When will Voyager 1 and 2 cross the termination shock?

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[1] Our Solar System moves through a warm (~6,500 K), partly ionized local interstellar cloud (LIC) with a relative speed of ~26 km/s. The solar wind interacts with the LIC to form a cavity around the Sun called the heliosphere. The solar wind meets the interstellar charged component at the heliopause, where solar wind pressure balances the pressure of the LIC. Before reaching the heliopause, the supersonic solar wind is decelerated at an extended shock wave, the heliospheric termination shock (TS). The two Voyager spacecraft are cruising away from the Sun and approaching the termination shock. Here we present predictions of when the Voyagers will encounter the termination shock by calculating the position of the TS using a numerical multi-component model of the heliospheric interface and improved measurements of interstellar H atoms. Interstellar atoms penetrate into the heliosphere where they are ionized and detected as pickup ions by the SWICS instrument on Ulysses. We conclude that the most probable crossing of the termination shock by Voyager 1 will occur between 2007 and 2012. *INDEX TERMS:* 2124 Interplanetary Physics: Heliopause and solar wind termination; 2152 Pickup ions; 2162 Solar cycle variations (7536); 2144 Interstellar gas; *KEYWORDS:* heliospheric termination shock, pickup ions, local interstellar cloud, Voyager spacecraft, interstellar atoms. **Citation:** Izmodenov, V., G. Gloeckler, and Y. Malama, When will Voyager 1 and 2 cross the termination shock?, *Geophys. Res. Lett.*, *30*(7), 1351, doi:10.1029/2002GL016127, 2003.

1. Introduction

[2] The solar wind interacts with the LIC to form the heliospheric interface, which separates pristine interstellar medium from the unperturbed solar wind. At the heliopause, which separates the solar wind from the interstellar charged components, the solar wind pressure balances the pressure of the LIC. Since the solar wind is a supersonic flow, the heliospheric termination shock (TS) is expected be formed, making the solar wind subsonic before it reaches the heliopause. The Voyagers 1 and 2 spacecraft are moving away from the Sun at 3.6 and 3.3 per year respectively and are thus approaching the termination shock believed to be roughly around 100 AU.

[3] In January 2003 Voyager 1, the most distant spacecraft, will be at about ~87 AU. The termination shock crossing by Voyagers has been anticipated for a long time and it is therefore important to update predictions when each of them will cross the termination shock.

[4] Different types of remote diagnostics can be used to estimate the time of Voyagers' encounters with the termination shock. A summary of five different methods previously used to estimate the termination shock location was presented recently by *Stone* [2001], who concluded that Voyager 1 would most likely have one or more encounters with the termination shock by 2005.

[5] In this paper we use updated measurements of pickup H^+ by the Solar Wind Ion Composition Spectrometer (SWICS) on Ulysses [*Gloeckler et al.*, 1992] in the slow solar wind at ~5 AU and low latitude. This method provides the most accurate determination of the density of interstellar H atoms inside the heliosphere near the TS. We will use results of this determination of the neutral H density as one of the constraints on the LIC proton and neutral hydrogen densities which determine the dominant components of the LIC pressure.

2. Model of the Heliospheric Interface

[6] In this work we used the heliospheric interface model developed and advanced by the Moscow group [*Baranov and Malama*, 1993; *Izmodenov et al.*, 1999; *Alexashov et al.*, 2000; see also *Zank*, 1999; *Izmodenov*, 2001] to calculate the neutral hydrogen density at the termination shock and to predict its location. In this axisymmetric model, a one-fluid approach is used to describe plasma component (electrons, protons and pickup ions), while a kinetic approach is used to describe H atoms in the heliospheric interface. The latter approach is required to describe H atoms because their mean free path is comparable to the size of the heliosphere [see, e.g., *Izmodenov et al.*, 2000]. The charged and neutral components interact by charge exchange. We have included a weak magnetic field, $B = 2 \times 10^{-6}$ Gauss in our model, but find that such a field has only a minor effect on the location of the termination shock and on the atomic H distribution [*Alexashov et al.*, 2000]. Influence of pickup ions on the solar wind plasma flow in the outer heliosphere is taken into account using the relevant parts of momentum and energy equations for the plasma components. In the global model we assume immediate assimilation of pickup protons into the solar wind flow. This approach is reasonable for prediction of the TS location, because it satisfies basic conservation laws of mass, momentum and energy.

