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ROSINE LALLEMENT*

The interaction of the heliosphere with the interstellar medium

> Far out in the uncharted backwaters of the unfashionable end of the western spiral arm of the Galaxy lies a small unregarded yellow sun.

This first sentence of *The Hitch Hiker's Guide to the Galaxy*, Douglas Adams' fiction book, could serve as an introduction to this chapter, and paraphrasing his style (without his talent, I am afraid) I could add:

This small and unregarded yellow sun has encountered a tiny and insignificant interstellar cloud, which is so tenuous that the extremely weak wind of the yellow sun blows in the tiny cloud a cavity, which extends far beyond the planetary system attached to the yellow sun. Amazingly, trying to cross the edge of this cavity is one of the favorite games of a small group of obstinated individuals, who belong to the very primitive life forms on one of the orbiting planets.

Here I try to relate the story of the discovery of the small cavity carved by the solar wind in the local interstellar cloud, our heliosphere. Being in the middle of this structure, i.e. with a very limited and biased view of it, it has not been easy to infer its existence, and the first steps in the understanding of its structure in the 60's and 70's have required a strong imagination of the pioneers in this field. Then, during the last thirty years, the high number of new observations have made the subject more and more fascinating.

1 INTRODUCTION

1.1 A multidisciplinary field

The research area described in this chapter is by essence a multidisciplinary field, dealing with the properties of gases, radiation, and fields at distances from the Sun varying between a few solar radii and tens of parsecs, that is from the solar corona and the birth of the solar wind, to the edges of the heliosphere at about 100 AU, where the solar wind stops and comes into equilibrium with the galactic interstellar medium, and finally to the stars which are used as targets for measurements of the local interstellar medium properties, located at distances ranging between 1 and 100 pc from the Sun (1 pc = 200,000 AU, 1 AU = 215 solar radii, 1 solar radius = 700,000 km).

This multidisciplinary aspect is reflected in the large number of spacecraft whose instruments have recorded relevant data. I remember that during the first meeting held in the newly created International Space Science Institute in Bern in 1986, a meeting entitled "The Heliosphere in the Local Interstellar Cloud," I counted more than 20 spacecraft whose data were presented or discussed: Ulysses, Prognoz 5 and 6, Voyager 1 and 2, Pioneer 10 and 11, Pioneer-Venus, Galileo, IUE, HST, ISEE 3, IMP 8, AMPTE, Copernicus, EUVE, SOHO, ROSAT, WISCONSIN survey, DXS, and SAMPEX (and I must certainly have forgotton some others). Results obtained from ground using neutron monitors, telescopes and radio telescopes are also used in conjunction with space data. Such a variety (and such a "flotilla") has made this field so interesting during the last few decades. The expectation of the crossing of the boundary of our helio-sphere by one of the deep-space probes adds to the suspense.

An additional proof of the variety of the field is given by the (almost) contemporary historical overviews of S. Suess (1990), T. Holzer (1989), V. Baranov (1990), and I. Axford (1990). They give an idea of how different the descriptions by experts in solar wind, in plasma physics, and in cosmic

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rays can be. At variance with these reviews, the present chapter will have a neutral gas/interstellar medium "flavor."

Over the years, the number of erroneous interpretations in this field has been quite large, but this happens commonly, and we know from K. Popper that empirical disproof is a seminal event in the scientific process. All these errors have indeed stimulated the next advances. Also, while in some cases new instruments have been built specifically for a defined goal, for example the GAS experiment on board Ulysses for the "*in situ*" detection of interstellar neutral helium, other findings have occurred in a totally unexpected way. One of the best examples was the first detection of the "echoes" from the heliospheric boundary by the Voyager radio experiments in 1983. These echoes today remain, to a large degree, mysterious.

1.2 The heliosphere: a solar wind "bubble" in the ambient interstellar gas

Our Sun, an ordinary late-type star in the Local Arm (or Orion Arm), is presently traveling through a small interstellar cloud, the Local Cloud, whose size is of the order of a few parsecs (Figure 1). This cloud belongs to a small group of partially ionized clouds whose temperatures and densities are of the order of 5,000–10,000 K and 0.1 particles per cm^3. This group of clouds is embedded in a 100 pc wide volume, the Local Bubble (LB), believed to be filled with an extremely tenuous ($0.002\,cm^{-3}$) and hot (10^6 K) gas. The origin of the LB is still a matter of much debate.

