THE SHADOW OF COMET HALE–BOPP IN LYMAN-ALPHA

An Absolute Measurement of H Production Rate with SOHO/SWAN⋆

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Abstract. For a few months around perihelion, the central part of the Hale–Bopp hydrogen cloud has been optically thick to the solar Lyα radiation, and has significantly reduced the solar flux available for the resonance glow of interstellar hydrogen beyond the comet. This shadowing effect on the interstellar gas is the first ever observed comet shadow. It is modeled and compared with SWAN observations. Shadow modelling will help to constrain the comet water production and radiative transfer effects in the interstellar ionisation cavity.

Keywords: Comets, interstellar medium, solar system

1. Introduction

We present the first ever observation of the shadow of a comet on the background of interstellar Hydrogen cloud flowing through the Solar System. We also provide a simple model for the shadowing effect. The source of light is the Sun and its strong Lα emission; the mask (the object which casts the shadow) is the huge cloud of H atoms produced from H_2O and possibly other molecules from photodissociation in the coma of Comet C/1995 O1 Hale–Bopp. The cloud of interplanetary H atoms acts as the "screen" on which the shadow is projected. These H atoms are of interstellar origin and pass continuously through the Solar System where they are ionised mainly by charge exchange with solar wind protons. Near the Sun this ionisation mechanism creates a cavity with a lower density of detectable H atoms. Thus, the study of the shadow will provide information both on the mask (the cometary H cloud) and the "screen" (the interplanetary H atoms).

This shadowing effect was detected by the SWAN instrument on board the SOHO spacecraft. The main objective of SWAN is to determine the latitude distribution of the solar wind and its evolution with the solar cycle. This is done by recording – typically three times per week – the Lα emission of the interplanetary

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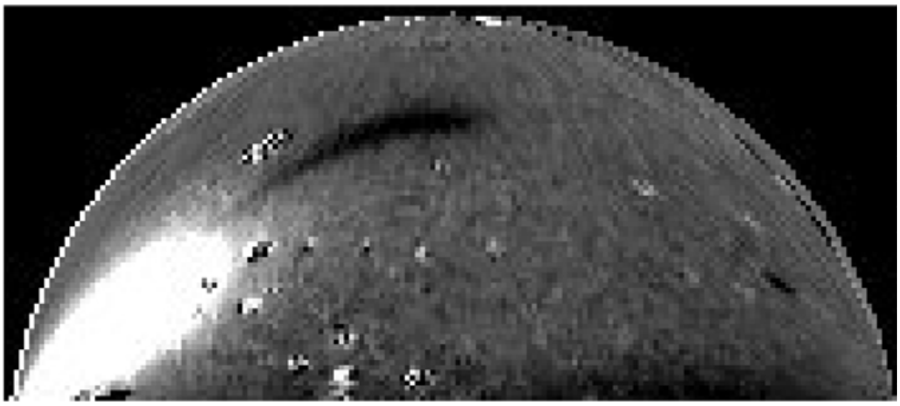

Figure 1. Hale–Bopp H cloud (bright patch) and its shadow (dark feature): Hemispherical map made from SWAN Lyα data. For each line of sight the ratio of the intensities recorded in 1997 and 1996 for the same Earth longitude (April 17) is shown.

