near Venus on February 11, 1982 when Venera 13 and 14 were coming to land on the planet around which Pioneer Venus was orbiting. The same event was seen now by three spacecraft with a separation of about 6×10^6 km downstream and 4×10^6 km transverse to the flow. Again,

[1] ESS, University of California, Los Angeles, California, USA.
[2] IGPP, University of California, Los Angeles, California, USA.
[3] Center for Space Science and Engineering Research, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA.
[4] Solano Scientific, Solano Beach, California, USA.
[5] Space Science Laboratory, University of California, Berkeley, California, USA.

0094-8276/10/2010GL042618

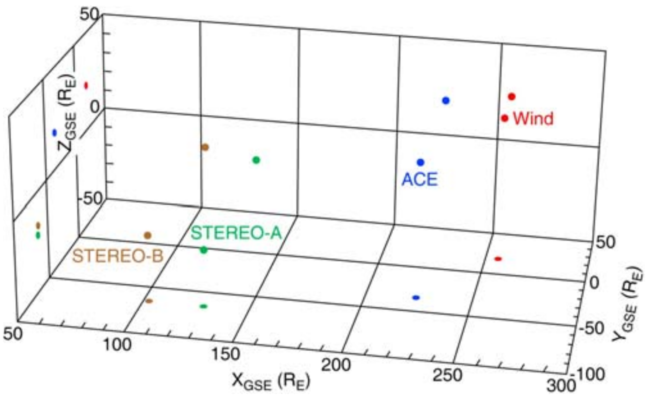

Figure 1. The locations of the ACE, Wind, and STEREO A and B spacecraft as the IFE crossed them in GSE coordinates. Positions are displayed in 3D and also projected on the 3 orthogonal planes.

the timing was consistent with a phase front perpendicular to the solar wind flow and convection at the solar wind speed, but again this could not be proven with only three spacecraft [*Russell et al.*, 1985]. Finally, shortly after the launch of the twin STEREO A and B spacecraft when they were well separated but still in near-Earth space, an IFE passed over them as well as Wind and ACE, and a set of the needed four-spacecraft measurements became available.

3. IFE of December 24, 2006

[6] On December 24, 2006, STEREO A and B were in the solar wind upstream of the Earth aligned almost along the solar wind flow and separated by a distance of 0.17 M km. Wind and ACE were 0.59 M km and 0.29 M km to the side of STEREO A and B and upstream of them, as illustrated in Figure 1. A clear IFE signature was seen at STEREO A and B, while Wind and ACE saw degraded versions of the STEREO magnetic signature. Figure 2 shows the magnetic

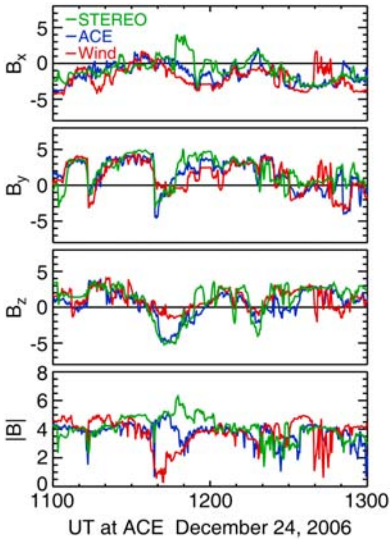

Figure 3. Superimposed magnetic field measurements at the STEREO A spacecraft (green), ACE (blue) and Wind (red) at the times that maximized the intercorrelation between the magnetic components.

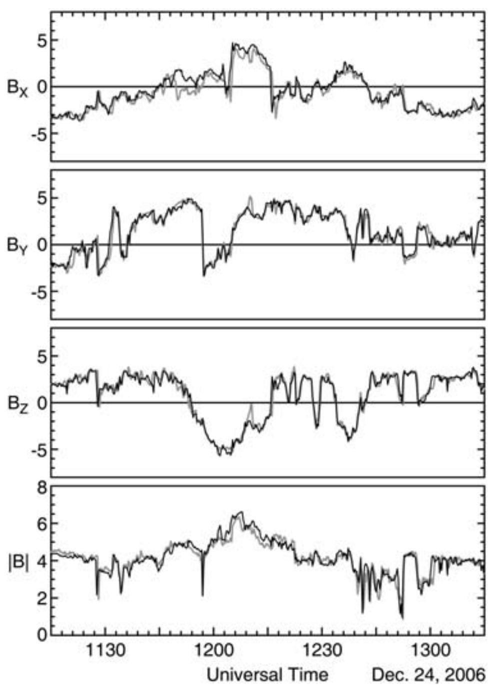

Figure 2. Magnetic field components and field strength measured over a two-hour period on December 24, 2006, by STEREO A and B spacecraft separated by 0.18 M km along the Earth-Sun line. Coordinate system is GSE with X toward the Sun, Z along the ecliptic pole and Y completing a right-handed coordinate system in the order X, Y, Z.