The relative motion between the Sun and the interstellar medium (ISM) creates a permanent flow of interstellar gas and dust around our star, the so-called interstellar wind (Figure 2). The flow velocity is of the order of $25\,km\,s^{-1}$ (4 AU per year). When the gas approaches the Sun, the ionized part of the interstellar gas and the interstellar neutrals are expected to behave differently: according to models, the plasma is decelerated, heated, and deviated, and flows around the heliopause, the contact discontinuity between the confined solar wind and the interstellar plasma. At variance with charged species that behave collectively, neutrals, to a first approximation, flow freely across the interface between the two plasmas. This behavior is due to their large mean free path with respect to neutral–ion (and –electron) interactions (of the order of tens of AU) and neutral–neutral collisions (hundreds of AU). Neutral atoms having successfully entered the heliosphere approach the Sun, and are increasingly affected by the solar wind and the solar radiation fluxes.

Around the Sun the so-called ionization cavity is formed, a volume devoid of neutrals, much smaller (about 10 AU for hydrogen and less than 1 AU for He) than the heliosphere. Nevertheless, a fraction of the atoms can approach close enough to scatter the solar UV lines by resonance, creating the so-called interstellar glow, which allows them to be detected from Earth orbit. The glow is like the patch of light surrounding a street lamp on a foggy night, except that it is not spherically symmetric, but has a conspicuous maximum on the so-called upwind side, where the interstellar wind originates, for the hydrogen Lyman-alpha glow (Figure 3), and on the contrary on the downwind side for the helium 58.4 nm glow (Figure 5). These differences arise because helium is ionized much closer to the Sun as compared to hydrogen, and thus can be focused by the Sun's gavitational field on the downwind side before becoming ionized. Actually, the helium density reaches its maximum in the focusing cone at about 1 AU. Historically, such a focusing of interstellar matter was first proposed by Lyttleton in 1950, not for atoms but for dust particles, to explain the formation of comets. Danby and Camm (1957) refuted this idea by showing that random thermal motion in the interstellar dust flow prevents the required "perfect" focusing. Contrary to the case of helium, the ionization time for hydrogen atoms as a function of the distance r to the Sun is such that hydrogen atoms traveling at about 20 $km\,s^{-1}$ have a 50% chance of surviving ionization at about 5 to 10 AU. Thus there is no focusing cone, and instead a cavity of this order of magnitude is formed. The maximum emissivity at Ly-alpha, the resonance wavelength for hydrogen, which varies roughly as the product of the density and r^{-2}, is upwind at 1.5–2.0 AU, that is, very close to the orbit of the Earth (Figure 3). After ionization, the newly formed particles (the so-called pickup ions) are convected outward by the solar wind electromagnetic field.

While interstellar helium is mainly photoionized, hydrogen photoionization is a minor effect and hydrogen atoms are preferentially ionized through charge exchange with the solar wind protons. It is important to note that charge exchange between a hydrogen atom and a proton (H^+) produces a "new" proton and a "new" atom, each one having essentially the same momentum as the former particle. In other words, it is almost exactly as if the electron had just left the hydrogen atom to become attached to the proton, while the two nuclei continue on their way. This means that all newly formed neutral atoms flow radially at the solar wind speed ($300–800\,km\,s^{-1}$) and leave the inner Solar System very rapidly. This is why charge exchange is a loss process for the neutral flow. Moreover, these fast atoms no longer scatter the solar radiation, since, due to their high velocity, the resonance wavelength in their rest frame is shifted out from the solar Ly-alpha line which has a finite width of about 1 Å. They become invisible. From the dynamical point of view (trajectories of neutrals having escaped ionization), we know now that even in the absence of a strong ionization, hydrogen atoms would not be gravitationally focused, since radiation pressure due to the solar resonant photons balances the gravitation. All these effects

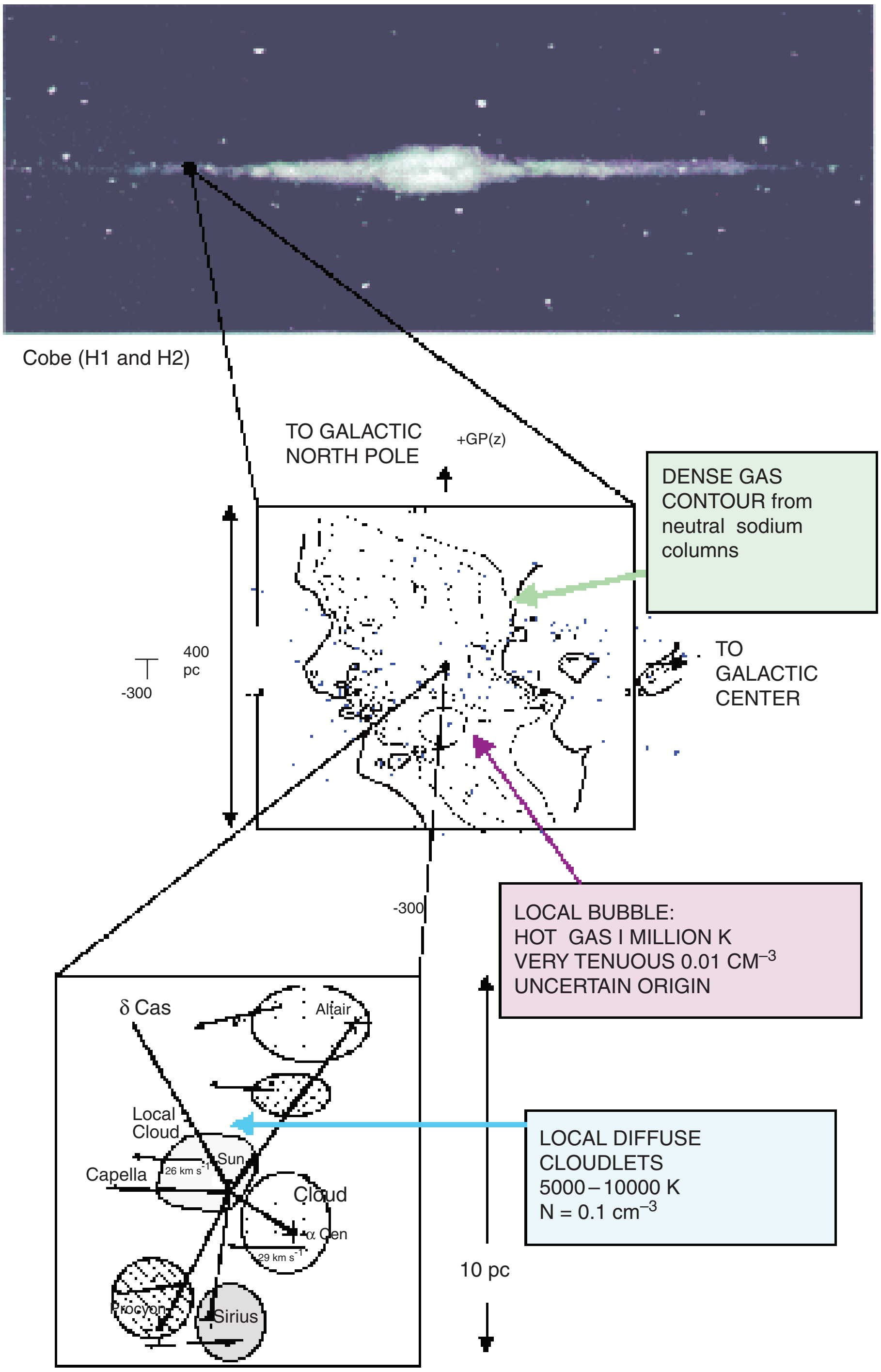

Figure 1 The solar environment at different scales: the Galaxy (here a combination of COBE results from Hauser *et al.* 1995), the local arm (local bubble contours from interstellar neutral sodium absorption, results of Sfeir *et al.* 1999), and the local cloudlets (derived from absorption lines towards very nearby stars (Lallement *et al.* 1995)).

were modeled for the first time in a realistic way by T.E. Holzer (1977). As we will see, charge exchange plays a fundamental role in the structure of the heliosphere, not only close to the Sun, but also at the heliospheric interface itself.

