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Heliospheric Hydrogen Beyond 15 AU: Evidence for a Termination Shock

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The Voyager and Pioneer 10 spacecraft are moving upstream and downstream into the local interstellar flow, monitoring H Lyman α radiation resonantly scattered from heliospheric hydrogen. Voyager Cruise Maneuver observations obtained between 15 and 35 AU reveal that H Lyman α intensities in the upstream direction fall as $r^{-0.75\pm0.05}$. Beyond 15 AU downstream, Pioneer 10 intensities fall as $r^{-1.07\pm0.1}$. These trends cannot be simultaneously reproduced using a hot H distribution model that does not include termination shock structure. Radiative transfer calculations using the hot H model predict that upstream intensities should fall more rapidly as a function of heliocentric distance than downstream intensities, precisely opposite to the observed trends. The Voyager H Lyman α intensities also show a distinctive trend to decrease less rapidly with increasing heliocentric distance. Between 15 and 20 AU, Voyager intensities fall as r^{-1}, whereas between 30 and 35 AU they fall as $r^{-0.35}$. This flattening trend implies that the upstream H density is increasing rapidly with heliocentric distance beyond ≈25 AU. A simple analysis suggests that the density distribution changes from nearly uniform between 15 and 20 AU, to $r^{0.65}$ dependence between 30 and 35 AU. This steepening trend is significant because similar H density gradients are predicted in models which include the effects of the termination shock. Taken together, the Voyager and Pioneer 10 H Lyman α observations beyond 15 AU imply the existence of a solar wind termination shock, suggesting that it lies between 70 and 105 AU in the upstream direction.

1. INTRODUCTION

Heliospheric H Lyman α (1216-Å) resonance emissions were first detected in the pioneering rocket experiment of *Morton and Purcell* [1962]. The first extensive observations were obtained in 1969 by two instruments aboard the Orbiting Geophysical Observatory 5 satellite [*Thomas and Krassa*, 1971; *Bertaux and Blamont*, 1971]. Since then, several spacecraft have explored the distribution of heliospheric H Lyman α [*Ajello et al.*, 1987]. The prospect of determining the properties of the very local interstellar medium (VLISM) from the distribution of emission is a basic goal of research on the data. The VLISM is probably relatively unperturbed beyond ≈1000 AU [*Holzer*, 1989], but our information is limited because the majority of H Lyman α measurements have been obtained within 2 AU of the Sun, where the intensities are dominated by scattering from within 10–20 AU. Inside about 20 AU, the atomic hydrogen distribution is strongly affected by interactions with the near-solar environment (i.e., solar wind and EUV ionization, gravitation, and radiation pressure). Outer solar system H Lyman α intensities are therefore more sensitive to the larger structure of the heliosphere, such as the existence and position of a termination shock.

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Several authors have shown that the patterns of H Lyman α detected within 2 AU are reproduced reasonably well using the "hot" model of the heliospheric H distribution [see *Fahr*, 1974; *Thomas*, 1978; *Ajello et al.*, 1987, and references therein]. This model considers a spatially uniform Maxwellian hydrogen gas flowing past the solar environment. It includes effects of solar ionization, gravitation and radiation pressure, but neglects possible outer heliospheric structure. The prevalent feature of the hot H distribution is a teardrop-shaped ionization cavity within 3–10 AU of the Sun, elongated in the downstream direction of the interstellar flow. Despite the relative success of the hot H model within 2 AU, it fails to reproduce data obtained at greater distance. For instance, *Wu et al.* [1981] note significant differences between the model and Pioneer 10 data between 2 and 14 AU. *Lallement et al.* [1991] show that Voyager observations out to 18 AU show systematic deviations from the hot model that require explanation.

Both Voyagers are moving upstream, into the local interstellar flow. The Pioneer 10 trajectory parallels the downstream direction. Beyond 15 AU, Voyager and Pioneer 10 H Lyman α measurements looking outward from the Sun, adjusted for solar flux variations, are roughly characterized as follows: Voyager intensities fall as $r^{(-0.75\pm0.05)}$ for $15 < r < 35$ AU; whereas between 15 and 50 AU Pioneer 10 intensities fall as $r^{(-1.07\pm0.1)}$. A radiative transfer analysis using the hot H distribution does not reproduce these trends. For all reasonable solar and VLISM parameters, the hot H model predicts that upstream H Lyman α intensities should fall more quickly as a function of heliocentric distance than downstream intensities. This is precisely opposite to the trends observed by the spacecraft. The Voyager observations show a continuously increasing deviation from the expected H Lyman α emission with increasing heliocentric distance. *Lallement et al.* [1991] also find excess upstream emission, and mention the effect could be due to hydrogen density gradients associated with the termination shock. Voyager observations are consistent with a progressively increasing atomic hydrogen density beyond ≈25 AU upstream.