[7] Among interstellar parameters influencing the heliospheric interface structure, the LIC velocity relative to the Sun and the temperature of the local interstellar gas are now well established by direct measurements of interstellar helium atoms by the GAS instrument on Ulysses [*Witte et al.*, 1996]. In this paper we use the latest values for temperature of the interstellar gas of 6500 K and the speed

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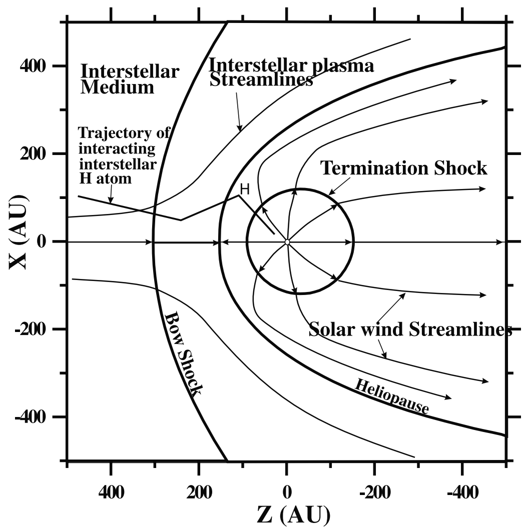

Figure 1. Structure of the heliospheric interface, the region of interaction of the solar wind with the Local Interstellar Cloud, based on results of numerical modeling.

of the LIC relative to the Sun of 26.4 km/s [Witte, private communication].

[8] The temperature and speed determine the Mach number, which is about 2 for the interstellar medium. Since the solar wind is also supersonic, a two-shock interface is formed in the LIC/SW interaction (Figure 1).

[9] We use the Ulysses (SWOOPS) averaged solar wind parameters for the 2-year time period 1997.108–1999.108 to determine the average locations of the boundaries shown in Figure 1. The average values of the solar wind speed and proton number density at 1 AU were 432 km/s and 7.39 cm^{-3}, respectively.

[10] The remaining two important input parameters required to calculate the location of the TS are the interstellar proton number density, $n_{p,LIC}$ and the neutral H number density, $n_{H,LIC}$. These parameters cannot be measured directly. To obtain best estimates of these important LIC parameters that influence the position of the termination shock we use the following constraints in this paper: (1) SWICS/Ulysses measurements of pickup ions; (2) measurements of ionization of interstellar helium by the Extreme Ultraviolet Explorer [*Wolff et al.*, 1999], and (3) the standard universal H/He ratio [*Anders and Grevesse*, 1989]. Based on these constraints, described in more detail in the next section, the best values for $n_{p,LIC}$ and $n_{H,LIC}$ are 0.06 ± 0.015 cm^{-3} and 0.17 ± 0.02 cm^{-3} respectively. The best value for the ionized interstellar He density, which also contributes to the dynamic pressure and thus affects the location of the TS, $n_{He^+,LIC}$ = 0.008 ± 0.002 cm^{-3}. With these input parameters the mean location of the termination shock in the upwind direction (direction of relative motion) is ∼98 AU from the Sun.

3. Determination of Number Densities of H Atoms and Protons in LIC

[11] Charge exchange processes in the heliospheric interface lead to a predictable reduction, or filtration, of interstellar atomic hydrogen that enters the heliosphere. The most accurate determination of the density of interstellar H atoms inside the heliosphere comes from measurements of pickup H^+. Pickup ions are created from interstellar atoms inside the heliosphere by photoionization and charge exchange with the solar wind. An example of a typical proton velocity distribution is given in Figure 2. This spectrum was observed with SWICS on Ulysses in the slow solar wind at ∼5 AU during quiet times at low latitudes.

