

Letter to the Editor

Heliospheric and *astrospheric* hydrogen absorption towards Sirius: no need for interstellar hot gas^{*}

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Abstract. We use an updated self-consistent kinetic/gasdynamic model of the solar wind/interstellar flow interaction to compute the Lyman- α absorption by hydrogen atoms of both interstellar and solar origin generated in the heliospheric interface. We apply this model to the direction of the star Sirius. We show that the neutralized, compressed solar wind from the heliosheath explains the extra absorption at positive redshifts observed in the Lyman- α line with the HST/GHRS. This removes the need for the interstellar hot gas previously proposed to explain this extra absorption. We also show that extra absorption in the blue wing can possibly be explained by H atoms formed in an *astrosphere* around Sirius, providing the stellar wind is at least as massive and fast as the solar wind.

Key words: ISM: abundances – ISM: clouds – ISM: structure – stars: winds, outflows – Sun: solar wind – ultraviolet: ISM

1. Introduction

There is a long-standing debate on the properties of the hot ($T \approx 10^6$ K) gas which fills the so-called Local Bubble, the soft X-ray emitting region around the Sun (see Breitschwerdt et al. 1997 for updated information). The cold and warm diffuse clouds embedded in the hot gas, like the group of cloudlets in the solar vicinity, are supposed to be surrounded by a shell of semi-hot gas at an intermediate temperature ($T \approx 10^5$ K), and one way to detect this gas is through the neutral hydrogen absorption at Ly- α . It is worthwhile here to recall that a small quantity of hot gas ($T \approx 10^5$ K) can produce an absorption

equivalent width in Ly- α comparable to that of a 3 or 4 orders of magnitude larger quantity of warm gas ($T \approx 10^4$ K).

Indeed, spectra obtained with the Goddard High Resolution Spectrometer (GHRS) on board the Hubble Space Telescope (HST) show hot neutral H absorption along the line-of-sight to a few nearby stars, including Sirius A and ϵ CMA (Bertin et al. 1995, hereafter BVL95; Gry et al. 1995). The origin of this absorption, however, has been a matter of debate. For the Sirius line-of-sight, BVL95 proposed that a hot conductive interface is responsible for excess Ly- α seen on the red side of the absorption profile, and Bertin et al. (1995b) proposed that absorption from Sirius's wind accounted for excess Ly- α absorption on the blue side. In other cases, detected hot H components are undoubtedly linked to the neutral gas formed either around our own heliosphere, due to the interaction of the solar wind with the ambient interstellar medium of the Local Interstellar Cloud (LIC) (Linsky & Wood 1996, hereafter LW96), or to neutral gas around other *astrospheres* due to the corresponding interaction between the stellar winds and the ambient neutral interstellar gas (Wood et al. 1996). But for Sirius A and ϵ CMA, the combination of conductive interface and stellar wind absorption has remained the most likely source.

There are 3 different types of heliospheric H atoms, in addition to the unperturbed interstellar neutral H called primary interstellar atoms or PIA's: i) the compressed, decelerated, and heated interstellar atoms (HIA's) formed by charge exchange with heated interstellar protons outside the heliopause, ii) the neutralized, decelerated, and heated solar wind atoms (HSWA's) formed in the heliosheath by charge exchange between the neutral interstellar gas and the hot protons of the decelerated and compressed solar wind, and iii) the neutralized supersonic solar wind atoms (SSWA's). Only the HIA's and HSWA's are of interest here since the SSWA component is flowing radially at very large velocities and will not produce absorption in the central part of the Ly- α lines, and the PIA's are indistinguishable from the normal interstellar gas. The HIA's on the upwind side of the heliosphere (i.e. the direction from which the interstellar wind flows) collectively make up the so-called "H-wall", which is the gas that has been detected towards α Cen (LW96).

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The properties of the HSWA's are the most difficult to calculate, since this hot gas has a very large mean free path and its characteristics at one location in the heliosphere depend on the properties of all the source regions everywhere in the heliosheath. Indeed, significant differences between multi-fluid models and kinetic models have been found by Williams et al. (1997). These authors have also suggested that the mixing between the hot and warm populations in the heliospheric tail through H-H collisions could be the origin of the hot gas absorption observed towards Sirius. While recent computations show that H-H collisions are negligible compared to charge-exchange processes (Izmodenov et al. 1999b), our conclusions below will ultimately be similar to their original idea.

