OBSERVATION OF LYMAN–α EMISSION IN INTERPLANETARY SPACE

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ABSTRACT

The extraterrestrial Lyman-α emission was mapped by the OGO 5 satellite, when it was outside the geocorona. Three maps, obtained at different periods of the year, are presented and analyzed.

The results suggest that at least half of the emission takes place in the solar system, and give strong support to the theory that in its motion towards the apex, the sun crosses neutral atomic hydrogen of interstellar origin, giving rise to an apparent interstellar wind.

INTRODUCTION

At our request, OGO 5 was temporarily placed in a special spinning mode on three occasions: 12–14 September 1969, 15–17 December 1969, and 1–3 April 1970. These spinup operations, referred to as SU 1, SU 2, and SU 3, respectively, took place when OGO 5 was well outside the geocorona (above 90,000 km altitude).

Two different experiments on board OGO 5 were able to map the Lyman-α background from these maneuvers. One was the two-channel photometer of C. Barth and G. Thomas, from the Laboratory for Atmospheric and Space Physics, University of Colorado, which will be referred to as the LASP instrument [*Thomas and Krassa,* 1971]. The other was a monochromatic photometer built at the Service d'Aéronomie du Centre National de la Recherche Scientifique, referred to as the Paris instrument [*Bertaux and Blamont,* 1970].

Although based on different principles and independently operated, both instruments provided the same results. Data were analyzed independently and compared after completion of the analysis. We use the Paris data here since their agreement with LASP data is excellent, but for a difference in calibration of about 25 percent, and they give essentially the same information.

DESCRIPTION OF THE DATA

The extraterrestrial Lyman-α emission could be provided by the free atoms of hydrogen in *interstellar space,* which are excited by light emission of the stars at the wavelength of Lyman-α. Then it is expected that they would absorb and re-emit Lyman-α photons. This emission could have two possible angular distributions:

1. The emission could come directly from the distant parts of the galaxy. Because of Doppler shifting, the emission would not be completely absorbed by the interstellar hydrogen. Then a map of this Lyman-α (±40Å) hydrogen emission would coincide with a map of the galaxy. This is the interpretation of the observations of Mariner and Venera given by *Barth,* [1970] and *Kurt and Dostovalov* [1968], and it can be termed the *anisotropic galactic distribution.*
2. The emission of the distant parts of the galaxy could be completely absorbed and re-emitted far away from the solar system and the anisotropy of the source would be completely obliterated; around the solar system the interstellar hydrogen would scatter the remnants of this Lyman-α emission, resulting in an *isotropic distribution* of Lyman-α at the solar system.

The first distribution must be rejected on the basis of our data, but the second distribution, corresponding to a maximum intensity of 200 R, cannot be completely ruled out. Superimposed on this emission, a strong emission due to scattering of the solar Lyman-α radiation by the hydrogen of the interplanetary space is to be expected.

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SU 1 RESULTS

When plotted in celestial coordinates in which α is the right ascension and δ is the declination (fig. 1), the emission shows the following features.

1. There are no small-scale emission features apparent except a diffuse glow covering the whole celestial sphere with an intensity varying slowly with the direction of observation.
2. There is no apparent symmetry to the galactic plane.
3. A maximum of intensity of 500 R originates from the region $230° < \alpha < 250°$, $0° > \delta > -40°$. The center of this maximum is not far away from the plane of the ecliptic.
4. A deep minimum of 200 R is located in the region $0° < \alpha < 80°$, $40° > \delta > 0°$. The center of this minimum is not far from the plane of the ecliptic, and is located in the region $40° < \alpha < 60°$, $20° < \delta < 40°$.

