Heliospheric Lyman-α Absorption Toward Voyager 2

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Abstract. Motivated by recent Voyager 2 (V2) measurements of surprisingly high plasma temperatures outside the heliopause, we study the heliospheric hydrogen Lyman-α absorption observed by the Hubble Space Telescope for the closest available line of sight to the V2 direction, δ Pav, which is 9° from V2. The absorption is well reproduced by a typical global heliospheric model that predicts outer heliosheath temperatures of $T \approx 20,000$ K. Arbitrarily increasing these temperatures by a factor of two to be more consistent with the initial $T=30,000-50,000$ K values measured by V2 leads to significant overprediction of absorption. Thus, the high plasma temperatures first encountered by V2 near the heliopause cannot be present throughout the outer heliosheath.

1. Voyager 2 in the Outer Heliosheath

The twin Voyager spacecraft are the first manmade probes to cross the heliopause (HP), the contact interface separating the plasma flows of the solar wind and interstellar medium. Voyager 1 (V1) was the first to make the crossing, in 2012 August at a distance of 122 AU from the Sun [1, 2]. However, the plasma instrument on V1 has not worked since the Saturn encounter decades ago, limiting the spacecraft’s ability to study the interstellar plasma outside the HP. Direct measurement of the plasma had to wait for Voyager 2 (V2) to reach the HP.

In 2018 November, V2 crossed the HP at a distance of 119 AU from the Sun [3, 4]. Even with an operating plasma instrument, measurement of the interstellar proton properties is difficult due to the slow flow speeds outside the HP, which results in particle energies that are near the detection threshold of 10 eV. Nevertheless, rough measurements of plasma properties could be made, the most notable of which was a surprisingly high inferred temperature of $T=30,000-50,000$ K [3].

Most models of the global heliosphere predict significantly lower temperatures in the outer heliosheath. (We here use the term “outer heliosheath” to refer to the heliospheric interaction region outside the HP.) Estimates of the temperature of the local interstellar medium (LISM), from either LISM absorption line studies or direct measurements of LISM neutral He flowing through the solar system, typically infer values of $T \approx 7500$ K for the LISM [5, 6, 7]. Even in the limit of a strong bow shock, this temperature is not expected to increase more than a factor of 4 as the interstellar flow collides with the heliosphere and piles up outside the HP, implying $T<30,000$ K in the outer heliosheath. Furthermore, given that the Mach number of the LISM flow is close to 1, the heating is actually expected to be well below that implied by the strong shock limit, and it is in fact questionable whether a bow shock exists around the heliosphere at all [8]. Heliospheric models therefore typically
predict lower temperatures of T≈20,000 K in the outer heliosheath, whether the models include a bow shock or not [8, 9, 10].

Before V1 and V2 crossed the HP, the only observational diagnostic of the bulk thermal particle population in the outer heliosheath was Lyman-α absorption from neutral H in the outer heliosheath, observable in UV spectra of nearby stars from the Hubble Space Telescope (HST). First detected nearly 25 years ago [11], this absorption is from a population of neutrals created by charge exchange between LISM neutral H and the heated, compressed, and decelerated protons in the outer heliosheath, creating what has been referred to as a “hydrogen wall” surrounding the heliosphere [13, 14, 15]. With V1 and V2 having crossed the HP they are now finally in the hydrogen wall region from which this Lyman-α absorption signature originates, allowing us for the first time to compare the HST absorption diagnostics with the direct in situ measurements of Voyager. In particular, we can assess whether the HST absorption is consistent with the surprisingly high temperatures first indicated by V2 just outside the HP.

2. The δ Pav Line of Sight Observed by HST
The hydrogen wall Lyman-α absorption signature has been observed toward many lines of sight, generally in the upwind direction of the LISM flow [12]. For our purposes here, it makes sense to focus on the line of sight that is closest to V2. The nearest line of sight to V2 with detected heliospheric absorption is that towards δ Pav, a G8 IV star only 6.1 pc away. Figure 1(a) shows the location of δ Pav relative to the track of V2 across the sky from 1990-2030. In 2018, at the time of the V2 HP crossing, δ Pav was 9° from V2’s position. This separation will decrease to 6° by 2030, by which time V2 will probably no longer be operating.

