Update of the Solar Lyα Profile Line Model

Izabela Kowalska-Leszczynska1, Maciej Bzowski1, Marzena A. Kubiak1, and Justyna M. Sokół1,2

1 Space Research Centre PAS (CBK PAN), Bartycka 18A, 00-716 Warsaw, Poland; ikowalska@cbk.waw.pl
2 NAWA Bekker Fellow, Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA

Received 2020 January 15; revised 2020 February 24; accepted 2020 February 28; published 2020 April 3

Abstract

We present a modification of a model of solar cycle evolution of the solar Lyα line profile, along with a sensitivity study of interstellar neutral hydrogen to uncertainties in radiation pressure level. The line profile model, originally developed by Kowalska-Leszczynska et al., is parameterized by the composite solar Lyα flux, which recently was revised. We present modified parameters of the previously developed model of solar radiation pressure for neutral hydrogen and deuterium atoms in the heliosphere. The mathematical function used in the model, as well as the fitting procedure, remain unchanged. We show selected effects of the model modification on interstellar neutral H properties in the heliosphere, and we discuss the sensitivity of these quantities to uncertainties in the calibration of the composite Lyα series.

Unified Astronomy Thesaurus concepts: Heliosphere (711); Solar spectral irradiance (1501)

1. Introduction

The solar resonant radiation pressure in the Lyα spectral line is an important factor determining the distribution of the interstellar neutral H (ISN H) in the inner heliosphere (Tarnopolski & Bzowski 2009). The density of ISN H near 1 au from the Sun (hence, consequently, the distribution of the heliospheric backscatter glow in the sky) and the flux of ISN H are sensitive functions of the magnitude of the solar radiation pressure.

Tarnopolski & Bzowski (2009) developed a model of the evolution of the solar Lyα line profile integrated over the solar disk during the varying solar activity. This model was parameterized by the solar Lyα composite flux and was routinely measured by Laboratory for Atmospheric and Space Physics, University of Colorado (LASP), Boulder (Woods et al. 2000). The baseline data for the Tarnopolski & Bzowski model were observations of the solar Lyα line profile from the Solar Ultraviolet Measurement of Emitted Radiation (SUMER)/Solar and Heliospheric Observatory for a dozen dates during approximately half of the solar cycle (Lemaire et al. 2002, 2005).

With observations of the line profile from more than 40 dates covering a full solar cycle (1996–2009), published by Lemaire et al. (2015), Kowalska-Leszczynska et al. (2018a) developed a more refined model of the dependence of this profile on the magnitude of the solar Lyα composite flux, which will be referred to as the IKL model of radiation pressure. In this model, the line profile is composed of three main components: (1) a kappa-like general profile; (2) a Gaussian central reversal, responsible for the characteristic self-reversed structure with two horns; and (3) a linear background (foot). The parameters of the functions defining these components were assumed to be linear functions of the line- and disk-integrated Lyα intensity, available as the LASP composite flux.3 The original profiles observed by Lemaire et al. (2015) and the model by Kowalska-Leszczynska et al. (2018a) both used the same version of the composite Lyα flux, namely Version 3 (Woods et al. 2005).

Machol et al. (2019) recalibrated the composite Lyα flux, using observations corrected based on an improved model of instrument aging and a more advanced method of filling the inevitable gaps in daily observations using different proxies. The resulting Version 4 of the Lyα composite flux is compared with Version 3 in Figure 1 as well as in Figure 5 in Machol et al. (2019). Version 4 of the composite flux has been improved by using the Solar Radiation and Climate Experiment (SORCE) Solar Stellar Irradiance Comparison Experiment (SOLSTICE) instead of those from the Upper Atmosphere Research Satellite (UARS) SOLSTICE as the reference data from and also by using the solar radio flux F10.7 (Tanaka & Kakinuma 1957) instead of the F10.7 (Tapping 2013) flux wherever possible. Also there was an issue with a 1 au correction of the F10.7 radio flux in Version 3 that is now removed. As a result, Version 4 is a major improvement with respect to Version 3. Typical differences between the two versions are ~ ±10%. Generally, the magnitudes of the flux during the minimum of solar activity are somewhat higher in Version 4 than in Version 3. The ratio of the irradiances Version 4/Version 3 after 2005 is approximately constant and equal to 1.04, but for earlier dates, it oscillates inside ~ ±5%, with occasional departures to ±10% and sometimes even to ±20% (several days in 1991). During solar maxima, the ratio of the irradiances Version 4/Version 3 after 2005 is approximately constant and equal to 1.04, but for earlier dates, it oscillates inside ~ ±5%, with occasional departures to ±10% and sometimes even to ±20% (several days in 1991). During solar maxima, the ratio of the irradiances Version 4/Version 3 after 2005 is approximately constant and equal to 1.04, but for earlier dates, it oscillates inside ~ ±5%, with occasional departures to ±10% and sometimes even to ±20% (several days in 1991).

