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# Search for the heliosheath with Voyager 1 magnetic field measurements

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[1] The magnetic field measured by Voyager 1 (V1) near 85 AU from 2002.0 to 2003.17 has the expected properties for the heliospheric magnetic field at that distance and epoch of the solar cycle. These V1 magnetic field observations do not provide evidence for exit from the solar wind, entry into a subsonic region such as the heliosheath, or transit of the termination shock near 85 AU. *INDEX TERMS:* 2164 Interplanetary Physics: Solar wind plasma; 2134 Interplanetary Physics: Interplanetary magnetic fields; 2124 Interplanetary Physics: Heliopause and solar wind termination. **Citation:** Burlaga, L. F., N. F. Ness, E. C. Stone, F. B. McDonald, M. H. Acuña, R. P. Lepping, and J. E. P. Connerney, Search for the heliosheath with Voyager 1 magnetic field measurements, *Geophys. Res. Lett.*, *30*(20), 2072, doi:10.1029/2003GL018291, 2003.

## 1. Introduction

[2] The heliosphere is the vast region of space around our Sun created by the supersonic expansion of the solar wind, a hot, low density, collisionless plasma streaming outward from the Sun. The existence of a shock at which a stellar wind makes a transition from supersonic flow to subsonic flow was suggested by *Weymann* [1960]. A formula for the position of the termination shock (TS) in the solar wind was given by *Parker* [1963], which predicts that the TS presently is between 70 and 140 AU, using realistic parameters [*Holzer*, 1989]. Information from several sources suggests that the TS is between 80 and 100 AU [*Stone*, 2001].

[3] The location of the TS is thought to vary with the solar cycle [*Whang and Burlaga*, 1993, 2000; *Karmesin et al.*, 1995; *Wang and Belcher*, 1999; *Scherer and Fahr*, 2003, and *Whang et al.*, 2003]. The TS is expected to move toward the Sun when the solar wind speed is low (e. g., near the recent solar maximum in 2000) and away from the Sun when the solar wind speed is high (e. g., in the declining phase after solar maximum). The predicted variation in the location of the TS during a solar cycle is ≈20 AU in the solar equatorial plane and ≈50 AU at 35°, near the latitude of Voyager 1 (V1) [*Whang et al.*, 2003]. Smaller scale fluctuations in the location of the termination shock can produce multiple crossings of the TS by V1.

[4] We shall study recent V1 magnetic field strength observations from 2002.0 to 2003.17, which we refer to as the interval 2002+. During this interval V1 was at 34°N and moved from 83.4 to 87.6 AU from the Sun, while solar activity was decreasing. This interval is an opportune time to search for the crossing of the TS and entry into the heliosheath by V1. Estimates of the TS strength [*Zank*, 1999; *Zank and Pauls*, 1996; *LeRoux and Fichtner*, 1997] are varied, typically between 2 and 3. A shock strength of ≈2.9 at the distance and latitude of V1 during 2002 was estimated by *Whang et al.* [2003], assuming a moving MHD shock and including pickup ions.

[5] *Krimigis et al.* [2003a] and *Decker et al.* [2003] suggested that V1 entered a new region, in which the speed was subsonic (<50 km/sec) for more than 6 months [*Krimigis et al.*, 2003b]. They argued that V1 exited the solar wind to a new subsonic region in mid-2002 and reentered the solar wind in early 2003. *Krimigis et al.* [2003b] give the crossing times as 2002, day 213 ± 5 and about 200 days later (≈2003, day 48), respectively. Throughout this paper "day" refers to calendar day, January 1 = day 1. We demonstrate that V1 was not in a subsonic flow such as the heliosheath for a substantial part of the interval 2002+.

## 2. Observations of the Magnetic Field Strength

[6] The magnetic field instrument on V1 [*Behannon et al.*, 1977] has two identical triaxial sensors mounted on a 13 m boom. The "primary" sensor is mounted on the end of the boom, and the "secondary" sensor is mounted at about 2/3 the boom length. Comparison of the measurements from the two sensors provides a means of correcting for spacecraft-generated fields and a measure of the effectiveness of those corrections. The output of each magnetic field sensor has a digitization step size of 0.004 nT, and the primary sensor noise is ≈0.003 nT RMS. The 1-σ uncertainty in a daily average of B is ±0.015 nT for the 2002+ data, which is exceptionally low owing to the relatively small changes in spacecraft magnetic field between rolls during 2002+.