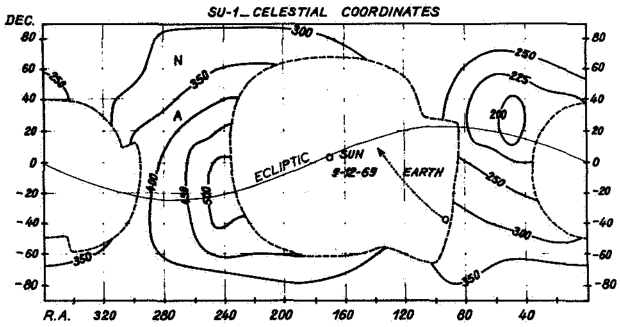

Figure 1 *Contour map of the Lyman-α intensity in celestial coordinates for SU 1. Contour curves are graduated every 50 R. The dotted line represents the movement of the earth as seen from OGO 5. The dashed line is the limit of the area covered on the sky during SU 1, after removal of geocoronal measurements. The letter A indicates the position of the apex; the letter N indicates the position of the ecliptic north pole.*

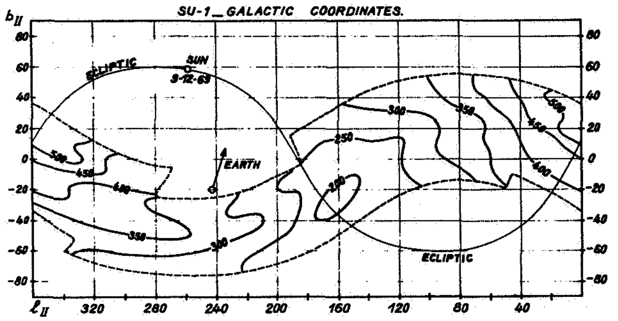

Figure 2 *Contour map of Lyman-α intensity in galactic coordinates for SU 1;* l_{II} *is the galactic longitude measured from the direction of the galactic center;* b_{II} *is the galactic latitude. The dotted line represents the movement of the earth as seen from OGO 5. There is no evident correlation between intensity and regions of low galactic latitude.*

When the signal is plotted in galactic coordinates (fig. 2), it becomes even more obvious that the galactic plane is not a privileged emission area, since the minimum already described extends over the galactic equator between the galactic longitudes of 130° to 180°, and the maximum located in longitude near the galactic center is displaced toward 20° N of galactic latitude. Then the galactic origin of the Lyman-α emission observed by the Venera and Mariner spacecraft becomes extremely doubtful.

The Emission Minimum

Figure 2 shows no obvious anisotropic emission that could be directly attributed to a distant part of the galaxy; thus, the 200 R observed at the minimum must have another origin – a source inside or near the solar system. Since the direction from which the mininum is observed is not *a priori* privileged, an intensity of at least 200 R must be available in all directions arising from a relatively local source and if there is any distant galactic source, it will have to be superimposed on these 200 R.

The Emission Maximum

This feature, which coincides both in intensity and situation with the emission observed by Barth, Kurt, and others, originates from a region that is: (1) broadly centered around the constellation of Sagittarius, (2) broadly centered around the ecliptic plane, and (3) distant by 50° from the direction of the solar apex.

Interpretation

Two explanations can be given for the experimental results of SU 1: (1) There is a local background of about 200 to 250 R *and* an emission originating from the direction of Sagittarius with an intensity of no more than 50 to 100 R corresponding to the enhancement measured in this region; or (2) there is *no* galactic emission observed but a local (interplanetary or near the solar system) emission with a symmetry more or less related to the ecliptic plane where both the maximum and the minimum are situated, with the maximum lying 50° away from the apex.

SU 2 RESULTS

The data obtained during SU 2 provide information on the part of the celestial sphere that could not be observed during SU 1 (fig. 3). The SU 2 data essentially

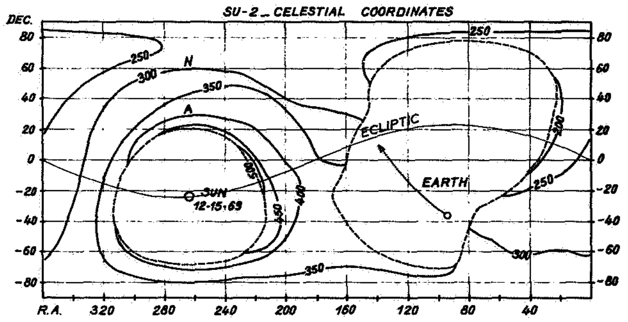

Figure 3 *Contour map of the Lyman-α intensity in the celestial coordinates for SU 2.*