The concept of a solar wind termination shock was introduced by *Davis* [1955] and is reviewed by *Holzer* [1989]. The solar wind is observed to be highly supersonic, and as it expands into the VLISM, it most likely decelerates to subsonic speeds via a hydromagnetic shock. Beyond this, in the upstream region, a boundary layer exists where shock-heated solar wind protons undergo momentum and charge exchange collisions with penetrating VLISM H atoms. This both cools and helps to turn the subsonic solar wind flow toward the downstream direction [see *Suess*, 1990]. Several authors including *Patterson et al.* [1963], *Dessler* [1967], *Wallis* [1975], *Ripken and Fahr* [1983], *Bleszynski* [1987], *Baranov et al.* [1991] and *Hall* [1992], have suggested that hydrogen-proton charge exchange occurring in the boundary layer should significantly affect the heliospheric H distribution. Specifically, the process is expected to filter many incoming H atoms as they traverse the heliospheric interface, creating gradients in the bulk H density as well as a population of "suprathermal" H atoms with temperature $>10^6$ K. The process may also slow the bulk H flow in the direct upstream direction, an effect that has been observed in Prognoz spacecraft hydrogen absorption cell observations [*Lallement and Bertaux*, 1990; *Quémerais et al.*, 1992]. The additional upstream H Lyman α emission required by the Voyager observations is predicted by termination shock theory.

2. OBSERVATIONS

On January 1, 1993, the heliocentric distances of the Voyager 1 and 2 and Pioneer 10 spacecraft were 51, 39, and 56 AU respectively, moving outward at speeds of a few astronomical units per year. Table 1 lists heliocentric radii (r), longitude (λ), and latitude (β) of the spacecraft for the period of this study. Figure 1 illustrates their trajectories projected onto the ecliptic plane. The direction of the local interstellar flow, which lies within about 7° of the ecliptic [*Bertaux*, 1984], is shown as the dashed line. The cones on each trajectory in Figure 1 schematically illustrate the pointing directions of the UV instruments. In Figure 2 the Voyager and Pioneer 10 intensities are plotted as a function of spacecraft heliocentric distance. To account for solar variations, the intensities are divided by the estimated sub-spacecraft solar H Lyman α line center flux. The data are normalized at 15 AU; our analysis does not depend on the absolute calibrations of the instruments.

2.1. *Solar H Lyman α Flux*

Backscattered heliospheric H Lyman α lines reflect variations in solar line center H Lyman α flux. Direct observations of the solar line center flux at 1 AU, $\pi\mathcal{F}_o$ (ph cm^{-2} s^{-1} Å^{-1}), are not available. However, the integrated line flux at 1 AU, $\pi\mathcal{F}$ (ph cm^{-2} s^{-1}), may be estimated using the equivalent width of the He 1083-nm solar chromospheric absorption feature as a proxy [*Donnelly et al.*, 1986; *Skinner et al.*, 1988; *Lean*, 1990]. The integrated flux varies by a factor of ≈1.5 over the solar cycle [*Lean*, 1991]. The relationship between $\pi\mathcal{F}_o$ and $\pi\mathcal{F}$ may also vary over the solar cycle and with solar latitude, but such variations in line shape are poorly constrained [*Lean*, 1987].

Before correction for solar flux variations, the Pioneer 10 and Voyager H Lyman α data clearly show an 11-year periodicity superimposed on their variation with distance from the Sun. Pioneer 10 data between 15 to 50 AU were acquired over a 12-year interval. The combined Voyager data