[12] To model the pickup ion distribution (labeled 'pi' in the figure) we first compute the predicted phase-space density of pickup protons in the solar wind frame of reference at the location (R, θ) of Ulysses (with R the heliocentric radial distance in AU and θ the angle between the direction of motion of the Sun relative to the interstellar cloud and the Sun-Ulysses line) using the "hot model" of *Thomas* [1978] for the spatial distribution of hydrogen atoms in the heliosphere and equations (9) and (10b) of *Vasyliunas and Siscoe* [1976] derived under the assumption of rapid pitch-angle scattering and hence isotropy the phase-space density of the resulting pickup protons. We then make the coordinate transformation to the spacecraft frame and finally integrate the model phase space density in the spacecraft frame over the view directions of SWICS. This predicts what the SWICS instrument would measure. Model

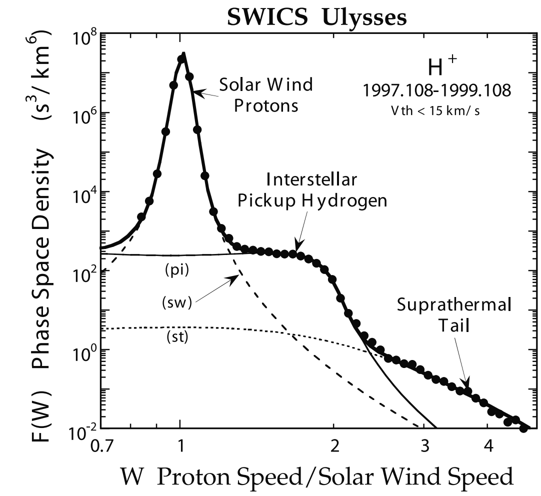

Figure 2. Two-year-averaged phase space density of H^+ versus normalized speed W (proton speed divided by solar wind speed) observed with the Solar Wind Ion Composition Spectrometer (SWICS) on Ulysses in the slow solar wind at ∼5 AU and low latitude. Only quiet-time periods, characterized by a low solar wind thermal speed (<15 km/s) were used in this average. Interstellar pickup hydrogen is the dominant component in the flat portion of the spectrum between W ∼ 1.3 and ∼2.2. Solar wind protons, modeled by curve (sw), dominate below W ∼ 1.3 and accelerated protons form the suprathermal tail above W ∼ 2.2, modeled by curve (st). During quiet time periods used here, the solar wind distribution is sufficiently narrow and the suprathermal tail sufficiently weak, to reveal more fully the pickup ion component of the spectrum. The curve labeled (pi) is computed using model parameters given in the text. The atomic hydrogen density at the termination shock is found to be 0.090 ± 0.008 cm^{-3}.

parameters, in particular the neutral hydrogen density at the termination shock, are adjusted until the best fit to the measured spectrum is obtained. The assumption of isotropic pickup ion distributions is justified in this case because at 5 AU in the ecliptic plane the average magnetic field direction is nearly perpendicular to the solar wind flow direction.

[13] Heliospheric parameters affecting the model pickup ion distribution are well known from direct measurements. During the 2-year time period of Figure 2 the average photoionization rate for hydrogen, derived from Lyman alpha measurements on SOHO was 0.8×10^{-7} s^{-1} [*D. R. McMullin and D. L. Judge*, private communication]. The ionization rate from charge exchange, a product of solar wind flux (measured with SWICS) and charge exchange cross section [*Maher and Tinsley*, 1977] was 5.4×10^{-7} s^{-1}, giving a total loss rate of 6.2×10^{-7} s^{-1}. The total production rate of pickup hydrogen is somewhat smaller (5.1×10^{-7} s^{-1}) because the average solar wind flux for time periods of low thermal speed was measured to be lower than for the entire two year time period. The ratio of the solar radiation pressure to solar gravitation, μ, is 1-16. With these values for the loss and production rates and μ an excellent fit to the measured pickup proton distribution is obtained and the number density of atomic H at the termination shock is determined to be 0.090 ± 0.008 cm^{-3}.