Kowalska-Leszczynska et al. (2018b) demonstrated a high sensitivity of the density and flux of ISN H near 1 au to details of the solar Lyα line profile, studying differences between predictions of the Warsaw Test Particle Model (nWTPM; Tarnopolski & Bzowski 2009) run with radiation pressure models from Tarnopolski & Bzowski (2009) or, alternatively, from Kowalska-Leszczynska et al. (2018a). The high sensitivity of the ISN H to details of radiation pressure inferred from this analysis stimulated us to update the model of Kowalska-Leszczynska et al. (2018a) based on the updated time series of the LASP Lyα composite flux and to investigate how this update modifies the ISN H inside the heliosphere. An added benefit from this analysis is an illustration of the sensitivity of

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1 Available from http://lasp.colorado.edu/lisird/data/composite_lyman_alpha/.
2. Updated Model of Solar Radiation Pressure

2.1. Renormalization of the Profile Line Observations

In the original paper by Lemaire et al. (2015), the absolute scaling of the observed profiles was done by satisfying the requirement for the integrated spectral irradiance measured by SUMER to be equal to the magnitude of the composite Lyα irradiance for the day of observation. The observed profiles were normalized using the total Lyα irradiance Version 3. We rescaled the Lyα profiles published by Lemaire et al. (2015) using the updated, Version 4 of the composite Lyα flux. The rescaling factors are ratios of \( I_{\text{tot},V4}(t_i) \) to \( I_{\text{tot},V3}(t_i) \) in Lemaire et al. (2015) to \( I_{\text{tot}} \) in Version 4:

\[
f_{\text{rs}}(t_i) = \frac{I_{\text{tot},V4}(t_i)}{I_{\text{tot},V3}(t_i)},
\]

respectively, for \( t_i \). We next multiplied the original line profiles by the appropriate \( f_{\text{rs}} \) coefficients.

The difference between the original and the rescaled profiles is shown for two example profiles, presented in the top left panel of Figure 2 with gray (Version 3) and blue markers (Version 4). The profiles were taken during solar minimum (1996 December 5) and solar maximum (2001 October 28) and they are equivalent to the profiles investigated in our previous paper (Kowalska-Leszczynska et al. 2018b). The original and rescaled profiles taken during solar maximum in 2001 are almost identical, while the rescaled profiles taken during solar minimum are systematically different; Version 4 predicts a stronger line than Version 3. This is easily understandable since the recalibration of the total irradiance (Figure 1) resulted in very little modification of \( I_{\text{tot}} \) values during solar maximum and a larger change during solar minimum. The effect is very subtle. The rescaling factor for the profile from 1996 December 5 is \( f_{\text{rs}}(t = 1996 \text{ December 5}) = 0.9985 \), while the profile from 2001 October 28 is \( f_{\text{rs}}(t = 2001 \text{ October 28}) = 1.0577 \).

2.2. Updated Model Parameters

With the original rescaled profiles, we repeated the least-squares fitting of the model parameters defined in Equations (8)–(11) in Kowalska-Leszczynska et al. (2018a) to all 43 profiles observed by Lemaire et al. (2015). The best fitting values of the parameters along with the nominal errors of the fitting procedure are shown in Figure 3. Blue points with error bars represent the new values based on Version 4 of the composite \( I_{\text{tot}} \) time series, and the gray points, based on Version 3, are shown for comparison. All parameters are plotted as functions of \( I_{\text{tot}} \). Additionally, the linear correlations used to express each parameter as a linear function of \( I_{\text{tot}} \) are shown as solid lines. The numerical values of the coefficients of the linear functions, defined as \( P = \beta(1 + \alpha I_{\text{tot}}) \), are listed for all parameters in Table 1 for hydrogen and in Table 2 for deuterium.