[7] We focus on the daily averages of B observed by V1 during the 426-day interval from day 1, 2002 through day 61, 2003. Only the days for which data from both sensors are available are considered (420 days). Eight days of observations were excluded from the analysis because of outliers with $B_s - B_p > 3\sigma$, giving a data set of 412 days. $B_p$ and $B_s$ are the magnetic field magnitudes measured by the primary and secondary sensors, respectively. Typically there is a large data gap of ≈8–16 hours each day owing to limited DSN (Deep Space Network) coverage; the data coverage for 2002+ was ≈60%.

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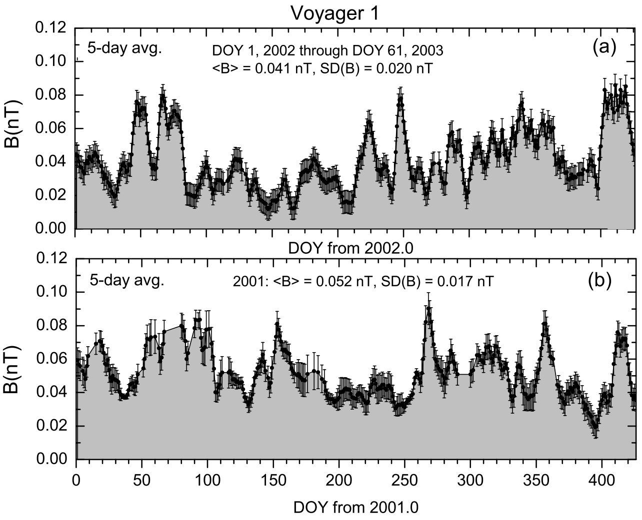

**Figure 1.** Magnetic field strength versus time. **(a)** Running 5-day averages of daily averages of the magnetic field magnitude $B_p$ measured by the primary sensor on Voyager 1 from 2002.0 to 2003.17. **(b)** $B_p$ measured by the primary sensor on Voyager 1 from 2001.0 to 2002.17.

[8] Five-day running averages of daily averages of $B_p$ versus time are shown in Figure 1a. A linear least squares fit gives the relation $B_p(\mathrm{nT}) = (0.033 \pm 0.001) + [(3.94 \pm 0.27) \times 10^{-5}] \times \mathrm{day}$. The slope of the line is only 0.014 ± 0.001 nT/year, indicating little net change in $B_p$ from 2002.0–2003.17. The average $B_p$ is $\langle B_p \rangle = 0.041$ nT, as shown in Figure 1a. The secondary sensor gives the same result, $\langle B_s \rangle = 0.04$ nT. These averages are within the range ≈0.036 to ≈0.046 nT that is expected for the heliospheric magnetic field strength at the position of V1 for this epoch of the solar cycle, based on an extrapolation of the results in *Burlaga et al.* [2003]. These results indicate that V1 was not in the heliosheath for any extended period during 2002+.

[9] Large-amplitude fluctuations in $B_p$ are evident in Figure 1a. These fluctuations are typical of the large-scale fluctuations observed in the distant heliosphere. For example, Figure 1b shows the magnetic field magnitude observed by V1 during 2001 ($\langle B \rangle = 0.052$ nT). (The first 61 days of 2002 are also plotted in Figure 1b so that the time series has the same length as that in Figure 1a). Comparison of Figure 1a and Figure 1b shows that the fluctuations of B observed by V1 during 2002+ are similar to those observed during 2001. The standard deviation of the running 5-day averages of $B_p$, $SD(B_p)$, was 0.020 nT during 2002+ and 0.017 nT during 2001.

[10] The $SD(B)/\langle B \rangle$ for hourly averages of B was approximately constant for each year from 1980 through 1994 [*Burlaga and Ness*, 1998]. The mean value of $SD(B)/\langle B \rangle$ for this 14-year period is 0.62 ± 0.03. For the hourly averages of B observed by V1 during 2002, $SD(B)/\langle B \rangle = 0.55 \pm 0.02$, similar to the earlier heliospheric observations.

