PROPERTIES OF NEARBY INTERSTELLAR HYDROGEN DEDUCED FROM LYMAN α SKY BACKGROUND MEASUREMENTS

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ABSTRACT   For a sufficiently rapid relative motion of the solar system and the nearby interstellar gas, neutral atoms may be expected to penetrate the heliosphere before becoming ionized. Recent satellite measurements of the Lyman α emission above the geocorona indicate such an "interstellar wind" of neutral hydrogen emerging from the direction of Sagittarius and reaching to within a few astronomical units of the sun. We present here a detailed model of the scattering of solar Lyman α from the spatial distribution of neutral hydrogen in interplanetary space. This asymmetric distribution is established by solar wind and solar ultraviolet ionization processes along the trajectories of the incoming hydrogen atoms. The values of the interstellar density, the relative velocity, and the gas temperature are adjusted to agree with the Lyman α measurements. The results may be interpreted in terms of two models, the "cold" model and the "hot" model of the interstellar gas, depending on whether galactic Lyman α emission is present at its maximum allowable value or negligibly small. The cold model predicts densities between 0.03 and 0.06 cm^{-3}, temperatures below a few hundred degrees K, and a wind velocity of about 10 km/sec. The hot model predicts densities between 0.09 and 0.12 cm^{-3}, temperatures in the range 10^3 to 10^4 °K, and a wind velocity of about 6 km/sec. Since it is unlikely that any appreciable galactic emission is present, the results suggest that the solar system is within a large turbulent cell of hot tenuous gas, the so-called intercloud medium.

INTRODUCTION

We are concerned with the small part of the energy emitted from the quiet sun that is dissipated in the local interstellar medium. This energy is mainly in the form of extreme ultraviolet radiation (EUV) below the Lyman continuum ($\lambda < 911$ Å) and the fast-moving protons in the solar wind. The deposition of both types of energy results in ionization of the local medium. The interstellar neutral hydrogen, whose abundance is of the order of 90 percent, undergoes photoionization and charge exchange with solar wind protons. The spatial distribution of the resulting ionization about the sun is a sensitive function of the relative velocity of the sun and the local gas. For the special case of zero relative motion, an

extensive HII region will be formed similar to the classical Stromgren sphere. The radius of this region depends on the interstellar hydrogen density n_H and has been calculated by *Williams* [1965] to be $\sim 1500\, n_H^{-2/3}$ in AU. A balance between ionizations and recombinations is established on a time scale of the order of 10^6 years [*Brandt*, 1964].

For such a large time scale, it is a simple matter to show that a relative velocity of as little as 500 cm/sec can destroy this equilibrium state. For a relative velocity of the order of 1 km/sec or greater, the distribution of ionization may be described by a dynamic equilibrium [*Blum and Fahr*, 1970a]. The basis of this description is the probability of ionization $P(r)$ of an interstellar hydrogen atom at the distance r from the sun and is given by

$$P(r) = \exp\left[-\int_r^\infty ds\, J(r')/V_r(r')\right] \quad (1)$$

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where $J(r')$ and $V_r(r')$ are the total ionization rate and the relative velocity at the point r'. The integration is performed over the particle trajectory to the point r. The neutral density is calculated by adding up the contributions from all trajectories passing through the point. Detailed calculations have been performed by *Blum and Fahr* [1970a], hereafter referred to as BF, who show that for a relative velocity of 20 km/sec an asymmetrical ionization cavity is formed. The small dimension of the cavity lies in the forward direction of flow and is of the order of 1 to 5 AU, depending on solar activity.

The BF theory does not include the effects of the bow-shock termination of the solar wind, which probably occurs well outside the effective boundary of the ionization cavity [*Axford et al.*, 1963; *Hundhausen*, 1968; *Blum and Fahr*, 1969]. Blum and Fahr show that neutral hydrogen flows through this region with negligible interaction. The countereffect of the ionization cavity on the location of the shock front has been recently studied by *Semar* [1970]. His results suggest that this interaction is not likely to be important for the range of interstellar densities determined in this paper $(0.03\text{-}0.12 \text{ cm}^{-3})$. Accordingly, these regions may be considered as separate and independent and we will refer hereafter only to the ionization cavity.

How can such an ionization cavity be observed? It was first suggested by *Kurt* [1967] that the Lyman α sky background emission represents the scattering of solar Lyman α from beyond the cavity. *Kurt and Germogenova* [1967] calculated the diffuse radiation field within a spherical cavity surrounding the sun as a function of the cavity radius. Using the measured intensity of Lyman α emission from the Venus probe Zond 1 of 75 R ($1R = 10^6/4\pi$ photons cm^{-2}-sec^{-1}) they obtained a value of 3500 AU.

The more recent Lyman α measurements of *Chambers et al.* [1970] have been cited as evidence by *Blum and Fahr* [1970b] for their model of a cavity of much smaller dimensions. These measurements showed a smoothly varying Lyman α emission with a maximum in the direction nearest the apex of the solar motion. (Hereafter we refer to this direction as simply the apex.) It is located at the coordinates RA = 270°, δ = 30° [*Allen*, 1964]. A minimum was observed at a direction about 180° from the maximum. As pointed out by Blum and Fahr this is the variation of scattered solar Lyman α expected from hydrogen outside a cavity elongated in the direction of the apex. The inflowing hydrogen atoms would approach most closely in the direction of motion. They would be most likely to be ionized in the opposite (downwind) direction.

We have recently reported extensive Lyman α background measurements taken from a spinning OGO satellite [*Thomas and Krassa*, 1971; *Bertaux and Blamont*, 1971]. Our intensity amps clearly show that the Lyman α intensity reaches its greatest value in the direction RA $\cong$ 263°, δ = -22°. (It is now clear that the measurements of *Chambers et al.* [1970] could not define its precise location but only a meridian of maximum brightness, since all their scans were made over a single great circle in the sky.) This suggests that the nearby hydrogen possesses its own peculiar velocity, which combined with the solar system apex motion produces the observed direction of the "interstellar wind."

When we compared two sets of measurements separated by an interval of 7 months, we discovered a parallax effect in the intensity distribution (recently confirmed from a preliminary examination of recent OGO data taken in September 1970). This finding is the most direct evidence of a nearby source of scattering and makes it possible to triangulate to determine the effective distance of the scattering region.

We will describe a theory of the distribution of hydrogen in the solar system, similar to that of Blum and Fahr, but including two important effects neglected by them. The first of these is the outward solar Lyman α radiation pressure force, which nearly balances the inward gravitational force [*Wilson*, 1960; *Brandt*, 1961], causing the inflowing hydrogen atoms to pass the solar vicinity in straight-line trajectories. Furthermore, the velocities of the hydrogen atoms at all solar distances are unvarying and equal to the relative velocity of approach at infinity. This results in a considerable mathematical simplification of the theory. It also disposes of the necessity to account for the absence in all the measurements of a cusp-like feature predicted by BF as a result of gravitational focusing in the downwind direction.

The second effect we consider is that of a random (thermal) component of velocity in the interstellar medium. In the absence of gravitational focusing, the OGO measurements demand a considerable "filling-in" of the downwind direction. If this is not provided by an external source of diffuse emission from the galaxy, then a rather high temperature (up to 10^4 °K) of the nearby medium is needed. As discussed in the final section, such a high temperature is in agreement with 21-cm measurements of the temperature of the low-density intercloud medium.