The goal of this letter is to show that when one uses updated parameters of the circumsolar interstellar medium and a very precise kinetic/gasdynamic self-consistent model of the heliosphere, HSWA's produce a non-negligible absorption in almost all directions, with a maximum effect on the downwind side. We reconsider the Sirius A HST Ly- α spectrum and show that the red wing of the absorption is very well fitted using our model. Then we show using simple analogies that the additional absorption on the blue wing could be produced by HSWA's and HIA's around Sirius itself, if the star is embedded in the neighboring cloud detected towards the star by Lallement et al. (1994) and if the star produces a wind, which is likely.

1.1. Heliospheric absorption towards Sirius

A description of our self-consistent heliospheric model of the solar wind-interstellar gas interaction can be found in Baranov & Malama (1993), Baranov et al. (1998), and Izmodenov et al. (1999a). We have updated the interstellar parameters to take into account recent advances in the field, such as the velocity and temperature determinations of the LIC from *in situ* helium measurements and stellar spectroscopy (Witte et al. 1993; Lallement & Bertin 1992; Bertin et al. 1993), as well as estimates of the neutral H and electron density in the circumsolar interstellar medium (Lallement et al. 1996; Izmodenov et al. 1999a). In what follows, the assumed interstellar parameters are then: $T = 6000$ K, $V = 25$ km/s, $N(HI) = 0.2$ cm $^{-3}$, $N(e^-) = 0.07$ cm $^{-3}$. The upwind direction is taken as $\lambda = 254.5^\circ$, $\beta = 7.5^\circ$ (ecliptic coordinates), which translates into $l_{II} = 186^\circ$, $b_{II} = -16^\circ$ (galactic coordinates). The assumed solar wind parameters at 1 AU are: $n(p) = 7$ cm $^{-3}$, $V = 450$ km/s. The model does not include an interstellar magnetic field, but our estimates should not be significantly changed in the presence of a moderate field. The boundary of the model grid is at a distance of about 2000 AU in the direction of Sirius.

Fig. 1a is a sketch of the heliosphere and shows the direction of Sirius on the downwind side. The predicted absorption by HSWA's and HIA's in the direction of Sirius at an angle of 139° from the upwind direction is displayed in Fig. 1b. The absorption is shown in a heliocentric rest frame. It can be seen that the HSWA's are the main absorbers, and that their absorption is far from negligible.

1.2. Heliospheric and interstellar absorption towards Sirius

The 2.7 pc long line-of-sight to Sirius has been shown to cross two clouds: i) the LIC, which in this direction is seen at a positive redshift of 19 km s $^{-1}$, and ii) a second cloud at a Doppler shift of 13 km s $^{-1}$ (Lallement et al. 1994), which is probably of the same type as our Local Cloudlet. Using the angularly close star ϵ CMa, Gry & Dupin (1998) have argued that the LIC extent in that direction is not longer than ≈ 0.6 pc.

Fig. 1c shows the Sirius spectrum around the Ly- α line, and a simple polynomial fit to the continuum surrounding the D and H absorption. Superimposed on the data is the expected profile after absorption by the two clouds at $V = 13$ and 19 km s $^{-1}$, respectively, with an assumed temperature of $T = 6000$ K. The column densities of the two clouds are both 1.6×10^{17} cm $^{-2}$, in agreement with the D absorption and a D/H ratio of 1.65×10^{-5} (Linsky et al. 1995, BVL95). Our conclusions are not sensitive to either the exact value of D/H, or to the exact interstellar temperature. The absorption has been convolved by the instrumental profile corresponding to the G160M/SSA settings of the GHRS spectrograph.

It is clearly seen that with warm interstellar gas only, absorption is missing on both sides of the line, as already noticed by BVL95. After adding the modeled absorption by the heliosphere, the resulting profile is substantially modified on the red part of the line. To make the heliospheric effect clear in Fig. 1c, the additional absorption is shown as a hatched area. It can be seen that the red part of the observed spectrum is well fitted by the model. Thus, while the heliosphere cannot be made responsible for the absorption in the blue wing, there is *no need to propose additional absorption from interstellar hot gas* along the line-of-sight to fit the red side of the absorption line.

2. Heliospheric, interstellar, and Siriospheric absorption towards Sirius

Bertin et al. (1995b) have suggested that the additional absorption on the blue side is due to neutral gas associated with Sirius's wind, a counterpart of Mg II absorption detected at this velocity. Here we consider another possibility, that the absorption is from the interaction area between Sirius's wind and the interstellar gas around the star.