TABLE 1. Trajectories of the Pioneer 10 and Voyager Spacecraft

Year[a]	Pioneer 10			Voyager 1			Voyager 2		
	r, AU	λ, deg	β, deg	r, AU	λ, deg	β, deg	r, AU	λ, deg	β, deg
1977	11.8	42.4	3.0						
1978	14.7	50.2	3.1	1.9	75.7	1.0	1.9	76.2	4.6
1979	17.6	55.2	3.1	4.9	123.6	0.6	4.5	126.9	1.7
1980	20.5	59.0	3.1	6.9	161.7	1.9	6.0	155.4	1.5
1981	23.4	61.8	3.1	9.7	184.2	4.3	8.1	180.8	2.3
1982	26.2	63.9	3.1	12.1	201.1	15.6	9.7	200.0	2.2
1983	29.0	65.7	3.1	15.1	212.8	22.1	11.0	222.4	1.5
1984	31.8	67.2	3.1	18.4	220.9	26.0	13.2	238.7	0.8
1985	34.5	68.3	3.1	22.9	226.9	28.4	15.9	250.0	0.3
1986	37.3	69.4	3.1	25.4	231.3	29.9	18.9	257.8	0.0
1987	40.0	70.3	3.1	29.0	234.7	31.0	21.7	266.3	0.3
1988	42.7	71.1	3.1	32.6	237.4	31.7	24.8	272.9	0.6
1989	45.4	71.8	3.1	36.3	239.6	32.3	28.0	278.0	0.8
1990	48.0	72.4	3.1	39.9	241.4	32.7	31.1	281.1	-0.8
1991	50.7	72.9	3.1	43.6	243.0	33.1	33.6	281.9	-5.0
1992	53.4	73.4	3.1	47.2	244.3	33.4	36.3	282.6	-8.6

[a]Positions tabulated for the first day of the year.

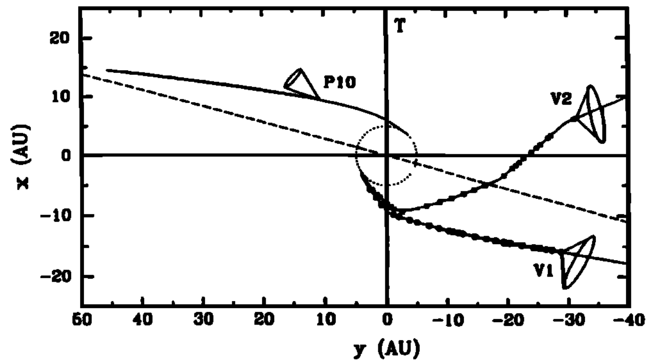

Fig. 1. The trajectories of the Voyager 1, Voyager 2, and Pioneer 10 spacecraft projected onto the ecliptic plane. For scale, the dotted circle represents the orbit of Jupiter. Both Voyagers are heading generally upstream, into the local flow direction, illustrated as the dashed line. Since its encounter with Saturn (≈10 AU), Voyager 1 has traveled northward of the ecliptic plane. Voyager 2 was redirected southward at Neptune (≈30 AU). The Pioneer 10 trajectory lies nearly in the ecliptic plane directed downstream. The cones illustrate the directions the UV instruments aboard each spacecraft obtained the H Lyman α observations plotted in Figure 2. Pioneer 10 collects data averaged on a cone 20° from the anti-Earth direction. At each point marked on the Voyager trajectories, the spacecraft performed Cruise Maneuver observing sequences which are combined to produce averages over the schematically illustrated 65° antisolar cones.

from 15 to 35 AU span an 8-year period. These data constrain the relationship between line center and integrated solar H Lyman α flux. We investigate this using the relationship $\pi\mathcal{F}_0 \propto (\pi\mathcal{F})^\eta$. Apparent solar cycle variations are best removed from the Pioneer 10 data for $\eta = (0.95 \pm 0.1)$. In order to make normalized Voyager 1 and 2 intensities between 15 and 35 AU track one another to within statistical uncertainty, η must lie in the range 0.8–1.1. Both of these results are consistent with a constant solar line shape ($\eta = 1.0$). They are similar to the relationship developed by *Chassefiére et al.* [1990] on the basis of *OSO* spacecraft observations ($\eta = 1.15$) and are within the reported error of the solar H Lyman α flux proxies reviewed by *Paxton et al.* [1988].

Here we assume negligible solar H Lyman α line shape variation during the period spanned by the observations and use the line shape of *Lemaire et al.* [1978] with integrated fluxes given by the He 1083-nm proxy. This is the simplest method of accounting for solar flux variations based on direct measurement and reasonably consistent with all available data. However, the conclusion that upstream H Lyman α intensities fall more gently as a function of r than downstream intensities is not sensitive to the solar flux correction. All values of η in the range 0.5–1.5 produce solar flux corrected Voyager intensities that, on average, fall less rapidly than Pioneer 10 intensities beyond $r = 15$ AU.

2.2. *Pioneer 10 Observations*

The design and performance of the Pioneer 10 UV instrument is described in detail by *Judge and Carlson* [1974] and *Carlson and Judge* [1974]. It is a two-channel photometer measuring H 1216-Å and He 584-Å emissions. The optical axis spins about the Earth-spacecraft line at an angle of 20.24°, as illustrated in Figure 1. Pioneer 10 H Lyman α heliospheric observations beyond the orbit of Jupiter are described and analyzed by *Wu et al.* [1981, 1988], *Gangopadhyay et al.* [1989], and *Gangopadhyay and Judge* [1989]. The Pioneer 10 photometers are sensitive to particles and gamma radiation as well as UV photons. Within 5 AU of the Sun,

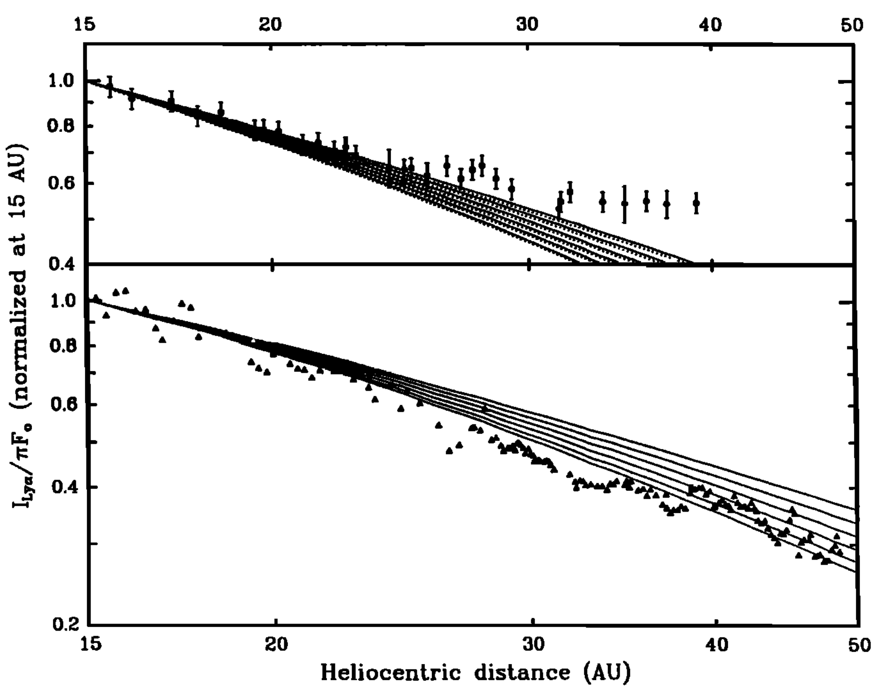

Fig. 2. Voyager and Pioneer 10 heliospheric H Lyman α intensities adjusted to constant solar flux and normalized at 15 AU plotted with hot H model radiative transfer simulations. In the top panels Voyager 1 and 2 data are shown as circles and squares respectively. The solid and dotted lines show the hot H model Voyager 1 and 2 simulations respectively. In the lower panel, Pioneer 10 observations and models are shown. The RT simulations account for the specific trajectories and instrument orientations of the observations and use the hot model H distribution tabulated by *Thomas* [1978]. Six RT simulations are shown for each spacecraft using H densities at infinity of 0.04, 0.06, 0.08, 0.10, 0.12, and 0.14 cm^{-3} (from top to bottom in all cases).

the H Lyman α channel signal was affected significantly on some occasions by solar wind particles. However, *Wu et al.* [1981] conclude that outside of 5 AU, particle contamination is negligible except during periods of intense solar activity. In 1991 ($r \approx 50$ AU) the signal in the H Lyman α channel was ≥ 150 counts s^{-1} with a noise contribution of ≈ 3 counts s^{-1}.