THE OGO DATA AND THE INFERRED MOTION OF THE LOCAL HYDROGEN

Figures 1 and 2 are maps of Lyman α isointensity contours for the periods September 12–13, 1969 (SU 1) and
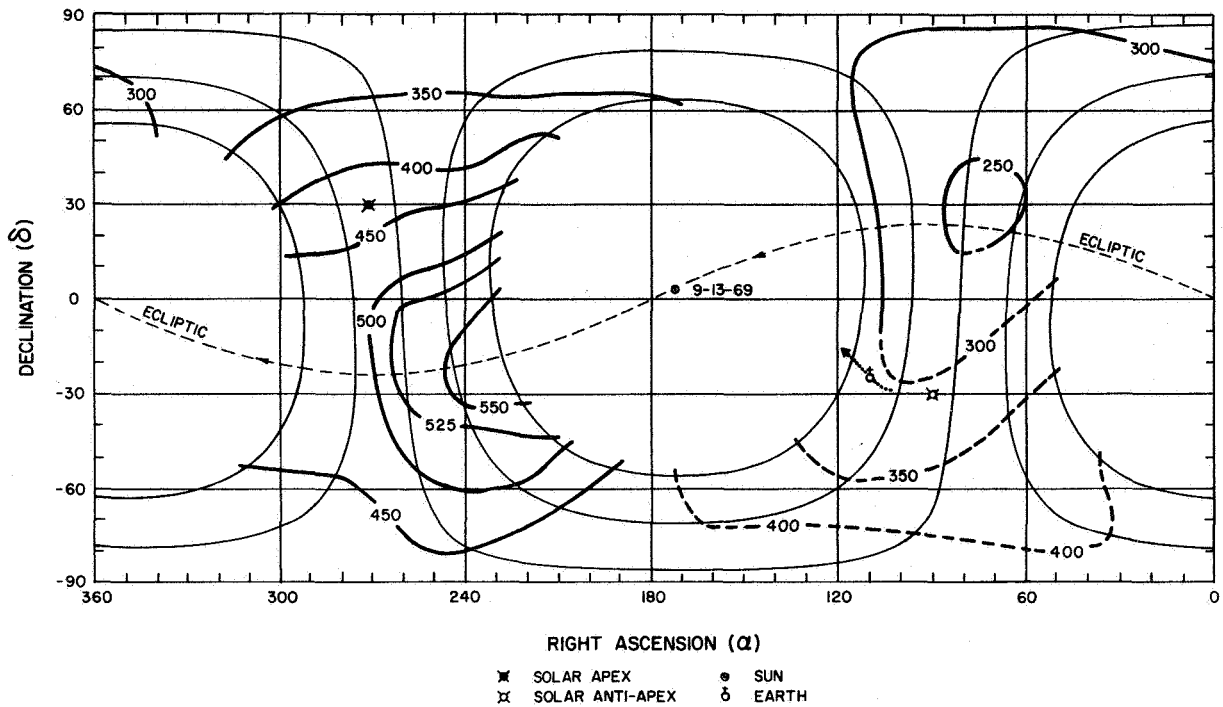
Figure 1   *LASP contour map of the Lα sky background in celestial coordinates for SU 1. The units labelling the contour lines are Rayleighs. The light curves indicate the paths of the field of view. The path of the earth between 2000 GMT, 12 September 1969, and 1000 GMT, 13 September 1969, as seen from the satellite is shown as a dotted line. The data used for constructing the map were all taken in this period. The dashed lines are the contour lines which have been interpolated beneath the geocorona.*
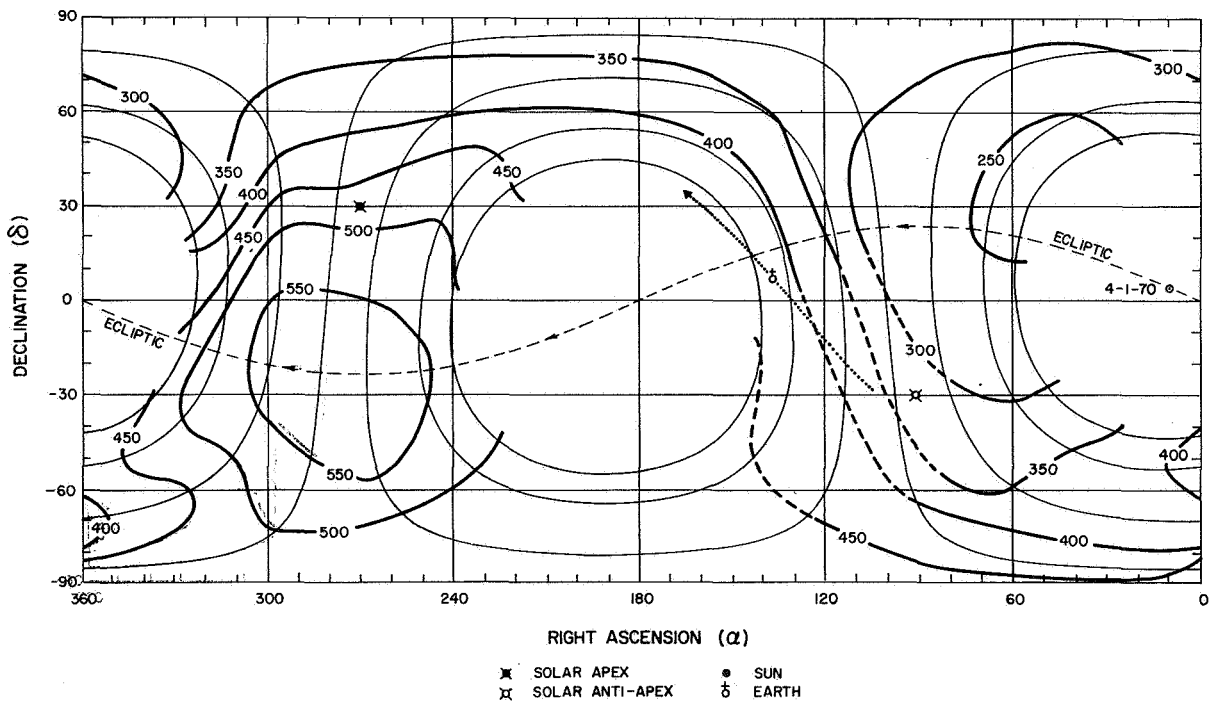
Figure 2   *Contour map of the Lα sky background in celestial coordinates for SU 3. The path of the earth is shown between 0600 GMT, 1 April 1970, to 2200 GMT, 2 April 1970.*

April 1-2, 1970 (SU 3). These data were taken by the Laboratory for Atmospheric and Space Physics at the University of Colorado (LASP). The Paris maps [*Bertaux and Blamont*, 1971] are very similar. Figure 3 is a comparison of the two sets of data plotted along the ecliptic
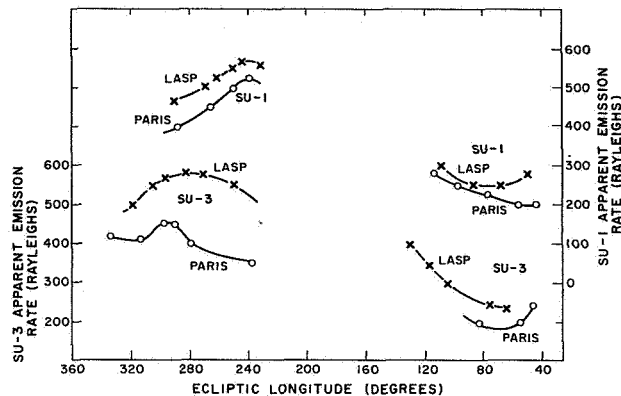

Figure 3 *The LASP and Paris Lyman α data plotted along the ecliptic/equator for the two spin-up periods SU 1 and SU 3.*

equator. This plane passes very nearly through the points of maximum and minimum Lyman α intensity and is a convenient coordinate plane for displaying the important spatial variations. We do not consider the overall disagreement of about 30 percent significant in view of absolute calibration difficulties in the ultraviolet. The discrepancies in the location and shape of the maximum and minimum are probably a result of minor problems in the removal of unresolved stars from the background in the LASP data, and in the removal of effects of charged particles and statistical noise in the Paris data.

The important features of the data for this discussion are the shifts along the ecliptic in the positions of the maximum and the minimum that occurred between the two dates. For the LASP data these displacements amount to $37°$ and $20°$, implying effective distances of 3 AU and 6 AU for the source regions of the maximum and minimum, respectively. The Paris data show a larger displacement of the maximum ($50°$) but indicate a motion of only $10°$ for the minimum that is opposite to that expected for a parallax motion. Because of the greater difficulty of accurately locating the position of the minimum, it is possible that this effect is not real. Indeed, there is a $13°$ discrepancy between the two sets of data for the SU 3 period in locating the maximum. This suggests that errors of at least this magnitude must be present in the low brightness regions of the maps.

Accordingly, we will place more emphasis on the parallactic motion of the maximum.

The mean position of the Lyman α maximum is located at $RA = 263°$. This is assumed to be the true direction of the "interstellar wind" V_r, which is the result of two velocities V_H and $-V_\Theta$ shown in figure 4; V_H is the velocity of the interstellar gas and V_Θ is the velocity of the solar system (20 km/sec), both relative to the local standard of rest (LSR). The wind speed V_H and the angular separation ζ of the vectors V_r and V_H are given by

$$V_H^2 = V_\Theta^2 + V_r^2 - 2V_r V_\Theta \cos \xi \qquad (2)$$

$$\cos \zeta = \frac{V_r - V_\Theta \cos \xi}{V_H} \qquad (3)$$

ξ is the angle ($53°$) between the mean position of the Lyman α maxima and the apex. In a later section we
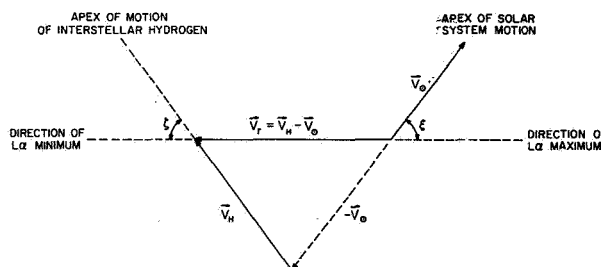

Figure 4 *The geometry of the interstellar wind. The relative velocity V_r is the difference between the hydrogen velocity V_H and the solar system velocity V_Θ. The ecliptic plane passes through and is perpendicular (within $10°$) to the line connecting the Lyman α maximum and minimum (the direction of V_r).*

show that V_r is of the order of 5 to 10 km/sec. From equation (2) the value of V_H is calculated to be about 19 km/sec for both values of V_r, with corresponding values for ζ of $111°$ and $96°$. This indicates that the "true" velocity of the interstellar hydrogen is directed from the vicinity of the constellation Triangulum Australe, making an angle of about $30°$ with the galactic plane.

At first sight this conclusion appears to contradict the findings of *Venugopal and Shuter* [1967] and previous radio investigations. On the basis of 21-cm line shifts from nearby hydrogen they found no systematic differential motion between neutral hydrogen and the LSR. However, the average distance of the observed hydrogen emission can be estimated to be ~100 parsecs from the galactic latitude of their measurements (±20 to ±45°). Even though small on a galactic scale this distance (~10^7 AU) is still enormous compared with the size of the region (~10 AU) probed by solar Lyman α scattering. It is possible that 21-cm measurements represent an average over a large number of irregularities in the velocity field.
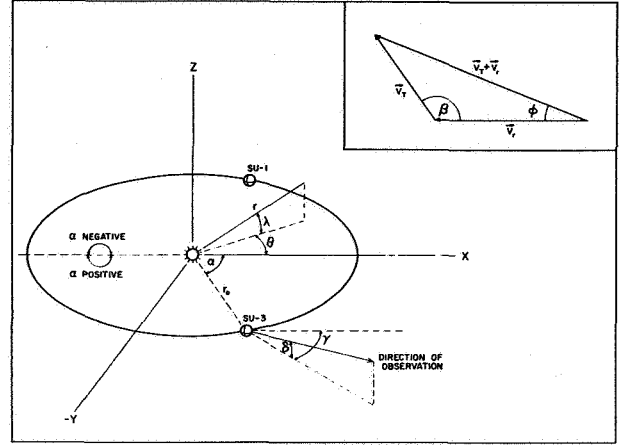
THE DISTRIBUTION OF INTERPLANETARY HYDROGEN

We will refer to as "interplanetary" those nearby interstellar hydrogen atoms that have survived ionization and make an appreciable contribution to the scattering of solar Lyman α in the vicinity of the earth. The Lyman α scattering plays two roles: it renders the neutral hydrogen visible to ultraviolet photometers and it produces a force that effectively balances the gravitational force. To demonstrate the latter role, we note that the average force on a hydrogen atom is the product of the photon momentum $h\nu/c$ and the number of photons scattered per second. The latter quantity is known as the g factor and is useful in expressions relating an airglow intensity to the column density of scattering atoms along the line of sight [*Chamberlain*, 1961]. *Barth* [1969] calculates this value to be 2.1×10^{-3} sec^{-1}. We have used the high-resolution solar Lyman α measurements of *Bruner and Rense* [1969] and the photon flux reported by *Hinteregger* [1970] to calculate a slightly larger value $g = 2.3\times10^{-3}$ sec^{-1}. For the latter value, the outward radiation force and the gravitational force differ by only 2 percent.

The "Cold" Model of Interstellar Hydrogen

We first consider the case of a unidirectional streaming velocity, the "cold" model. With no gravitational bending of the trajectories, the continuity equation for the density of neutral hydrogen n_H is

$$\frac{d}{dx}\,n_H = -\frac{(\sigma\Phi + J)n_H}{V_r} \tag{4}$$

where x is the coordinate measured along the streaming axis (fig. 5), σ is the charge exchange cross section, and Φ is the solar proton flux. The quantity J is the photoionization rate per atom and is given by

Figure 5 *The coordinate system for describing the interplanetary distribution of hydrogen. The X Y plane is the ecliptic plane. The earth's positions at the two spin-up periods SU 1 and SU 3 are shown. The inset shows the addition of the thermal velocity V_T to the relative velocity of flow (i.e., the mean flow) V_r.*

$$J = \int k_\lambda F_\lambda\, d\lambda \tag{5}$$

k_λ is the ionization cross section of atomic hydrogen and F_λ is the solar photon flux. In equation (4) a term of order V_r/V_{sw} is ignored. Here V_{sw} is the (constant) solar wind velocity (~300 km/sec). As we will show $V_r < 30$ km/sec and hence the ignored term is < 10 percent.

Assuming that Φ and F_λ vary as r^{-2} over the region of interest, equation (4) may be integrated along the streaming direction from $+\infty$ to the point $r(r,\theta,\lambda)$. The result is

$$n_H(r) = n_H(\infty)\exp\left\{-\frac{r_c X}{r}\left[\frac{\pi}{2} - \tan^{-1}(X\cos\lambda\cos\theta)\right]\right\}$$

where (6)

$$r_c = \frac{r_e^2(\sigma\Phi_e + J)}{V_r} \tag{7}$$

$$X = (\cos^2\lambda\sin^2\theta + \sin^2\lambda)^{-1/2} \tag{8}$$

Φ_e and J_e are, respectively, the solar wind flux and photoionization rate at $r_e = 1$ AU; $n_H(\infty)$ is the interstellar hydrogen density; r, θ, and λ are the sun-centered coordinates of the point r shown in figure 5. Since the measured positions of the maximum and minimum are nearly in the ecliptic plane we will identify γ with the ecliptic longitude measured from the meridian passing through the +X axis (ecliptic longitude, 263°). Similarly,

the angle δ shown in figure 5 is the ecliptic latitude measured from the earth. For points in the ecliptic (XY) plane ($\delta = 0$), equation (6) reduces to expressions given by Semar [1970] and Tinsley [1971].

$$n_H = n_H(\infty)\exp\left[-\frac{r_c f(\theta)}{r}\right] \qquad (9)$$

where

$$f(\theta) = \frac{\theta}{\sin\theta} \qquad (0 \leqslant \theta \leqslant \pi/2)$$

$$= \frac{\pi}{2} + \frac{\theta - \pi/2}{\sin\theta} \qquad (\pi/2 \leqslant \theta \leqslant \pi) \qquad (10)$$

The quantity r_c is the "effective cavity radius" in the forward direction ($+X$) of streaming. It depends on the wind velocity and the total loss rate but is independent of $n_H(\infty)$.

The "Hot" Model of Interstellar Hydrogen

We now include in the theory the possibility of a random component of velocity superimposed on the streaming velocity. It is sufficient to assume that in the moving frame a single velocity V_T is distributed isotropically. Since the mean free path of hydrogen is $\sim 10^3$ AU the atoms will describe collisionless trajectories. For simplicity the equations will apply to points in the XY plane. The generalization to three dimensions is straightforward. The density at any point is due to contributions from atoms whose velocities lie within a cone of half-angle ϕ, where

$$\tan\phi = -\frac{(V_T/V_r)\sin\beta}{1 - (V_T/V_r)\cos\beta} \qquad (11)$$

where β is the angle between the velocities V_r and V_T shown in figure 5. The resulting $V_r + V_T$ has a component along the streaming direction of

$$V_x = (V_r^2 - 2V_r V_T \cos\beta + V_T^2)^{1/2} \qquad (12)$$

Since the random velocity V_T is distributed isotropically each stream (defined by ϕ) is weighted only by its probability of ionization. The total is therefore a sum over all angles β, that is

$$n_H = \frac{n_H(\infty)}{2\pi} \int_{-\pi}^{\pi} d\beta \exp\left\{\frac{-r_c V_r f[\theta - \phi(\beta)]}{r V_x(\beta)}\right\} \qquad (13)$$

Given the distribution of hydrogen n_H, the single-scattered Lyman α intensity is calculated from

$$4\pi I = g_e \int_0^{\infty} ds\, n_H r_e^2/r^2 \qquad (14)$$

where ds is an element of length along the direction in which the intensity is to be calculated, and g_e is the g factor at the radial distance r_e (1 AU). For the direction outward from the sun ($\gamma = \alpha, \delta = 0$) the integration over s may be performed analytically for both models:

"Cold" model

$$4\pi I(r_o) = \frac{g_e r_e^2 n_H(\infty)}{r_c f(\theta)} \left\{1 - \exp\left[\frac{-r_c f(\theta)}{r_o}\right]\right\} \qquad (15)$$

"Hot" model

$$4\pi I(r_o) = \frac{g_e r_e^2 n_H(\infty)}{2\pi r_c} \int_{-\pi}^{\pi} d\beta\, \frac{1 - \exp[-r_c A(\beta)/r_o]}{A(\beta)} \qquad (16)$$

where

$$A(\beta) = \frac{V_r f[\theta - \phi(\beta)]}{V_x} \qquad (17)$$

For more general directions of viewing, it is necessary to perform a numerical integration of equation (14).

COMPARISON WITH OGO LYMAN α MEASUREMENTS

The adjustable parameters of the theory are $n_H(\infty)$, V_T/V_r, and r_c. The important observational quantities are the values of the Lyman α intensity, the ratio of the maximum and minimum intensities, and the parallactic displacements of the maximum derived from measurements taken at different periods. The uncertainties attached to each of these quantities (insofar as the LASP data are concerned) are estimated to be: (1) *intensity* — a factor of 2 is not unlikely in the laboratory calibration [Pearce et al., 1971]; (2) *maximum/minimum ratio* — estimated to be accurate to within 5 percent, this ratio involves the relative accuracies, together with the small degree to which the effect of stars influences the determination of the sky background; and (3) *parallactic displacement* — a maximum or a minimum is defined by a

smooth curve through at least three points on three different circular scans of the sky (as in fig. 3). The maximum error in this quantity is of the order ±5°, causing the error in the parallax measurement to be about ±7°. If similar errors are present in the Paris data, it is clear the discrepancies of figure 3 are not unexpected. Rather than carry the estimated formal uncertainties through each of the derived quantities of the theory, we prefer to be conservative and assume that these quantities will lie somewhere in the range defined by the LASP and Paris data.

The procedure in fitting the cold model to the OGO measurements is to vary the parameter r_c in the intensity calculations that apply to the periods SU 1 and SU 3. The ecliptic longitude of the earth on those dates was 351° and 191°, respectively, corresponding to values of α (see fig. 5) of −88° and +72°. From the intensities calculated on the two dates, the angular separation of the intensity maxima is obtained and is plotted in
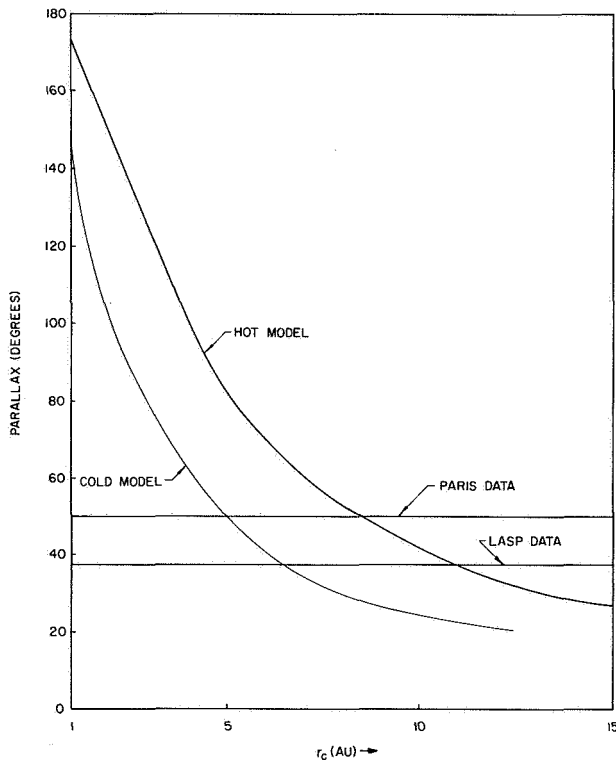

Figure 6 *The separation in degrees along the ecliptic of the Lyman α maxima for the periods SU 1 and SU 3, denoted by "parallax" versus the parameter r_c, the "effective cavity radius." The horizontal lines show the measured values of the separation for the two OGO experiments.*

figure 6 as a function of r_c. The value implied for the LASP data is $r_c = 6.4\pm1.0$ AU, and for the Paris data, $r_c = 5.1$ AU, with a similar uncertainty.

Figure 7 is a plot of the density for the cold model in the $\theta = 0°$ direction as a function of r. This also shows the "source function" $n_H(r)/r^2$, which is the integrand in equation (14) for the direction $\alpha = 0°$, $\gamma = 0°$. This illustrates that the effective distance of the emitting direction is about 3 AU, the value obtained from a simple geometrical parallax calculation.

For the direction $\alpha = 180°$, $\gamma = 180°$, the intensity calculated from the cold model should be zero, a consequence of complete ionization for this direction. This can be seen in equation (9), since $f(\theta) \to \infty$ as $\theta \to \pi$. For the actual positions of the earth (and the OGO satellite) the predicted intensity is finite but extremely small for this general "downwind" direction. To account for the measurement of 240 R in this direction, it is necessary to invoke an outside Lyman α source. The most likely candidate is the diffuse Lyman α radiation from the galaxy. *Adams* [1971] has considered the detailed history of Lyman α photons originating in recombination in HII regions with subsequent scattering in HI regions and the possibility of absorption on interstellar dust grains. His upper limit of a few hundred Rayleigh for the diffuse sky background corresponds to the case of no dust absorption. Therefore, although it is unlikely, we cannot absolutely exclude 240 R of isotropic galactic Lyman α as a possible contribution to the OGO measurements. When this value is added to the prediction of the cold model and the total normalized to the LASP measurement at the maximum, the value for $n_H(\infty)$ is 0.061 cm^{-3}.

For the hot model, the intensity in the downwind direction is provided by scattering from neutrals that enter the "shadow" region by virtue of their inclined trajectories. For $V_T > V_r$, a wind from all directions occurs. For this case, neutral atoms may approach the solar system from the opposite direction of the flow. For $V_t \gg V_r$, the wind flux and thus the scattered intensity is nearly isotropic. The observed maximum/minimum ratio of 2.38 (for the LASP data) is achieved with a thermal velocity equal to 1.44 times the wind velocity. With the quantity V_T/V_r known, the parallax may now be calculated from equations (13) and (14) as a function of r_c. The results are shown in figure 6, from which the values of r_c may be deduced as before. Finally, the parameter $n_H(\infty)$ is adjusted until the maximum intensity is matched. The interplanetary density for the hot model is plotted in figure 8 for both the upwind ($\theta = 0°$) and downwind ($\theta = 180°$) directions,
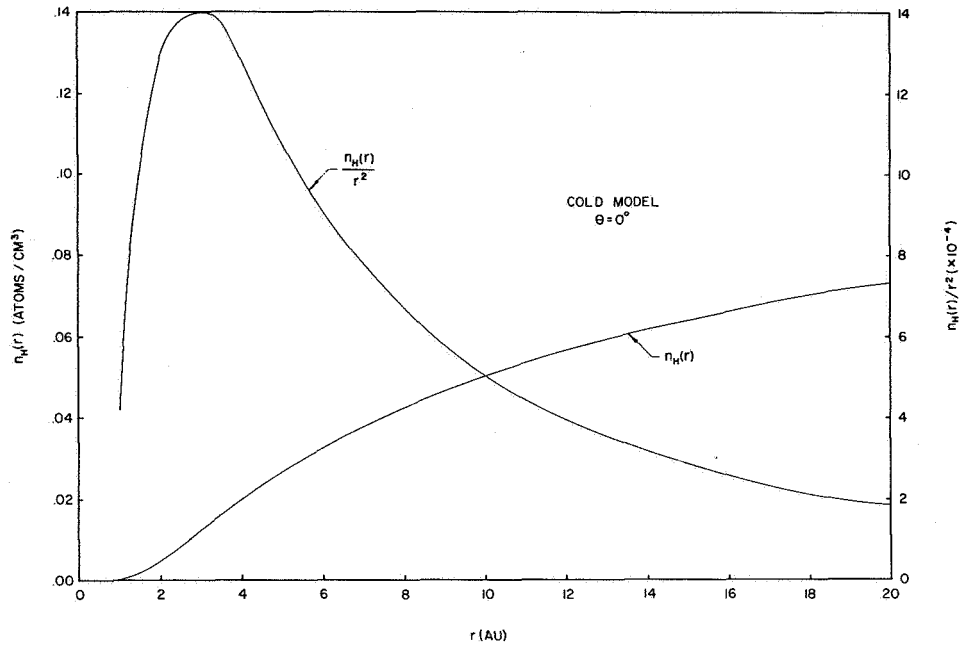
Figure 7 *The distribution of neutral hydrogen $n_H(r)$ and the source function for Lyman α scattering, $n_H(r)/r^2$, plotted against radial distance from the sun for the direction of maximum Lyman α scattering.*
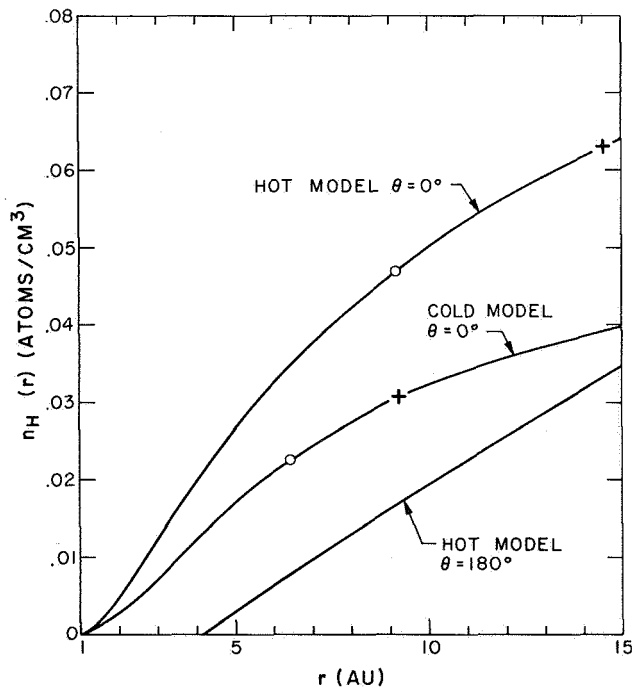

Figure 8 *The distribution of neutral hydrogen for the "cold" and "hot" models as a function of radial distance from the sun. The symbols + and 0 indicate positions where the interstellar density is reduced by the amounts 50 percent and (1/e), respectively.*

and is compared with that of the cold model. Figure 9 is a comparison of the LASP measurements and the theory for both models.

With the knowledge of the ionization rates $\sigma\Phi$ and J, and the quantity r_c, we can determine the wind speed V_r from equation (7). Furthermore if V_r is known, the random velocity V_T may be determined from the ratio V_T/V_r. Using the data of *Hinteregger* [1970] for the ionizing flux F_λ between 911Å and 280Å, and the cross section k_λ given by *Allen* [1964], the value of J_e is calculated to be $6.89 \times 10^{-8}\,\mathrm{sec}^{-1}$, corresponding to a 10.7 cm solar radio flux of 144 (in units of $10^{-22}\,\mathrm{watts\ m^{-2}\ Hz^{-1}}$). The average value for $F_{10.7}$ for the 6 months preceding each of the two spinup periods was 148 [*Solar-Geophysical Data*, 1970]; thus, no scaling to a different radio flux is needed. (A 6-month average was selected since the interplanetary atoms will move through about 2 AU during that time, the approximate width of the source function region shown in figure 7.)

Typical quiet-time solar wind fluxes of $1.6 \times 10^8\,\mathrm{cm^{-2}\ sec^{-1}}$ are reported by *Hundhausen* [1970]. Increases in flux as large as $6 \times 10^8\,\mathrm{cm^{-2}\ sec^{-1}}$ can occur during the passage of a disturbed magnetic sector region [*Neugebauer and Snyder*, 1966]. However, these transient effects are expected to exert very little influence on the average ionization rate. The charge-exchange

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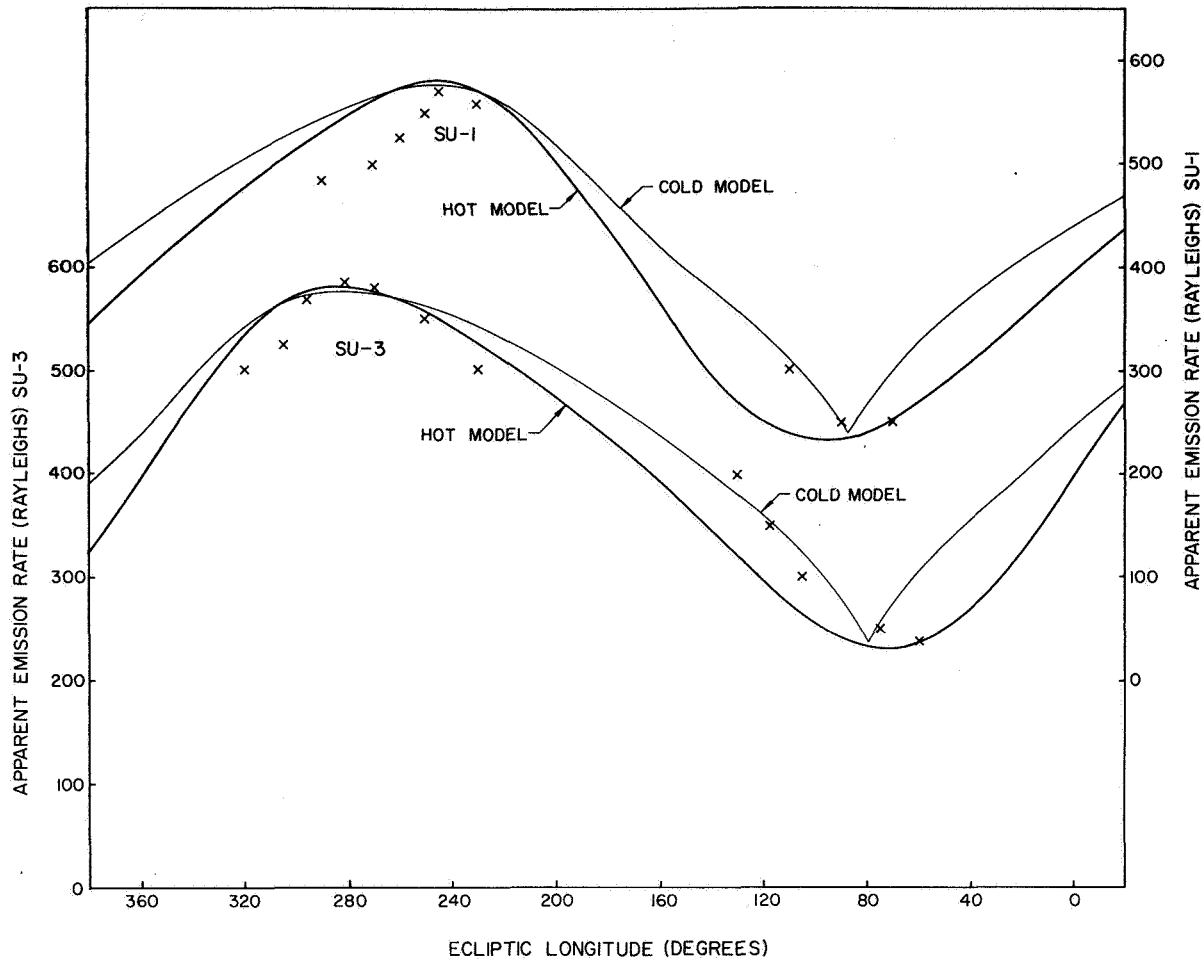
Figure 9 *The comparison with the LASP data of the theoretical Lyman α scattering intensity for the "cold" and "hot" models of the interstellar gas. The cold model contains an isotropic intensity of 240 R.*

cross section is about $2\times10^{-15}\,cm^2$ [*Fite et al.*, 1962]. Table 1 is a summary of the final results using $\sigma\Phi = 3.2\times10^{-7}\,sec^{-1}$. The temperatures for both sets of data are derived from the relative flow velocities V_r and the ratio $V_T/V_r = 1.44$, using the formula $m_H V_T^2 = 2kT$; m_H is the mass of the hydrogen atom and k is Boltzmann's constant. The reader may scale these results according to any total ionization rate he chooses.

ADDITIONAL EFFECTS NOT CONSIDERED IN PRESENT ANALYSIS

Temporal Effects

A perfect balance of radiation pressure and gravitation is not expected. Furthermore the net force will vary during the solar rotation period in response to 27-day changes in the line-center region of solar Lyman α [*Meier*,

Table 1 *Basic heliosphere parameters for "hot" and "cold" models.*

Experiment	Deduced quantity	Cold model	Hot model
LASP	r_c (AU)	6.4	10.9
	V_r (km/sec)	9.1	5.3
	T (°K)	0.0	3.56×10^3
	n_H (cm^{-3})	0.061	0.12
Paris	r_c (AU)	5.0	8.5
	V_r (km/sec)	11.6	6.9
	T (°K)	0.0	5.87×10^3
	n_H (cm^{-3})	0.030	0.090

1969]. The net force may also vary appreciably along the trajectory due to a Doppler shift of the resonant frequency within the self-reversed solar Lyman α line profile. The use of a constant net radial force (assumed here to be zero) and constant values of the EUV and solar wind fluxes are justified because of the small distances covered by the interstellar hydrogen atoms (0.1–0.2 AU) during one solar rotation period. This produces a strong averaging effect on the photoionization as discussed by *Blum and Fahr* [1970c].

Secondary Ionization

In addition to the loss processes considered here, neutral hydrogen will be lost by impact ionization from fast protons and neutrals (the latter created by charge exchange). The measured value of the relevant cross section for 9 keV hydrogen atoms is $6 \times 10^{-17} \text{cm}^2$ [*Allison*, 1958], only 3 percent of the charge-exchange cross section. This process is therefore of negligible importance.

Doppler Shifts

For relative velocities ranging from 5 to 10 km/sec, the center of the absorption profile will be shifted by as much as 0.02 to 0.04Å, respectively. (The earth's orbital velocity of 30 km/sec can add up to ±0.12Å to the measured line shift.) The high-resolution solar Lyman α line profile of *Bruner and Rense* [1969] shows that such shifts can *increase* the resonance g factor over its line-center value by only a small amount. This could cause a slight sharpening of the intensity maximum predicted for a constant g factor, a desirable gain for the theory in view of the measured sharpness shown in figure 9. However, it would also lead to a broadening of the minimum, probably to a greater extent than the data indicate, although more measurements are needed in this portion of the sky before this can be stated with certainty. Such modifications would be most important for the cold model and for the higher values of V_r.

Additional Solar Wind Loss Processes

Hundhausen et al. [1968] have suggested that the asymmetrical charge-exchange process

$$He^{++} + H \rightarrow He^{+} + H^{+}$$
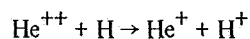
can modify the ionization state of the solar wind by conversion of outflowing He^{++} to He^{+}. The measured cross section for this process is $\sim 3 \times 10^{-16} \text{cm}^2$ [*Fite et al.*, 1962]. Even with the admixture of as much as 15 percent He^{++} in the solar wind [*Hundhausen et al.*,

1967], the loss rate of neutral hydrogen by this mechanism would not exceed 3 percent of the charge-exchange loss.

Hundhausen and his coworkers also suggested that the anomalously high concentration of He^{+} measured in the solar wind could be explained by this process if the incoming neutral hydrogen flux were $\sim 2 \times 10^6 \text{cm}^{-2} \text{sec}^{-1}$. However, none of our models gives fluxes greater than $1 \times 10^5 \text{cm}^{-2} \text{sec}^{-1}$ even at large distances from the sun.

Photoionization of H_2, OH, and H_2O in the Interstellar Medium

Although the concentrations of these molecules are expected to be very small in the interstellar medium, it is of some interest to estimate the effects of the breakup of these molecules in the inflowing gas. Consider first the effects of EUV and solar wind on an H_2 molecule. Since charge exchange occurs readily and photoionization is more likely than photodissociation, an H_2 molecule will be converted mainly into an H_2^{+} ion rather than into two hydrogen atoms. These ions will be accelerated very quickly by the $\nu \times B$ electric field and swept away by the solar wind. Thus H_2 would probably not contribute to the interplanetary hydrogen atom population, unless it has a much greater abundance than H in the nearby interstellar medium.

The H_2O molecule is readily dissociated in the solar ultraviolet with a photodissociation rate of about 10^{-5}sec^{-1} [*Anderson*, 1971]. Thus, the breakup of water molecules occurs at distances ten times greater than hydrogen atom ionization. The interplanetary distribution of H atoms would be nearly the same as if the interstellar medium were originally composed of H atoms and OH radicals.

The ultraviolet absorption cross sections of the OH molecule have not been measured. However, if the interplanetary hydrogen were primarily a dissociation product of OH (or equivalently of H_2O), interplanetary O atoms would be present in comparable numbers to H atoms. This possibility could be tested by searching for the 1304Å sky background emission. Unfortunately, the g factor is only 1.5×10^{-6} [*Barth*, 1969] due to a very faint solar 1304Å line. The long-wavelength channel of the LASP ultraviolet photometer [*Thomas and Krassa*, 1971] could have detected an intensity greater than 20 R. This imposes only the weak restriction that the interplanetary atomic oxygen is less than about 1 cm^{-3}.

The above discussion is intended only to show that the measurements themselves do not necessarily exclude photodissociation of interstellar molecules as the origin

of the observed interplanetary hydrogen. To definitely rule out such possibilities it is necessary to calculate a detailed spatial distribution of the "hot atoms" produced by photodissociation and the Lyman α scattering expected from such a distribution. This would permit the assignment of upper limits to the abundances of hydrogen-bearing molecules in the nearby gas.