The most affected by the change of \( I_{\text{tot}} \) are parameters that describe the general shape of the profile and the background \((A_K, A_r, b_{\text{bg}})\). \( A_K \) is the height of the kappa-component of the profile, \( A_r \) is the depth of the central reversal, and \( b_{\text{bg}} \) is the slope of the remnant background in the model. The other parameters changed so little that the modifications of the correlation lines in Figure 3 are barely visible. The change in \( A_K, A_r, b_{\text{bg}} \) is understandable given the results of the \( I_{\text{tot}} \) update: the contrast between solar minimum and maximum levels is reduced, so the slope of \( A_K(I_{\text{tot}}) \) is smaller. Similarly, the depth of the central reversal is reduced for larger total intensities, and the spectral background is less sensitive to \( I_{\text{tot}} \). The other parameters of the model, corresponding to the widths of the baseline profile and of the self-reversal as well as to the spectral shift of the central reversal, are very little affected by the update of line-integrated irradiance.

3. Effects of the Model Update on the Selected Effects inside the Heliosphere

In this section we briefly compare the effect of updating the radiation pressure model on the density of ISN H in select locations inside the heliosphere and on the model ISN H flux observed by the Interstellar Boundary Explorer (IBEX; McComas et al. 2009). An extensive study of the sensitivity of various ISN H-related quantities to various aspects of
radiation pressure was presented by Kowalska-Leszczynska et al. (2018b). Here, we show the difference between selected aspects of ISN H inside the heliosphere, simulated using the old and the updated versions of the radiation pressure model. The simulations were done using the nWTPM model of the distribution of ISN H inside the heliosphere. All parameters and other assumptions were identical to those used by Kowalska-Leszczynska et al. (2018b) except for the radiation pressure, which is now based on the model presented in our paper.

3.1. ISN H Density

Figure 4 presents the ratio of the ISN H density based on $I_{\text{tot}}$ Version 4 to that based on Version 3 during minimum (the top panel) and maximum of solar activity (the bottom panel). The
simulations were performed in the ecliptic plane for five distances from the Sun from 1 to 10 au. As expected, the biggest effect occurs at 1 au, where, in the downwind direction, the density based on Version 4 is significantly lower. While in the downwind direction, especially close to the Sun, the hydrogen density is very small; even the slightest change in radiation pressure causes a strong effect on the model density magnitude in this region. Therefore, it is important to use in simulations the most updated and accurate model of radiation pressure, should a precise calculation of the density and related quantities be needed.

In Figure 5, the ratio of hydrogen density based on Version 4 to that based on Version 3 is shown as a function of time for the downwind (the top panel) and upwind (the bottom panel) directions. The simulations were performed for the same set of distances from the Sun as for the previous plot. Again, the

\begin{table}[h]
\centering
\begin{tabular}{ccc}
\hline
Parameter ($\rho_i$) & $\beta_i$ & $\alpha_i$
\hline
$A_K$ & 6.523 & 0.619 \\
$\mu_K$ & 5.143 & -1.081 \\
$\sigma_K$ & 38.008 & 0.104 \\
$\kappa$ & 2.165 & -0.301 \\
$A_R$ & 580.37 & 0.28 \\
$d_\mu$ & -0.344 & -0.828 \\
$\sigma_R$ & 32.439 & -0.049 \\
$b_{\kappa_{bg}}$ & 0.035 & 0.184 \\
$\sigma_{bg}$ & 0.411 \cdot 10^{-4} & -1.333 \\
\hline
\end{tabular}
\caption{Updated Coefficients of the Linear Correlations between the Model Parameters for H and the Total Irradiance in Ly$\alpha$, as Defined in Equation (13) in Kowalska-Leszczynska et al. (2018a).}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{ccc}
\hline
Parameter ($\rho_i$) & $\beta_i$ & $\alpha_i$
\hline
$A_K$ & 3.264 & 0.619 \\
$\mu_K$ & -76.237 & 0.213 \\
$\sigma_K$ & 38.008 & 0.104 \\
$\kappa$ & 2.165 & -0.301 \\
$A_R$ & 290.41 & 0.28 \\
$d_\mu$ & -0.344 & -0.828 \\
$\sigma_R$ & 32.439 & -0.049 \\
$b_{\kappa_{bg}}$ & 0.017 & 0.184 \\
$\sigma_{bg}$ & 0.206 \cdot 10^{-4} & -1.333 \\
\hline
\end{tabular}
\caption{Updated Coefficients of the Linear Correlations between the Model Parameters for D and the Total Irradiance in Ly$\alpha$, as Defined in Equation (13) in Kowalska-Leszczynska et al. (2018a).}
\end{table}

Note. The model along with the parameter values is available online: http://users.cbk.waw.pl/~ikowalska/index.php?content=lya.
biggest effect is for the closest distances and in the downwind direction (even up to 50%). The density change is relatively large inside 2–3 au, where the percentage change is larger than the percentage change in radiation pressure (see the bottom panel of Figure 1). The sensitivity is larger in the downwind hemisphere. Outside ∼3 au, the effect of the solar Lyα flux recalibration on the ISN H density becomes negligible. In consequence, the effect of variation of absolute calibration of $I_{\text{tot}}$ on H+ PUIs is less than 5% for distances greater than 10 au, and thus we can assume it is insignificant, especially at the TS.

