Interstellar Pioneer 10 EUV Data: Possible Constraints on the Local Interstellar Parameters

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Abstract. The neutral hydrogen and proton densities of the local interstellar cloud are still not well known even after many decades of space research. There is, however, a lot of diagnostic data available to investigate these parameters. We have used one such data set, the Pioneer 10 (P10) Lyman Alpha data obtained between the heliocentric distances 20 to 45 AU, to estimate the local interstellar hydrogen and proton densities. We have used state of the art neutral-plasma and radiative transfer models for the interpretation of the P10 EUV data. The results are presented and possible constraints are discussed.

INTRODUCTION

The heliospheric interface, formed due to the interaction between the solar wind and the local interstellar cloud (LIC), is a very complicated phenomenon where the solar wind and interstellar plasmas, interstellar neutrals, magnetic field, and cosmic rays play prominent roles. The heliosphere provides a unique opportunity to study in detail the only accessible example of a commonplace but fundamental astrophysical phenomenon - the formation of an astrosphere. The heliospheric interface is a natural "environment" of our star and knowledge of its characteristics is important for the interpretation and planning of space experiments.

Remote sensing of the heliospheric interface through the study of the interstellar hydrogen atoms is possible since H atoms play a very important role in the formation of the heliospheric interface. Interstellar H atoms are strongly coupled with plasma protons by charge exchange. Distribution of H atoms inside the heliosphere has imprints of the heliospheric interface. Thus, interstellar hydrogen atoms provide excellent remote diagnostics on the structure of the heliospheric interface. The study of the neutral hydrogen atoms in the outer heliosphere has been made possible by the presence of four deep space spacecraft, Pioneers 10 and 11 (P10 and P11), and Voyagers 1 and 2 (V1 and V2). The USC photometers on-board P10 and P11 and the ultraviolet spectrometers (UVS) on-board V1 and V2 have measured the interplanetary Ly α background radiation for more than twenty years. Various studies of P10/11 and V1/2 Ly α data have been published. Yet, the estimation of the interstellar H atom density varies greatly from study to study, ranging between 0.03 and 0.3 cm^{-3} [1].

In this paper we present the first results of our reanalysis of the P10 Ly α data to improve our knowledge of the very local interstellar neutral hydrogen and proton densities. This reanalysis uses the latest state of the art neutral hydrogen-plasma and radiative transfer models outlined in the later sections.

HELIOSPHERIC INTERFACE MODEL

The interaction of the solar wind with the interstellar medium influences the distribution of interstellar atoms inside the heliosphere. Further, it is now clear that the Local Interstellar Cloud is partly ionized and that the plasma component of the LIC interacts with the solar wind plasma to form the heliospheric interface (Figure 1). Interstellar H atoms interact with the plasma component through charge exchange. This interaction strongly influences both the plasma and neutral components. The main difficulty in the modeling of the H atom flow in the heliospheric interface is its kinetic character due to the large, i.e. comparable to the size of the interface, mean free path of H atoms with respect to the mean free path for charge exchange process. In this paper to get the H atom distribution in the heliosphere and heliospheric interface structure, we use the self-consistent model developed by Baranov and Malama in [2]. The kinetic equation for the neutral component and the hydrodynamic Euler equations were solved self-consistently by the method of global interactions. To solve the kinetic equation for H atoms, an advanced Monte Carlo method with splitting of trajectories [3] was used. Basic results of the model were

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reported in [4-7].

RADIATIVE TRANSFER MODEL

The LISM neutral hydrogen gas is an optically thick medium for solar Lyman Alpha photons. The scattering path length for neutral hydrogen density of 0.1 cm^{-3} will be of the order of 10 to 15 AU. This implies that the radiative transfer calculation of Lyman Alpha photons at heliocentric distances greater than 15 AU must necessarily take into account multiple scattering. In fact, a full treatment of the solar Lyman Alpha radiative transfer problem must include the actual self-reversed solar line shape, multiple scattering, full angular and frequency redistribution function, Doppler and aberration effects, heliosphere-wide hydrogen temperature and velocity changes and Voigt Lyman α absorption profile. Details of our radiative transfer model are given in [8].