[11] Previous observations showed that B has approximately a lognormal distribution throughout most of the heliosphere [*Burlaga*, 1995]. Daily averages of $B_p$ and $B_s$ from V1 during 2002+ also show a lognormal distribution of B. This is illustrated in Figure 2, which shows the cumulative distribution of counts in percent on a probability scale versus log B; points scattered about a straight line indicate a lognormal distribution in this format. There is good agreement between the distributions of $\log(B_p)$ and $\log(B_s)$ down to ≈0.015 NT, when $B_s$ is corrected for a constant offset of 0.016 nT, indicating the exceptionally high quality of the V1 observations during 2002+. The distribution of the daily averages of $\log(B_p)$ measured by V1 during 2001 is shown in Figure 2 for comparison. This distribution is lognormal from $B_p \approx 0.1$ nT to ≈0.04 nT, the limit of measurement accuracy for the observations made in 2001. The difference between the cumulative distribution for 2001 and that for 2002 is the result of the larger uncertainties in the measurements for 2001.

[12] A correlation between changes in the >70 MeV GCR (galactic cosmic ray intensity) and B over the course of a year (the "CR-B relation") has been observed beyond 11 AU for every year since 1981 [*Burlaga et al.*, 1985, 2003; *McDonald and Burlaga*, 1997]. When $B < B_{1yr}$ (the average value of B during 1 year), GCR increases at nearly a constant rate. When $B > B_{1yr}$, GCR decreases at a rate proportional to B. When $B \approx B_{1yr}$, GCR tends to fluctuate about a constant value. Figure 3b shows the GCR relative counting rate of the high-energy telescope (HET Pen L rate) from the experiment of *Stone et al.* [1977] on V1. Figure 3 shows the same correlation between B and the GCR that has been observed in the heliosphere for ≈20 years, except in a brief interval labeled "B" in Figure 3. When $B_p$ is less than $\langle B_p \rangle = 0.04$ nT in interval D, GCR increases nearly linearly with increasing time. When $B_p \approx 0.04$ nT in intervals A and E, GCR shows little net change. Finally, when $B_p > 0.04$ nT in intervals C and F, GCR decreases, as expected from the CR-B relation. This consistency with previous observations supports our analysis, which implies that the observed variations of magnetic field strength during 2002+ are predominantly due to changes in the heliospheric magnetic field with the observed intensities. We can conclude that 1) the CR-B relation observed by V1 from 2002.0–2003.17

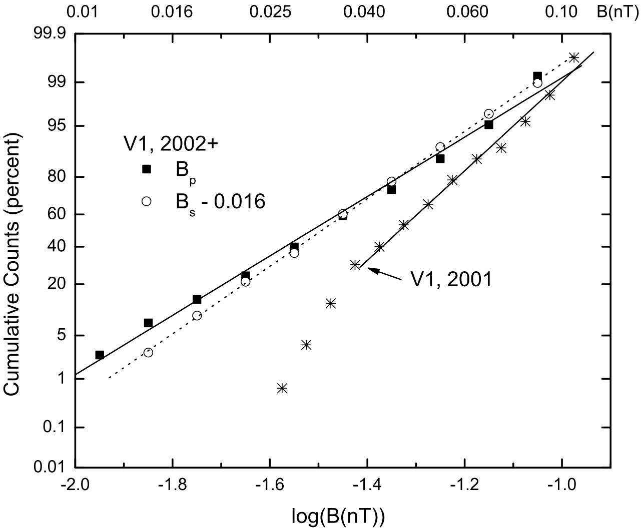

**Figure 2.** Distribution of log B observed by the primary and secondary magnetometers on Voyager 1 from 2002.0 to 2003.17 and by the primary magnetometer during 2001. The ordinate is such that for a lognormal distribution of B the points would fall on a straight line.