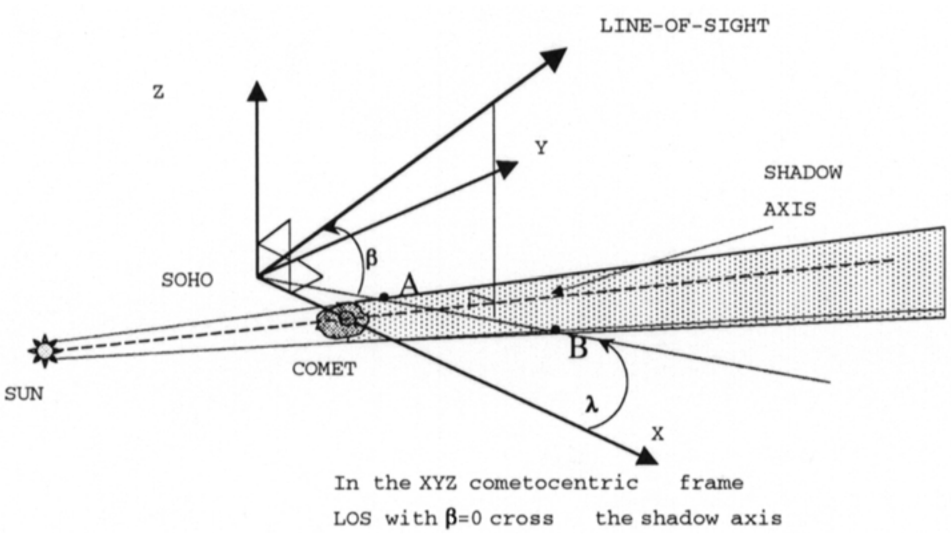

Figure 2. The geometry of the shadow observations

H atoms over the whole sky. A description of the instrument and first results can be found in Bertaux et al. (1997).

In addition, the Lα emission of many comets was observed by SWAN and water production rates of these comets could be derived (i.e., Mäkinen et al., 2001). Comet C/1995 O1 Hale–Bopp produced a gigantic cloud of H atoms that extended over more than 10^8 km and was detectable through its cometary Lα emission over more than 40 ° in the sky. The geometry of the shadow observations is illustrated on Figure 2. The cometary H cloud scatters the Lα solar photons, which are thus no longer available to illuminate the interplanetary H atoms further downstream, creating a shadow cone of infinite extension and with focus point in the Sun. The size of the mask (the cometary H cloud) is much larger than the Sun, therefore penumbra effects (like for solar and lunar eclipses) are negligible.

2. A Simple Quantitative Model of the Shadow

As seen from SWAN/SOHO (Figure 2), only the line of sight (LOS) which intersects the cone shadow will show a deficit ΔIp of interplanetary Lα emission Ip. Let S be the position of SOHO, A and B the points of intersections of the LOS with the shadow cone. The emission rate Ip can be written as integral of the Lα emissivity ϵ_0 (number of photons cm^{-3} s^{-1}) along the LOS:

$$\mathrm{Ip} = \int_0^\infty \epsilon_0 dl = \int_0^A \epsilon_0 dl + \int_A^B \epsilon_0 dl + \int_B^\infty \epsilon_0 dl. \quad (1)$$

Ip denotes the intensity in the case of no shadow, and Ips the one for the case when a shadow is present. We define the shadow intensities deficit ΔIp as the difference between Ip and Ips:

$$\Delta\mathrm{Ip} = \mathrm{Ip} - \mathrm{Ips} = \int_A^B \epsilon_0 dl. \quad (2)$$

Here we have assumed that the interplanetary hydrogen is optically thin, with only direct scattering of solar photons ϵ_0 contributing to the observed emission rate.

For a particular LOS that intersects the shadow cone, the length of segment AB, thus the deficit ΔIp, will depend on the size of the comet mask which is directly related to the H production rate Q_H of the comet. Therefore, measurements of this deficit and its geometrical extent on the sky provide a new method to determine Q_H, completely independent of the usual method of comparing the Lα cometary emission to a model for the H distribution produced from H_2O photo-dissociation. In principle, other sources of H can also contribute to the shadow.

More precisely, the angular extent of the geometrical shadow (defined by ΔIp $\neq$ 0) across the Sun-comet line depends only on Q_H (i.e., the size of the mask), while the magnitude of the deficit ΔIp depends on the size of the mask AND the exact value of ϵ_0:

$$\Delta\mathrm{Ip} = \int_A^B \epsilon_0 dl \approx AB\epsilon_0, \quad (3)$$

where the length AB is only a function of the LOS geometry and Q_H, while ϵ_0, the primary excitation of interplanetary H atoms, is a direct function of the density n of these atoms:

