HELIUM AND HYDROGEN BACKSCATTERING RESULTS AND THE VERY LOCAL INTERSTELLAR MEDIUM

HELIUM AND HYDROGEN OF THE LOCAL INTERSTELLAR MEDIUM OBSERVED IN THE VICINITY OF THE SUN

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ABSTRACT

The Sun is moving in respect to the nearby stars with a velocity of 20 km.s^{-1} in the direction of the Apex, $\alpha = 271°$ and $\delta = 30°$ (celestial coordinates). As the lights of a car illuminate the water droplets when driving in the fog, the Sun illuminates the Hydrogen and helium atoms of the interstellar medium which it travels through. As a result, the sun and the whole solar system are imbedded in a glow of the resonance lines of hydrogen (H Lyman α ; 121.6 nm) and helium (58.4 nm), which have been studied by several space instruments in the last 14 years.

From the intensity distribution of the glow in the solar system, one can derive the density of H and He in the LISM and the direction of the relative motion $\vec{V}_w$ between the sun and the LISM in the very vicinity of the sun. The velocity module V_W and the LISM temperature T are more adequately found from a measurement of the Lyman α line shape, which is an image of the velocity distribution of H atoms.

A summary of results will be presented, together with a discussion of the methods of interpretation and their difficulties. The vector $\vec{V}_w$ is found to be 20 $\pm$ 1 km.s^{-1} in the direction $\alpha = 254 \pm 3°$, $\delta = -17 \pm 3°$, quite different from the Apex direction. This means that the LISM is moving also in respect to the local frame of reference giving rise to the so-called Interstellar Wind. This wind blows in the galactic plane at 16 km.s^{-1}, in the direction $\ell_{II} = 124°$, significantly different from the direction $\ell_{II} = 169°$ found by interstellar absorption lines on stars within $\simeq$ 100 pc, pointing to a local significance of this flow. The temperature of the LISM is T = 8,000 $\pm$ 1,000 K, the density n (H) $\simeq$ 0.04 to 0.06 cm^{-3}, and the helium density n (He) $\simeq$ 0.015 to 0.020. The high helium/hydrogen ratio, in respect to the cosmological ratio, would imply that a substantial part of the hydrogen is ionized. Temperature, density and degree of ionization of the LISM are suggesting that the sun is now in an intermediate phase of the interstellar medium, at the interface between a hot and tenuous gas, and a dense and cold cloud of gas.

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INTRODUCTION

A great deal of what we know today about the Local Interstellar Medium (LISM) comes from observations of stellar spectra, on which are "printed" absorption features from atomic, ionic, and molecular species. These spectral features correspond most often to strong resonance lines and some corresponding resonance emission lines would also be expected. In fact, this emission is concentrated in a small region around each star, which is surrounded by a glow of resonance lines. Though it would be very interesting to study this glow which contains a local information on the LISM, it would be extremely difficult to observe from one star to another star, since it will be re-absorbed by interstellar matter (except in a few particular cases).

We are still left with one particular star, the Sun, which illuminates the LISM in which it is embedded. It is only since the early seventies that it was realized that neutral Hydrogen and Helium atoms from the LISM would become detectable through emission in the resonance lines Lyman- α HI 121.566 nm and HeI 58.4 nm. Since 1969, a number of space experiments have studied this resonance glow of the LISM, which takes place right in the solar system within a few astronomical units (AU) from the Sun.

Interestingly enough, it is not the usual LISM scientific community which has provided most studies in this field, but rather scientists dealing with UV instruments, distributed in Earth's orbit, other planets' orbits, and even solar system escape trajectory (Pioneer and Voyager missions).

My purpose in the present paper is not to present an exhaustive review of the numerous work performed by active group of scientists from different countries. Rather, my paper is addressed to the LISM community, which may not be totally familiar with the following problem : how safely can we deduce the characteristics of the very local interstellar medium (VLISM ?) by the study of the resonance glow of H and He in the Solar system ? Therefore, I will try to discuss some difficulties associated with the experimental methods of diagnostic, and present the most recent results on the VLISM characteristics : temperature, H and He densities, direction of the VLISM flow (an alternate acronym is SLISM, Solar System Local Interstellar Meidum).

The situation of the resonance glow around the Sun is comparable to the glow produced by a thick fog around a gas light. If you are near the gas light and observing the glow in a direction opposite to the gas light, the brightest is the glow, the densest is the fog. If there is some wind, it will not modify the distribution of light, which makes impossible to detect such a wind. The same situation happens sometimes when you are on a pair of skies in a thick fog ; sometimes you do not even realize if you are moving or not, a particularly uncomfortable feeling.

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ZERO DEGREE APPROXIMATION

As a first approach, let us consider the simple situation, similar to the fog case, in which the flow of interstellar gas is not modified by the Sun : the only interaction being that H and He atoms are illuminated by the solar resonance light.

For an observer at 1 AU looking opposite from the sun, the measured intensity is :

$$I = \frac{1}{4\pi} \quad \frac{\pi e^2}{m_e c} \; f . F_s \int_1^{\infty} n(r) \frac{dr}{r^2} \qquad (1)$$

in which F_s is the exciting solar flux (in photons /cm^2 s Å), $\frac{\pi e^2}{m_e c} f$ the integrated cross section of the resonance transition, and n (r) is the density distribution of the gas at distance r from the sun, which is uniform in the simple case considered here, and equal to n_∞, the LISM gas density. Introducing the excitation rate at one AU, $g_o = \frac{\pi e^2}{m_e c} f . F_s$, we have the simple relationship between the density n_∞ and the scattered intensity :

$$4 \pi I = g_o \, n_\infty \times 1 \text{ AU (in cm)} \qquad (2)$$

The intensity is measured with a photometer which has a certain sensitivity a, giving a signal S when the measured intensity is I.

$$S = a \, I$$

Since g_o contains the solar flux F_s, we finally arrive at the expression :

$$S = \gamma \, a \, F_s \, n_\infty \qquad (3)$$

where γ is a known coefficient. Such an expression would be valid for any direction of sight, the integral of (1) being modified, and its value integrated in the coefficient γ.

The diagnostic problem is to extract an estimate of n_∞ form a photometric measurement S. The solar flux suffers from some uncertainties, as well as the calibration factor ; the point to be made here is that the effect of a and the effect of F_s are not distinguishable from one another.

One possibility to overcome this problem is to use the same photometer to observe a known quantity of atoms, illuminated by the same solar flux F_s . This situation can happen in the upper atmosphere of planets, where other methods (like neutral mass spectrometers) can yield a value of the density. Therefore, a photometric observation of an upper atmosphere can provide the value of a F_s for the time of observation, which can then be used for the derivation of n_∞ with an improved accuracy.

The temperature and the flow velocity, both related to the velocity distribution of atoms, is accessible through high resolution spectrometric measurement. All atoms are re-emitting at the central wavelength λ_o in their frame of reference, but observed photons are at wavelengths shifted from λ_o through Doppler effect. With the provision that the solar flux F_s is constant over a reasonable wavelength interval, the observed line shape in a given direction is the exact velocity distribution of these atoms, projected on the line of sight and weighted according to the local excitation rate (r^{-2} decrease).

On Figure 1 are illustrated the various possible Doppler shift $\Delta\lambda$ in various directions, for an observer near the sun. It depends on the value of V_o (the wind velocity in respect to the sun) and on the angle α with the wind direction :

$$\Delta\lambda = \frac{\lambda_o}{c} V_o \cos \alpha \qquad (4)$$

Usually the vector $\vec{V}_o$ designates the velocity of the wind flow in respect to the sun, whereas $\vec{V}_w = - \vec{V}_o$ refers to the velocity of the sun relative to the local interstellar medium.

The temperature T of the LISM is related to the linewidth $\Delta\lambda_D$ (half width at 1/e) of the gaussian spectral profile :

$$\Delta\lambda_D = \frac{\lambda_o}{c} \quad \frac{2\ kT}{m} \qquad (5)$$

where m is the mass of the atom.

Therefore, if high resolution spectrometric measurements can be made over many points of the celestial sphere, it is possible to find where there is a maximum Doppler shift $\Delta\lambda_m$, which determines the direction of the wind flow, whereas the value of $\Delta\lambda_m$ gives immediately the modulus of V_o. At 90° from V_o, the Doppler shift is zero ; on the celestial sphere, there is a whole great circle with zero Doppler shift called the zero Doppler shift circle (ZDSC). Determining this ZDSC allows also to determine the direction of the flow.

Up to now, we have considered the very simple case of no interaction of the sun with the wind flow, and have described the physical ways to perform a diagnostic on the LISM characteristics. In such a case (zero degree approximation) the projected velocity distribution is a uniform gaussian. In reality, there are substantial interactions which modifies greatly the density and velocity distributions of H and He in the solar system as we will describe now. However, the physical ways to perform a diagnostic still remain valid : the density is still accessible through absolute photometric measurements, and the velocity distribution (connected to $\vec{V}_o$ and T) is still accessible to high resolution spectrometric measurements.

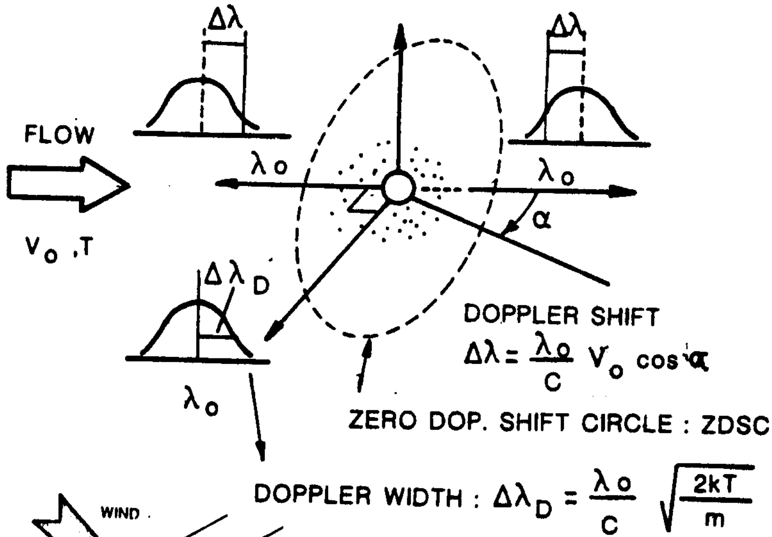

Figure 1. The Doppler width of the backscattered line profile is connected to the temperature ; the wavelength shift $\Delta\lambda$ depends on angle α between the line of sight and the flow direction.

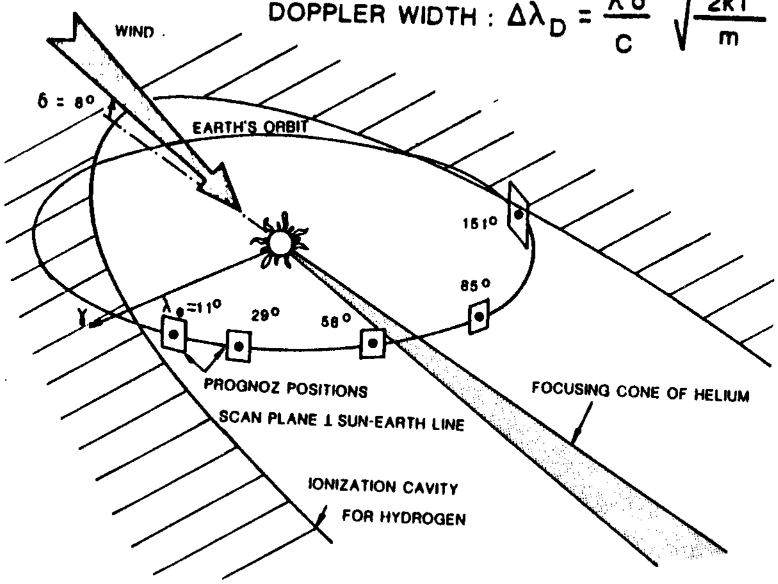

Figure 2. The main features of interstellar gas distribution in the solar system are i) a focusing cone of helium in the downwind direction ; ii) a cavity of ionization, void of atoms, elongated toward the downwind direction.

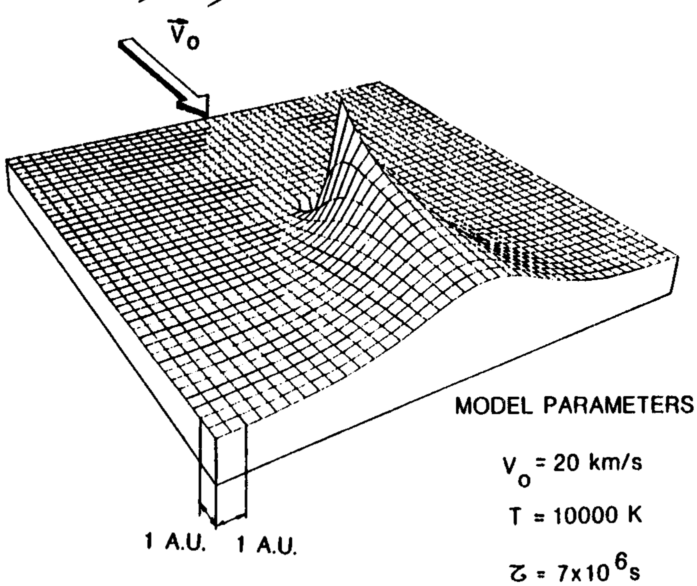

Figure 3. 3D representation of the density distribution in a plane containing the flow vector $\vec{V}_o$. The vertical coordinate is proportional to the He density in the horizontal plane (after Dalaudier et al., 1984).

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MODIFIED DENSITY DISTRIBUTION AND PHOTOMETRIC DIAGNOSTIC

Even before it was realized that the observed extraterrestrial Lyman-α glow was due to an interstellar flow of H in the solar system, Blum and Fahr (1970) had pointed out the effect of solar gravity, which bends individual trajectories into hyperbolae, and the ionization of atoms by solar wind charge exchange and solar EUV photoionization. In the case of hydrogen, the continuous scattering of solar Lα photons is acting as a radiation pressure F_r, which is of the same order of magnitude as the gravitation force F_g, but of opposite direction. The ratio $\mu = F_r/F_g$ is negligible for helium, but can vary between $\simeq 0.5$ and 1.5, for hydrogen, depending on the solar Lα flux which varies with solar activity. The solar flux which corresponds to $\mu = 1$ is $F_s = 3.32 \times 10^{11}$ photons $(cm^2.s.Å)^{-1}$.

The results of these effects on the H and He density distribution inside the solar system are illustrated on Figure 2. For helium atoms, if we assume that they are monocinetics (T = 0) all hyperbolae are crossing along a line determined by $\vec{V}_o$, in the downwind direction of the solar system, creating a density singularity on this line, and a region of greatly enhanced density around this line. If $T \neq 0$, the singularity disappears, but there is still a cone of gravitationnal focusing. A model computation by Dalaudier et al. (1984) illustrates this dramatic effect (Figure 3).

For hydrogen, ionization and Lα radiation pressure prevents H atoms to approach very near the sun, and there is a cavity of ionization "carved" into the H flow, elongated along the downwind direction, which would be void of H atoms if it were not for the filling in resulting from the velocity dispersion associated to the LISM temperature.

All these effects (which we call DEGREE ONE physical description) can be modeled on computer codes, basically with the use of Liouville's theorem and at the expense of a quadruple integration. Density distributions, emissivity distributions and spectral line shapes can be and have been predicted by several groups of research scientists.

Now we have to understand how these solar effects are going to modify the basic methods of diagnostic that were discussed above.

The purely photometric diagnostic method

1) Helium density distribution

The focusing effect allows to determine simply the downwind direction. The first attempt to observe this spectacular focusing cone of helium failed in 1972, when the french satellite D2-A polaire could not reach its orbit. Later, the Naval Research Laboratory group successfully mapped the Helium 58.4 nm emission distribution with an Earth orbiting spacecraft (STP-72) and determined the direction of the incoming flow $\vec{V}_w$ to be

[Weller and Meier, 1974] :

$\alpha = 252 \pm 3°$, $\delta = -15 \pm 3°$ (celestial coordinates)

which is slightly above the ecliptic plane.

The exact shape of the cone (its angular width about the downwind axis) depends slightly on the temperature T and on the bulk velocity V_o, and careful measurements compared to accurate modeling allows to determine an estimate of these parameters. A 58.4 nm photometer flown on soviet satellite PROGNOZ 6 in 1977 provided a series of swaths across the helium cone, compared to models at various temperatures. A summary of V_o and T determination from various space instruments performing purely photometric measurements is presented on Figure 4. The most recent PROGNOZ measurements [Dalaudier et al., 1984] indicates parameters in the range :

$T = 11,000 - 24,000$ K $\qquad V_w = 23 - 30$ km.s^{-1}

From the shape of the (V_w, T) domaine of Figure 4, it seems as if there is some coupling between parameters V_w and T ; in fact, it can be understood intuitively that the most important parameter is the ratio V_t/V_w of the thermal velocity V_t to the bulk velocity V_w.

One difficulty of the modeling is that the exciting solar line shape at 58.4 nm has to be taken into account, since its width is comparable to the velocity dispersion of He atoms (expressed in Doppler shifts). This line shape and its width are not very well known, but Dalaudier et al. (1984) showed that the derived parameters V_w and T did not change substantially when various spectral profiles were introduced in the modeling.

Besides the conspicuous focusing cone, the HeI 58.4 nm intensity distribution is very smooth in the other directions. The density n_∞(He) of helium atoms can be obtained with the help of equation (3), in which the coefficient γ includes a modeling of the He distribution in the solar system and the geometric conditions of observations. The difficulty of the absolute value of axF_s remains.

2) Lyman-alpha photometric observations of hydrogen distribution

For a typical set of LISM parameters and solar parameters, the resulting H density distribution has a cylindrical symmetry about the wind axis. The shape of the isodensity contours illustrates quite well the ionization cavity, elongated in the downwind direction. The corresponding emissivity distribution is obtained after multiplying by a r^{-2} factor and presents a broad region of maximum emissivity at 2 to 3 AU on the upwind axis.

An observer located at one 1 AU is well inside the ionization cavity. The resulting $L\alpha$ photometric pattern is characterized by a broad region of maximum intensity not far from the upwind direction $\vec{V}_w$ of the incoming flow of hydrogen (opposite to the focusing cone direction V_o), and a gradual decrease toward the opposite downwind direction.

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Therefore, a mapping of the $L\alpha$ interplanetary emission gives immediately the general direction of the wind. However, since the maximum emission region is very broad, it can not give, as in the case of the helium cone, a very accurate determination. Besides, since the maximum **emissivity** region is not far from the sun, there is a parallax effect : the direction of the maximum **emission** depends on the location of the observer. Indeed, when the first global mappings of extraterrestrial $L\alpha$ were made in 1969 with two $L\alpha$ photometers, placed on board OGO-5 satellite [Bertaux and Blamont, 1971 ; Thomas and Krassa, 1971], two mappings made at 6 months intervall revealed clearly a $\approx 40°$ displacement of the maximum region, definitely indicating that the source of $L\alpha$ emission was right in the solar system, and was not of galactic origin as it was thought before. The direction of the wind $\vec{V}_w$ was found to be $\alpha = 265°$, $\delta = -15°$, with a rather large uncertainty margin ($\pm$ 15°) [Bertaux and Blamont, 1971].

The filling of the ionization cavity depends on the temperature T, and one could hope that the shape of the ionization cavity (defined, for instance, by the ratio I_{max}/I_{min} of maximum to minimum measured intensities) would allow a measurement of this temperature from a purely photometric pattern. Unfortunately, the shape of the ionization cavity depends also on three other parameters : the flow velocity V_w, the ionization rate $\beta = T_D^{-1}$ and the solar $L\alpha$ flux through $\mu = F_r/F_g$. Several sets of different parameters can yield nearly identical intensity distribution, as shown by Lallement and Bertaux (1984). Five different sets of parameters were selected to give approximately the same ratio I_{max}/I_{min}, and all model curves were normalized at the same value of I_{max}, since the density at infinity $n_\infty(H)$ is an unknown free parameter which behaves linearly on the intensity.

All five curves are nearly identical. Since there are rather large uncertainties on the exact value of the solar parameters μ and β, this exercise clearly demonstrate that it is not possible to retrieve accurate LISM parameters V_w and T from only purely photometric measurements.

THE HIGH RESOLUTION SPECTROMETRIC METHOD OF DIAGNOSTIC

High resolution spectrometric measurements of line width, line shape and line position will yield, as explained in the first section, independent and crucial information on the LISM parameters, because through Doppler effect the line shape of the resonant emission is an image of the velocity distribution of atoms, projected on and integrated along the line of sight, and weighted by the resonance excitation rate.

However, gravitation, ionization and radiation pressure will modify the velocity distributions and corresponding line profiles.

For helium, two effects are playing an important role. First the velocity distribution of He atoms is strongly modified by the solar gravitation ; second, the solar line width is small enough that the resonant line shape is modified in respect to the velocity distribution, since atoms with a large Doppler effect respective to the sun will be excited at a lower rate, and may even not be excited at all.

In the case of H Lyα, the solar line is wide enough that it may be considered as flat on the interval of sun radial velocities of H atoms, and the line shape is strictly the image of the projected velocity distribution (weighted by the excitation rate).

The velocity distribution of H atoms may be modified in theory by the following effects :

- The unbalance between solar gravitation F_g and the Lyα solar radiation pressure F_r, described by the parameter $\mu = F_r/F_g$ provides a mechanical effect which bends individual trajectories into hyperbolae, as in the case of Helium, but to a lesser degree.

- The solar ionization is more effective on slow atoms than on fast atoms [Wu and Judge, 1979 ; Lallement, 1983]. As a result, the bulk velocity and the velocity distribution are modified.

- Heating by solar corpuscular emissions should be only a minor effect [Holzer, 1977 ; Wu and Judge, 1978 ; Kunc, Wu and Judge, 1983].

All these effects can be taken into account in predictive spectrometric models of line shapes of H and He emission and can be implemented on expensive computer codes ; see for instance Meier (1977) and Wallis and Wallis for an approximate formulation (1979). The two first effects are included in the DEGREE ONE physical description.

It could be thought that, since the solar Lα radiation pressure is approximately in equilibrium with solar gravitation, the H velocity distribution would not be too much modified from its Maxwell-Boltzmann shape at infinity. In the case $\mu = 1$, all H atoms trajectories are straight lines, and the same gaussian shape could be seen in all directions.

However, even in the case $\mu = 0.75$, not very far from $\mu = 1$, Wu and Judge (1980) computed that the velocity distribution was substantially modified. Assuming that the LISM temperature was $T = 10^4$ K, they showed that, for directions of sight toward the upwind region, the "effective temperature" T_e of the modified velocity distribution was 9,500 K (slight cooling effect due to ionization), increasing up to T_e = 13,500 K when looking toward the downwind region.

We now turn our attention to the observations, made with different experimental methods, their interpretation and the LISM results.

HYDROGEN Lα HIGH RESOLUTION SPECTROMETRIC OBSERVATIONS

With the UV spectrometer of Copernicus observatory, Adams and Frisch (1977) obtained a weak line of the LISM H Lyα emission, in only one direction of sight after six days of integration. They found a Doppler shift of 22 $\pm$ 3 km.s^{-1} and a width corresponding to 20,000 K or less.

It would have been impossible to look in many directions, as would be required to detect different Doppler shifts in different directions to determine $\vec{V}_w$ independently of photometric measurements. The temperature diagnostic is not very accurate either.

The use of resonance absorption cells associated to photometers is much more powerful than the use of high resolution spectrometers, mainly because of the much larger instrumental throughput, and the theory of its use will be now briefly described, as well as the experimental results obtained in 1976 and 1977 with a french experiment on soviet PROGNOZ satellites.

The Lyman-α photometer flown on Prognoz 5 and Prognoz 6 consisted of a solar blind photomultiplier as the detector, placed behind a hydrogen absorption cell, which is a teflon coated glass vessel with two MgF_2 windows. The entrance window is a lens, which focus is between the cell and the PM tube. A rectangular hole at the focus defines a field of view of 1.3 × 3°. The exit window of the cell is covered with an evaporated thin film filter, which defines a total bandwidth of $\sim$ 10 nm centered at Lyman-α. In the following, it will be assumed (unless otherwise specified) that the only radiation seen by the detector is resonance radiation from hydrogen atoms.

The cell is sealed and permanently filled with H_2 at a few mm Hg (a few hundreds Pascal) pressure. A tungsten filament placed inside the cell can be heated electrically, and H_2 molecules touching the filament are dissociated into atoms, creating an optical thickness τ of atomic hydrogen. When the filament is switched off, there is immediate (within $\simeq$ 0.05 seconds) recombination into molecules. Whereas H_2 is totally transparent to Lα, when the optical thickness $\tau = 10$ is created inside the cell, incoming photons lying near the resonance line center are scattered away from the direct beam and absorbed on the cell walls. The transmission function $T(\lambda)$ of the cell in its reference frame,looks like a rectangle with an equivalent width of absorption W = 30 mÅ or 7.4 km. s^{-1}. The cell may be regarded as a "negative" spectrometer with a bandwidth W = 30 mÅ ; the wavelength scanning is provided by varying the Doppler shift $\Delta\lambda_D$ between the interplanetary line and the cell. When the cell is not activated, the total Lα intensity I_0 is measured ; when it is activated, at the level $\tau = 10$, it is reduced to $I(\Delta\lambda_D)$ by a factor $R(\Delta\lambda_D)$ depending on the Doppler shift $\Delta\lambda_D$. The reduction factor $R = I(\Delta\lambda_D)/I_0$.

Looking in the sky at different directions of sight $\vec{u}$ a large wavelength exploration is obtained owing to the orbital velocity $\vec{V}_s$ of the spacecraft in the solar system, combined with the wind velocity $\vec{V}_w$ of ≈ 20 - 25 km. s^{-1}. The total relative velocity between the spacecraft and the H interstellar flow is $\vec{V}_R = \vec{V}_s + \vec{V}_w$. For Prognoz satellites, which spend most of their time at large distances of the Earth, and have at apogee a low orbital velocity which can be neglected, $\vec{V}_s \simeq \vec{V}_E = 30$ km. s^{-1}, where $\vec{V}_E$ is the Earth's orbital velocity.

The Doppler effect in the line of sight $\vec{u}$ is :

$$\Delta \lambda_D = \frac{\lambda_o}{c} V_R \operatorname{Cos} (\vec{V}_R, \vec{u}) = \frac{\lambda_o}{c} V_R \operatorname{Cos} \alpha = \frac{\lambda_o}{c} V_D \tag{6}$$

α being the angle between $\vec{u}$ and $\vec{V}_R$. Therefore, looking at various angles α provides a spectral scanning of the emission line through the variation of $\Delta \lambda_D$. A series of measurements $R(\Delta \lambda_D)$ can be deconvoluted to retrieve the spectral shape of $f(\lambda)$. This method can be described as the Doppler angular spectral scanning (DASS) method, and has been fully described by Bertaux and Lallement (1984). It should be noted that, since the reduction factor $R(\Delta \lambda_D)$ is a relative quantity, it is not required that the absolute intensity I_o be identical in all directions. It is only required that the **spectral shape** $f(\lambda)$ be the same in all directions, or in the sky region where it is applied.

The minimum reduction factor (maximum absorption effect of the cell) is obtained when the Doppler shift V_D is zero in the plane perpendicular to the vector $\vec{V}_R$, which intersects the celestial sphere along the zero Doppler shift circle ZDSC [Bertaux et al., 1976]. Therefore, a mapping of the R pattern allows to determine the position of the ZDSC circle, and the direction of vector $\vec{V}_R$.

From the study of Bertaux and Lallement (1984) we can summarize how the interstellar gas parameters can be determined from one single mapping of the R pattern of the complete celestial sphere with the Doppler angular spectral scanning (DASS) method, in the simple case of a uniform gaussian case (Figure 5) :

1. Minimum values of measured R are distributed alons a great circle of the celestial sphere (the ZDSC). The direction of $\vec{V}_R = \vec{V}_s + \vec{V}_w$ lies along the axis of this great circle (Figure 5).

2. The value of R_{min} directly determines the temperature T.

3. The module of V_R is determined from the angular width $\Delta\alpha$ of the absorption region along the ZDSC with the approximate relationship :

$$V_R \sin (\Delta\alpha) \simeq \frac{2\ kT}{m} \tag{7}$$

4. The vector $\vec{V}_R$ is determined ; since $\vec{V}_s$ is known, the vector $\vec{V}_w = \vec{V}_R - \vec{V}_s$ is therefore determined.

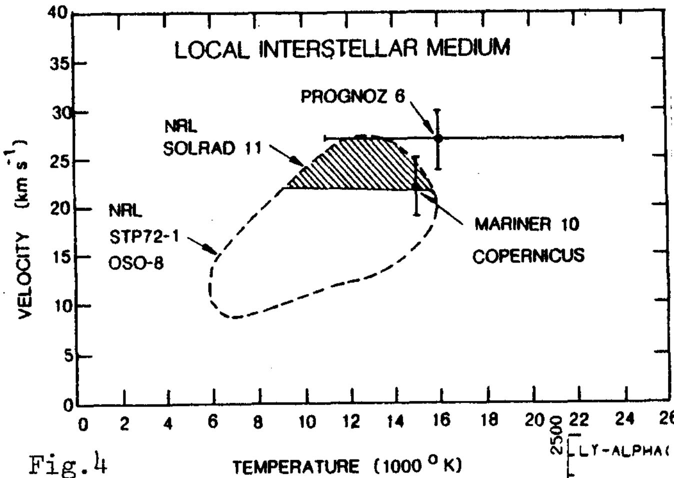

Fig.4

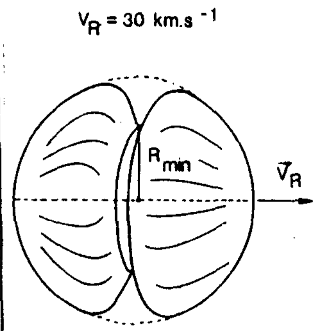

Fig.5

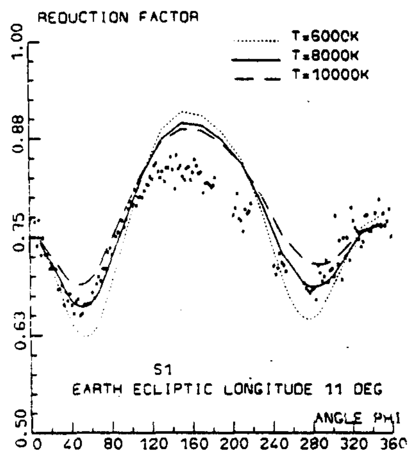

Fig.6

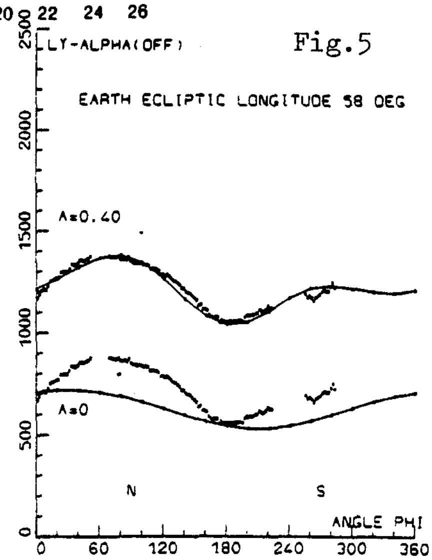

Fig.7

Figure 4. Determinations of V_o and T from photometric observations of the shape of the Helium focusing cone from various experiments. The spectrometric Lα observation of V_o by Copernicus was coupled to Helium observations by Mariner 10.

Figure 5. The pattern of the reduction factor R over the celestial sphere presents a "crunched-apple" shape. Along the plane perpendicular to the relative velocity vector $\vec{V}_R$, the reduction factor is at a constant minimum value R_{min}, linked to the temperature T. The width of the trough is linked both to T and the modulus V_R.

Figure 6. The distribution of the reduction factor R measured by PROGNOZ 6 in a plane perpendicular to the Earth Sun line is shown (data points) as a function of angle PHI with the Earth's velocity vector $-\vec{V}_E$ when the ecliptic longitude was 11°. Three curves are resulting from a model calculation at 3 different temperatures. The modulation of R is due to the variable Doppler shift. The fit with T = 8000 K is good everywhere except for 170 < PHI < 240, which corresponds to downwind region. Other parameters were fixed at μ = 0.75 and V_o = 20 km. s^{-1} (after Bertaux et al., 1984).

Figure 7. The Lα intensity distribution measured at an ecliptic longitude 58° (not far from the downwind axis) is compared to two models of the solar wind (solid lines). One is isotropic (A = 0) and the other (A = 0.40) corresponds to a decrease of 40 % of ionization rate at the solar pole (after Lallement et al., 1984). The intensity scale is in counts. s^{-1}. The lower curve has been displaced from the real curve by 500 counts. s^{-1}. The sensitivity is ≃ 3.6 counts per Rayleigh.

Up to now it was assumed that the only source of $L\alpha$ radiation is the interplanetary $L\alpha$ from the LISM. If there is a $L\alpha$ galactic background (which should be ≈ isotropic because of radiative transfer), Bertaux and Lallement (1984) have demonstrated that it is still possible to determine $\vec{V}_w$ with a purely geometric method (with three sets of observations at different places in the solar system). Once $\vec{V}_w$ is determined, the galactic $L\alpha$ contribution can be derived and also the temperature.

This DASS method was successfully applied by Lallement et al. (1984) to a series of measurements made with the H-cell $L\alpha$ photometer flown on Prognoz 5 and Prognoz 6, with the following results :

- an upper limit of 15 Rayleigh is found for the galactic background (whereas the interplanetary $L\alpha$ ranges from 200 to 1,000 Rayleigh).
- both the bulk velocity $\vec{V}$ and the thermal velocity spread of H atoms are changing with position in the solar system.

This was the first experimental evidence that the real situation departs from the uniform gaussian case. However, one can still define, for each direction of observation, an effective temperature T_e, because a projected velocity distribution can still be approximated by a gaussian. With the DASS method, the value R_{min} of the minimum reduction factor obtained in a plane of scanning allows to assign an effective temperature T_e for the direction where R_{min} is found, since the Doppler shift is known to be zero in this case.

Wu and Judge (1980) concluded that the first spectrometric temperature measurement of the VLISM (T = 8,800 ± 1 000 K), published by Bertaux et al. (1977) form an early use of the DASS method with Prognoz 5 results, had to be re-interpreted because of the velocity distribution perturbations by gravitation, radiation pressure and ionization, and that the VLISM temperature was in reality T = 7,000 K ± 1 000 K. In order to arrive at this result, they had to **assume** in their model a certain value of the solar parameters μ and β, whereas, if enough measurements of the H absorption cell can be obtained, they can be compared to the result of the interaction model with β and μ as free parameters. This was done by Bertaux et al. (1984) in their final analysis of the Prognoz results, which could extract from such a comparison the following set of both solar and VLISM parameters :

$\mu = 0.75 \pm 0.1$	Ecliptic Coordinates
$T = 8\,000 \pm 1\,000$ K	$\lambda_w = 254 \pm 3°$
$V_w = 20 \pm 1$ km s	$\beta_w = +6 \pm 3°$

In this global analysis, not only the values of R_{min} and the corresponding directions were used, but all measurements, many of them showing some absorption by the H cell.

The reduction factor measurements are compared for various models on Figure 6 from Bertaux et al. (1984). On each figure all parameters are fixed at their best final fit, except for T. Measured data were collected in scanning planes perpendicular to the Earth-Sun line at various places in the solar system, implying large differences for the relative vector $\vec{V}_R = \vec{V}_W + \vec{V}_E$, $\vec{V}_E$ being the Earth's orbital velocity. A visual estimate allowed to define the uncertainty bar for the various parameters. It can be noted that the fit is excellent for directions of sight probing upwind regions, but becomes poorer for downwind regions, corresponding to angle $120 < \phi < 240°$ for observations made when the Earth was on the right side of the wind flow (when $\vec{V}_E$ and $\vec{V}_W$ have opposite directions).

This is evidence that the observed heating effect is larger than predicted by DEGREE ONE approach. In particular, measurements toward the downwind region show still a significant absorption when the Doppler shift is large, which can be explained by a temperature of 20,000 K of the atomic hydrogen in the downwind region. This is probably the result of elastic collisions with the solar wind, as suggested by Lallement et al. (1984).

As Lallement and Bertaux (1984) pointed out, the ionization modifies substantially the line shape when the rate is changed from $\beta = 0$ to $\beta = 2.5 \times 10^{-7}\ s^{-1}$. Then, larger values (up to $10^{-6}\ s^{-1}$) do not modify substantially the line shape. Another effect is the convergence introduced by ionization.

In order to determine the ionization rate, the $L\alpha$ photometric results were used. The shape of the cavity, once T, V_W and μ are determined by the DASS H cell method, indicated that the ionization rate (during 1975-1976 period) was $\beta = 4 \times 10^{-7}\ s^{-1}$ in the equatorial plane, and decreasing with latitude up to a value $\beta = 2.4 \times 10^{-7}\ s^{-1}$ at the solar pole. This solar anisotropy is attributed to a 50 % decrease of the solar wind mass flux at high solar latitudes [Lallement et al., 1984], and is imposed by the photometric observations, as it is clear on Figure 7.

Once the ionization rate is known, formula (3) can be used to determine the neutral density "at infinity" $n_\infty(H)$ (when it is not perturbed by the heliosphere interaction). The coefficient γ contains an integral which takes into account all DEGREE ONE physical assumptions. Since the absolute value of μ is determined (by the bending of the H flow under gravitation/ radiation pressure), the solar flux F_S is determined. For the Prognoz photometer, a stellar observation of several hot stars allowed to derive in addition an estimate of the calibration factor a = 3.6 counts $.s^{-1}$ per Rayleigh, and the value of $n_\infty(H)$ could be deduced :

$$n_\infty(H) = 0.04 \text{ to } 0.06 \text{ atom.cm}^{-3},$$

the range allowing mainly for the uncertainty of the stellar calibration procedure.

HIGH RESOLUTION SPECTROMETRIC MEASUREMENTS OF HELIUM 58.4 NM LINE

The best results in this field were obtained with a helium absorption cell with a fixed value $\tau = 10^5$ during the Apollo Soyouz Test Project by Freeman et al. (1980). Their results are reproduced on Figure 8, where their measurements are compared with model calculations of the DEGREE ONE type. Though they clearly measured a substantial absorption, varying with the Doppler shift, their model calculations indicated an absorption very little sensitive to the temperature, and the comparison of the observed absorption to their model yielded a wide range of temperature from 5,000 to 20,000 K.

As discussed by Bertaux and Lallement (1984), this is mainly due to their choice of a large optical thickness $\tau = 10^5$. When the DASS method is used for $\tau = 10^5$, the absorption convolution profile ressembles very much the transmission curve $T(\lambda)$ of the helium cell, which is larger than the interplanetary He line. There are some experimental difficulties to use a low optical thickness within a Helium cell, because as it is a monoatomic gas, the corresponding pressure would be very small and quite difficult to measure and control. The use of a buffer gas is therefore recommended in such a case [Bertaux and Lallement, 1984] for a future space experiment.

The photometric measurements of the helium cone shape remain up to now the ones yielding the narrower temperature range of interstellar helium.

COMPARISON OF HYDROGEN AND HELIUM LISM PARAMETERS

The **direction** of the wind as determined from the helium cone or from H cell analysis are identical, within the $\pm$ 3° error boxes. At variance, there is a major discrepancy between Hydrogen and Helium for the module velocity V_w and the temperature T :

	Hydrogen	Helium
T (°K)	8,000 $\pm$ 500	16,000 $\pm$ 5,000
V_w (km. s^{-1})	20 $\pm$ 1 km.s^{-1}	27 $\pm$ 3
density $n_\infty(cm^{-3})$	4 to 6 $\times 10^{-2}$	1.5 to 2 $\times 10^{-2}$

It is quite difficult to admit that the temperature difference is intrinsic to the VLISM, since the local mean free path of atoms between collisions is 0.04 pc only. Collisions would also tend to equalize the velocity modulus.

In order to have the same direction of $\vec{V}_w$ but different velocity modulus it would require an extraordinary coïncidence, as pointed out by Lallement (1983). As explained on Figure 9, the velocity $\vec{V}_w$ of the solar

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system in respect to the VLISM is the composition of the solar motion $\vec{V}_a$ toward the Apex ($\alpha = 271°$, $\delta = 30°$) and the motion of the VLISM respective to the nearby stars forming the local frame of reference, the interstellar wind $\vec{V}_t = \vec{V}_a - \vec{V}_w$.

Applying this relationship for H and He separately and subtracting will yield :

$$\vec{V}_t\,(\mathrm{He}) - \vec{V}_t\,(\mathrm{H}) = \vec{V}_w\,(\mathrm{H}) - \vec{V}_w\,(\mathrm{He})$$

The difference of intrinsic velocity vector is parallel to $\vec{V}_w\,(\mathrm{H}) - \vec{V}_w\,(\mathrm{He})$, which is parallel to both V_w (H) and V_w (He), which are found to be in the same direction. But this direction is imposed by the solar vector $\vec{V}_a$, a random vector which is completely independent from the intrinsic difference between H and He interstellar flow.

Therefore, it is likely that the difference of modulus is an artefact of our diagnostic methods. Since high resolution spectrometric measurements are quite sensitive to the Doppler shift, I believe that the hydrogen determination is more accurate for the modulus than the photometric determination of the helium velocity.

Returning to Figure 4 representing the (V_w, T) parameters giving a good fit to the helium cone shape, it was remarked a certain coupling between V_w and T. If a lower velocity $V_w = 20$ km. s^{-1} was imposed, perhaps a lower temperature for helium would also result in the fitting process, which would alleviate somewhat the H-He temperature discrepancy too.

The celestial and **galactic** coordinates of the intrinsic interstellar wind $\vec{V}_t$ can be computed. Assuming the hydrogen determination to be correct, the motion of the VLISM in respect to the local standard frame of reference (LSR) is characterized by a velocity $\vec{V}_t$ of 16 ± 1 km. s^{-1}, which direction coordinates are :

Celestial	Galactic
$\alpha = 14 \pm 3°$	$\ell_{II} = 124 \pm 3°$
$\delta = 66.5 \pm 3°$	$b_{II} = 4 \pm 3°$

The ratio of neutral densities $n_\infty\,(\mathrm{H}) / n_\infty\,(\mathrm{He})$ is $\simeq 3$, whereas one would expect a cosmological ratio 10. This is easily explained by a substantial ionization of the VLISM. If x is the fraction of ionized hydrogen, (we drop ∞ in the following)

$$x = n\,(\mathrm{H}^+) / (n\,(\mathrm{H}) + n\,(\mathrm{H}^+)) = 1 - n\,(\mathrm{H}) / 10\,n\,(\mathrm{He})$$

it indicates that $f \simeq 0.7$ in the VLISM, the total density being $n\,(\mathrm{H}^+) + n\,(\mathrm{H}) + n\,(\mathrm{He}) = 0.11$ cm^3.

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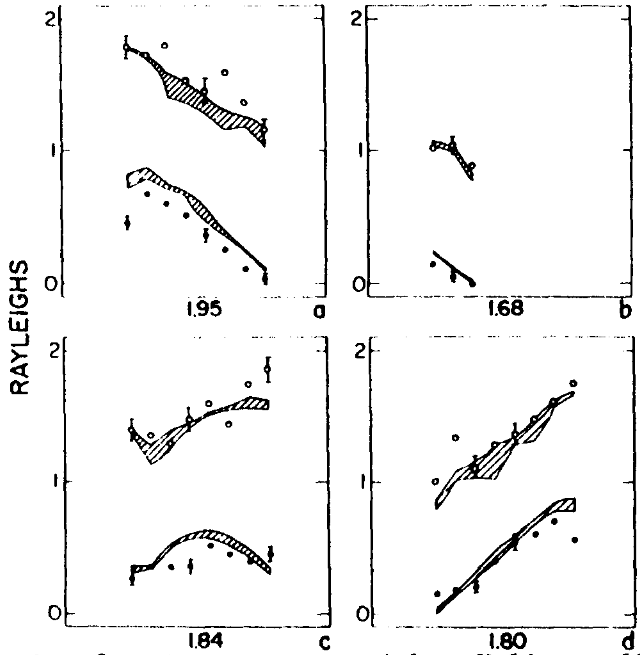

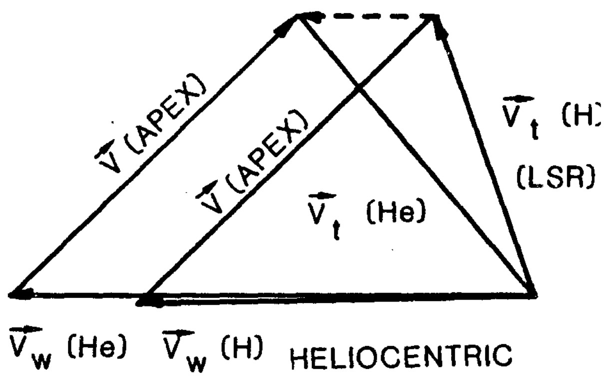

Fig.9 In the solar system, the vectors V_w (H) and V_w (He) have the same direction, but seems to have different modulus. Therefore, the difference $\vec{V}_w$ (H) - $\vec{V}_w$ (He), which is independant of the coordinates system, is parallel to V_w (H), which includes the particular motion of the Sun. This suggests an artefact in the determination of the modulus of V_w (He).

Fig. 8. Measurements with a Helium cell photometer on ASTP mission are compared with models. Open circle are with the cell empty. Black circle are with the cell filled with an optical thickness $\tau = 10^5$. The absorption of the cell is quite efficient and depends on the direction of sight because of variable Doppler shift (after Freeman et al., 1980). However, model predictions for a wide range of temperatures show little dependance on the temperature, because the optical thickness was too high.

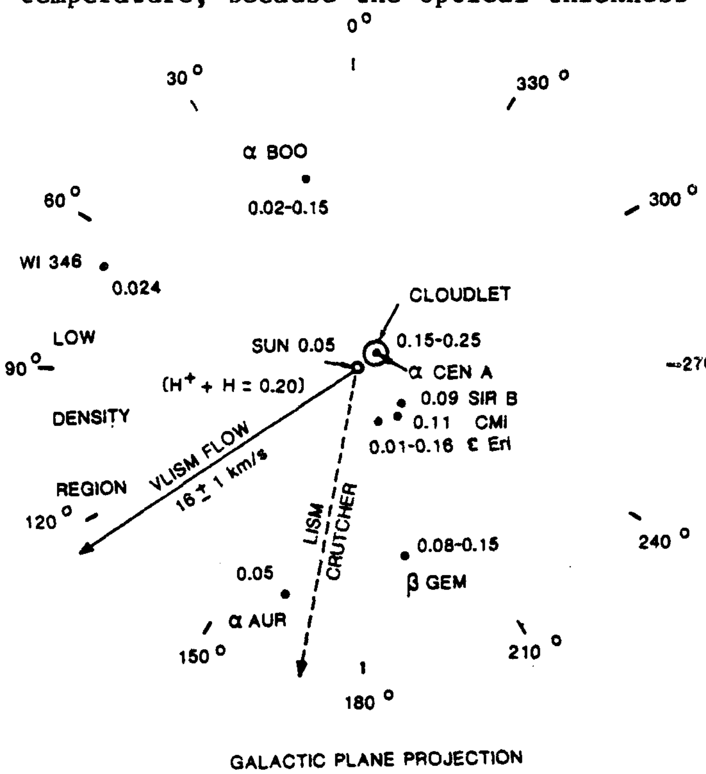

Figure 10 Some nearby stars (projected on the ecliptic plane) are shown, together with the average H density. A possible cloudlet of enhanced density is drawn around α Cen, toward the region of highest density. The VLISM vector, at ℓ_{II} = 124°, is exactly opposite to the direction of α Cen , and is significantly different from the LISM vector, as determined by Crutcher (1982) for interstellar absorption within ≈ 100 pc.

Of course, neither H^+ nor He^+ are accessible to studies in the solar system, since they are prevented to enter through the heliosphere.

We will discuss these VLISM results in the next concluding section, in the frame of the other LISM studies.

CONCLUSIONS

The study of H and He back-scattered resonance emissions in the solar system provides information on three different topics, which are of interest to three different scientific communities :

- The very local characteristics of the LISM.
- The interaction processes between the solar environment and the interstellar medium in which it is embedded, which is of broader interest than just solar system studies, since similar interactions can be encountered in other astrophysical conditions (i.e., Stellar wind expansions).
- Some basic solar parameters concerning the solar wind and the $L\alpha$ output at line center.

1. Solar parameters

The bending of the H atoms trajectories is determined with **relative** measurements with the H cell. It needs no calibrated instrument, and still yield a quite important **absolute** value of a solar parameter : with $\mu = 0.755 \pm 0.11$, the solar $L\alpha$ flux at line center is :

$$F_S = 2.5 \pm 0.25 \times 10^{11} \text{ phot } (\text{cm}^2 \text{ Å s})^{-1}$$

This value is an average over a $\simeq$ one year period (the typical time for one H atom to travel through the solar system), and holds for a period of minimum solar activity (1975-1976).

The decrease of H density along the VLISM flow, which can be measured with an uncalibrated $L\alpha$ photometer, allows to measure the **absolute** value of the ionization rate β. With weakly demanding physical assumptions,this ionization rate can be transformed into an **absolute** determination of the solar wind mass flux **at all latitudes** by remote sensing. The solar wind flux of protons F_p, averaged over one year, and for the 1975-1976 period (minimum solar activity), is :
$F_p = 1.87 \times 10^8$ protons $\text{cm}^{-2}\text{ s}^{-1}$ in the equatorial plane and a strong anisotropy is found, with a 30 % decrease toward the solar poles. Large scale properties of the solar wind flux, averaged over $\simeq$ one year, can be monitored through Lyman-alpha mapping. A correct interpretation of the results needs, however, the accurate knowledge of $\vec{V}_w$ and T which is now in our hands. In a near future, the study of other data (VOYAGER) will allow to check if this anisotropy persists during a maximum of solar activity.

2. Interaction processes

The DEGREE ONE physical assumptions are clearly verified in the data. however, the H cell spectral data on the H velocity distribution, together with the photometric mapping of the helium cone give slightly inconsistant VLISM results. It seems more and more obvious that some interaction between the sun and the neutral gas, not included in the DEGREE ONE approach, is of importance to describe completely the data and reconcile H and He results.

Mainly two kind of effects have been considered by various authors.

One is located at the boundary of the heliosphere (at several hundreds AU), where the solar wind plasma and the VLISM neutral-ionized matter are interacting. As a possible consequence, Ripken and Fahr (1983) predict a decrease of density of H by a factor of $\simeq 2$.

The second kind includes elastic collisions with the solar wind plasma. One difficulty is that these effects, if they are of importance, would have a tendency to heat more hydrogen atoms than helium atoms, whereas what is observed is that T (He) > T (H).

However, PROGNOZ observations toward the downwind region do indicate very hot hydrogen ($\simeq$ 20 000 K), **after** interaction with the solar environment. Together with the helium cone shape, both discrepancies are found in the downwind region, which is in my opinion a strong indication that deviations to the DEGREE ONE approach are more related to an interaction near the sun (i.e., elastic collisions with solar wind ions) than at the large distance of the heliosphere boundary.

3. The VLISM parameters

In the ISM description of Mc Kee and Ostriker (1977) small clouds of dense and cold neutral H (T = 80 K, n = 42 cm^{-3}) are embedded in a hot (10^5 - 10^6 K) low density (10^{-2} cm^{-3}) and totally ionized medium.

According to this model, there is an intermediate phase of the ISM at the interface between the cold and hot phase, composed of two distincts parts, both at 8,000 K (warm). The one on the side of the dense cloud is only weakly ionized (x = 0.15), and the one on the side of the hot ISM is substantially ionized, with x = 0.68, and a total number density of n = 0.25 cm^{-3} .

Though there is some discussion about the number of such cloudlets in the LISM (within $\simeq$ 100 pc) [Bruhweiler and Kondo, 1982], the characteristics found for the VLISM : T = 8,000 $\pm$ 1000 K, n = 0.11 cm^{-3} and x = 0.70 are strikingly reminiscent of the ionized part of this last interface phase as described by Mc Kee and Ostriker.

Therefore, it would mean that the Sun is presently within ≃ 2 pc from a dense cloud. The possibility that such a cloud is moving rapidly in our direction was discussed by Vidal-Madjar et al. (1978), on the ground of Copernicus LISM soundings, D/H distributions and EUV anisotropic radiation pattern. The estimated distance of the dense cloud was 0.03 pc, however, which seems uncompatible with the ≃ 1 pc thickness of the weakly ionized medium immediately surrounding the cold cloud in the description of Mc Kee and Ostriker (1977), and the strongly ionized medium in which the Sun is moving presently.

Figure 10 is an attempt to compare the characteristics of the VLISM, namely the density and the direction of the VLISM flow, with LISM densities measured on a few nearby stars, either with **Copernicus** or with IUE taken from Vidal-Madjar et al. (1977), and Bruhweiler and Kondo (1982).

If there is a dense cloudlet in the vicinity of the Sun, then it could very well be toward α CEN A, which is the nearest star (1.33 pc) and shows the largest averaged H neutral density of 0.20 ± 0.05 cm^{-3} [Dupree et al., 1977]. This neutral density is larger than the VLISM by a factor of ≃ 4, but is not very different from the total VLISM density (0.22 cm^{-3}).

One striking feature in that the VLISM flow is exactly opposite to the direction of this enhanced density, and is suggestive of an evaporation mechanism from the cold and dense cloudlet toward the hot and tenuous ISM. It should have therefore a quite local significance. However, accurate positionning of optical absorption lines on a number of stars in a range of 100 pc [Crutcher, 1982] shows a coherently moving piece of ISM of this scale around Sun. Suggesting that the ≃ 100 pc ISM around the Sun could be material which has been shocked and accelerated by stellar winds and supernovae associated with the Scorpio-Ophiucus OB stars, which lies approximately at the opposite of the VLISM flow. But, as indicated on Figure 10, the VLISM flow is near the galactic plane, at longitude $\ell_{II} = 124°$, whereas the Crutcher's vector (in respect to LSR) lies at $\ell_{II} = 169°$. This ≃ 45° difference points again to a local significance for the VLISM flow. In this respect, the recent detection of a dust cloud in the far infra-red around $\ell_{II} \simeq 315°$, extended over several tens of degrees [Caux et al., 1984], may confirm the proximity of a moderately dense cloud in the near vicinity of the solar system.

REFERENCES

ADAMS T.F., FRISCH P.C., 1977 - Astrophys. J., 212, 300.
BERTAUX J.L., BLAMONT J.E., 1971 - Astron. Astrophys., 11, 200.
BERTAUX J.L., BLAMONT J.E., TABARIE N., KURT V.G., BOURGIN M.C., SMIRNOV A.S., DEMENTEVA N.N., 1976 - Astron. Astrophys., 46, 19-29.
BERTAUX J.L., BLAMONT J.E., MIRONOVA E.N., KURT V.G., BOURGIN M.C., 1977 - Nature, 270, 156.
BERTAUX J.L., LALLEMENT R., 1984 - Astron. Astrophys., in press.
BERTAUX J.L., LALLEMENT R., KURT V.G., MIRONOVA E.N., 1984 - Astron. Astrophys., Submitted.

BLUM P.W., FAHR M.J., 1970 - Astron. Astrophys., 4, 280.
BRUHWEILER F.C., KONDO Y., 1982 - Astrophys. J., 259, 232.
CRUTCHER R.M., 1982 - Astrophys. J., 254, 82.
DALAUDIER F., BERTAUX J.L., KURT V.G., MIRONOVA E.N., 1984 - Astron. Astrophys., 134, 171-184.
CAUX et al., 1984 - Submitted to Astron. Astrophys.
FREEMAN J., PARESCE F., BOWYER S., LAMPTON L., 1980 - Astron. Astrophys., 83, 58-64.
HOLZER T.E., 1977 - Rev. Geophys. Space Phys., 15, 467.
KUNC J.A., WU F.M., JUDGE D.L., 1983 - Planet. Space Sci., 31, 1157.
LALLEMENT R., BERTAUX J.L., KURT V.G., MIRONOVA N.N., 1984 - Astron. Astrophys., In press.
LALLEMENT R., 1983 - Thèse de 3ème Cycle, Université P. et M. Curie.
LALLEMENT R., BERTAUX J.L., 1984 - Astron. Astrophys., Submitted.
MEIER R.R., 1977 - Astron. Astrophys., 55, 211.
McKEE C.F., OSTRIKER J.P., 1977 - Astrophys. J., 218, 148.
RIPKEN H.W., FAHR H.J., 1983 - Astron. Astrophys., 122, 181-192.
THOMAS G.E., KRASSA R.F., 1971 - Astron. Astrophys., 11, 218.
VIDAL-MADJAR A., LAURENT C., BRUSTON P., AUDOUZE J., 1978 - Astrophys. J., 223, 589.
WALLIS M.K. and WALLIS J., 1979 - Astron. Astrophys., 78, 41-45.
WELLER C.S., MEIER R.R., 1974 - Astrophys. J., 193, 471.
WELLER C.S., MEIER R.R., 1981 - Astrophys. J., 246, 386.
WU F.M., JUDGE D.L., 1978 - Astrophys. J., 225, 1045.
WU F.M., JUDGE D.L., 1979 - Astrophys. J., 231, 594-605.
WU F.M., JUDGE D.L., 1980 - Astrophys. J., 239, 389.