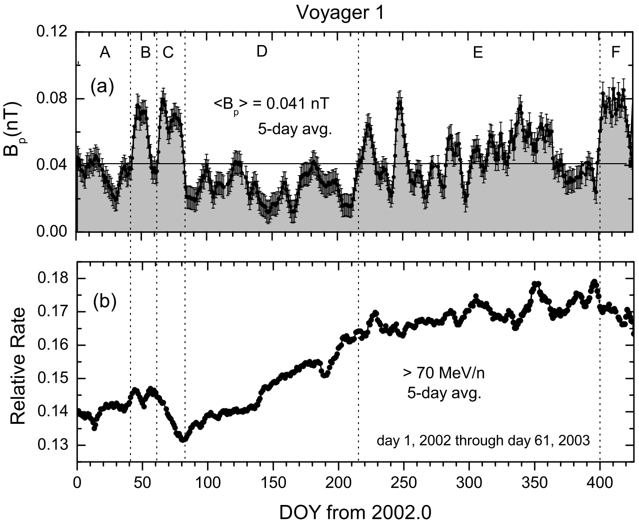

**Figure 3.** Magnetic field strength and its relation to cosmic rays. **(a)** Running 5-day averages of daily averages of the magnetic field magnitude $B_p$ measured by the primary sensor on Voyager 1. **(b)** The relative counting rate of >70 MeV/n cosmic rays measured by Voyager 1.

is consistent with previous observations made in the heliosphere, and 2) $B_p$ was relatively weak in interval D but near to the average value for the year in interval E.

[13] Figure 3 shows an increase in B by a factor of 1.7 from $\langle B\rangle_D = 0.027 \pm 0.008$ nT in interval D (from day 82 through 214, 2002) to $\langle B\rangle_E = 0.044 \pm 0.007$ nT in interval E (day 215, 2002 through day 33, 2003). Such changes in B have been observed in the heliosphere previously. For example, V1 observed an increase in B from 0.039 nT to 0.058 nT from the interval 2001.52–2001.72 to the interval 2001.72–2002.0 [see Figure 1b and *Burlaga et al.*, 2003]. The GCR data discussed in the previous paragraph indicate that the increase in $B_p$ from interval D to interval E was the result of a change from weak fields to near average magnetic field strengths, rather than entry into a region with relatively strong magnetic fields.

[14] Let us compare the average magnetic field strength $\langle B\rangle_E$ observed in interval E with the value $\langle B_P\rangle_E$ expected from Parker's model of the heliospheric field in the absence of a termination shock crossing during interval E. The value of $\langle B_P\rangle_E$ is given by the relation $B_P = 419.5\ B_1(1+ (419.5/V_1)^2)^{-1/2}\ R^{-1}V^{-1}\cos\theta$ [*Burlaga et al.*, 2002]. Here, $B_1$ is the magnetic field strength at 1 AU (assumed to be the same at $\theta = 0°$ and 35°, as indicated by Ulysses observations [*Balogh and Smith*, 2001]), $V_1$ is the speed at 1 AU, and V is the speed at the position R of V1; all the quantities correspond to the latitude θ. The formula is valid for $R > 10$ AU. *McDonald et al.* [2003] used cosmic ray observations to estimate that the average speed between V2 and V1 was 420 km/s, which we take as V. The average B measured by ACE (Advanced Composition Explorer) at 1 AU for 2001 was $B_1 = 7.0 \pm 0.2$ nT. Putting these values for V1, V and $B_1$, in the formula for $B_P$ gives the prediction $\langle B_P\rangle_E = 0.047 \pm 0.003$ nT at V1 during interval E. The observed $\langle B\rangle_E = 0.044 \pm 0.007$ nT, where the systematic error is estimated from Figure 4 in *Burlaga et al.* [2002], which gives $SD((B_P - B_{V1})/B_P) = 0.15$ from 1977 to 2001. Thus, the observed $\langle B\rangle_E$ is consistent with that predicted by Parker's model for the heliospheric field, indicating that V1 was in the supersonic solar wind during interval E.

[15] Next, assuming that $V_D$ and $V_E$ are known, the value of $B_E$ that would be expected from the conservation of magnetic flux for velocities that are radial and magnetic fields that are transverse to $\mathbf{V}$ is $B_E = \langle B_D\rangle \times V_D/V_E$. If the speed $V_E$ was <50 km/sec in interval E as suggested by *Krimigis et al.* [2003b] and if $V_D$ was ≈420 km/sec, as indicated by *McDonald et al.* [2003], then $B_E > 8 \times 0.027$ nT $= 0.216 \pm 0.064$ nT, which is not consistent with our observation that $\langle B\rangle_E = 0.044 \pm 0.007$ nT. If $V_D$ were 300 ± 30 km/sec as suggested by *Krimigis et al.* [2003b], then $B_E > 6 \times 0.027$ nT $= 0.162 \pm 0.048$ nT, which is also inconsistent with our observations.

