THEORY OF INTERSTELLAR MEDIUM DIAGNOSTICS

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Abstract. The theoretical interpretation of observed interplanetary resonance luminescence patterns is used as one of the most promising methods to determine the state of the local interstellar medium (LISM). However, up to now these methods have led to discrepant results that would be hard to understand in the framework of any physical LISM scenario. Assuming that the observational data are reliable, two possibilities which could help to resolve these discrepancies are discussed: a) The current modeling of resonance luminescence patterns is unsatisfactory and has to be improved, and b) the extrapolated interstellar parameters are not indicative of the unperturbed LISM state, but rather designate an intermediate state attained in the outer regions of the solar system. It is shown here that a quantitative treatment of the neutral gas - plasma interaction effects in the interface between the heliospheric and the interstellar plasmas is of major importance for the correct understanding of the whole complex.

ACCESS TO THE PARAMETERS OF THE INTERSTELLAR MEDIUM

According to a huge amount of observational material the interstellar medium is now considered to be highly structured into dense and dilute gas phases. Following theoretical models by McKee and Ostriker (1977) and McGray and Snow (1979) the bulk of the interstellar matter is concentrated in dense and cool clouds with densities $n \gtrsim 10^2\ cm^{-3}$ and temperatures $T \lesssim 10^2$ K, whereas the bulk of the interstellar space is filled with a very dilute and ionized interstellar medium of densities $n \simeq 10^{-2}\ cm^{-3}$ and temperatures $T \simeq 10^5$ K. The idea of McKee and Ostriker is that at the occurrence of supernova events, fast MHD shockfronts are emitted from the center of these events and partly evaporate the peripheral cloud material when passing over the dense clouds distributed in space. New intermediate gas phases are thus created, mainly under conditions of pressure equilibrium with the outer hot ionized medium (HIM). Two different phases are predicted to exist in the periphery of the CNM clouds (cool neutral medium): the WNM phase (warm neutral medium) which directly surrounds the CNM phase and which has densities of $n \simeq 0.3\ cm^{-3}$, temperatures of $T \simeq 8\ 10^3$ K, and an ionization degree of 15 percent, and a WIM phase (warm ionized medium) further away from the cloud with densities of $n \simeq 0.2\ cm^{-3}$, temperatures of $T = 8 \cdot 10^3$ to 10^4 K, and an ionization degree of 70 percent.

The question then arises as to which of these phases our local interstellar medium (LISM) belongs. To answer this question specific data relevant to LISM are needed. As it turns out, most of the observational methods appropriate for the analysis of the interstellar medium average over very large astronomical distances and therefore conceal the information on the LISM properties. Essentially three methods can give more specific local information on the LISM. The analysis of Lyman-alpha absorption contours in the continuum spectra of bright O- and B-stars can yield information on the average hydrogen density within the 10 to 70 pc environment of the sun. Average values of $n \simeq 10^{-2}$ cm^{-3} have been obtained here (Frisch, 1981 and references therein; Bohlin, 1975; Bohlin et al., 1978; Vidal-Madjar, 1978; Anderson and Weiler, 1978).

Access to even more local structures of the LISM is possible from interpretations of self-inversion structures in the contours of Lyman-alpha emission lines originating from relatively cool stars of the solar type. With this method the LISM is analyzed over distances of 1.3 to 5 pc. In these distance ranges average hydrogen density values of $n_H \simeq 10^{-1}$ cm^{-3} have been found (Moos et al., 1974, Evans et al., 1975, Dupree, 1975, McClintock et al., 1976).

This shows clearly that over distances of about 10 pc the LISM properties of our solar environment are subject to substantial changes, and thus the thermodynamic parameters of the LISM at the immediate periphery of our solar system can only be extracted from even "more local" observational methods. The most local information on the LISM available up to now is derived from theoretical modeling of interplanetary resonance luminescences originating from neutral interstellar hydrogen and helium that have propagated from the outside of the solar system into its inner regions (i.e. solar distances smaller than 5 AU). The principles of this method will be briefly reviewed here.

THEORY OF INTERPLANETARY RESONANCE RADIATION

Unlike the ionized component of the LISM, the neutral component, which consists essentially of H and He atoms, can traverse the outer regions of the plasma interface between the solar wind and the LISM plasma and thus reach the inner solar system. The motion of the atoms is characterized here by Keplerian orbits in the solar gravitational field which is partly compensated by solar radiation pressure (Fahr, 1968; Blum and Fahr, 1970; Axford, 1972; see also later reviews on this topic by Fahr, 1974; Thomas, 1978; Holzer, 1977). While moving along specific Keplerian trajectories the neutrals are subject to loss processes due to ionization by solar EUV photons, due to charge-exchange processes with solar wind ion species and due to electron impact ionization. (For specifics see reviews by Grzedzielski, 1982; Paresce, 1982.)

The change of the velocity distribution function $f(\vec{R},\vec{v})$ of the LISM neutrals during their approach towards the inner solar system is adequately described by Boltzmann differential equations that take into account only particle loss processes. The solution of these equations can be formally written down in the following simple form (Fahr, 1978, 1979):

$$f(\vec{R},\vec{v}) = f_o(\vec{v}_o)\, Ex(\vec{R},\vec{v}_o) \quad , \tag{1}$$

where $\vec{v}$ designates the particle velocity vector at a position $\vec{R}$ within the solar system and $\vec{v}_o$ is the velocity vector outside the solar system that is connected with the dynamical variables $\{\vec{v},\vec{R}\}$ by the particle trajectory. The vector $\vec{v}_o$ is distributed according to the velocity distribution function $f_o(\vec{v}_o)$ valid for the unperturbed state of the LISM and yielding, as its moments, the density n_o, the temperature T_o, the bulk velocity $\vec{V}_o$, the pressure tensor $\vec{P}_o$, and the heat conduction flow $\vec{Q}_o$.

The function $Ex(\vec{R},\vec{v}_o)$ calculates the integral loss probability for particles moving along a specific trajectory $\{\vec{R},\vec{v}\}$ from outside the solar system to point $\vec{R}$. This function is given by:

$$Ex(\vec{R},\vec{v}_o) = \exp\left[-\int_{\infty}^{s(R)} L(s')\frac{ds'}{v(s')}\right], \tag{2}$$

where L is the local particle loss rate, and where the line integration has to be carried out along the dynamical trajectory from very large solar distances to point $\vec{R}$. The integration variable is the line element s' on this trajectory. Evaluations of the integral in Eq. (2) for different cases can be found in Blum and Fahr (1970), Axford (1972), Holzer (1977), and Fahr (1978).

The moments $<\phi(R)>$ of the local distribution function can be obtained with Eqs. (1) and (2) in the form

$$<\phi(R)> = \int^3 f_o(\vec{v}_o)Ex(\vec{R},\vec{v}_o)\,\phi(\vec{v})d^3\vec{v} \tag{3}$$

which with the use of Liouville's theorem

$$\left|\frac{d^3\vec{v}}{d^3\vec{v}_o}\right|_{\vec{R}} = \left|J(\vec{v},\vec{v}_o\vec{R})\right| = \beta\,(\vec{v},\vec{v}_o,\vec{R}) \tag{4}$$

can be evaluated in a straightforward manner. Here J is the Jacobian of the transformation $\vec{v}_o\rightarrow\vec{v}$, and β is the focusing factor for particles with $(\vec{v}+d^3\vec{v})$ at $\vec{R}$ originating from particles with $(\vec{v}_o + d^3\vec{v}_o)$ at some distant position $\vec{R}$.

On the basis of the knowledge of f_o one is then able to calculate the resonance luminescence intensity as seen by a detector at $\vec{R}_{ob}$ in a direction $\vec{D}$ by using the expression

$$I_{res}(\vec{R}_{ob},\vec{D}) = G\int_o^{\infty} dz \int_o^{\gamma}\sin\gamma d\gamma \int_o^{2\pi} d\psi P(\theta)\int^3 F_{sol}(\nu')\left[{}^{R_E}/_R\right]^2 s_{res}(\nu')f\left(\vec{v},\vec{R}(z)\right)d^3\vec{v} \quad , \tag{5}$$

where G contains instrumental constants, F_{sol} is the solar EUV radiation intensity at R_E=1 AU, s_{res} is the resonant absorption cross section and $P(\theta)$ is the phase function giving the probability for a scattering process with an angle θ between $\vec{R}$ and $(\vec{R}_{ob}-\vec{R})$. At place $\vec{R}$, the frequency ν' is a specific function of the velocity $\vec{v}$ of the absorbing atom. The integration at a position $\vec{R}$ has to be carried out over all velocities and then also over the threedimensional source field within the angle of acceptance of the instrument with polar coordinates z, γ, and ψ.

As is evident from Eqs. (1) through (5), a theoretical representation of interplanetary resonance luminescence intensities requires the knowledge of the distribution function $f_o(\vec{v}_o)$ of the unperturbed interstellar neutrals. However, since the velocity moments $<\phi_o>$ of f_o are the unknown quantities which need to be determined as accurately as possible, one has to initiate a theoretical best-fit procedure of available luminescence data in order to arrive at reasonable values for the moments $<\phi_o>$, i.e. the LISM parameters. In this way, the function f_o is approximated as a shifted Maxwellian yielding the relevant LISM parameters.

DISCUSSION OF CURRENT MODELING TECHNIQUES

In the past, a large amount of Lyman-alpha and He-I (58.4 nm) interplanetary luminescence data was subject to the best-fit procedures mentioned above and was used to yield values for the desired LISM parameters (see for instance Morton and Purcell, 1962; Fahr, 1970; Thomas and Krassa, 1971; Bertaux and Blamont, 1971; Bertaux et al., 1972; Weller and Meier, 1974; Bertaux et al., 1977; Freeman et al., 1977; Fahr et al., 1978; Broadfoot and Kumar, 1978; Ajello, 1978; Ajello et al., 1979; Babichenko et al., 1971; Wu et al., 1981).

Looking over all these attempts to derive LISM parameters, one sees that the puzzling facts are not so much the relatively small differences in the values derived by different authors but rather the values themselves that are hard to understand in the framework of one single common physical LISM scenario.

For instance, at a recent workshop on these problems (Keller et al., 1978) the scientific community engaged in this field raised the following surprising points in the analysis of resonance luminescence data:

1) The LISM helium temperature $T_o(He)$ is found to be definitely higher than the corresponding hydrogen temperature $T_o(H)$. An average temperature excess of about $\Delta T_o = T_o(He) - T_o(H) \simeq 2000\ {}^oK$ is indicated. The problem: two different temperatures for neutral constituents belonging to the same physical environment are difficult to understand.
2) It is found that even in view of data-inherent uncertainties the helium-hydrogen density ratio seems fairly high when compared to the expected cosmic abundance ratio. The problem: the cosmic value of the helium-hydrogen abundance ratio could be conserved only if hydrogen is ionized by at least 50 percent.
3) The wind vectors $\vec{V}_o(He)$ and $\vec{V}_o(H)$ characterizing the directions from which the LISM helium and hydrogen are approaching the sun at least as derived from some observations are found to be inclined to each other by an angle of about 15^o. The problem: truly different bulk velocities of the two LISM constituents are difficult to understand.

Therefore the question is raised whether or not these surprising results concerning the LISM state are due to unsatisfactory modeling of the interplanetary luminescence radiation field. In view of the theoretical approach that is carried out according to the conventional formalism described by Eqs. (1) through (5), the following shortcomings could be made responsible for a failure of the modeling:

a) Generally, the theories are based on the assumption of a radial symmetry of the ionizing solar radiation fields, and the solar wind affecting the neutrals by charge-exchange reactions is also represented in a radial symmetry, though both the solar radiation field and the solar wind expansion are known to have pronounced asymmetries. Only a few attempts have been made to take account of these asymmetries (Blum and Fahr, 1970; Joselyn and Holzer, 1975, Witt, 1979; Witt, Ajello and Blum, 1981).
b) The loss rates taken into account are represented by simple $1/r^2$ dependencies (r = solar distance). Though this enables one to drastically simplify

the integral in the extinction function (2), it may well give rise to incorrect modeling due to a nonspherical divergence of the solar wind flow and due to electron impact ionization rates that are connected with solar wind electron temperatures. Attempts have been made by Petelski et al. (1980) and Ripken and Fahr (1981) to incorporate these effects.

c) Up to now the radiation field has been described on the basis of single scattering processes only. However, it has been discussed (Keller and Thomas, 1979; Keller et al., 1981) that at least at large distances multiple scattering effects might have some importance for the radiation intensity distribution.

d) Furthermore, it has also been pointed out by Wu and Judge (1979) that the exciting solar line profile changes with solar distance due to absorptions in interplanetary space. This could be important, especially for the calculation of the source functions at large solar distances.

e) The effect of the secondary hydrogen component on the interplanetary Lyman-alpha isophotes has never been adquately taken into account. Though this component arises from charge-exchange reactions of primary hydrogen with protons in the heliospheric plasma interface, i.e. at relatively large distances, it could nevertheless be of importance, especially for the hydrogen distribution in the downwind wake.

f) The galactic background radiation in the EUV/UV has not been taken into account properly. This is necessary in order to be able to derive more reliable information on the LISM properties.

In view of the list above, the question to answer then is whether or not the incorporation of all improvements a) through f) into the theory of the resonance radiation field could help to substantially resolve the conflicts in the results of the data analysis.

In our opinion the inclusion of effects c) through f), rather than lessening the problems, would tend to even increase them. For instance, the hydrogen temperature $T_o(H)$ is most effectively deduced from downwind Lyman-alpha resonance intensities. However, these would clearly be increased by effects c), e), and f) and thus would lead to an even lower value for the LISM hydrogen temperature than which is derived by current modeling from the data. In addition, if c), e), and f) would turn out to contribute anything at all to the single scattering radiation field, it would mean that an even lower hydrogen density $n_o(H)$ would be derived from the data.

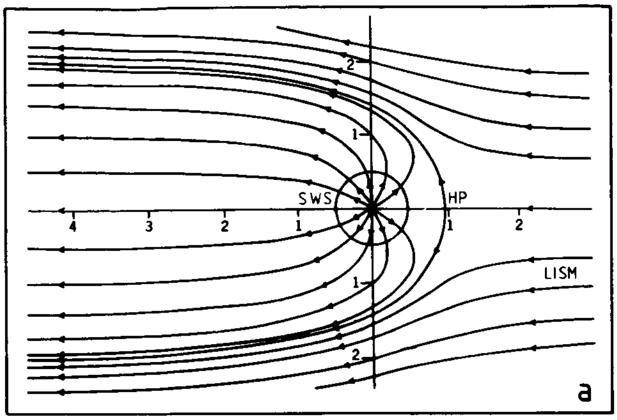
In our estimation, the only way out of this unsatisfactory situation if the data can be taken as reliable is to realize that the LISM parameters deduced on the basis of the above-mentioned theory represent intermediate values that are characteristic for the state of LISM neutrals in upwind regions of the solar system at distances between 50 and 100 AU. The change from the unperturbed LISM state to this intermediate one is then caused by modifications of the neutral interstellar gases during their traversal of the upwind heliospheric plasma interface. A quantitative description of this effect was recently given by Fahr and Ripken (1982) and Ripken and Fahr (1983). These papers may be consulted for details. Here we will only give a broad outline of the basic ideas.

The LISM plasma and the solar wind plasma interact in a magnetohydrodynamic way and form a contact discontinuity, the heliopause, separating the two plasma flows from one another. In the transheliopause region the state parameters of the LISM plasma and the LISM neutrals are decoupled from each other. The neutrals moving through this interface region are thus subject to non-vanishing production and loss terms due to charge-exchange reactions with the protons. A consequence of these charge-exchange reactions is a change of the velocity distribution function $f(\vec{R},\vec{v})$ of the neutrals. Due to the large H-p charge-exchange cross section, the LISM hydrogen atoms are strongly affected by these processes, whereas the LISM helium atoms, due to the relatively small He-p charge-exchange cross section, only undergo modifications of a negligible magnitude. The change of the hydrogen distribution function $f_H(\vec{R},\vec{v})$ is described adequately by the Boltzmann equation, which for the stationary case can be written in the following form:

$$\frac{d\, f_H(\vec{R},\vec{v})}{ds} = \frac{1}{v}\left[P_+(f_H,f_p) - f_H\, \bar{\nu}_-(f_p) \right]_{\vec{v}} \tag{6}$$

where ds is the differential line element on a trajectory of an atom moving with a velocity $\vec{v}$ at $\vec{R}$. The terms P_+ and $\bar{\nu}_-$ are the total production rate of atoms with velocity $\vec{v}$ at $\vec{R}$ and the average destruction frequency for such atoms. Both terms are functions of $\vec{v}$ and can be evaluated only with the knowledge of the proton velocity distribution function $f_p(\vec{R},\vec{v})$.

For the calculation of the distribution function $f_H(\vec{R},\vec{v})$ at some place $\vec{R}$ within the inner solar system all hydrogen atom trajectories reaching this point and originating in the unperturbed LISM have to be used. The integration along these trajectories starting from Eq. (6) will then yield a value for $f_H(\vec{R},\vec{v})$ at $\vec{R}$ for exactly those atoms which have a velocity $\vec{v}$. For these integrations it has to be assumed that at each place in the plasma interface the proton distribution function $f_p(\vec{R},\vec{v})$ is known. In the case of calculations carried out by Ripken and Fahr (1983) this knowledge is taken from theoretical models of the plasma interface by Parker (1963) and Baranov et al. (1976). Alternative forms of such interface models are shown in Figs. 1a and b. In Fig. 2 we show a solution for the first moment of f_H, i.e. the hydrogen density n(H), as a function of the solar distance on the upwind symmetry axis. The two solid curves show the decrease of the hydrogen density with decreasing solar distance for the interface models according to (A) Parker (1963) and (B) Baranov et al. (1979). To facilitate comparison, the unperturbed LISM proton $n_o(P)$ have been adopted to the case of a more realistic value $n_o(P) = 0.0135\ cm^{-3}$ and a subsonic interstellar wind model. In any case, however, the solutions given in this figure demonstrate that a decrease of the hydrogen density by at least a factor of 0.5 from the unperturbed value $n_o(H)$ to some intermediate value at about 50 AU is indicated. This means that due to the modification of the LISM hydrogen in the interface the hydrogen density value obtained from conventional Lyman-alpha resonance isophote interpretations has to be raised by a factor of about 2 in order to yield $n_o(H) \simeq 0.1\ cm^{-3}$. In contrast, the helium density value that was obtained earlier can be considered as being directly indicative for the unperturbed LISM helium density $n_o(He)$ due to the



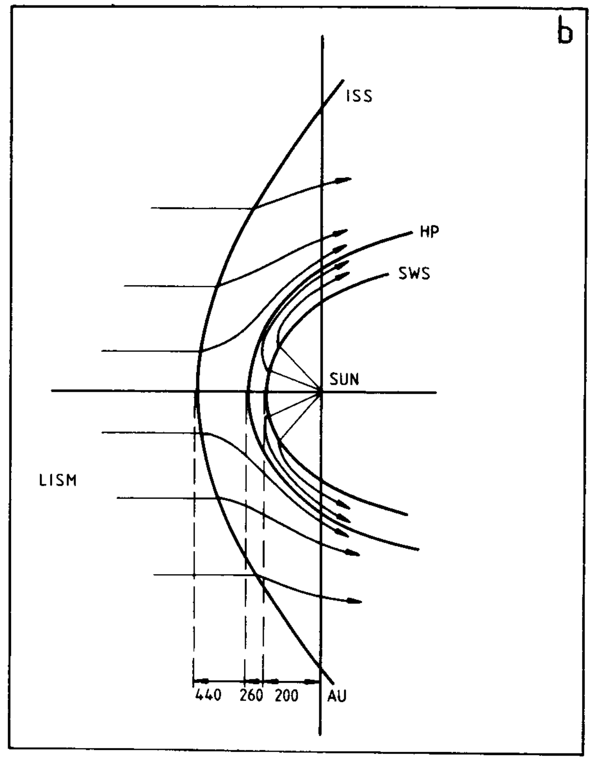


Fig. 1: Shown are theoretical models for the heliospheric plasma interface. a) Solar wind interacting with an incompressible subsonic LISM plasma flow, according to Parker (1963). b) Solar wind plasma interacting with an unmagnetized supersonic LISM plasma flow with double-shock structure according to Baranov et al. (1976).

absence of interface-induced modifications for this type of atom. These results now lead to a revised helium-to-hydrogen density ratio of $n_o(He)/n_o(H) = 0.1$ which now is very close to the cosmic abundance value.

Other results concerning interface-induced modifications of the higher moments of f_H are presented in Ripken and Fahr (1983) and are not discussed here. As a final point we want to mention that formerly neglected reactions of the LISM neutrals onto the LISM protons have been discussed by Baranov et al. (1981) and Gruntman (1982). The former authors treat a supersonic flow of the LISM plasma towards the solar system and show that the influence of LISM neutrals on this plasma flow is reflected in a reduction of the heliocentric distance of the outer LISM shockfront. An interesting additional point is raised by Gruntman (1982) who points out the possibility that an originally supersonic LISM plasma flow might be converted into a subsonic flow. This would occur due to secondary hydrogen atoms which originate from the supersonic solar wind region and react with the counter-streaming LISM plasma in the upwind portion of the heliosphere. In conclusion we would like to state that both theoretical models and experimental results need to be improved in order to refine our understanding of the local interstellar gas.

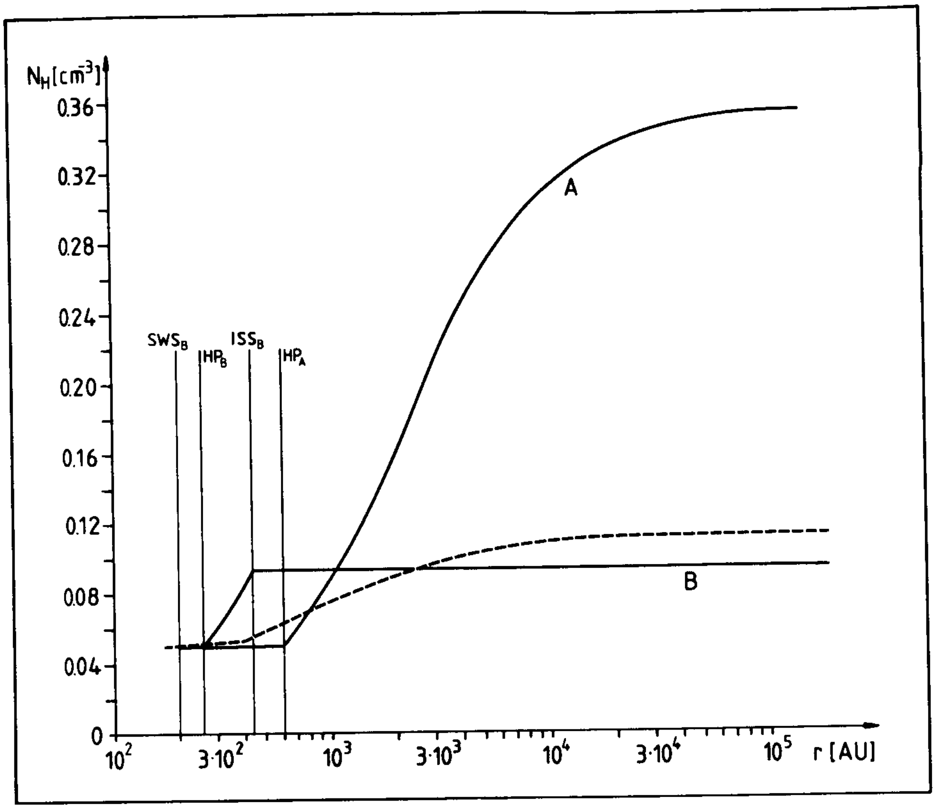


Fig. 2: Variation of the LISM hydrogen density with decreasing solar distance on the stagnation line. A: Subsonic interface model according to Parker (1963) for $n_o(P) = 0.024\ cm^{-3}$. B: Supersonic interface according to Baranov et al. (1976) for identical proton density $n_o(P)$. The dashed line shows the result for a subsonic interface according to Parker, but for a more realistic proton density of $n_o(P)=0.0135\ cm^{-3}$.

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