The HST Lyman-α spectrum of δ Pav is shown in Figure 1(b). The spectrum shows broad H absorption centered at 1215.6 Å, superposed on the chromospheric emission line, with much narrower and weaker deuterium absorption at 1215.28 Å. Analysis of the H absorption revealed excess absorption on both sides of the line that cannot be accounted for by the LISM [16]. The excess

Figure 1. (a) The position of V2 over time in ecliptic coordinates relative to the HST-observed line of sight to δ Pav. (b) The HST Lyman-α spectrum of δ Pav from [16], showing very broad hydrogen absorption centered at 1215.6 Å, and narrow deuterium absorption at 1215.28 Å. The upper solid line is the reconstructed stellar line profile. The dashed line is the absorption from the LISM alone. Excess absorption on the left and right is due to astrospheric and heliospheric absorption, respectively.
Figure 2. (a) The solid line plots the temperature of the neutral H component created by charge exchange in the outer heliosheath versus distance, based on a four-fluid model from [9], for the line of sight toward the star δ Pav. The dashed line shows the temperatures arbitrarily multiplied by two. (b) A close-up of the right side of the Lyman-α profile of δ Pav from Figure 1(b). The green line is the LISM absorption alone. The solid line is after the inclusion of the heliospheric absorption predicted by the heliospheric model, which matches the data well. The dashed line indicates the predicted absorption with the higher temperature profile from (a), which no longer fits the data.

Absorption on the right side of the line is the heliospheric absorption from the hydrogen wall around our own heliosphere. The excess absorption on the left side is due to astrospheric absorption from the hydrogen wall around δ Pav.

Astrospheric absorption detections are very important for providing the only available diagnostics for coronal winds of stars other than the Sun [17]. Detailed analysis of the astrospheric absorption toward δ Pav was discussed both in the original analysis of the data, and in this conference series two years ago [16, 18]. However, our focus here is on the heliospheric absorption seen toward δ Pav, which samples the outer heliosheath in a direction close to V2.

Confronting the Lyman-α absorption data with model predictions requires the use of global heliospheric models that properly treat neutral interactions within the heliosphere. This is not trivial, since the neutrals are not in equilibrium with the plasma. The type of model used here is a 2.5D axisymmetric four-fluid hydrodynamic model, with a single fluid component used to represent the plasma, but with multiple fluid components used to represent the neutrals, one component for each distinct region of the heliosphere where charge exchange yields a distinct neutral population through charge exchange: inside the termination shock, between the termination shock and HP, and outside the HP [15]. We have in the past also used more sophisticated models to confront the Lyman-α absorption data, including fully 3D MHD models, and models with a full kinetic treatment of the neutrals [8, 19]. However, our experience suggests that the simpler 2.5D four-fluid approach is just as successful at reproducing the hydrogen wall absorption signatures observed in upwind directions, in particular a specific model that we have been using for two decades to confront heliospheric hydrogen wall absorption data, labeled “Model 10” in [9]. (See [9] for details of this model.)

The global heliospheric model provides traces of flow velocity, temperature, and density for each neutral component along the line of sight toward δ Pav. The neutral component of particular interest here is the component associated with neutrals created by charge exchange in the outer heliosheath. This is naturally the dominant neutral component in the outer heliosheath, and is responsible for the Lyman-α absorption signature. The solid line in Figure 2(a) shows a trace of temperature versus distance for this component, with vertical lines indicating the locations of the HP and bow shock (BS),
at distances of about 150 AU and 320 AU, respectively. The temperature in the outer heliosheath between the HP and BS is $T \approx 20,000$ K, which as mentioned in the previous section is typical for models of this nature. An absorption prediction can be computed from the traces of density, temperature, and velocity provided by the model, and Figure 2(b) shows the result. This figure focuses on the right side of the $\delta$ Pav Lyman-$\alpha$ profile from Figure 1(b), where the heliospheric absorption is observed. The model is successful at reproducing the observed absorption toward $\delta$ Pav.

However, the outer heliosheath temperature reported by V2 just outside the HP is $T = 30,000-50,000$ K, roughly twice as high as the model suggests. The dashed line in Figure 2(a) shows the temperature profile of our model arbitrarily increased by a factor of two to be more consistent with the V2 measurement, and the dashed line in Figure 2(b) shows the resulting Lyman-$\alpha$ absorption prediction. The increase in temperature broadens the hydrogen wall absorption considerably, resulting in a significant overprediction of absorption.

We conclude that the 30,000-50,000 K temperature observed by V2 cannot be typical for the outer heliosheath. However, it still is not necessarily the case that there is any real inconsistency between the HST and V2 observations, as V2 has only sampled the outer heliosheath in one location very close to the HP, which may not be representative of the outer heliosheath as a whole. It will be interesting to see if V2 continues to infer high temperatures as it moves further from the HP. However, with V2 expected to run out of power around 2025, it will probably not be able to probe too far into the outer heliosheath before operations cease. A more complete picture of the outermost regions of the heliospheric interaction will probably require a future mission such as the proposed Interstellar Probe.

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