[14] The least known of the interstellar parameters are the LIC densities of atomic hydrogen and protons. We use (1) our measurements of the atomic H density at the TS (=0.090 ± 0.008 cm^{-3}), (2) measurements of the LIC atomic He density (=0.015 ± 0.002 cm^{-3}) [*Gloeckler and Geiss*, 2001; M. Witte, personal communication], (3) the standard universal ratio of the total H to He $(n_{p,LIC} + n_{H,LIC})/(n_{He^+,LIC} + n_{He,LIC}) = 10$, (4) measurements of local interstellar helium ionization rate of $n_{He^+,LIC}/(n_{He^+,LIC} + n_{He,LIC}) = 0.35 \pm 0.05$ [*Wolff et al.*, 1999]. Previously, similar methodology was used to determine interstellar H atom and proton number densities by *Lallement* [1996] and *Gloeckler et al.* [1997]. Here we use the latest measurements. With these constraints we find that the heliospheric interface model with $n_{He,LIC} = 0.17 \pm 0.02$ cm^{-3} and $n_{p,LIC} = 0.06 \pm 0.015$ cm^{-3} provides the best fit to SWICS Ulysses pickup hydrogen data. Interstellar hydrogen ionization fraction derived from our results is in agreement with recent calculations of the photoionization of interstellar matter within 5 pc of the Sun [*Slavin and Frisch*, 2002].

4. Predictions of Times of TS Crossing by Voyagers 1 and 2

[15] The location of the termination shock is not stationary because of solar-cycle-dependent variations of the solar wind parameters resulting in about a factor of 1.6 variation in the ram pressure. To estimate when the Voyagers will cross the termination shock we use results of the time-dependent version of the Baranov-Malama model of the heliospheric interface, which allows us to take into account effects of the solar cycle variations of the solar wind. Five-point running averages of six-month averages of the solar wind speed and density measured by the MIT plasma analyzer on IMP 8 (at 1 AU) from 1973 to 2001, and an average alpha to proton number density ratio of 0.03 were used to derive solar cycle variations of the distance to the termination shock. For interstellar parameters we used $n_{H,LIC} = 0.17 \pm 0.02$ cm^{-3}, $n_{p,LIC} = 0.06 \pm 0.015$ cm^{-3} and $n_{He^+,LIC} = 0.008 \pm 0.002$ cm^{-3}. Model calculations show that the termination shock reaches minimum heliocentric distance in a little more than two years after solar maximum. Using Ulysses/SWOOPS measurements of solar wind parameters during a 2-month period in 2002.8 when Ulysses was at +34 latitude, about the same as Voyager 1, places the predicted shock distance at 108 AU in 2004. We adjusted the solar-cycle curves (Figure 3) to that shock location in 2004. In the direction of travel of Voyager 1 the termination shock moves from its closest distance to the Sun, 99 AU, to the furthest distance, ~113 AU. The termination shock moves back and forth from its mean distance of 106 AU with amplitude of 7 AU. We note, however, that although we calculate the global heliospheric interfaces structure self-consistently, we neglect solar-cycle variation of filtration of