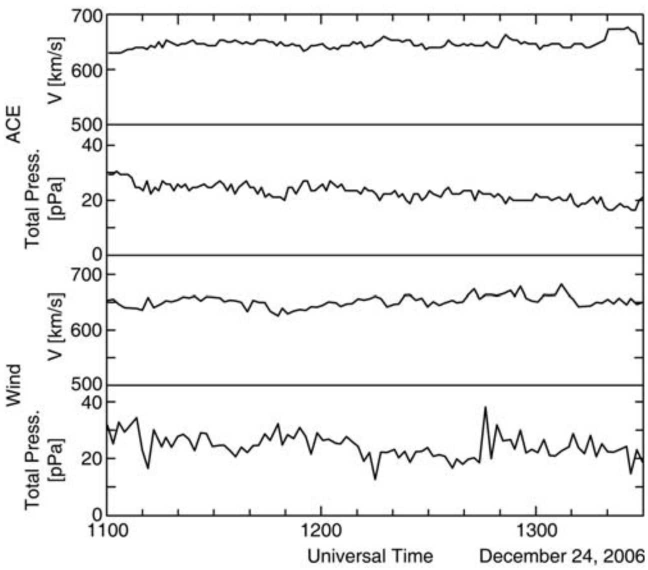

Figure 4. The solar wind speed and total pressure measured at ACE and Wind during the IFE passage, while the magnetic profile in Figure 3 was being seen at STEREO, Wind, and ACE. The total pressure is the sum of the magnetic plus thermal pressure perpendicular to the field. The thermal pressure is calculated from the proton measurements using the proton density and temperature, assuming a 4% He^{++} component at four times the proton temperature and an electron density that balances the positive charge with a fixed temperature of 130,000 K.

signature at STEREO A and B advanced by four minutes at B so that the signals aligned. The magnetic field strength signature therefore was traveling close to 650 km/s which was the reported speed observed at ACE and Wind. The STEREO solar wind analyzers were not yet operating. *Weimer et al.* [2002] and *Weimer and King* [2008] have developed cross-correlation techniques to predict the time of arrival of interplanetary structure at the Earth in order to study the control of geomagnetic activity by the solar wind. We can apply these techniques to the vector time series of the magnetic field at each of the four-time series. Doing so, we obtain a speed of 650 km/s very close to the two-spacecraft number using the almost aligned STEREO pair. In the interval surrounding the passage of the central current sheet, the normal to the phase front is pointing toward the Earth and away from the Sun in longitude and tilted south of the Earth by about 25°.

[7] The duration of the signatures of the IFE in the magnetic field strength is only about 20 minutes or about 0.005 AU along the solar wind flow. However, the duration of the correlated disturbance in the components is over an hour, or about 2.5 M km along the solar wind flow. The superimposed vector magnetic field in GSE coordinates and the field strength at STEREO A, ACE and Wind are shown in Figure 3. The B_Y component is the most similar at the three spacecraft. The B_Z component and the B_X component both have periods of different readings over the otherwise highly correlated hour. B_X at STEREO A and B (green trace) is quite different from B_X at ACE and Wind for about 10 minutes near 1150 UT and the B_Z component at Wind during the passage of the main disturbance is weaker than that at both STEREO and ACE. Wind is the spacecraft that is furthest to the side. Finally, the total field shown in the bottom panel exhibits a very interesting set of stacked profiles. The STEREO field strength is enhanced for the longest period of time. The field strength at ACE first increases and then decreases and recovers to "background." Meanwhile, the field at Wind suddenly drops while the field at the other sites is strengthening. Eventually the Wind field recovers and exactly matches first the ACE profile and later the STEREO profile. Clearly there is three-dimensional structure in the magnetic pressure enhancement of the IFE. Unfortunately with no plasma data being obtained at STEREO, we can only speculate on the nature of the gradient in the plasma pressure but we note that during other events seen after the commissioning of the plasma detector, the IFEs tend to be in pressure balance with the increase in the magnetic pressure being compensated by a decrease in thermal pressure.

4. Discussion and Summary

[8] The magnetic structure of IFEs is carried with the solar wind. It is not a wave propagating with respect to the flow, nor is it a structure being dragged through the solar wind at a slower speed as a cometary body might produce. The magnetic field profile in Figure 3 implies the structure has a magnetic pressure gradient force. This force should produce a propagating wave unless it were balanced by some other force in the plasma such as a charged mass or a counterbalancing pressure profile in the plasma. In Figure 4 we show the solar wind speed and the total pressure from ACE and Wind and we see that at both spacecraft the sum of the magnetic pressure and the plasma pressure are nearly constant, as is the solar wind speed. The lack of any measurable net pressure force is consistent with the pick-up of one or more small dust particles, since the mass of micron-sized particles would be far too small to cause a pressure maximum discernible on this scale as they moved outward in the Sun's gravitational potential. However, we note that we cannot test the pressure balance in this event at the two STEREO spacecraft; and they are clearly nearer the center of the disturbance.