$$\epsilon_0 = \frac{g_0}{r^2} n, \quad (4)$$

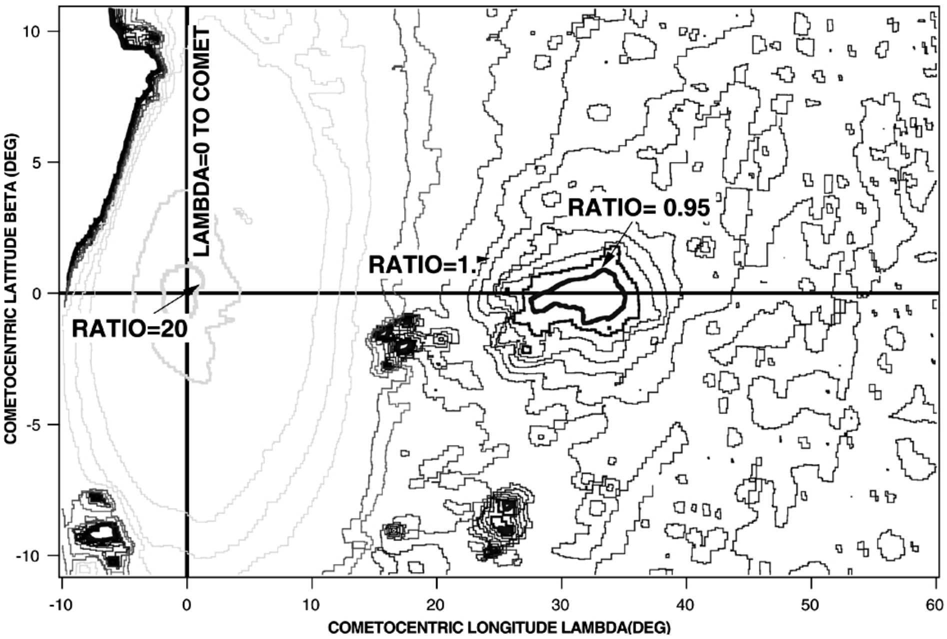

Figure 3. Iso-ratio contours in the comet-shadow region in the reference frame of Figure 2.

where g_0 is the excitation rate of H atoms at 1AU ($g_0 = 1.8 \times 10^{-3}$ s^{-1} for a solar flux of 3.3 10^{11} photons cm^{-2} $s^{-1}Å^{-1}$) and r is the distance to the Sun (in AU) for the point in the shadow. Equation (3) shows that, once Q_H and therefore the length AB are determined, the measured deficit ΔIp allows to determine ϵ_0 = ΔIp/AB. This is a unique way to get a local measurement of ϵ_0 and n, since otherwise the Lα sky emissions are integrated along LOS extending to infinity. This is very important, since the 3-D distribution of H in the solar system depends on some factors which are not very well known: (1) The H density "at infinity" n_∞ (before significant ionisation, say at $\approx$ 50 AU), (2) the magnitude of ionisation by solar wind and solar EUV. Therefore, the quantitative study of the comet shadow will not only serve to provide an independent determination of Q_H, but it will also provide new and important data on the distribution of interplanetary H in the solar system.

For Comet Hale–Bopp the shadow was detected over several weeks, covering various geometrical configurations, and probing n at various places in the solar system.

One complication arises from the fact that, in reality, the single scattering approximation in the interplanetary H is not fully valid, because the density is of the order of 0.1 to 0.2 H atom cm^{-3}, yielding an optical thickness of 0.1 to 0.2 per AU outside of the ionised region. In our simple model, this effect is not taken into account.

3. The Data

On each sky map recorded before and after perihelion the huge cloud of H atoms of the comet is a conspicuous bright feature which makes it difficult to reveal the shadow. However, when compared to a map of the sky recorded one year earlier, subtle differences show up. Indeed, the map of Figure 1 has been obtained by dividing the Lα intensity map recorded by SWAN on 17 April 1997 by the intensity recorded in April 1996.

The one-year interval is taken because SOHO was at the same position in the solar system as one year before, i.e., for the same viewing geometry for the pattern of interplanetary Lyα emission. In the intensity ratio map the shadow of the comet is visible as a dark area that is elongated into the anti-sunward direction as seen from the comet. The Lyα emission of the cometary coma appears as a bright elliptic feature.

It is more convenient to plot these ratio data in a new coordinate system, defined by its origin O at SOHO, axis OX directed towards the comet's nucleus, and the plane OX-OY containing the Sun (see Figure 2). In principle, the OX-OY plane should be the plane of symmetry between cometary coma and shadow, and indeed, this is what is found in the contour ratio map plotted in Figure 3. High ratios are found for the comet itself at left. Outside the coma emission and its "shadow", the initial ratio is different from 1. This is caused by a combination of several small factors: (1) The Lα solar flux F_s has increased from 1996 to 1997, (2) the interplanetary density distribution has changed due to a change in the ionisation pattern, (3) the calibration factor of the SWAN instrument might have been different from what was assumed to convert the counting rates in Rayleighs units, and – possibly more important – (4) the strong Lα emission of the comet is an additional source illuminating also the interplanetary H atoms, thus contributing to their emissivity and to the intensity displayed in the map of 17 April 1997. A detailed calculation of this contribution Ic is deferred to a later study, but it probably does not exceed about 20 % of the Sun-induced interplanetary emission Ip. In addition, there is no shadow on this extraneous emission. In order to measure the actual depth of the shadow, all intensity ratios have been normalized to 1 outside of the shadow region.