The Pioneer 10 photometer has suffered a gain loss since mid-1986 ($\approx$40 AU). This was identified when the photometer was turned on and off periodically after initiation of spacecraft instrument power sharing. Presently, the count rate registered after instrument turn-on decays from an initial and correct value to a lower stable value over a period of some hours. The interpretation is that during instrument off-time, charge diffuses to the surface of the Bendix 4028 channeltron detector and, when the instrument is turned on, the accumulated charge is liberated. Gain degradation appeared in 1986, continued until late 1989, after which it has remained stable for the data reported here. The corrected Pioneer 10 data are plotted in Figure 2, which shows the intensities averaged over the spacecraft spin angle. The earlier prediction of a termination shock distance of 50–80 AU by *Gangopadhyay et al.* [1989] needs to be revised upward because the distant data near 40 AU included in their paper did not incorporate the gain change correction discussed above.

2.3. *Voyager Observations*

The Voyager ultraviolet spectrograph (UVS) instruments are described in detail by *Broadfoot et al.* [1977, 1981]. The optical assembly is a compact design in which a grating disperses UV light onto a linear multichannel detector. The UVS detectors are sensitive to particle and gamma radiation. These signals are monitored and removed from UVS spectra as dark counts. Repeated observations of standard stars [*Holberg et al.*, 1991, 1982] have demonstrated that in the post-Jupiter encounter period the photon sensitivities of both UVS instruments have remained stable to within detection limits.

At each point marked on the Voyager trajectories in Figure 1, the spacecraft performed Cruise Maneuver sequences. During the maneuvers, the spacecraft spin about their yaw and/or roll axes for a period of 4 to 20 hours. As the spacecraft spin, the UVS gather spectra that are compiled into partial maps of the sky in H Lyman α. *Hall* [1992] discusses the UVS Cruise Maneuver H Lyman α data obtained beyond 5 AU. The Voyager intensities plotted in Figure 2 are Cruise Maneuver observations combined to produce averages over the 65° antisolar cones illustrated in Figure 1.

2.4. *Power Law Description of the Intensities*

If the data plotted in Figure 2 are modeled using a power law in heliocentric distance, a least squares analysis shows that between 15 and 50 AU Pioneer 10 intensities fall as $r^{-1.07\pm0.1}$. Voyager intensities fall on average as $r^{-0.75\pm0.05}$ from 15 to 35 AU. However, in contrast to Pioneer 10, a simple power law does not reproduce the character of the Voyager data. Voyager intensities show a distinctive upward curvature, or a tendency to decrease less rapidly with increasing heliocentric distance. A least squares polynomial fit analysis indicates that the data fall as r^{-1} between 15 and 20 AU, but this changes to a considerably flatter $r^{-0.35}$ dependence between 30 and 35 AU. As is discussed below, this is significant because it suggests that the H density is increasing as a function of heliocentric distance.

3. RADIATIVE TRANSFER ANALYSIS

Current estimates of the VLISM hydrogen gas density and temperature are highly model dependent and vary from experiment to experiment; representative values are $n_\infty = 0.1$ cm^{-3} and $T_\infty = 10^4$ K [*Ajello et al.*, 1987]. The scattering path length for a H Lyman α photon in such a hydrogen gas is 10 to 20 AU. Therefore the analysis of H Lyman α obtained beyond 15 AU requires a radiative transfer (RT) calculation to account for multiply scattered photons. *Keller and Thomas* [1979] and *Keller et al.* [1981] discuss the transfer of H Lyman α photons through the heliosphere, and use a Monte Carlo technique to calculate the Lyman α radiation field in the hot model H distribution. Their results are reproduced in the analysis of *Hall* [1992], where the details of the RT calculations used in this work may be found. *Hall* [1992] uses a finite element, iterative technique to estimate the multiply scattered component of the H Lyman α radiation field. In the calculation, the heliospheric system is broken up into a series of volume elements. In each, the velocity distribution of the hydrogen gas is approximated as a Maxwellian, with effective temperature and bulk flow velocity determined by integrating the hot model H distribution function over velocity space. The Sun is approximated as an isotropic point source of photons with the H Lyman α line shape measured by *Lemaire et al.* [1978]. Scattered photon frequencies are assumed to be redistributed according to the complete frequency redistribution approximation [*Mihalas*, 1978], using Doppler profiles for absorption and emission. Doppler shifts and widths are calculated using the bulk flow velocities and effective temperatures tabulated for each volume element. Singly scattered volume emission rates are calculated for each volume element by multiplying the solar flux (appropriately degraded by scattering loss) by the absorption profile and integrating over photon frequency. The H Lyman α scattering phase function [*Brandt and Chamberlain*, 1959] is used to calculate singly scattered intensities. Then, using the singly scattered radiation field as a source, an iterative calculation determines multiply scattered emission rates. An isotropic scattering phase function is used to calculate multiply scattered intensities. The total H Lyman α intensity is the sum of the singly and multiply scattered components.

One fundamental RT result found by both *Keller et al.* [1981] and *Hall* [1992] is that, in a uniform hydrogen gas illuminated by a point source, antisolar intensities (i.e., those detected by instruments looking radially outward) fall approximately as r^{-1} out to about one line center optical depth from the source. Beyond this, they gradually assume an approximate r^{-2} dependence. In nonuniform systems the dependence of antisolar intensities on r is affected by both this RT effect as well as the radial variation of the H density. In systems where the density varies as r^{κ} ($0 \leq \kappa \leq 1$), antisolar intensities fall approximately as $r^{\kappa-1}$ within about one optical depth and decline more rapidly beyond. This trend also applies to the 20° and 65° antisolar angle intensities of the Pioneer 10 and Voyager measurements.

3.1. *Hot Model H Distribution RT Analysis*

Radiative transfer models of the Voyager and Pioneer 10 heliospheric H Lyman α observations based on the hot H distribution [*Hall*, 1992] are plotted in Figure 2. In the top panel, the Voyager 1 and 2 models are the solid and dotted lines respectively. Pioneer 10 models are shown below. The RT simulations account for the specific spacecraft trajectories and instrument orientations of the observations and use the hot model H distribution tabulated by *Thomas* [1978]. Six RT models are shown for each spacecraft using H densities at infinity of 0.04, 0.06, 0.08, 0.10, 0.12, and 0.14 cm^{-3} (from top to bottom in all cases). The other parameters for the hot H distribution are: the VLISM flow speed, $v_\infty = 20$ km s^{-1}, VLISM temperature, $T_\infty = 10^4$ K, the H ionization rate at 1 AU, $\beta_e = 5 \times 10^{-7}$ s^{-1}, and the ratio of H Lyman α radiation pressure force to gravitational force, $\mu = 0.75$.

The basic disagreement between the data and the RT models is that observed upstream intensities fall more gently than downstream intensities, whereas the hot H model predicts the opposite behavior. This discrepancy is not removed by varying the input parameters of the hot H model. In fact, no reasonable set of VLISM and solar parameters yields satisfactory fits to both sets of data simultaneously. This includes increasing the VLISM flow speed to 26 km s^{-1}, as implied by recent studies [*Lallement*, 1992; *Witte et al.*, 1992]. The results are also insensitive to the model VLISM temperature; values in the range 7500–12500 K yield essentially the same results. All of the Voyager model curves in Figure 2 show a significant downward curvature. This characteristic is a fundamental RT effect and cannot be removed by varying the hot model input parameters. But the Voyager data show a distinctive upward curvature. For these reasons, the hot H distribution model and the combined Voyager and Pioneer 10 data are irreconcilable.

3.2. *An Improved Fit to the Observations*

The quality of the fit to the Voyager data beyond $\approx$25 AU is improved by including a constant additive intensity of about 20 to 30% of that observed at 15 AU. However, the Pioneer 10 fit is degraded by including such a background but improved by decreasing the H atom ionization rate. Figure 3 shows an improved fit to the combined data by making such ad hoc modifications. The H distribution is the hot model using the *Thomas* [1978] parameters but with the H loss rate decreased to $\beta_e = 4 \times 10^{-7}$ s^{-1}. A constant intensity equal to 25% of that observed at 15 AU is added to the upstream Voyager models. These adjustments are mutually inconsistent and are not intended to represent a rigorous model of the observations, but serve as indicators of how the real heliospheric H distribution deviates from the hot H model. For example, decreasing the loss rate improves the agreement in the downstream direction. This makes the downstream cavity less elongated than in the *Thomas* [1978] hot model density tabulation, indicating that the real downstream distribution may be characterized by a more truncated downstream ionization cavity.