[9] In summary, this four-spacecraft measurement of an IFE has confirmed earlier indications that IFEs move with the solar wind. This is a significant conclusion, for if the IFE does contain charged-dust particles, the particles would also be traveling at the solar wind speed and be potentially harmful to spacecraft that it encountered. Fortunately, these events are rare and the chance of collision is very small. This study points the way to future progress in IFE studies: examining the joint behavior of the magnetic field and the plasma on the STEREO mission after the plasma instruments were commissioned, to understand the forces within the plasma and if and how these structures respond to differing solar wind conditions. Perhaps the most difficult issue to resolve is, if these disturbances are caused by small dust particles, how do such small particles lead to disturbances many orders of magnitude larger than the Debye length beyond which they should not be sensed by the solar wind? Possibly these structures are the product of inter-meteoroid collisions in which many small particles are exposed to the solar EUV and the solar wind simultaneously and remain bunched by the solar wind forces.

[10] **Acknowledgment.** The work at UCLA was supported by the National Aeronautics and Space Administration under NASA contract NAS5-00133.

References

Arghavani, M. R., C. T. Russell, J. G. Luhmann, and R. C. Elphic (1985), Interplanetary magnetic field enhancements in the solar wind: Statistical properties at 1 AU, *Icarus*, *62*, 230–243, doi:10.1016/0019-1035(85)90120-4.

Jones, G. H., A. Balogh, C. T. Russell, and M. K. Dougherty (2003), Possible distortion of the interplanetary magnetic field by the dust trail of comet 122P/De Vico, *Astrophys. J.*, *597*, L61–L64, doi:10.1086/379750.

Meyer-Vernet, N., M. Maksimovic, A. Czechowski, I. Mann, I. Zouganelis, K. Goetz, M. K. Kaiser, O. C. St. Cyr, J. L. Bougeret, and S. D. Bale (2009), Dust detection by the wave instrument on STEREO: Nanoparticles picked up by the solar wind?, *Sol. Phys.*, *256*, 463–474, doi:10.1007/s11207-009-9349-2.

Russell, C. T. (1987), Interplanetary magnetic field enhancements: Further evidence for an association with asteroid 2201 Oljato, *Geophys. Res. Lett.*, *14*, 491–494, doi:10.1029/GL014i005p00491.

Russell, C. T., M. M. Mellott, E. J. Smith, and J. H. King (1983), Multiple spacecraft observations of interplanetary shocks: Four spacecraft determinations of shock normals, *J. Geophys. Res.*, *88*, 4739–4748, doi:10.1029/JA088iA06p04739.

Russell, C. T., M. R. Arghavani, and J. G. Luhmann (1984a), Interplanetary field enhancements in the solar wind: Statistical properties at 0.72 AU, *Icarus*, *60*, 332–350, doi:10.1016/0019-1035(84)90194-5.

Russell, C. T., R. Aroian, M. Arghavani, and K. Nock (1984b), Interplanetary magnetic field enhancements and their association with the asteroid 2201 Oljato, *Science*, *226*, 43–45, doi:10.1126/science.226.4670.43.

Russell, C. T., K. Schwingenschuh, J. L. Phillips, and M. R. Arghavani (1985), Three spacecraft measurements of an unusual disturbance in the solar wind: Further evidence for a cometary encounter, *Geophys. Res. Lett.*, *12*, 476–478, doi:10.1029/GL012i007p00476.

Weimer, D. R., and J. H. King (2008), Improved calculations of interplanetary magnetic phase front angles and propagation time delays, *J. Geophys. Res.*, *113*, A01105, doi:10.1029/2007JA012452.

Weimer, D. R., D. M. Ober, N. C. Maynard, W. J. Burke, M. R. Collier, D. J. McComas, N. F. Ness, and C. W. Smith (2002), Variable time delays in the propagation of the interplanetary magnetic field, *J. Geophys. Res.*, *107*(A8), 1210, doi:10.1029/2001JA009102.

J. G. Luhmann, Space Science Laboratory, University of California, Berkeley, CA 94701, USA.

N. Omidi, Solano Scientific, 777 Pacific Coast Hwy., Solano Beach, CA 92075, USA.

C. T. Russell, L. K. Jian, and R. J. Strangeway, IGPP, University of California, Los Angeles, CA 90095-1567, USA. (ctrussel@igpp.ucla.edu)

D. R. Weimer, Center for Space Science and Engineering Research, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA.