THE INTERPLANETARY HYDROGEN AND HELIUM GLOW AND THE INFERRED INTERSTELLAR GAS PROPERTIES

Darrell L. Judge
University of Southern California
Los Angeles, California 90089-1341

ABSTRACT

Observations of the interplanetary hydrogen and helium glow have been obtained by a number of spacecraft and rocket experiments during the past fifteen years. Important results have been established on the temperature, density, velocity, spacial dependence, and hydrogen to helium ratio. However, only four spacecraft launched to date are investigating the outer solar system and of these four the Pioneer 10 spacecraft is the farthest out at 28 A.U. Observations from this spacecraft at great distances have permitted an improved analysis of the effects which are only evident at large distance from the sun. Perhaps the most significant result in this regard is the clear evidence of the importance of multiple scattering of solar Ly-α; an effect which has not been observed in earlier work. Ignoring this effect can lead to a gross overestimate of the local galactic glow. In the present paper current best estimates of the galactic glow and the local interstellar wind parameters obtained by the Pioneer 10 photometer at great distances are presented, in addition to complementary experimental observations of particular interest.

INTRODUCTION

The interstellar wind consists primarily of atomic hydrogen and helium and results from the relative motion of our solar system with respect to the nearby interstellar gas. It can be studied "locally" by observing the resonantly scattered solar light at 1216Å (hydrogen) and 584Å (helium). A primary purpose of such observations is to determine the characteristics of the local pristine interstellar wind as well as to determine how it is modified as it traverses our solar system. This wind (actually a light breeze when compared to the solar wind) requires about forty years to traverse the region dominated by the solar wind i.e., the heliosphere. Thus the time scale for interaction and modification is indeed large.

As the interstellar wind passes through the solar system, it is gravitationally attracted by the sun, repelled by solar radiation, and ionized by charge exchange, photoionization, and electron ionization. The net result of these interactions is to focus helium, create a small helium cavity, and to weakly focus hydrogen and create a rather large hydrogen cavity, leaving a helium rich region within the first few A.U. of the sun.

In order to determine the spatial distribution and the physical parameters which characterize the inflowing gas a number of techniques have been employed. Isophotes and direct velocity and temperature measurements have been most useful in this regard. Velocity measurements of the interstellar wind have been obtained by Adams and Frisch (1977) by measuring the doppler shift of the Ly-α line using the high resolution spectrometer on board the Copernicus spacecraft, assuming the direction of the wind was known from the downwind isophote observations of the gravitationally focused helium. Hydrogen and helium absorption cells have been used to infer both the temperature and velocity of these two components by measuring the width and the amplitude of the signal transmitted through them (Freeman et al. 1977; Bertaux et al. 1976). Using such direct observations of important model parameters it has been possible to greatly limit the remaining model parameters available to fit the observed isophotes. A brief review and summary of the inferred parameters is given in the next section.

SOLAR SYSTEM OBSERVATIONS

THE INNER SOLAR SYSTEM:

There has been a wealth of data obtained on the interplanetary glow from within the inner solar system and most of the earlier results are included in the reviews of Thomas (1978) and Holzer (1977). These earlier observations have provided an extensive set of data which have been fit to models of the inflowing interstellar wind. The model parameters presented at the Lindau workshop in 1981 based on several such data sets are given in Table I, in addition to the most recent density data obtained by Pioneer 10.

The earlier data will not be further discussed here other than to comment on the difficulties inherent in making observations in a region strongly affected by local solar effects. Specifically, local heating and doppler shift of the scatterers can be significant (Wu et al. 1981; Kunc 1980). For example, doppler shift of the He 584 Å emission can drastically change the emission intensity for helium atoms moving radially toward the sun even at the unaccelerated wind speed of 20 Km/sec since the solar helium linewidth is of the order of 100 mÅ. The doppler shifted wavelength in the radial direction is

$$\Delta \lambda \approx \lambda v/c = 40 \text{ mÅ} \quad ,$$

which is well outside the core of the solar line. Because of such considerations as the above it is clearly desirable to limit the importance of the "local" effects (solar distances less than ≈ 10 A.U.) by examining data at large solar distances. Nonetheless, the considerable data available from measurements within the inner solar system are quite important for determining the interstellar wind flow direction and local anomalies in solar wind flow, as well as local temperatures, velocities, and densities.

Of these inner solar system measurements the observations of emissions near the solar poles are of particular interest with respect to the latitudinal dependence of the solar wind flow velocity. (The other inner solar system data will not be further discussed here since they have been extensively discussed in the literature and have been summarized in the reviews by Thomas (1978) and Holzer (1977)).

The specific data of interest have been obtained with the Mariner 10 spectrometer. These data show a distinct enhancement of the Ly-α glow over the solar poles which is interpreted as a latitude dependence of the solar wind proton flux or velocity, but not both (Witt et al. 1981; Ajello et al. 1979; Isenburg and Levy 1978). They conclude that the lifetime against ionization increases with increasing latitude and they obtain an asymmetry parameter which

TABLE I. SUMMARY OF DENSITY/TEMPERATURE DETERMINATIONS FOR THE LOCAL INTERSTELLAR MEDIUM

Spacecraft and Date	Experiment	References	Derived Density (cm^{-3})	Derived Temp. ($\times 10^4$ °K)	Results
OGO-5 1969 - 1971	Ly-α photometer (3° FOV)	Thomas & Krassa (1971,1974); Thomas (1972)	$n_H = .12$	.35	"Hot" model
OGO-5 1969 - 1971	Ly-α photometer (40 arc min FOV)	Bertaux & Blamont (1971); Bertaux, Ammar & Blamont (1972)	$n_H = .1 - .2$	.1 - 1	"Hot" model
Rockets 1970, 1973	584 Å photometer	Paresce et al. (1974 a, b)	$n_{He} = .032$	.4 - .6	Temperatures are lower limits
STP 72-1 1972 - 1973	584 Å photometer	Weller & Meier (1974); Meier (1977)	$n_{He} = .009 - .024$	.25 - .1* .5 - 1**	*Uses modified cold model. ** Uses Meier's more accurate model.
Mars 7 1972 - 1973	Ly-α photometer plus H resonance cell	Bertaux et al. (1976)		1.1 - 1.3	Value of temperature assumes galactic Ly-α intensity is zero.
D2-A 1971	Ly-α photometer plus H resonance cell	Cazes & Emerich (1977)		.8 - 1.2	Observed ~10% interstellar polarization; verified that μ < 1 in 1971.
Mariner 10 Dec. 1973 & Jan. 1974	Spectrometer measured simultaneously 1216 Å and 584 Å	Broadfoot & Kumar (1977); Ajello, Kumar & Broadfoot (1977)	$n_H = .03 - .09$ $n_{He} = .006 - .012$	1 - 2	He/H = .15 ± .1
Prognoz-5 1976	4-channel photometer includes 1216 Å, 584 Å plus H resonance cell	Bertaux et al. (1977)		.78 - .98	
Apollo-Soyuz 1975	EUV telescope & broad-band photometer	Freeman et al. (1977)	$n_{He} = .002 - .006$		
Pioneer 10/11 1972 - present	2-channel photometer 1216 Å and 584 Å	Wu et al. (1981)	$n_H = .04$ $n_{He} = .01$		He/H = .23 ± .1; r = 1.5 (1972) to 14 A.U. (1981)
Black Brant IVB Rocket 1976	584 Å photometer and He resonance cell	Fahr, Lay & Wulf-Mathies (1977)	$n_{He} = .004 - .01$		

describes the solar wind latitudinal dependence. In the absence of direct measurements of particle flux at high solar latitudes, UV photometric observations are quite useful and provide information on the product of solar wind proton flux and the velocity dependent cross section. It is indeed quite likely that high latitude coronal holes are responsible for the observed increased Ly-α emission at high solar latitudes since it is known that coronal holes are sources of solar wind and that streams with velocity twice the normal wind of 400 km/sec and half the density characterize them. If the solar wind flux is constant then the cross section for ionization of hydrogen should decrease by about 30% of the increase in solar wind velocity, and thereby result in enhanced hydrogen over the poles. The increased solar wind velocity at high latitudes has in fact also been inferred from interplanetary scintillation measurements (Coles and Maagoe 1972).

THE OUTER SOLAR SYSTEM:

At large heliocentric distances the most important model parameters become the density of the interstellar gas and the galactic glow, which can be determined quite accurately, subject only to the reliability of the observing instrument calibration.

Before proceeding to the results it is informative to briefly review the glow equations to see how the measurements relate to the inferred parameters. In the equations below the measured quantity is I, the measured glow. Using the appropriate phase function, $P(\gamma)$, the volume emissivity, and I_G, the galactic glow, are adjusted until a suitable fit to the data is obtained. Since the volume emissivity depends on the solar flux, as seen below, it is clearly evident that the wind parameters determined depend upon a correct absolute measure of the observed glow and a correct value of the solar flux.

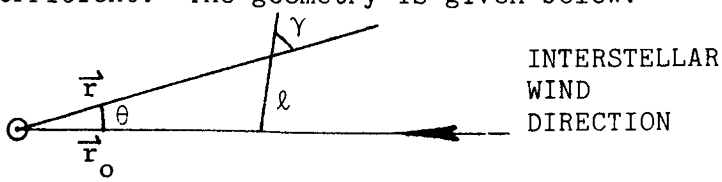
$$I = I_G + \int_{r_o}^{\infty} \varepsilon(r, \theta)\, P(\gamma)\, d\ell ,$$

where $\varepsilon\,(r, \theta)$ is the volume emissivity and $P(\gamma)$ is the light scattering phase factor.

The volume emissivity is given by

$$\varepsilon\,(r, \theta) = \lambda^2/c \int_{-\infty}^{\infty} \pi F_\lambda\, \alpha_\nu\,(r, \theta)\, d\nu ,$$

where λ is the wavelength of interest, πF_λ the solar flux, and α is the absorption coefficient. The geometry is given below:



From the above equations it is clear that uncertainties in the solar flux and instrument calibration can introduce significant errors. The absorption cross sections, however, are well established and are not a significant source of error. Differences in the time at which observations were obtained, as well as the observation distance from the sun, can also lead to different conclusions about the values of the interstellar wind parameters, particularly for measurements obtained within the inner solar system. Thus, the relatively good agreement among the various experimental observations shown in Table I is encouraging.

Since the Pioneer 10 measurements are currently being obtained at large heliocentric distances and, as mentioned above, the glow at large distances is largely unaffected by local heating, gas temperature, or look direction, the Pioneer 10 results at great distances are of particular interest. Model calculations showing the relative independence of near solar effects are given in Figures 1 and 2 where temperature and viewing direction are varied and plotted vs. distance from the sun. The model parameters in the figures have the conventional meanings (See Wu et al. 1981).

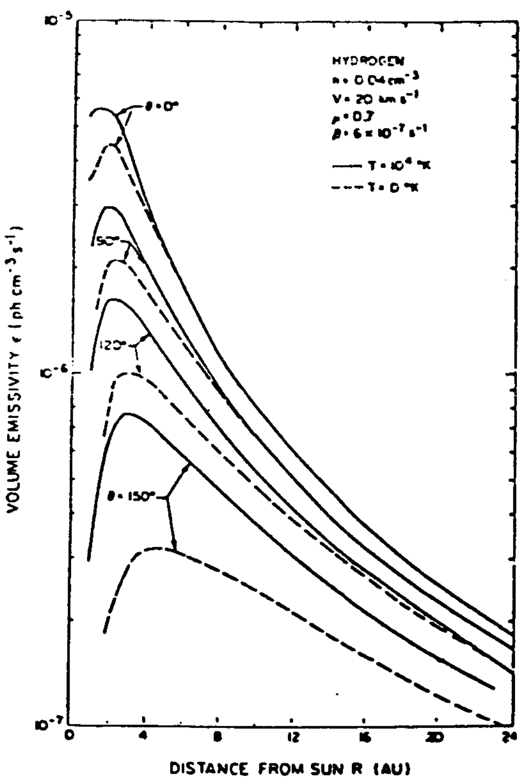


Figure 1

Figure 1. Calculated volume emissivity of interplanetary H Ly-α for various look angles θ. The model parameters are given in the figure.

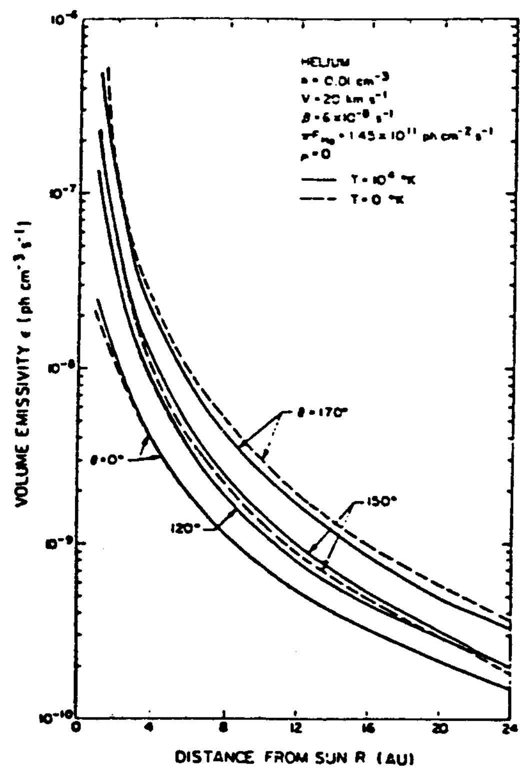


Figure 2

Figure 2. Calculated volume emissivity of interplanetary He 584 Å line for various look angles θ. The model parameters are given in the figure.

By fitting the Pioneer 10 data to such curves the parameters most evident only at large solar distances can be readily determined. A parameter of particular interest which can be determined at great distances is that of the galactic glow. As observed from the inner solar system it is now clear that the apparent galactic glow is heavily contaminated by multiple scattering of solar Ly-α. The Pioneer 10 evidence for this arises from the fact that the galactic glow parameter I_g must be continually reduced as data at greater solar distances is included in the data base to be fit by the model. Thus, the "galactic glow" actually consists of the true value of the glow plus a multiply scattered component. Since the true galactic glow contribution to I_g is independent of radial distance from the sun it becomes evident only at large solar distances where single and multiple scattering of solar light within the heliosphere are greatly reduced, as observed by a photometer looking outward toward the heliosphere boundary.

As a final comment it should also be mentioned that the contribution to the glow by the multiply scattered component should vary with solar flux. In a preliminary investigation (Shemansky, Judge, in preparation) of the results obtained with the Voyager spectrometers which are observing from distances much closer to the sun (about 11 A.U.) an I_g of about 450 R for Ly-α is inferred from the model fit during the present time of high solar activity. This is an incredibly large value and one which reflects primarily the importance of multiple scattering at Ly-α. By comparison, the Pioneer 10 value is ≈ 30 R and still dropping as new data are added. As expected, there is no evidence for multiple scattering at the 584 Å helium resonance line.

Thus, it seems clear that (a) ongoing theoretical work must include hydrogen Ly-α multiple scattering and (b) that the true galactic glow in both the light of hydrogen Ly-α and helium 584 Å is quite weak. It should further be noted that the observations to date are still being obtained from well within the heliosphere. The "galactic glow" inferred here may thus include a contribution due to a splash component at the heliosphere boundary as well as other modifications to the inflowing "pristine" interstellar wind. However, such modifications will probably not change the inferred values by more than a factor of two.

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REFERENCES

Adams, T.F., Frisch, P.C., "High Resolution Observations of the Lyman Alpha Sky Background," Astrophys. J., 212, 300, 1977.

Ajello, J.M., Witt, N., Blum, P.W., "Four UV Observations of the Interstellar Wind by Mariner 10: Analysis with Spherically Symmetric Solar Radiation Models," Astron. Astrophys., 73, 260, 1979.

Bertaux, J.L., Blamont, J.E., Tabarie, N., Kurt, V.G., Bourgin, M.C., Smirnov, A.S., Dementeva, N.N., "Interstellar Medium in the Vicinity of the Sun: A Temperature Measurement Obtained with Mars-7 Interplanetary Probe," Astron.

Astrophysics, 46, 19, 1976.
Coles, W. A., and Maagoe, S., "Solar-Wind Velocity from IPS Observations," J. Geophys. Res, 77, 5622, 1972.
Freeman, J., Paresce, F., Bowyer, S., Lampton, M., Stern, R., Margou, B., "The Local Interstellar Helium Dencity," Astrophys. J., 215, 83, 1977.
Holzer, T.E., "Neutral Hydrogen in Interplanetary Space," Rev. Geophys. Space Phys., 5, 467, 1977.
Isenberg, Philip A., Levy, E.H., "Polar Enchancements of Interplanetary Lα Through Solar Wind Asymmetries," Astrophys. J., 219, L59, 1978.
Kunc, Joseph A., "Survival Probabilities for Interstellar Hydrogen Flowing into the Interplanetary System from Far Regions of the Heliosphere," Planet. Space Sci., 28, 815, 1980.
Thomas, G.E., "The Interstellar Wind and Its Influence on the Interplanetary Environment," Ann. Rev. Earth Planet. Sci., 6, 173, 1978.
Witt, N., Ajello, J.M., Blum, P.W., "Polar Solar Wind and Interstellar Wind Properties from Interplanetary Lyman-α Radiation Measurements," Astron. Astrophys., 95, 80, 1981.
Wu, F.M., Suzuki, K., Carlson, R.W., Judge, D.L., "Pioneer 10 Ultraviolet Photometer Observations of the Interplanetary Glow at Heliocentric Distances from 2 to 14 AU," Astrophys. J., 245, 1145, 1981.