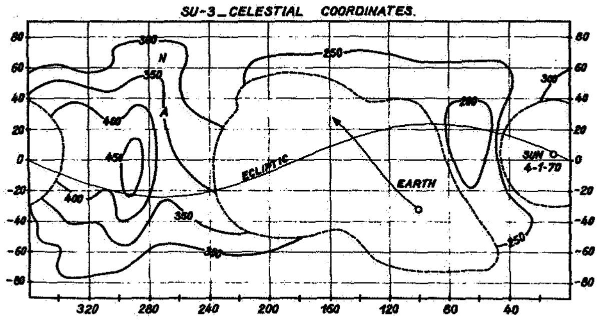

Figure 4 *Contour map of the Lyman-α intensity in celestial coordinates for SU 3.*

confirm the results obtained with SU 1; no small-scale emission features appear; there is no privileged situation near the galactic equator.

No noticeable new features appear from these data. The center of both the maximum and the minimum discovered during SU 1 is situated in the part of the sky not observable with the spacecraft configuration and maneuvers during December 1969; however, the SU 2 observations cover regions of strong and weak intensities that continue the regions of the maximum and minimum of SU 1.

The large intensity regions (500 to 400 R) appear near the sun ($\alpha \sim 220^\circ$, $+10^\circ > \delta > -20^\circ$) and extend over a part of the sky not observed before ($\alpha > 180^\circ$, $-10^\circ > \delta > -50^\circ$. The weak-intensity region continues the weak region of SU 1 around $\delta = +30^\circ$, $-40^\circ > \alpha > 0^\circ$ with the absolute minimum of less than 200 R at $30^\circ > \alpha > 20^\circ$, $50^\circ > \delta > 0^\circ$.

SU 2 did not produce startling new results, essentially because the position of the sun near the maximum of emission was not very favorable; however, it was essential to confirm the situation described by the SU 1 data and complete the sky mapping.

SU 3 RESULTS

The SU 3 data provide essentially the same map as SU 1 and confirm the earlier findings as described above (fig. 4): the absence of small-scale features, absence of galactic predominance over the distribution of the emission, presence of a maximum of emission of 450 R and of a minimum of emission around 200 R.

However, a new fact of prime importance emerges from the SU 3 data. The maximum and the minimum were not situated in the same direction as they were during SU 1. The coordinates of the maximum are now $\alpha = 290^\circ \pm 5^\circ$, $+15^\circ > \delta > -15^\circ$. From SU 1 to SU 3, the direction of the center of the maximum region changed from $\alpha = 240^\circ$, $\delta = -20^\circ$ to $\alpha = 290^\circ$, $\delta = -10^\circ$, representing a displacement of 50° on the celestial sphere; the direction of the center of the minimum region changed from $\alpha = 50^\circ$, $\delta = 30^\circ$ to $\alpha = 60^\circ$, $\delta = 20^\circ$, representing a displacement of only $\sim 10^\circ$.

The difference between the two sets of measurements is the position of the earth in its orbit, and the displacement of the maximum could be very well interpreted as a parallax effect when the earth moved by 2 AU between SU 1 and SU 3. In this case, *the distance to the sun of the region where the maximum of Lyman-α emission appears would be of the order of 2.5 AU.* The direction of this region, as seen from the sun, would be $\alpha = 265^\circ$, $\delta = -15^\circ$. From this parallax effect we would expect a displacement of the minimum from SU 1 to SU 3 in the opposite direction that the one which was measured ($\sim 10^\circ$). However, the direction of such a small displacement should not be considered very significant, for it is difficult to accurately draw isophotes in a region where the gradient of emission is very low. What is more significant is that the displacement of the minimum, if any, *is* small ($< 10^\circ$), indicating that the zone of emission in the direction of the minimum is at least at 15 AU.

COMPARISON OF SU 1, SU 2, AND SU 3 DATA ORIGINATING FROM ONE REGION

The Paris instrument observed a region clear of parasitic sources during all three maneuvers, the region of the north ecliptic pole, indicated by the letter N on the celestial maps. The emission of the south pole was contaminated by geocoronal emission. The intensity originating from the north ecliptic pole during each maneuver was for SU 1, 320 R; SU 2, 280 R; and SU 3, 330 R. The relevant fact is the lower intensity at SU 2. The geometry of the situation is given by figure 5 where the intensity of Lyman-α in the region of the maximum has been represented over a celestial sphere. If this intensity originated from a distant isotropic source, the direction of observation of the north ecliptic pole would be