[16] Finally, assume that V1 crossed from the heliosheath or a low-speed region back to the solar wind on ≈2003, day 48 ± several days as suggested by *Krimigis et al.* [2003b]. Such a crossing implies a decrease in B by a factor of >4.6 if the speed increased from <50 km/sec to 230 ± 25 km/sec [*Krimigis et al.*, 2003b] or by a factor of >3 if V1 crossed the TS. The decrease in B implies an increase in the cosmic ray intensity if the CR-B relation is valid. The GCR actually decreased during this time interval [*McDonald et al.*, 2003]. The magnetic field strength increased rather than decreased on ≈day 41, 2003 from 0.044 ± 0.007 nT in interval E to 0.073 ± 0.025 nT in the interval day 41 to day 61, which is not consistent with a crossing from the heliosheath or some other subsonic region to the solar wind.

## 3. Summary

[17] We examined the heliospheric magnetic field strength B observed by Voyager 1 near 85 AU and 34°N latitude to search for evidence that V1 might have been in a subsonic region such as the heliosheath from ≈2003, day 213 to ≈2003, day 48 ± several days, as suggested by *Krimigis et al.* [2003a, 2003b] and *Decker et al.* [2003].

[18] The fluctuations of B observed from 2002.0 to 2003.17 resemble those observed during 2001. From 2002.0 to 2003.17, the distribution of B was lognormal, and the $SD(B)/\langle B\rangle = 0.55$ for hour averages of B, consistent with previous heliospheric observations. The average B in the interval was $\langle B\rangle = 0.041$ nT, which is consistent with B expected from extrapolation of previous heliospheric observations and significantly lower than predicted for subsonic flow in the heliosheath. The changes in the intensity of >70 MeV/n particles were correlated with changes in the magnetic field strength profile, as observed by V1 in the heliosphere for many years beyond ≈11 AU. We conclude that between 2002.0 and 2003.17 the properties of the large-scale magnetic field strength and the associated cosmic ray variations observed by V1 were consistent with V1 being in the solar wind.

[19] The average B from day 215, 2002 through day 33, 2003 (region 'E') equals 0.044 ± 0.007 nT, which is consistent with the heliospheric magnetic field predicted by Parker's model ($\langle B_P\rangle = 0.047 \pm 0.003$ nT). If V1 entered a region in which the flow speed is <50 km/sec, as suggested by *Krimigis et al.* [2003b], then the average B in region E would be ≈4 to 5 times the observed value. Similarly, observations of an increase in B and a decrease in

CRS at the end of interval E on ≈day 48 ± several days are qualitatively inconsistent with the suggestion of *Krimigis et al.* [2003b] that V1 moved from a subsonic region to the solar wind at this time. Hence, our observations do not support the view that V1 passed from the solar wind to a subsonic region such as the heliosheath and back to the solar wind.

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## References

Balogh, A., and E. J. Smith, The heliospheric magnetic field at solar maximum: Ulysses observations, *Space Sci. Rev.*, *97*(1–4), 147–160, 2001.

Behannon, K. W., M. H. Acuna, L. F. Burlaga, R. P. Lepping, N. F. Ness, and F. M. Neubauer, Magnetic field experiment for Voyagers 1 and 2, *Space Sci. Rev.*, *21*(3), 235–257, 1977.

Burlaga, L. F., Interplanetary Magnetohydrodynamics, Oxford Univ. Press, New York, 1995.

Burlaga, L. F., and N. F. Ness, Magnetic field strength distributions and spectra in the heliosphere and their significance for cosmic ray modulation: Voyager 1, 1980–1994, *J. Geophys. Res.*, *103*(A12), 29,719–29,732, 1998.

Burlaga, L. F., N. F. Ness, Y.-M. Wang, and N. R. Sheeley Jr., Heliospheric magnetic field strength and polarity from 1 to 81 AU during the ascending phase of solar cycle 23, *J. Geophys. Res.*, *107*(A11), 1410, doi:10.1029/2001JA009217, 2002.

Burlaga, L. F., N. F. Ness, F. B. McDonald, J. D. Richardson, and C. Wang, Voyagers 1 and 2 observations of magnetic field and associated cosmic ray variations from 2000 through 2001: 60–87 AU, *Astrophys. J.* (Part 1 (1)), 582, 540–549, 2003.