RESULTS

Monte Carlo radiative transfer calculations were carried out for seven models of neutral hydrogen density (Table 1). The calculated results, I_{model}, were then compared with P10 EUV data. An example of this is shown in figure 2. In order to properly compare the data with the calculated results, it was necessary to calculate the optimum P10 instrument calibration factor (CF) for each of the density models. This step is necessary since it is known that the P10 and V1/2 instrumental calibrations differ by a factor of 4.4 at Lyman α. The difference between the P10 photometer and V2 spectrometer calibration factors forces one to reproduce the distance dependence of the data rather than rely on the absolute value of the measured intensity. It should be stated here that the P10 photometer calibration did not drift with time during the period 1979-1988 considered here. The degradation of the P10 Bendix channel multipliers has been studied in the laboratory. It has been found that the electron multipliers can deliver about 16 coulombs of charge without any sign of fatigue. The P10 electron multiplier for the hydrogen channel is estimated to have delivered at most 4 coulombs of charge by 1988. The early degradation observed in the hydrogen channel of the P11 instrument is attributed to damage due to the hostile environment encountered by P11 during its flyby past Saturn. The optimum calibration factor for a density model is calculated by minimizing the least squares sum, LSS, where LSS is calculated by the following equation

$$LSS = \sum (I_{model} + bg - CF * I_{P10data})^2, \qquad (1)$$

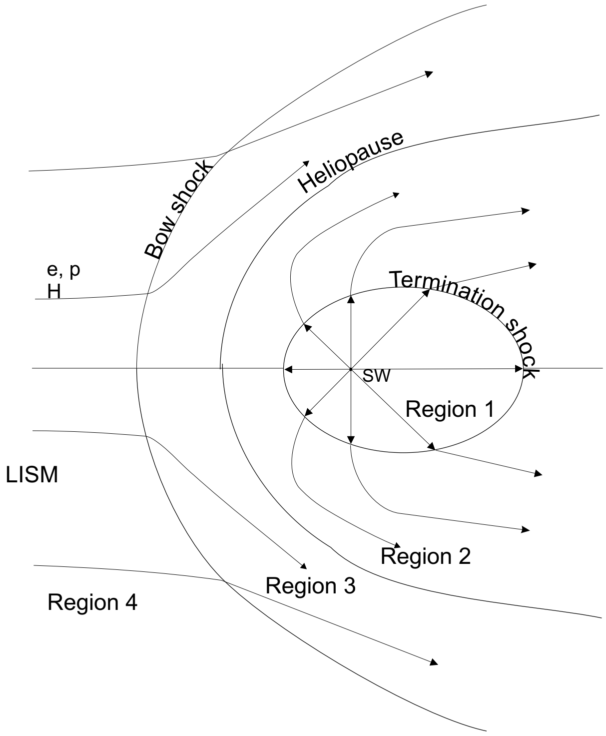

FIGURE 1. The heliospheric interface is the region of the solar wind interaction with LIC. The heliopause is a contact discontinuity, which separates the plasma wind from interstellar plasmas. The termination shock decelerates the supersonic solar wind. The bow shock may also exist in the interstellar medium. The heliospheric interface can be divided into four regions with significantly different plasma properties: 1) supersonic solar wind; 2) subsonic solar wind in the region between the heliopause and termination shock; 3) disturbed interstellar plasma region (or "pile-up" region) around the heliopause; 4) undisturbed interstellar medium.

where summation is over the P10 data points and bg is the Lyman α galactic background. Both CF and bg were varied to obtain the minimum LSS. Once the optimum *CF* and bg are found then P10 data are multiplied by *CF* and compared with the calculated intensity. Both *CF* and *LSS* for each of the 7 density models are given in Table 1.

It is clear from Table 1 that the model with the VLISM neutral hydrogen density of 0.15 cm^{-3} and proton density of 0.07 cm^{-3} yields the lowest *LSS* and so best reproduces the P10 data. The next best fit occurs for the model with neutral hydrogen density of 0.2 cm^{-3} and proton density of 0.2 cm^{-3}. It is not at present possible to choose between the two neutral densities used in these two models as it is necessary to calculate model results for other ionization ratios for both of these cases and compare with P10 data. The Lyman α background, bg, was determined to be negligibly small for all the density models. In fact the best fit was obtained for bg equal

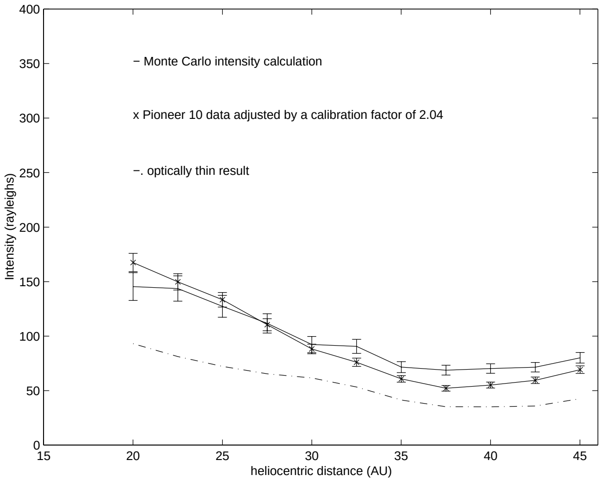

FIGURE 2. Comparison of Monte Carlo calculation using heliospheric model with neutral hydrogen density of 0.15 cm^{-3} and proton density of 0.07 cm^{-3} and Pioneer 10 Lyman α glow data adjusted by the constant calibration factor as function of heliocentric distance. Comparison with optically thin model is also shown.