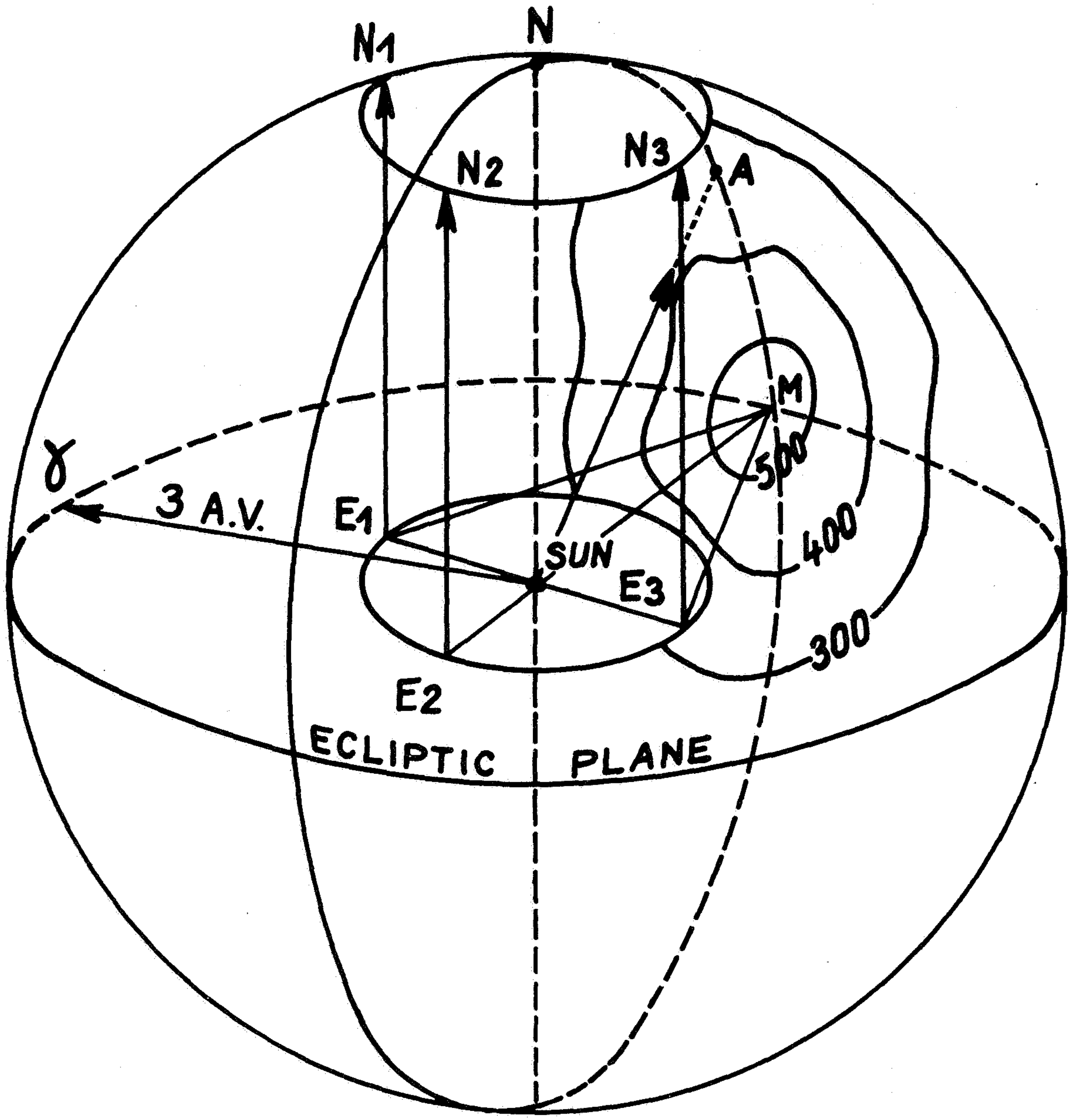

Figure 5 *E_1, E_2, and E_3 are the positions of the earth on its orbit around the sun, respectively, for SU 1, SU 2, and SU 3. Contour map of the maximum region is projected on the inside surface of a sphere of 3 AU of radius. The direction of first point of Aries is ϒ; M is the approximate location of the center of the maximum region; A is the direction of apex; N is the direction of north ecliptic pole. The intersections N_1, N_2, and N_3 are with the sphere of lines of sight in the direction of north ecliptic pole when the earth was in E_1, E_2, and E_3, respectively. N_2 is farther away from M than N_1 and N_3.*