4. Modelling the Comet Absorption of the Solar Flux and the Effect on the Interplanetary Emission

4.1. The Comet Model

The H atoms in the coma have a certain velocity distribution, and therefore they absorb the solar Lα radiation very selectively, i.e., at a single rest frame wavelength λ_0 = 1215.66 Å. The wavelength integrated absorption cross-section is σ_λ = 0.544 $\times\ 10^{-14}$ cm^{2}Å. The wavelength scale may be also determined as a velocity scale with the appropriate Doppler shift conversion, and the velocity integrated cross-section becomes:

$$\sigma_v = 1.3410^{-12}\ \mathrm{cm}^2(\mathrm{km/s}). \qquad (5)$$

Therefore, the optical thickness $\tau(V_x)$ of the comet H cloud at velocity V_x is: $\tau(V_x) = \sigma_v dN/dVx$ with dN/dV_x is the integrated line density of H atoms per cm^2 per unit velocity (1 km/s). The integration in the comet cloud is along the line from the Sun to the point where the shadow deficit must be calculated.

The attenuation of the solar flux is defined by the transmission of the cloud: $T(V_x) = exp(-\tau(V_x))$. We are using a simplified comet model, the Haser model which assumes isotropic and homogeneous outflow of the gas species through the coma. Therefore, the coma is spherically symmetric, and the quantity dN/dV_x is determined only by $Q(H)$, by the impact parameter p of the line (distance to the nucleus center) and by the velocity distribution of H atoms. In the following it is assumed that H atoms have two radial velocities, 20 and 8 km/s, corresponding to the photo-dissociation of H_2O and OH. Let v be one of these velocities. Along a line of integration, for this particular population of H atoms, there is only one point (if any) where the projected velocity is V_x. It can be shown with some simple maths that:

$$dN = n(r)\frac{p}{v}\frac{1}{(1-(\frac{v_x}{v})^2)^{\frac{3}{2}}}dV_x \qquad (6)$$

where the local density n(r) is computed according to the Haser's formula, found for instance in Bertaux et al (1998) for the analysis of the emission in Comet Hyakutake Lα. The transmission of each population, and the total transmission (product of both transmissions) is computed as a function of $Q(H_2O)$ and the impact parameter. The 20 km/s population has a broader absorption, but shallower than the 8 km/s population, which has an optical thickness larger than unity even at 10^7 km from the nucleus. This whole absorption pattern has then to be displaced by the Doppler shift of the comet nucleus, i.e., 7.5 k ms^{-1} radial heliocentric velocity at the time when our data were taken.

4.2. The model of interplanetary hydrogen and Lα emission

The distribution of H atoms in the solar system $n(rs, \theta)$ is of the so-called hot model type, with formulas that are established in Lallement et al (1985). It is a function of the radial distance to the sun, rs, and the angle θ with the wind axis. The H distribution is axi-symmetric around the wind vector. The following parameters were taken: temperature T of interstellar H at infinity, i.e., T = 11000 K as derived from an analysis of SWAN maps (Costa et al., 1999); direction of incoming wind (upwind direction seen from the Sun): λ; β = 252; 7 deg.; density n_∞ and lifetime

T_D of H against ionisation are free parameters, typically around 0. 13 cm^{-3} and 1.2×10^6 s, respectively.

The computation of the emissivity at a point given by (rs, θ), takes into account the actual velocity distribution of H atoms at this point, and the solar profile, modified by the cometary absorption up to the point (rs, θ) as explained above. The solar line shape in the self reversal region is fit to a parabola according to the last SOHO/SUMER profile measurements (Lemaire, private communication). The model emission rate (intensity) seen from SOHO is obtained by integrating the emissivity along the line of sight. In addition, the self-absorption by interplanetary H atoms along the line of sight is taken into account. Except for this last attenuation factor, the intensity is therefore calculated with a pure optically thin approximation. It was found by experience that the total intensity calculated with a full radiative transfer model (Quemerais, 2000) models this self-absorption attenuation in a better way.

5. Comparison of Model to Data

The model intensity was computed for both, the case with (I_{m1}) and without the comet (I_{m0}). The absolute deficit $I_{m0}-I_{m1}$, the relative deficit $\delta m = (I_{m0}-I_{m1})/I_{m0}$ and the simple deficit ratio I_{m1}/I_{m0} were derived.

Figure 4 shows the measured intensity ratio map along a cut perpendicular to the shadow axis, at an angle of 32 degrees behind the comet. The intersection of the LOS with the Sun-comet line is at a distance of $\approx$ 5 AU from the comet and $\approx$ 6 AU from the Sun. The shadow is clearly seen as a depression on an otherwise smoothly varying background that is approximated by a linear fit. The map has then been divided by this linear function; this allows to determine the relative shadow deficit δ as fraction of the sky intensity.

The model was run for two different values of the production rate of the comet: $Q = 0.9 \times 10^{31}$ H_2O mol.s^{-1} (the quantity estimated from the Lα emission of the comet recorded by SWAN, Combi et al., 2000), and twice this value. Indeed, the model with the higher production rate shows a larger deficit (smaller minimum ratio or larger relative absorption), and also a wider angular size. Clearly, the results favor the value of Combi et al.

In Figure 5 we compare the data with the model, now along a longitudinal cut at a fixed latitude of 0 ° (along the projected shadow axis). The upper panel shows the solar distance of LOS intersection with the shadow axis in AU, extending to infinity at a longitude of 38 °. The lower panel shows both the data and the model for the same value of $Q = 0.9 \times 10^{31}$ mol.s^{-1}, but this time for two different values of the ionisation lifetime, i.e., for $T_D = 1 \times 10^6$ and 2×10^6 s, thus showing the influence of the interplanetary H density.

The data is clearly in contradiction with the models, showing a smaller maximum absorption than the model predicts, and the maximum occurs when the LOS

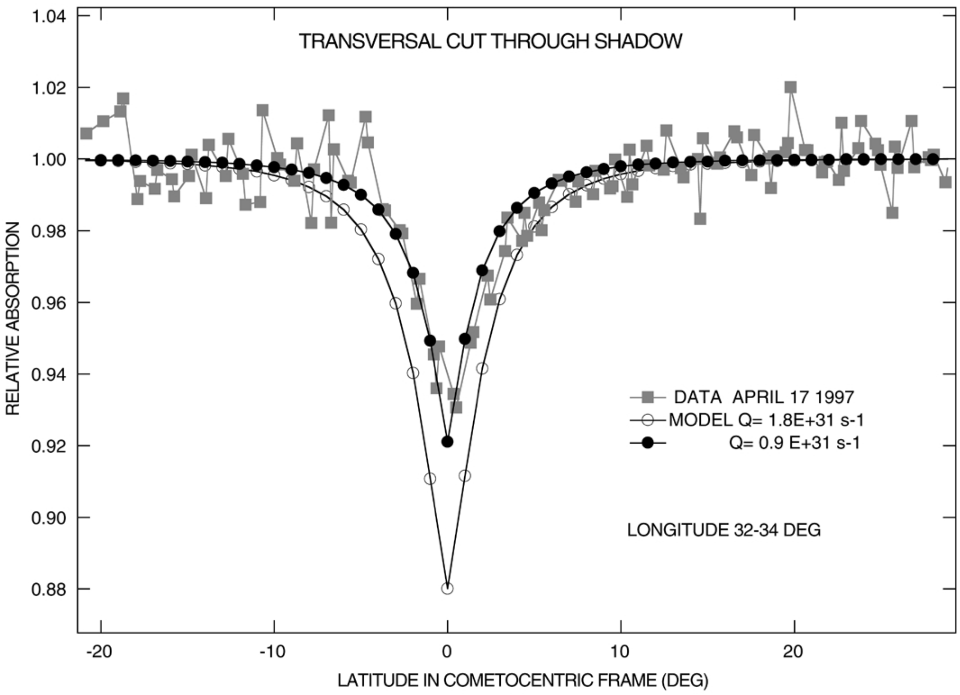

Figure 4. Transversal cut through the shadow: Data and model.

crosses the shadow about 3 degrees closer than predicted. Varying the water production (not shown here), or the ionisation modifies somewhat the pattern but does not help in reproducing the location of the maximum absorption. Clearly some physical effect is not taken into account in our modeling (see below).