In the following, we make a series of assumptions:

- Sirius is embedded in the “blue cloud” seen at the Doppler shift of 13 km s $^{-1}$. This is a very reasonable assumption, owing to the very small length of the line-of-sight.
- Sirius has a wind with a terminal velocity of the same order of magnitude as the solar wind velocity (say 400 – 1500 km s $^{-1}$), and a mass flux at least that of the solar wind. These assumptions are compatible with the predictions of radiatively driven wind models or coronal winds (see Bertin et al. 1995b).
- The gas near the Siriopause is not fully ionized by the EUV radiation from Sirius B. Using model results of Paerels et al. (1987) for a $25,000$ K pure H white dwarf, the EUV flux of Sirius B balances the travel time associated to a star/ISM relative motion of ≈ 25 km s $^{-1}$ at distances of about 200 AU, which

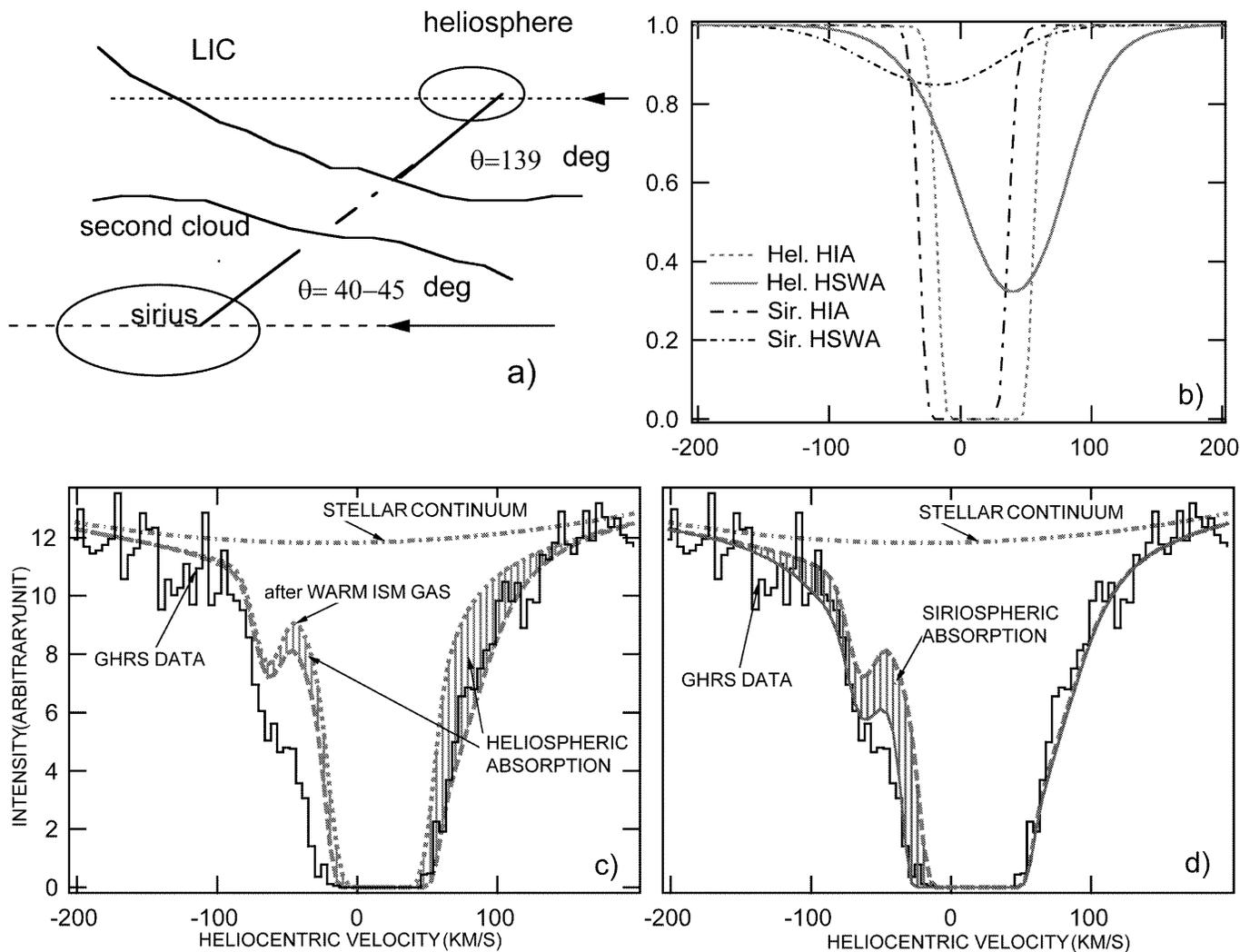


Fig. 1. **a** Schematic view of the Sun-Sirius line-of-sight. **b** Transmission as a function of Doppler shift in the solar rest frame through heliospheric HIA's and HSWA's in the direction of Sirius, and through the siriospheric H atoms in conditions described in the text. **c** The GHRs spectrum, the simulated profile after ISM absorption, and the profile after ISM + heliospheric absorption. **d** Simulated profile after ISM + Heliospheric + Siriospheric absorption, where a good fit to the data is obtained for a column density of HIA and HSWA atoms two times the heliospheric column for the same orientation.

implies that if the size of the siriosphere is of this order or larger, neutral atoms of the cloud can penetrate within it. Such a size is very likely reached, since the Sirius wind is probably stronger than the solar wind and then the equilibrium with the ISM is reached at larger distances.