3.3. Helioglow

Another quantity potentially affected by the changes of $I_{\text{tot}}$ and consequently of the radiation pressure, is the intensity of the hydrogen backscatter glow. The source function of the backscatter glow is proportional to the magnitude of the solar illuminating flux ($I_{\text{tot}}$) and the local density of ISN H, and inversely proportional to the square of solar distance. The helioglow intensity is a line-of-sight integral of the source function. Regions where the source function attains maximum values are located around ∼1.5 au upwind and ∼10 au downwind (see, e.g., Figure 10 in Ruciński & Bzowski 1995). This is largely outside the region strongly affected by the update of the solar flux model. Even though the relative change of the source function close to the Sun may be large (especially in the downwind region because of the large change of the density), its effect on the backscatter glow intensity is expected to be relatively small. A higher Lyα intensity increases the illumination of ISN H on the one hand, but on the other hand results in an increase of radiation pressure and a decrease of the density.

3.2. H+ PUIs

The change in the ISN H density influence also the H pick up ions (H+ PUI) density. The most affected are PUIs at distances where the ISN H density is the most altered. However, the H+ PUI density is greater than 10% of the H+ PUI density at the Termination Shock (TS) for distances greater than 1 au (Sokół et al. 2019), where the effect of the change of ISN H density due to the $I_{\text{tot}}$ change is negligible. In consequence, the effect of variation of absolute calibration of $I_{\text{tot}}$ on H+ PUIs is less than 5% for distances greater than 10 au, and thus we can assume it is insignificant, especially at the TS.
yet another aspect where radiation pressure might play an important role is the flux of ISN H at 1 au, which is sampled by IBEX (Saul et al. 2012; Galli et al. 2019; Rahmanifard et al. 2019). The flux vector is given by:

\[ \mathbf{F} = v_{pr} n_{pr} + v_{sc} n_{sc}, \]  

(2)

where \( v_{pr} \) and \( v_{sc} \) are the velocity vectors of the primary and secondary populations relative to the Sun, and \( n_{pr} \) and \( n_{sc} \) are their densities. In our previous paper (Kowalska-Leszczynska et al. 2018b), we analyzed the expected differences between the signal simulated using the radiation pressure model by Tarnopolski & Bzowski (2009) and that by Kowalska-Leszczynska et al. (2018a). We showed that the effect of this change of the radiation pressure model is clearly visible in the simulated signal. Here, we show a similar comparison for the transition from the IKL radiation pressure model based on the solar composite Ly\( \alpha \) flux Version 3 to Version 4. We made this estimate for the same IBEX-Lo observation seasons as Kowalska-Leszczynska et al. (2018b): for solar minimum (2010) and solar maximum (2014). The results are shown in Figures 6 and 7, respectively. The first panels in these figures present the IBEX-Lo flux based on Version 3 (the gray dashed line) and Version 4 (the blue solid line). The second panels present the ratio of these quantities. The third and fourth panels show the differences in relative speeds and energies at IBEX-Lo, respectively. The aforementioned quantities are shown for individual IBEX orbits as a function of the IBEX spin angle.

The change in the total flux observed by IBEX results from the change in the absolute flux of ISN H relative at Earth’s orbit. We show the ratios of the fluxes obtained from the old and new model of radiation pressure in the last panel of Figures 6 and 7. This illustrates that IBEX samples ISN H in a region where a change in radiation pressure by \( \sim 4\% \) results in...
a large change in the flux magnitude. This change is as much as 20%–25% at the beginning of the ISN observation season to 10% in the region of Earth’s orbit where the ISN H flux maximum is observed. On the other hand, while the change in flux magnitude is relatively large in comparison with the change in radiation pressure, the direction of the flow is changed relatively little, by less than 1.5°.