6. Conclusions

There is an important discrepancy between the model and the data when the LOS intersects the shadow axis at more than 6–10 AU, where the observed deficit is smaller than the modelled one. We interpret this as a deficiency of the model which assumes an optically thin interplanetary H medium. The atoms in the shadow of the comet are not illuminated by the Sun, but they are still illuminated by all the other atoms of the interplanetary space which are not in the shadow, after second and higher orders scattering. This effect is not taken into account in our model. It increases with the H atom density at infinity, i.e., the larger n_∞, the lower the contribution of first scattering to the total emission rate, the only one obscured by the comet. Potentially, one can derive the true value of n_∞ from an analysis of the comet shadow. Clearly, one has to use a more sophisticated radiative transfer model (Quémerais, 2000) that takes into account all orders of scattering. This, however, was beyond the scope of this first simple model for the comet shadow,

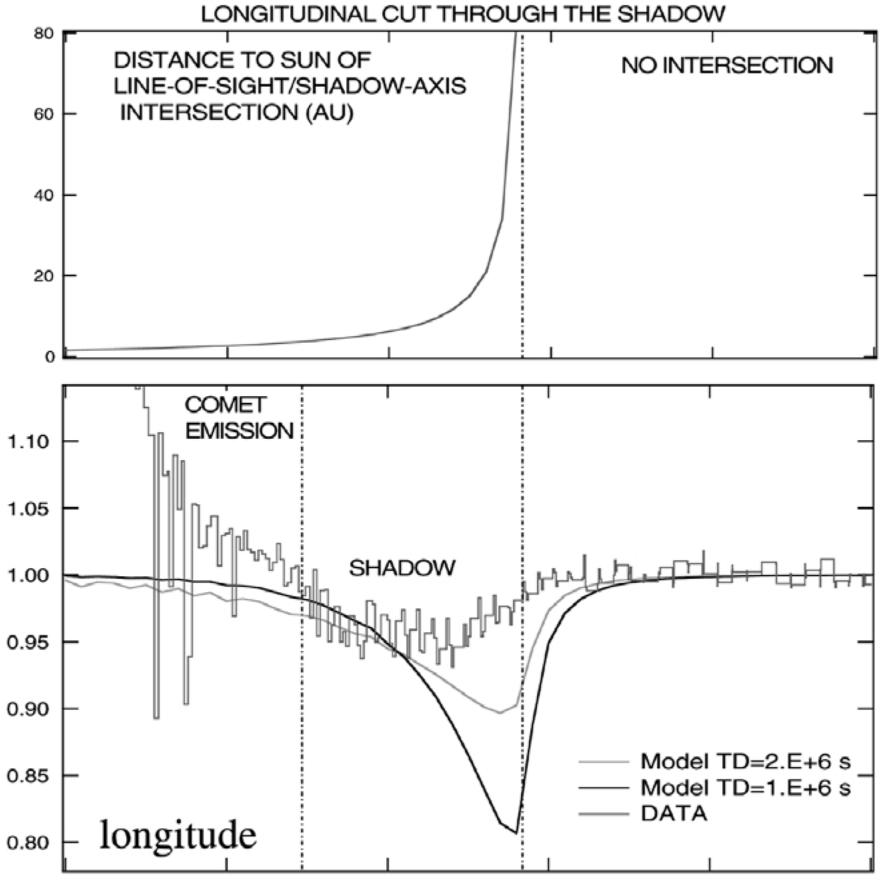

Figure 5. Longitudinal cut through the shadow (bottom) and distance to Sun of the LOS intersection with the shadow (top).

a phenomenon observed with SWAN for Comet Hale–Bopp thanks to its gigantic production rate. The data of the absolute and relative flux deficit spanning two months in time and various positions in the solar system, will be instrumental to disentangle the 3 unknowns that we hope to derive from this exercise: The production rate Q, the density of interstellar H at infinity n_∞, and the ionisation lifetime T_D under the action of the solar wind and solar EUVE radiation.

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