– The axis of symmetry of the siriosphere, determined by the relative motion between the star and the ambient gas, makes an angle $\theta \approx 40^\circ$ with the line-of-sight direction. We know the 3D motion of Sirius A from ephemerides for the orbital system, combined with the radial velocity of Sirius A at the time of the observations, $v_r = -5 \text{ km s}^{-1}$, but we do not know the 3D motion of the cloud. Multiple clouds have been observed for many short lines of sight besides Sirius, but their projected velocities are never far from that of the LIC; the separation is only 6 km s^{-1} for the non-LIC cloud seen towards Sirius. Thus, assuming the motions of these additional clouds are identical to

that of the LIC is a reasonable approximation, and making this assumption for the Sirius cloud leads to an estimated angle of $\theta \approx 40^\circ$.

Under these assumptions, we can estimate some characteristics of the HIA and HSWA populations around Sirius. The distance at which pressure equilibrium between the wind and the ISM is reached depends on the ISM pressure and the stellar wind momentum flux. If the mass flux and/or the velocity of the Sirius wind are larger than the solar wind flux and velocity, which is likely, the HIA component will be created at larger distances from the star in comparison with the solar case. But for the interstellar gas outside the discontinuity, the conditions of deceleration and heating should be about the same as for the heliosphere, since the gas has to decelerate in both cases by about the same quantity to be at rest with the star (the relative velocity between the star and the ISM). In the solar case, the

relative velocity is 25.5 km s^{-1} . For Sirius, we can estimate this velocity to be about $20\text{--}40 \text{ km s}^{-1}$. The velocity is $\approx 31 \text{ km s}^{-1}$ if the surrounding cloud motion is assumed to be identical to the LIC. However, since its projected velocity (13 km s^{-1}) is lower than the LIC's projected velocity (19 km s^{-1}), the actual relative velocity is likely to be lower than 31 km s^{-1} and therefore not too different from the solar case. In this instance, the absorption will be found at velocities between 13 km s^{-1} (projection of the cloud's velocity) and -5 km s^{-1} (the projection of the stellar motion). Fig. 1b shows the resulting theoretical absorption.

The compressed stellar wind should also have properties similar to the compressed solar wind, although possibly formed at larger distances and possibly hotter. We have computed the absorption in the solar frame for $\theta = 45^\circ$, which should be equivalent to what would be seen by an observer on Sirius. Then, we have changed its sign and added -5 km s^{-1} to represent what would be seen for an observer at rest with the Sun and looking towards Sirius. Fig. 1b shows the predicted absorption. It can be seen that the HIA and especially the HSWA absorptions fall at the location of the “missing” absorption in the blue wing.

Fig. 1d shows the consequences of this additional absorption on the simulated spectrum. In order to obtain a complete “filling” of the line we have multiplied by 2 the column density of the HIA and HSWA components, which corresponds to a cloud two times denser than the LIC, or distances in the siriosphere two times larger, or any combination. It is beyond the scope of this paper to investigate all solutions since there are too many. However, from this crude estimate we conclude that *siriospheric* absorption could possibly account for the extra absorption observed in the blue wing.

3. Conclusion and discussion

We have used the most precise and updated model of the Sun-LIC interaction to calculate the Ly- α absorption by the neutral gas in and around the heliosphere along the line-of-sight towards Sirius. We find that the neutralized solar wind from the heliosheath is mainly responsible for the absorption, and that the red side of the absorption line is very well fitted when adding this absorption to the normal interstellar absorption. In these conditions, there is no need to propose interstellar hot gas from a conductive interface to explain the red wing absorption, as BVL95 did in their analysis.

Using analogies with the solar case, we also show that the remaining missing absorption on the blue side could be explained in the same way by a “siriosphere”, if Sirius is embedded in the neighboring cloud seen towards the star, if it has a stronger

wind than the Sun, and if Sirius B does not completely ionize the hydrogen in and around the siriosphere. In this interpretation, there is no need for neutral H associated with a supersonic wind like that proposed by Bertin et al. (1995b).

We also point out that the model results show that heliospheric absorption cannot be neglected in *any* Ly- α analysis, whatever the line-of-sight direction, if the interstellar absorption is relatively low ($N(\text{HI}) \leq 10^{18.5} \text{ cm}^{-2}$).

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