1.3 Four coincidences concerning the Sun's motion through the interstellar medium

Despite our ordinary Sun and ordinary Local Cloud, nothing is actually simple in our galactic environment and there

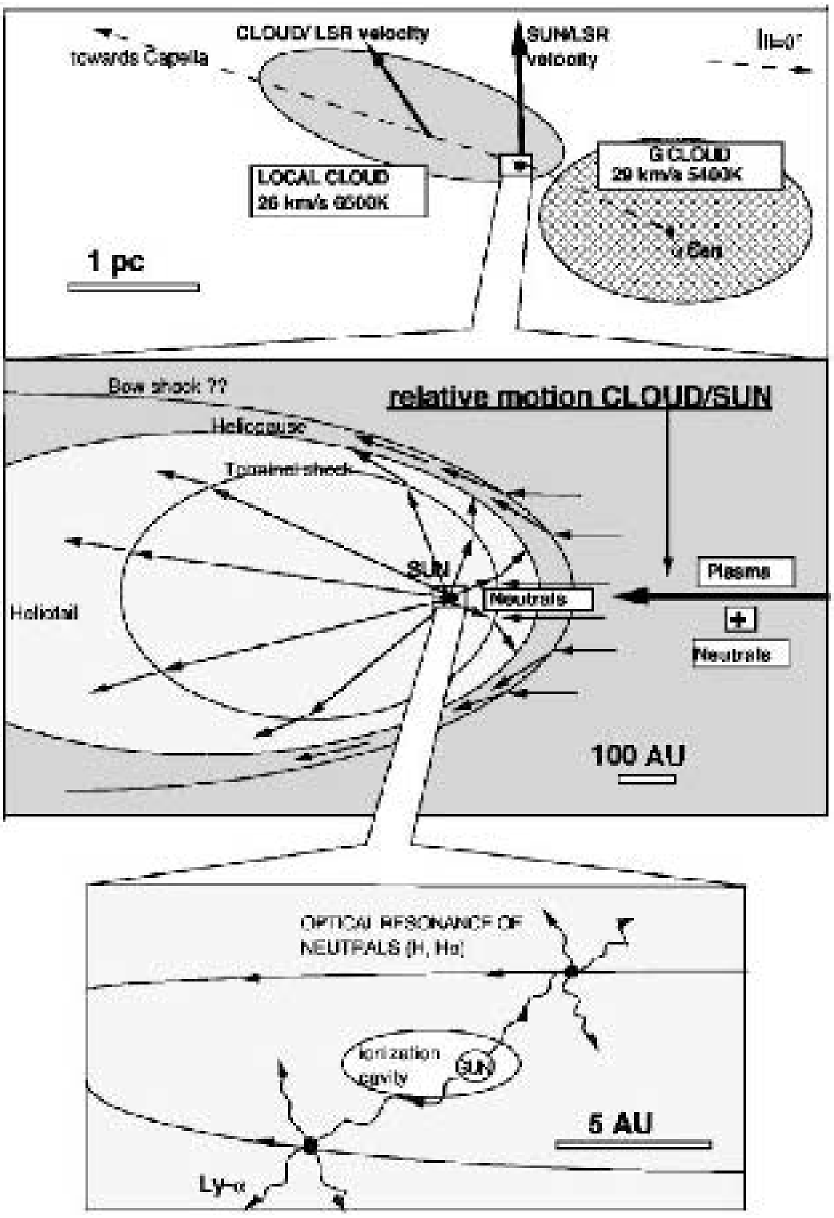

Figure 2 The solar environment at different scales: schematics of the two local clouds, the heliosphere, the interstellar hydrogen flow around the Sun and the "H glow." (From Lallement 1998.)

are (at least) four peculiarities about the Sun's motion in the Local Cloud. The first three have caused problems and have somewhat delayed the progress in the field during the last 30 years.

(1) In the rest frame of the Sun, the interstellar gas of the Local Cloud flows from a direction which points at 15° from the galactic center. In other words, for an observer at the Sun, the interstellar wind seems to flow from the central part of the Galaxy (the Sagittarius area). This is purely coincidental. The Sun is too old to be still embedded in its parent gas (the primordial cloud), it left it billions of years ago, and has already circled a few times around the galactic center. For the Sun, the Local Cloud is nothing more than one of the numerous interstellar galactic clouds it has already traveled through. The motion of the Local Cloud and the motion of the Sun are thus totally unrelated. It just happens that, by chance, the difference between the two velocity vectors points close to the galactic center (Figure 2). But this also implies that the interstellar gas emission glow has a maximum in the direction of the galactic center. As we will see, this has had (and still has) some consequences.

The emission is a maximum on the so-called upwind side, simply because it corresponds to the location of closest approach to the Sun of the inflowing interstellar atoms,

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