Burlaga, L. F., F. B. McDonald, M. L. Goldstein, and A. J. Lazarus, Cosmic ray modulation and turbulent interaction regions near 11 AU, *J. Geophys. Res.*, *90*(A12), 2027–2039, 1985.

Decker, R. B., S. M. Krimigis, E. C. Roelof, and M. E. Hill, Angular distributions and energy spectra of energetic particles observed at Voyager 1 at 85–88 AU, in 28th International Cosmic Ray Conference, pp. 3773–3776, 2003.

Holzer, T. E., Interaction between the solar wind and the interstellar medium, *Ann. Rev. Astron. Astrophys.*, *27*, 199–234, 1989.

Karmesin, S. R., P. C. Liewer, and J. U. Brackbill, Motion of the termination shock in response to an 11-year variation in the solar wind, *Geophys. Res. Lett.*, *22*(9), 1153–1156, 1995.

Krimigis, S. M., R. B. Decker, E. C. Roelof, and D. Lario, Energetic particle intensity at Voyagers 1 and 2 during 2002–03, in 28th International Cosmic Ray Conference, pp. 3769–3772, 2003a.

Krimigis, S. M., R. B. Decker, M. E. Hill, T. P. Armstrong, G. Gloeckler, D. C. Hamilton, L. J. Lanzerotti, and E. C. Roelof, Evidence that Voyager-1 exited the solar wind at ~85 AU, *Nature*, in press, 2003b.

Le Roux, J. A., and H. Fichtner, A self-consistent determination of the heliospheric termination shock structure in the presence of pickup, anomalous, and galactic cosmic ray protons, *J. Geophys. Res.*, *102*(A8), 17,365–17,380, 1997.

McDonald, F. B., and L. F. Burlaga, Global merged interaction regions in the outer heliosphere, in Cosmic Winds and the Heliosphere, edited by J. R. Jokipii, C. P. Sonett, and M. S. Giampapa, Univ. of Arizona Press, Tucson, 389–423, 1997.

McDonald, F. B., A. C. Cummings, E. C. Stone, B. Heikkila, N. Lal, and W. R. Webber, Unusual enhancements of MeV ions and electrons as Voyager 1 approaches the heliospheric termination shock, *Nature*, in press, 2003.

Parker, E. N., Interplanetary Dynamical Processes, Interscience Publishers, New York, 1963.

Scherer, K., and H. J. Fahr, Solar cycle induced variations of the outer heliospheric structures, *Geophys. Res. Lett.*, *30*(2), 1045, 2003.

Stone, E. C., Perspectives: Planetary science - news from the edge of interstellar space, *Science*, *293*(5527), 55–56, 2001.

Stone, E. C., R. E. Vogt, F. B. McDonald, B. J. Teegarden, J. H. Trainor, J. R. Jokipii, and W. R. Webber, Cosmic ray investigation for the Voyager missions; Energetic particle studies in the outer heliosphere – and beyond, *Space Sci. Rev.*, *21*, 355–376, 1977.

Wang, C., and J. W. Belcher, The heliospheric boundary response to large-scale solar wind fluctuations: A gasdynamic model with pickup ions, *J. Geophys. Res.*, *104*(A1), 549–556, 1999.

Weymann, R., Coronal evaporation as a possible mechanism for mass loss in a red giant, *Astrophys. J.*, *132*, 380, 1960.

Whang, Y. C., and L. F. Burlaga, Termination shock - solar-cycle variations of location and speed, *J. Geophys. Res.*, *98*(A9), 15,221–15,230, 1993.

Whang, Y. C., and L. F. Burlaga, Anticipated Voyager crossing of the termination shock, *Geophys. Res. Lett.*, *27*(11), 1607–1610, 2000.

Whang, Y. C., L. F. Burlaga, Y.-M. Wang, and N. R. Sheeley Jr., Solar wind speed and temperature outside 10 AU and the termination shock, *Astrophys. J.*, *589*, 635–643, 2003.

Zank, G. P., Interaction of the solar wind with the local interstellar medium: A theoretical perspective, *Space Sci. Rev.*, *89*(3–4), 413–688, 1999.

Zank, G. P., and H. L. Pauls, Modelling the heliosphere, *Space Sci. Rev.*, *78*(1–2), 95–106, 1996.

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