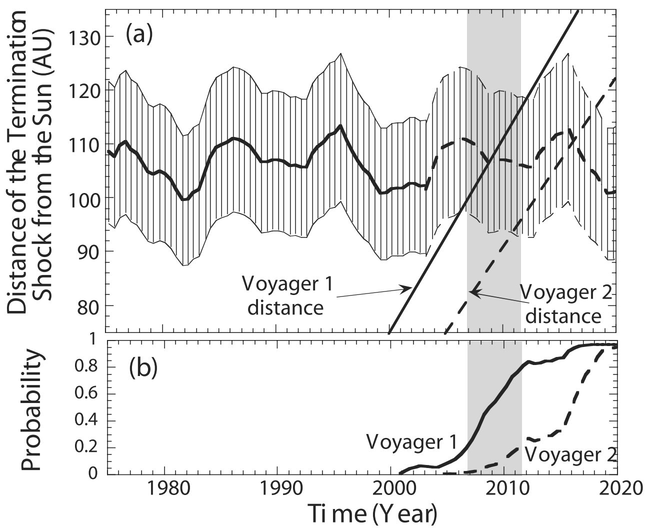

Figure 3. (a) Mean (bold curves) and 1σ- limits (light curves) of the termination shock heliocentric radial distance (in astronomic units) as a function of time at 30 from the upwind direction, calculated using the models described in the text. IMP 8 solar wind parameters were used for the time period between 1975 and 2001 (solid curves) to establish the solar-cycle dependence of the termination shock location. The distance-time curves were then repeated with a 20-year lag corresponding to the approximate period of the magnetic field reversal cycle of the Sun (dotted curves). Using Ulysses measurements of solar wind parameters during a 2-month period in 2002.8 when Ulysses was at +34 latitude, about the same as Voyager 1, places the predicted shock distance at 108 AU in 2004. We adjusted the solar-cycle curves to that shock location in 2004. The Voyager 1 and 2 distances from the Sun are indicated by the labeled lines. (b) Probability of termination shock crossing for Voyager 1 (solid curve) and Voyager 2 (dotted curve) as a function of time. The probability of shock encounter is calculated as a function of time t by integrating the gaussian probability distribution (with mean $\langle R(t) \rangle$ and $\sigma(t)$ from the upper panel) from minus infinity to the radial distance from the Sun of Voyager 1 or 2 respectively. The most probable encounter of the termination shock by Voyager 1 is between 2007 and 2012, indicated by the shaded region.

interstellar atoms. We do not expect that these variations will change our results significantly.

[16] In the direction of travel of Voyager 1, approximately 30° from the upwind direction, the most probable heliocentric distance of the termination shock is 102 AU in 2002 as shown in Figure 3. In August 2002, Voyager 1 was at ~86 AU. As the solar cycle goes from maximum to minimum, the termination shock starts to move away from the Sun at about the same speed as Voyager 1. The termination shock reaches its furthest distance from the Sun in about 2006 before starting to move in again with the transition from solar minimum to solar maximum. From Figure 3, the most probable encounter of Voyager 1 with the termination shock will therefore be between 2007 and 2012. However, should solar maximum conditions of the present solar cycle persist a year longer than predicted, then there is about a 20% chance that the encounter will take place in the next several years. The most probable encounter of the termination shock by Voyager 2 is estimated to be between 2011 and 2018.

[17] Our present axisymmetric model does not allow us to include any variations of solar wind speed and density with latitude. The TS location at Voyager 1, now ~30 degrees northward from the ecliptic, may be influenced by different solar wind conditions at that latitude. In this study we assumed that the interstellar magnetic field is parallel to the interstellar flow. We believe that inclusion of 3D effects would change our prediction only slightly. Finally, we only used average values of the solar wind alpha to proton abundance ratio, α/p, which varies from 0.02 at solar minimum to 0.045 at solar maximum [*Aellig et al.*, 2001]. We estimate that for α/p = 0.02 the TS location moves inward by about1 AU, while for α/p = 0.045 the shock moves outward by 2 AU. These variations are less than our error bars shown in Figure 3.

5. Summary

[18] In this paper we use our global heliospheric interface model to predict Voyager 1 and 2 crossings of the termination shock. To constrain the least known of the interstellar parameters the LIC densities of H ($n_{H,LIC}$) and protons ($n_{p,LIC}$) in the LIC, we use (1) SWICS Ulysses measurement of pickup ions of H^+ and He^+ to determine the atomic H density at the termination shock, (2) measured ionization fractions of LIC He, and (3) the standard universal H/He abundance ratio. With these constraints we find $n_{H,LIC}$ = 0.17 0.02 cm^{-3} and $n_{p,LIC}$ = 0.06 ± 0.015 cm^{-3}. In the direction of travel of Voyager 1 the termination shock location varies from 99 AU to ~113 AU. We find that the most probable encounter of Voyagers 1 and 2 with the termination shock will be between 2007 and 2012 and between 2011 and 2018 respectively.

[19] **Acknowledgments.** We thank D. R. McMullin and D. L. Judge for making the photoionization rates derived from SOHO measurements available to us, J. D. Richardson and A. J. Lazarus for their IMP8 solar wind data, and D. J. McComas for the SWOOPS solar wind data. We thank the International Space Science Institute (ISSI) staff for their hospitality during our visit to ISSI where discussions leading to results of this publication were initiated. This work was supported in part by NASA/Caltech grant NAG5-6912, NASA/JPL contract 955460, the International Space Science Institute in Bern, INTAS grant 2001-0270, and Russian Foundation for Basic Research (RFBR) grants 01-02-17551, 02-02-06011 and 01-01-00759.

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