Solar Lyman α Attenuation

At a sufficiently great radial distance, the solar Lyman α will be appreciably depleted in parts of the line so that solar radiation pressure no longer plays an important role. Therefore, the incoming atoms will initially be accelerated. This acceleration continues until the atom approaches sufficiently close so that the attenuation is no longer effective, or until its Doppler shift causes the resonance wavelength to move into a spectral region where attenuation is unimportant. The resulting distribution of velocities with distance will cause an originally cold gas to scatter the solar line as if it were at a finite "effective temperature" T_e. The value of T_e may be estimated by first calculating the distance R_1 at which the line-center optical depth is unity for a variety of gas temperatures. The distance $R_1(T)$ ranges from 8 AU at $T = 10^2$ °K to 20 AU at $T = 10^4$ °K. We next assume that the incoming atoms are accelerated by solar gravitation beyond R_1 (and maintain a constant speed and direction for $r < R_1$). The velocity increments $\Delta V(R_1)$ are then computed from $(V_r^2 + 2M_\odot G/R_1)^{1/2} - V_r$, where V_r is the initial relative velocity, $M_\odot$ is the solar mass, and G is the gravitational constant. The velocity increment ΔV may be converted to an effective temperature $T_e = m_H \Delta V^2/2k$ as a function of R_1. At the point where $T_e(R_1) = T(R_1)$, we obtain the velocity increment and effective temperature that is reached by the accelerating gas before it becomes balanced by solar radiation pressure. For an initial velocity of 10 km/sec (see table 1), ΔV is calculated to be ~ 3 km/sec, and $T_e \sim 600°$ K. For an initially finite gas temperature the effect is to add ΔV to the thermal velocity. This argument is valid for the $\theta = 0°$ direction only. For $\theta \neq 0°$, the velocity increment along the radial direction and hence T_e will be somewhat less.

The major conclusion that was drawn from the cold model was that the unidirectional streaming velocity could not fill in the downwind direction with neutral atoms. This is not quite true with the above modifications, since those trajectories for $\theta \neq 0°$ will be slightly bent toward the sun and will produce a nonzero population along the $\theta = 180°$ axis. However, our calculations show that unless $V_T > V_r$ ($T > 5 \times 10^3$ °K for $V_r = 10$ km/sec) the effect of filling in the shadow is

very small as far as the Lyman α scattering intensity is concerned.

Multiple Scattering of Lyman α Photons

Since the mean free path for scattering of Lyman α (8–20 AU) is not much greater than the effective dimension of the source region (fig. 7), the effects of multiple scattering may not be negligible. A rule of thumb for estimating its importance at a distance r is to compare the number of solar photons N_s available for scattering to the number N_g available for rescattering from the surrounding gas. If $N_s \gg N_g$, multiple scattering may be ignored. At 1 AU, $N_s = 1 - 4 \times 10^{10}$ photons cm^{-2} sec^{-1} and the value of the mean scattered intensity $N_g \approx 4.5 \times 10^8$ photons cm^{-2} sec^{-1}; N_s decreases as r^{-2} out to the attenuation distance R_1 and then rapidly falls to zero. According to equation (15) or (16) the outward first-order scattered intensity initially falls rapidly with r, and then approaches a variation of r^{-1}. However, we may estimate the average (over all solid angles) falls off approximately as r^{-1} at all distances. The value of r for which $N_s = 10N_g$ is therefore about 4 AU. When $N_s = 2N_g$, $r \approx 20$ AU. Thus, in the source region of the Lyman α scattering (1–8 AU), second-order scattering is likely to be only 10 to 20 percent of the primary scattering. At greater distances, the effect becomes more important, but the number of photons available for scattering is very small. Thus we do not consider this effect a serious one in our analysis.

DISCUSSION

If the galactic Lyman α emission is as high as 200 to 240 R, the interstellar hydrogen density is between 0.03 and 0.06 cm^{-3}. In this model, the interstellar gas temperature is low ($\sim 10^2$ °K) and the interplanetary hydrogen is completely ionized in the downwind direction. On the other hand, if the galactic contribution is negligible, the gas temperature must be high (up to 10^4 °K) to fill in the downwind region with neutral hydrogen. An intermediate value of the galactic emission leads to a "warm" model of the gas with $0.03 < n_H < 0.12$ cm^{-3}. Knowledge of the galactic emission is not very important in determining the interstellar density; however, it is critical in determining the gas temperature. *Adams* [1971] has suggested a means of differentiating the galactic and local components by measuring the line width of the Lyman α sky background. The galactic component will be broad (1 to 3Å). The present analysis predicts a width of the interplanetary component to be of the order of 0.05Å. Its Doppler shift (up to 0.12Å) depends on the direction of viewing and the season of observation.

Previous determinations of the interstellar HI density from radio measurements give average values of 0.4 to 0.7 cm^{-3} [see *Brandt et al.*, 1971 for a recent discussion of these measurements]. *Jenkins* [1970] has calculated an upper limit of 0.04 cm^{-3} for the average hydrogen density along the 100-pc distance to α Vir from rocket measurements of the Lyman α interstellar absorption by A. Smith. A rocket-borne spectrometer measurement of an enhancement of 1216Å emission from α Bootes (Arcturus) has been recently reported by *Rottman et al.* [1971]. Assuming the emission line width of Lyman α is comparable to that of the sun ($\sim$1Å), we can calculate the column density of hydrogen that would barely extinguish the emission line. Over the 11-pc distance, the average hydrogen density would be no larger than 0.05 cm^{-3}. For distances of a few hundred pc where a number of bright ultraviolet stars are available for Lyman α absorption measurements, the average densities are on the order of 0.1 cm^{-3} [*Jenkins*, 1970]. The well-publicized discrepancy between the 21-cm results and the Lyman α absorption results has apparently not yet been resolved. Our results lend support to the Lyman α absorption measurements; however, it should be emphasized that our value refers to a very much smaller distance scale than either of the above techniques. Small-scale irregularities in density could easily account for the discrepancy between our result and the radio measurements. Irregularities are apparently incapable of resolving the problem of the 21-cm versus the Lyman α absorption measurements [*Jenkins*, 1970].

The 21-cm observational evidence for the thermal state of the intercloud medium indicates temperatures between 1×10^3 and 5×10^3 °K [*Rohlfs et al.*, 1969].

A current theory of the heat balance of HI regions predicts two stable phases of the neutral gas existing in pressure equilibrium [*Spitzer*, 1968; *Field et al.*, 1969]. These ideas can account for the known existence of dense, cold clouds ($n_H \sim 10$ cm^{-3}, $T \sim 10^2$ °K) and a tenuous, hot intercloud medium ($n_H \sim 0.1$ cm^{-3}, $T \sim 10^3$–10^4 °K) if the medium is postulated to be heated by a large subcosmic ray flux. Another theory favors the mechanism of heating by soft X rays [*Werner et al.*, 1970]. A time-dependent model involving the possible contributions from supernova outbursts has been advanced by *Bottcher et al.* [1970].

Since the hydrogen clouds occupy only 10 percent of the galactic volume, we would expect from pure chance that the solar system is contained within the intercloud medium. Our results for the density of the nearby gas clearly indicate that this is the case. Our results are also consistent with the intercloud gas temperatures deduced from radio measurements, provided the galactic Lyman α contribution is not too large.

SUMMARY
Our recent Lyman α sky background measurements have provided much new information on the nature and location of the scattering sources. They indicate that most if not all the emission is interplanetary in origin, and place the effective scattering distance within about 3 AU of the sun. Through the use of a simple model of the distribution of the neutral interplanetary hydrogen we have shown that the OGO data are consistent with an interstellar hydrogen density between 0.03 and 0.12 cm^{-3}, an interstellar gas temperature as high as 10^4 °K, and an interstellar wind velocity between 5 and 10 km/sec. The interstellar hydrogen velocity relative to the local standard of rest is calculated to be about 19 km/sec, directed from the southern hemisphere at an angle of about 30° with the galactic plane.