equal for the three observations. On the other hand, should the source be near the orbit of the earth, for instance localized on a sphere of radius 3 AU, the north pole direction of observation at SU 2 would correspond to an intersection with this sphere farther from the position of the maximum than at SU 1 and SU 3, and they would correspond to a weaker intensity, as is found experimentally. This comparison directly confirms the proximity of the emission maximum, which is independent of the first evidence related only to SU 1 and SU 3 observations.

DISCUSSION

The heliosphere – the region of undisturbed solar wind extension – moves toward the direction of the apex $\alpha = 270^\circ$, $\delta = +30^\circ$ with a velocity of 20 km/sec, through the interstellar medium, which contains a certain number of hydrogen atoms/cc and possibly protons if the solar system is embedded in a H*II* region.

A shock front [*Axford et al.*, 1963] is produced at the boundary in the forward direction of the heliosphere due to the reaction of the solar wind against the galactic magnetic field and charge-exchange collisions with the interstellar neutral hydrogen. The distance of the outer part of the shock front to the sun is not well known, but could be anywhere from 20 to 80 AU.

The interstellar ("cold") hydrogen and part of the hydrogen created from the solar wind protons by charge exchange ("hot" component) penetrate into the heliosphere from the boundary that constitutes a source, which has been considered among others by *Patterson et al.* [1963], *Dessler* [1967], *Hundhausen* [1968], and *Blum and Fahr* [1970].

Blum and Fahr have shown that the major part of the hydrogen penetrating inside the solar system must be assigned to the cold component, which then defines an interstellar wind characterized by the macroscopic motion of the interstellar medium relative to the sun in the vicinity of the heliosphere – that is, a direction, a hydrodynamic velocity, and a hydrogen number density. When moving toward the sun, the number density of hydrogen atoms decreases because of photoionization by the EUV solar radiation and charge exchange with solar wind components. *Blum and Fahr* [1970] have computed the hydrogen density distribution as a function of the distance to the sun, taking into account the focusing effect of the solar gravitational field but not the Lyman-α radiation pressure, which is nearly equal to the gravitation, or might even compensate for it. This is a point that must be corrected.

Then using this distribution of hydrogen, Fahr has computed the Lyman-α emission to be observed. The Lyman-α measurements provide information only on the interstellar wind and not on the hot component; not only does the hot component correspond to a small number density compared to the density of the cold hydrogen, but it has a velocity of the order of 300 km sec^{-1}, producing Doppler shifts up to 1.2 A (depending on the direction of travel), to be compared with the half width of the exciting solar line of 0.5 A. It must also be remarked that one should be careful when deriving densities of neutral hydrogen from extraterrestrial Lyman-α observations. When doing the calculations, it is generally admitted that the solar Lyman-α profile is flat. However, according to the measurements of *Bruner and Parker* [1969], the solar Lyman-α line is deeply self reversed. The Doppler effect of cold atoms moving with a speed of 20 to 30 km/sec relative to the sun will shift the resonance wavelength by 0.12 Å, from the bottom of the reversal to one side of the reversal, increasing the useful resonant flux by at least 20 percent. Notwithstanding, by normalizing the *Blum and Fahr* [1970] theoretical results with the 160 *R* of Lyman-α emission measured by *Chambers et al.* [1970] in the apex direction from the Vela 4 spacecraft at 110,000 km of altitude in 1967, Fahr obtained a density of 0.06 cm^{-3} for the interstellar wind. This wind penetrates deeply because the loss mechanism is not very strong. Blum and Fahr find a penetration distance, depending on the density of the interstellar wind, of the intensity of the solar EUV radiation and of the intensity of the solar proton flux, which varies from 1 AU at low solar activity to 7 AU for large solar activity.