The upward curvature of the Voyager data suggests that there is an upstream H Lyman α source beyond $\approx$25 AU that is unaccounted for in the hot model. The possibility that this could be due to an asymmetric galactic H Lyman α background aligned with the VLISM flow is physically unlikely, even though the galactic center lies roughly in the upstream direction. *Thomas and Blamont* [1976] discuss the transfer of galactic H Lyman α. Using a radiative transfer model they conclude that H Lyman α photons travel less than 400–1000 pc before they are absorbed by interstellar dust. This strongly suggests that the galactic H Lyman α

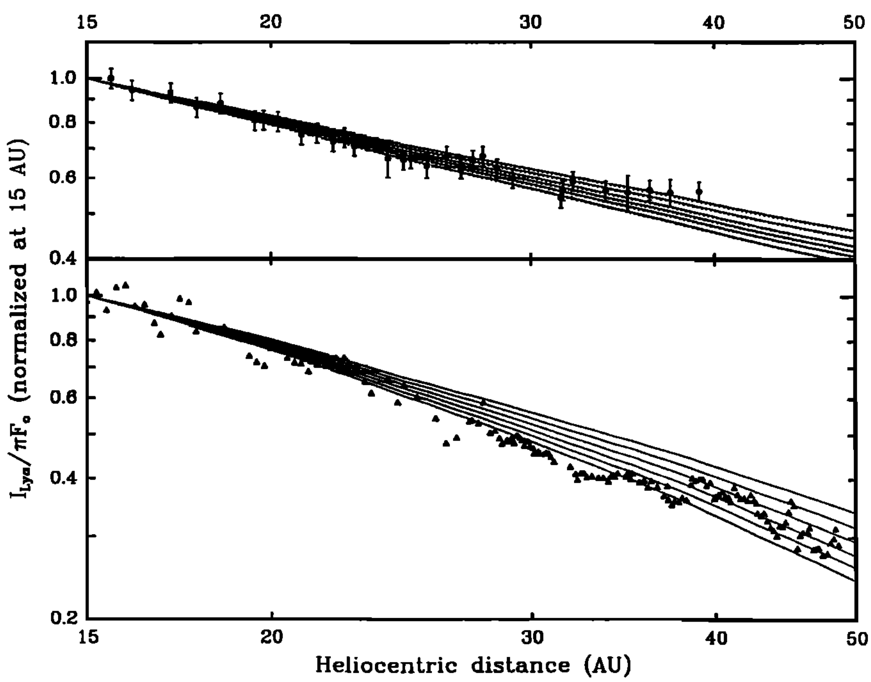

Fig. 3. Voyager and Pioneer 10 heliospheric H Lyman α intensities adjusted to constant solar flux and normalized at 15 AU plotted with RT simulations using the hot heliospheric distribution and including an additive upstream H Lyman α background. The line and symbol formats are the same as in the previous figure. The parameters for the hot distribution are $v_\infty = 20$ km s^{-1}, $T_\infty = 10^4$ K, $\beta_e = 4 \times 10^{-7}$ s^{-1}, and $\mu = 0.75$. The upstream background is equal to 25% of the intensity observed at 15 AU.

background should be isotropic in the solar vicinity, unless there exists a strong source (such as an OB stellar group) within about 400 pc of the Sun. Using H Balmer α observations, *Thomas and Blamont* [1976] limit galactic H Lyman α background levels to <10 R, a factor of $\approx$10 lower than that required to fit the Voyager observations.

When the possibility of a galactic background asymmetry is dismissed, the upward curvature of the Voyager data must be due to heliospheric structure, specifically gradients in the H density or scattering from suprathermal hydrogen gas. A preliminary analysis indicates that the brightness of H Lyman α scattered from upstream suprathermal gas is inadequate by a factor of the order of 50. Thus the Voyager data indicate significant H density gradients beyond $\approx$25 AU upstream.

3.3. *Radial Density Variations*

Beyond $\approx$20 AU upstream, the hot model H distribution levels off, approaching uniform density. The RT models plotted in Figure 2 show a significant downward curvature, reflecting the trend for intensities in a uniform medium to fall as r^{-1} close to the central source with an r^{-2} asymptote beyond. The opposing trend of the Voyager H Lyman α intensities implies that the heliospheric H density is increasing with heliocentric distance beyond $\approx$25 AU upstream. A polynomic fit to the Voyager data indicates that the intensity varies as r^{-1} between 15 and 20 AU and as $r^{-0.35}$ from 30 to 35 AU. Thus, if the density increases as r^{κ} between 15 and 20 AU, beyond 30 AU the density must increase more rapidly than $r^{\kappa+0.65}$. In the optically thin limit, the data imply that the H density changes from a uniform value between 15 and 20 AU, to an $r^{0.65}$ dependence between 30 and 35 AU. In the optically thick limit, the implied density gradients are even greater.