TABLE 1. Sets of model parameters and results

$n_{H,LIC}$	$n_{p,LIC}$	**sqrt(Least squares sum)**	**Calibration factor**
0.15	0.07	40.9	2.04
0.15	0.10	52.2	1.96
0.18	0.15	59.4	1.84
0.2	0.05	71.8	3.16
0.2	0.10	50.7	2.26
0.2	0.20	50.4	1.80
0.25	0.10	56.9	3.08

to zero although the deviation of the data from the best fit curve was from + 22 to - 16 Rayleighs. The background glow is assumed to be approximately the same for all data points since the look directions are approximately the same with respect to the galactic plane. A look at Table 1 shows that the largest deviation from the P10 data occurs for the model in which neutral density is 0.2 cm^{-3} and proton density=0.05 cm^{-3}. The ionization ratio ($n_p/(n_H+n_p)$) for this model is 0.2.

The value 0.2 might well be the lower limit of the LISM ionization ratio. This is because the LISM neutral hydrogen density can not be too high because of the growing evidence that the neutral hydrogen density inside the termination shock is of the order of 0.1 cm^{-3} or less. For example, Wang and Richardson suggest in [9] that the Voyager 2 solar wind observations are best fitted with an interstellar neutral hydrogen density of 0.08 cm^{-3} at the termination shock. Such a low neutral hydrogen density at the termination shock would imply a neutral hydrogen density of 0.16 cm^{-3} at "infinity" even assuming that the neutral hydrogen suffers a 50 % depletion at the interface. Similarly, *Gloeckler and Geiss* in [10] found that the neutral hydrogen density at the termination shock is 0.115 cm^{-3} and obtained a value of 0.18 cm^{-3} for the interstellar hydrogen density assuming a 58 % filtration effect. We did not use a very high interstellar neutral hydrogen density as that will imply a large neutral density inside the heliosphere which would contradict observational evidence [9, 10].

It is possible to estimate the upper limit to the ionization ratio from the fact that the model with neutral and proton densities equal to 0.2 cm^{-3} (ionization ratio =0.5) gives better fit to the Pioneer 10 data than the models discussed previously except for the first model in Table 1. However, such a high proton density is ruled out as it would imply a solar wind shock too close to the sun contrary to observations. Thus, an ionization ratio as high as 0.5 would imply a low neutral density and a ratio higher than 0.5 is extremely unlikely. The relatively high value of the ionization ratio (0.2 to 0.5) estimated in this work clearly shows that the VLISM neutral hydrogen density can not be as high as 0.25 cm^{-3}. This is because it is clear from figure 8 in [8] and from the better fit obtained for the model with both proton and neutral densities equal to 0.2 cm^{-3} that an ionization ratio substantially higher than 0.3 would be necessary to better fit the neutral density, 0.25 cm^{-3}, model with the P10 data. However, even an ionization ratio of 0.4 for a neutral hydrogen density of 0.25 cm^{-3} would imply a proton density of about 0.18 cm^{-3} which would move the solar wind termination shock too close to the sun.

Another issue that needs to be discussed is the possible reasons for the deviation of the model calculation from the P10 data. The obvious reason is, of course, the difference of the model neutral hydrogen density from the actual heliospheric neutral density. Another reason is the possible variation of the solar Lyman α line center flux with respect to the integrated line [11]. We have plotted the ratio of the model intensity to the P10 data against solar Lyman α flux in order to see if the deviation is due to the variation in line center flux. There is a trend for the ratio to decline from greater than 1 to less than 1 as the solar flux increases. This trend might be due to the line center flux variation.

Figure 2 also shows a comparison between optically thick and optically thin radiative transfer calculations. The difference is significant. This result suggests that the interstellar gas is optically thick.

SUMMARY

The comparison of predicted Lyman Alpha glow using state of the art heliosphere model and Monte Carlo radiative transfer calculations with P10 data has yielded several constraints on the VLISM parameters. The ionization ratio is found to vary between 0.2 and 0.5. The upper limit to the neutral hydrogen density is found to be less than 0.25 cm^{-3}. It is found that the Lyman Alpha galactic background is negligibly small (less than a Rayleigh). The optimum calibration factor was found to vary from 1.8 to 3.2 for the seven models used in this work. The calibration factor is found to be 2 for the model ($n_{H,LIC}$ =0.15 cm^{-3}; $n_{p,LIC}$ = 0.07 cm^{-3}) that best fit the data. This work suggests that P10 UV photometer flux data values need to be increased by a factor of 2. Thus the difference in calibration factor between P10 photometer and V2 spectrometer is reduced from 4.4 to about 2.

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