In this model, the Lyman-α emission due to this interstellar wind would present a maximum in the direction of the velocity of the solar system relative to the surrounding medium, because it is in this direction that a maximum of density of interplanetary hydrogen would arise; a minimum would arise in the opposite direction where the interstellar hydrogen has been swept by the passage of the sun and consequently the hydrogen density reduced to a low value, in such a way that the cavity extends farther in the aft region of the heliosphere than in the forward direction (possibly to 60 AU) if solar radiation pressure is taken into account.

Then it is obvious that this model of Lyman-α emission is compatible with the data which are characterized by the existence of a broad maximum and a broad minimum, and by a position of the maximum at a distance from the sun not greater than 2 to 4 AU when the solar activity is on the high side.

It is interesting to note [*Tinsley*, 1971] that the emission rate per unit volume in the apex direction can be written as

$$S = g_{12} n_O (r_E/r)^2 \exp(-r_O/r)$$

where

$n_O \exp(-r_O/r)$	is the radial distribution of density in the apex direction if n_O is the density at infinity and the penetration distance $r_O = 4$ AU according to *Blum and Fahr* [1970].

g_{12}	is the number of Lyman photons scattered per atom per sec for hydrogen at 1 AU.
$(r_E/r)^2$	is the inverse square decrease of solar Lyman-α intensity normalized at the earth.

Then S_{max} is obtained for $dS/dr = 0$ or $r = r_o/2 = 2$ AU. This agreement is surprisingly good. However, the direction of the maximum does not coincide with the solar apex, as would be expected from this model, but rather coincides with the projection of the apex direction on the ecliptic plane and is a vector located at the intersection of the ecliptic plane and of the galactic plane – that is, a vector contained in both these planes. We are therefore left with two possible explanations:

First, the direction of the maximum coincides with the direction of the velocity of the solar system relative to the ambient. Then, since the direction of the motion of the solar system is well known, the medium surrounding the heliosphere must move at an angle of 50° to the apex direction as seen from the sun. This displacement of the interstellar hydrogen around the heliosphere takes place in the galactic plane in the sense inverse to the displacement of the heliosphere. There is nothing wrong with this explanation, but the coincidence of the direction of the interstellar wind vector with the ecliptic plane is surprising. If this explanation proved to be correct, it might have some implications for the origin of the solar system.

Second, the direction of the maximum is not directly related to the direction of the interstellar wind but to the real maximum of the distribution of interplanetary hydrogen (in contrast to the Blum and Fahr model). The density, for some reason yet unknown, would present a symmetry to the ecliptic plane with a maximum in this plane. Note that a shift of the maximum from the apex would be caused by the interplanetary magnetic field since the interstellar wind would be more attenuated in the direction of field lines if they channel a flow of solar wind plasma [*Parker*, 1963]. Our observation of the maximum could be explained by the interaction of the interstellar wind coming from the apex with a preferential flow of solar wind plasma created by a symmetry of the interplanetary magnetic field to the ecliptic plane far from the sun. We would then only observe secondary properties of the interstellar wind – that is, properties of the interstellar wind after its interaction with this anisotropic component. However, it would be difficult to explain the direction of the minimum near the ecliptic plane, and the first hypothesis consequently appears more plausible.

CONCLUSION

The data presented in this paper can be described as follows:

1. The Lyman-α hydrogen emission observed from outside the geocorona shows no enhancement or diminution in the galactic plane.
2. The emission has a smooth variation from a maximum region of 500 *R* to a minimum region of 200 *R*.
3. The direction of the maximum changes by 50° between September and March; then the region where the maximum originates is situated near the earth at about 2 AU.
4. The direction of the maximum coincides with the intersection of the galactic plane and the ecliptic plane.
5. The region where the minimum originates is situated at 15 AU at least.
6. The direction of the minimum is roughly opposite to the direction of the maximum.

These data are consistent with the following alternate interpretations:

1. The galactic component has an intensity less than 50 *R*; then all the emission observed is due to hydrogen present in the solar system (varying from 500 to 200 *R*).
2. The galactic component has an intensity up to 200 *R* and is isotropic; then the interplanetary component varies from 300 to 50 *R* or less.

Whatever the value attributed to the galactic component, the interplanetary component can be interpreted as due to: (1) an interstellar wind with a velocity vector located in the ecliptic and in the galactic plane and not in the apex direction; or (2) an interstellar wind in the apex direction interacting with a solar wind whose symmetry is not radial but ecliptic.

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