4. DISCUSSION AND CONCLUSIONS

The Voyager and Pioneer 10 observations are incompatible with the hot H distribution model. In particular, the data indicate that the Voyager spacecraft are currently traveling outward through an atomic hydrogen density rising at an increasing rate. Several models predict that the H distribution is significantly filtered by hydrogen-proton charge exchange in the heliospheric boundary layer. The *Baranov and Malama* [this issue] model predicts that the associated density gradients extend within the position of the upstream termination shock. On this basis, the Voyager and Pioneer 10 observations represent a definitive indication of the existence of the solar wind termination shock and associated outer heliospheric structure.

Comparisons of inner solar system observations to intensities calculated using the hot H model have been used extensively to determine many of the kinetic properties of the VLISM hydrogen gas [see *Ajello et al.*, 1987, and references therein] as well as the anisotropy of the solar wind and H Lyman α flux fields [*Pryor et al.*, 1992; *Lallement and Stewart*, 1990; *Ajello*, 1990; *Witt et al.*, 1979]. In the light of the new results presented here, these analyses need to be reevaluated. This is especially true for determined properties of the unperturbed VLISM, such as the H density, n_∞, temperature, T_∞, and flow speed, v_∞.

Estimates for n_∞ based on hot H model analyses vary between 0.04 and 0.12 cm^{-3}, with most falling near 0.07 cm^{-3} [*Ajello et al.*, 1987]. However, *Shemansky et al.* [1984] estimate n_∞ using a method independent of instrument calibration which does not rely on the hot H model. They analyze Voyager 2 and Pioneer 10 observations obtained in 1982. Both data sets clearly show 25 day variations in backscattered H Lyman α that are directly associated with an active sector on the Sun rotating with the solar rotation period. The relative amplitudes of the variations are used to estimate the asymptotic H density beyond the spacecraft, yielding 0.16 cm^{-3} for Voyager 2 and 0.11 cm^{-3} for Pioneer 10. Their results are consistent with those presented here, in that they cannot be reconciled with the hot H model, and thereby suggest the effects of outer heliospheric structure. Their results also suggest that the downstream H density within $\approx$100 AU may be significantly lower than the upstream value. This effect is predicted in the *Hall* [1992] distribution model, which considers a subsonic VLISM flow. It is also predicted by *Baranov et al.* [1991] who consider the implications of a supersonic flow and accompanying interstellar shock.

Observations by the *Prognoz* hydrogen absorption cell experiments have yielded estimates of the VLISM hydrogen gas temperature, flow direction and speed [*Lallement et al.*, 1984; *Bertaux and Lallement*, 1984; Bertaux et al., 1985]. However, reanalyses by *Lallement and Bertaux* [1990] and *Quémerais et al.* [1992] indicate that the speed of the flow along the upstream axis is significantly lower than that about 35° off to the side. They attribute this net deceleration to H–p charge exchange in the upstream heliospheric interface. Their analysis is consistent with the results presented here in suggesting the existence of outer heliospheric structure through its effect on the atomic hydrogen velocity distribution.

The two-shock H distribution model of *Baranov et al.* [1991] appears to be qualitatively compatible with all of the Voyager and Pioneer 10 observations. Their calculation is a zeroth-iteration, Monte Carlo solution for the H distribution in the presence of an interstellar shock. In addition to predicting the upstream/downstream difference reported by *Shemansky et al.* [1984], it predicts a "wall" of enhanced H density near the upstream boundary layer. An improved (i.e., multi-iteration) version of the *Baranov et al.* [1991] model suggests that the associated density gradients extend well within the position of the upstream termination shock [*Baranov and Malama*, this issue], consistent with the observed upward curvature of the Voyager Cruise Maneuver observations. Hydrogen density gradients of the magnitude estimated here for the 35 AU region begin to occur in the *Baranov and Malama* [this issue] model at a third to half the distance to the upstream termination shock. This suggests that the upstream shock lies between 70 and 105 AU. A more accurate prediction may be available soon, with the addition of recently collected data and further development of Monte Carlo H distribution models considering both subsonic and supersonic VLISM flow. Currently, work is in progress to analyze the data more extensively using the *Baranov and Malama* [this issue] H distribution combined with the *Hall* [1992] RT model.

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