The differences in the flux are largest for the early orbits during the yearly observation seasons, where mostly the secondary ISN H population is observed. However, in this region, there is a dominant component of the secondary He population (Kubiak et al. 2014), and the H component has not been clearly identified so far. The magnitude of the ISN H flux differences can be assessed by an inspection of the second panel, where a ratio of the fluxes is shown. During solar minimum, the change due to the modification in radiation pressure model varies within (+10%, −5%). During solar maximum, the change is larger, but the magnitude of the flux has so far precluded its clear detection (Saul et al. 2013; Galli et al. 2019). Changes in the relative speed and, consequently, in the relative energy are within 0.5 km s⁻¹ and ∼0.4 eV and are almost negligible.

Throughout the IBEX observation interval (starting at the beginning of 2009), the Version 4/Version 3 ratio of \( I_{\text{tot}} \) is almost constant. Therefore, this study illustrates the sensitivity of the flux of ISN H to radiation pressure well. As shown by Galli et al. (2019), ISN H is best visible late during the yearly observation season, when the Earth with IBEX is at ecliptic longitudes of 175°–200°. Within individual orbits, the flux difference varies systematically from ∼ +5% to ∼ −5% and again back to ∼ +5% during solar minimum conditions. This suggests that there is an almost 1:1 sensitivity of the observed ISN H flux to small variations in radiation pressure. This sensitivity during solar maximum is of a similar magnitude, even though the behavior of the Version 4/Version 3 flux ratios is more complex.

### 3.5. ISN D

Since the line profile for deuterium is just shifted in radial velocity due to the isotope effect and scaled in the magnitude of radiation pressure due to the mass difference, all above considerations apply to that element as well. The simulated density of deuterium is very small (Tarnopolski &
Bzowski 2008), and the expected flux at IBEX combined with detection efficiency results in an expected yearly count of detected D atoms at IBEX of just several atoms (Kubiak et al. 2013). Therefore, we will not show detailed a analysis of ISN D here. The radiation pressure model parameters for D are listed in Table 2.

4. Summary and Conclusions

Following an update in the absolute calibration of the composite solar Lyα flux (Machol et al. 2019), we re-evaluated the parameters of the IKL model of solar radiation pressure acting on H and D atoms in the heliosphere (Kowalska-Leszczynska et al. 2018a). The new values of the model coefficients are listed in Table 1 for H and Table 2 for D. The updated flux (Figure 1) is changed by ±10%, with occasional spikes to ±20%. After ~2005, the change in I_sat is by an almost constant factor of ~4%. In the radiation pressure model, the change mostly affects the coefficients responsible for the total height of the profile and for the depth of the central reversal. In general, the contrast between the magnitudes of radiation pressure during solar maximum and minimum is slightly reduced.

We studied the effect of the change in radiation pressure on the distribution of ISN H density inside 10 au from the Sun and on the ISN H flux at 1 au observed by IBEX-Lo. The change in the simulated density may reach as much as 50% (at 1 au downwind) but is typically much less and fades quickly with increasing solar distance. The IBEX-Lo signal is affected by ~10% or less, but in the regions of the Earth orbit where the ISN H signal has been identified, the variation is on the level of ±5%. The magnitude of the variation varies from one orbit to another and with the spacecraft spin angle.

While the changes due to the new calibration of the composite Lyα flux are mild and only affect regions inside a few au, we recommend adopting the new model of radiation pressure in the heliospheric research, which can be easily implemented and only requires replacing the parameters given by Kowalska-Leszczynska et al. (2018a) with those listed in Table 1 for H and Table 2 for D.

This analysis can be regarded as a study of the sensitivity to ISN H to variations in radiation pressure. In this respect, a most favorable comparison interval starts in 2005, when the change in radiation pressure is by an almost constant factor of 1.04. We showed that this sensitivity increases with decreasing distance from the Sun and from the upwind direction toward downwind, as shown in Figure 5.

The authors would like to kindly thank Janet Machol and Martin Snow for providing access to a preprint of their manuscript before it was published. This study was supported by National Science Center, Poland, grants 2018-31-D-ST9-02852 and 2015-19-B-ST9-01328. J.M.S. work was supported by the NAWA Bekker Program Fellowship PPN/BEK/2018/1/00049.

ORCID iDs

Izabela Kowalska-Leszczynska @ https://orcid.org/0000-0002-6569-3800
Maciej Bzowski @ https://orcid.org/0000-0003-3957-2359
Marzena A. Kubiak @ https://orcid.org/0000-0002-5204-9645
Justyna M. Sokół @ https://orcid.org/0000-0002-4173-3601

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