The deduced motion of the nearby gas may be a manifestation of a turbulent motion on a scale that is probably much greater than a mean free path (10^3 AU) but much smaller than the thickness of the galactic plane (10^7 AU). The gas temperature required of the "hot" model is consistent with 21-cm evidence of the high temperature of the galactic intercloud medium. However the measurements are also consistent with a cold model of the gas, provided about 200 R of galactic emission is present in the sky background. Removal of this uncertainty will require high spectral resolution measurements above the geocorona, or measurements made from spacecraft traveling to the outer boundaries of the solar system.

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DISCUSSION

T. E. Holzer   I have two comments. The first is with regard to the Lyman α that you observed in the tail or null region. For a cold gas coming in at $100°$ or something like that, you find that the absorption cross section at the center of the line is approximately 100 times larger than the average absorption cross section calculated in the optically thin approximation. In general this makes a very small difference in all calculations with regard to Lyman α and so the optically thin approximation is very good. But this difference has two effects. The first is that it can produce a variable addition to the gravitational field from the sun so that the field may change from inward at larger distances to an outward field at smaller distances. This would effectively give a large temperature effect and throw some particles into the null region and thus give you a small Lyman α flux there. I don't know the magnitude of this effect, so I don't know whether it's enough to account for the observations. But from the calculations I made with regard to something else I think it may be.

My second point is also with regard to the optically thin approximation for the absorption at the center of the line. Even though the gas is generally optically thin, this absorption will tend to increase the density that you would predict. At 0.1 particle/cm^3 the increase can be as much as a factor of 2. Consequently, instead of from 0.03 to 0.12 cm^{-3}, your density might be from 0.06 to 0.24 cm^{-3}. As you may have noted, this difference makes a considerable difference in the effect of the interstellar gas on the solar wind.

G. E. Thomas   In regard to the first point concerning the effect of absorption on the solar Lyman α as it progresses outward, I would point out that this absorption is due to a scattering by hydrogen atoms so that eventually the center of the line is eaten out by neutral hydrogen. But, as I recall, the mean free path for Lyman α proton with these sorts of densities is of the order of 10 AU or so. I can't remember exactly. We decided that such an effect was really unimportant, that is, out to about 5 AU or so. Such things might happen beyond 5 AU, but they would not strongly affect the Lyman α scattering measurements.

Now let me comment on the second point concerning the importance of multiple scattering. If you again take the mean free path to be about 10 AU, it turns out that multiple scattering effects produce an intensity that is small compared to the singly scattered intensity we calculated. If you turn the argument around and suppose there's a lot of multiple scattering, then you quickly come to the conclusion that you shouldn't get the large asymmetries that are observed. As you see the ratio between the maximum and the minimum is better than 2/1. If multiple scattering were dominant, it would tend to wipe out that difference between the maximum and the minimum.

T. E. Holzer   I was talking about absorption near the center of the line with regard to the second point as well as the first. With regard to the second point, it does make a factor of 2 difference. With regard to the first point, it may or may not be significant; it's

hard to say.

G. E. Thomas   Those are difficult calculations.

J. C. Brandt   What is the absorption cross section in the center of the line?

T. E. Holzer   I can't give you a number, but if you assume that the Lyman α line has a flat topped peak 1Å wide and then you assume the temperature of the neutral gas to be 100° you can calculate the cross section of the center of the line and you can calculate a mean cross section for the whole line. The cross section of the center of the line is a factor of 100 larger than the mean cross section. Actually, it's a factor of 300 larger for a temperature of 100° and the other assumptions.

J. C. Brandt   Take it at the center line, and you'll get the maximum value.

T. E. Holzer   Right. But the point is that there is a factor of 100 or 300 between the average cross section and the central cross section, because in taking the mean cross section one tends to neglect the effects of any absorption of the line. In any case, I wanted to suggest that the actual absorption effects are somewhat important because, although they don't change Dr. Thomas' results basically, they can increase the density by a factor of 2.

G. E. Thomas   I think the importance of multiple scattering depends very much on the temperature. For the hot model, the cross section at the center of the line is much smaller than in the cold model, and mean free paths are larger so the net effect is to reduce the importance of multiple scattering. For reasons I have already given, I tend to believe the hot model.

F. Scherb   I would like to mention a likely perturbation on the picture that you presented. As I understand it, the axis along which the flow is directed lies nearly in the ecliptic plane. If I have done the arithmetic correctly, about a year from now Jupiter will cross this axis at 5 AU; thus, Jupiter, a source at 3 AU, and the sun will lie on a line, and the gravitational perturbations by Jupiter might be observable if one were observing the Lyman α distribution in this region of the sky. The perturbations might not be entirely negligible in view of the fact that the sun's gravity appears to be virtually absent as far as the hydrogen is concerned.

G. E. Thomas   Well, it might be interesting to look for a bright spot and I agree, the bright spot might be there, but I'm not sure what we would learn by it.

J. C. Brandt   Jupiter's shadow also might be quite long. I'm sure it couldn't be done with the wide-resolution instruments on OGO 5. Instruments with better spatial resolution might see the shadow. I'm sure it's quite long, approximately 1 AU.

C. P. Sonett   Just one very short note, which I think bears on this. There is a considerable body of work now indicating that the temperature of some interstellar clouds is quite high, perhaps due to heating by low-energy cosmic rays.

J. C. Brandt   You can get a good argument on that particular point with any group of astronomers containing two or more people. Some of us have been discussing a process of heating the interstellar medium with 304Å (He*II*) photons from a supernova event. The calculations indicate that the process contributes. However, in all of the colloquia and discussions I've heard on this subject recently, people just throw up their hands at the end. Ultimately, this will be sorted out, but I don't think there's any agreement at the present time.

W. I. Axford   Could I ask if anyone knows what is the status of observations of the temperature of the neutral hydrogen, apart from the 21-cm measurements? Is there anything based on the width of absorption lines that suggests there might be a high temperature somewhere?

J. C. Brandt   If you look, for example, at the spectra, of the kind that Münch takes, or used to take, the lines are very narrow and very closely spaced and in fact very hard to tell apart. The gas appears to be cool.

E. N. Parker   The only comment I could add is that if one sees a broad absorption line, he attributes it to turbulence rather than to the high temperature of the neutral hydrogen. So I don't know that one can unravel it by standard observations apart from those of the 21-cm lines.

J. C. Brandt   Yes, there is the random component of 10 or 20 km/sec.

W. C. Feldman   Concerning what you would learn by looking at Jupiter when it comes around, I would like to point out that you have the same sort of gravitational focusing effect as was shown by Axford, and the only thing that limits the cusp is temperature. By looking at the size and brightness of the spot you might get an indication of the temperature of the gas.

F. Scherb   With regard to the temperature of the neutral gas there is a program under way now at Wisconsin to measure Balmer emission lines from the neutral gas due to recombination of ionized hydrogen. By making measurements of H_α and H_β you can in fact infer the temperature of the gas because the probability of emission of an H_β photon is virtually independent of the temperature at which the recombination occurs, whereas this is not true for H_α. This effect is most useful for temperatures below $1000°$ K. Above $1000°$ one just measures the line profile. So it should be possible, with the proper sensitivity and spectral resolution, to infer the temperatures by studying the H_α and H_β emission from the clouds.

J. C. Brandt   Where in the galaxy do you expect to get sufficient brightness to be able to observe this?

F. Scherb   This has already been observed by looking just off the Crab, far enough so that the Crab itself was not in the field of view. The $H\beta$ emission was detected. The program will be continued, with better equipment, at the Goddard Space Flight Center over the next 2 years.

W. I. Axford   One way of getting an answer to this question of the temperature would be to look at the scattered radiation from helium atoms at 584A. Helium atoms are not affected by radiation pressure and their thermal speed is half that of hydrogen atoms. Therefore, if the gas is relatively cold, the focusing effect will be quite pronounced. Although one expects that the general intensity from the helium will only be perhaps 1 to $10R$ depending on the width of the solar line, the bright spot associated with the helium cusp could be very much more intense if the gas is cold. It might well be $100R$ or so in a small area, and I believe that this could be detected quite easily.