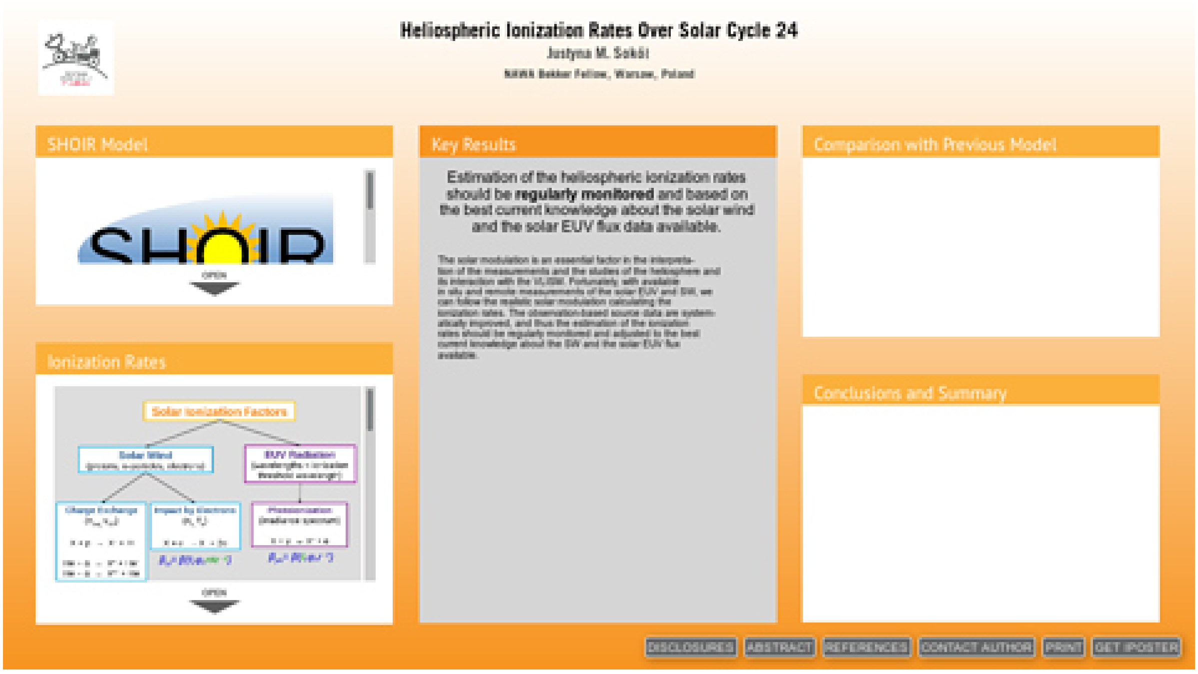
Heliospheric Ionization Rates Over Solar Cycle 24



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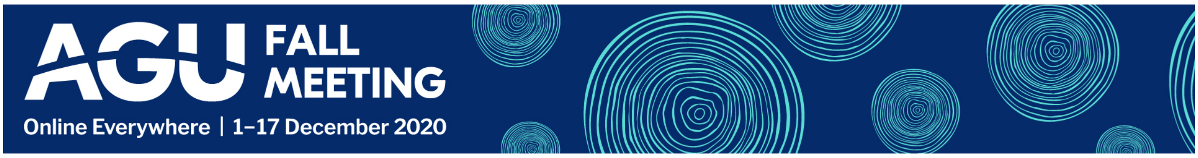


SHOIR IN SC 24

In Solar Cycle 24 (SC 24) happened several revisions and new releases of solar wind and solar EUV data,

which are used to estimate ionization rates for interstellar particles inside the heliosphere. The changes are because of various reasons and collectively affect estimation of the ionization rates. Here, we present the most recent estimates of ionization rates for SC 24.

Sokół et al. 2020 (https://doi.org/10.3847/1538-4357/ab99a4) discuss in detail the data revision for the past solar cycles and provide a full descirption of

SHOIR (Sun–Heliosphere Observation-based Ionization Rates)

model to estimate ionization rates for interstellar particles inside the heliosphere. SHOIR model allows us to calculate ionization rates for H, He, Ne, and O. It uses available solar data, which are regularly revised to account for solar modulation of the ionization rates as accurately as possible. This includes the measurement-based in-ecliptic variations of the solar wind based on OMNI (https://omniweb.gsfc.nasa.gov/ow.html) data collection, and in-ecliptic variations of solar EUV flux measurements based on TIMED (https://lasp.colorado.edu/home/see/) and solar EUV proxy data. SHOIR also includes the latitudinal variations of the solar wind from 1985 onward using the solar wind speed determined from the interplanetary scintillation (IPS) observations by ISEE (http://www.isee.nagoya-u.ac.jp/en/).

The in-ecliptic solar wind

speed and density remain more or less stable during the first half of SC 24 and increase during the second half slightly, as shown in Figure 1. Alpha-to-proton abundance follows the variation of the solar activity, increasing during ascending phase and decreasing during descending phase of the solar activity.

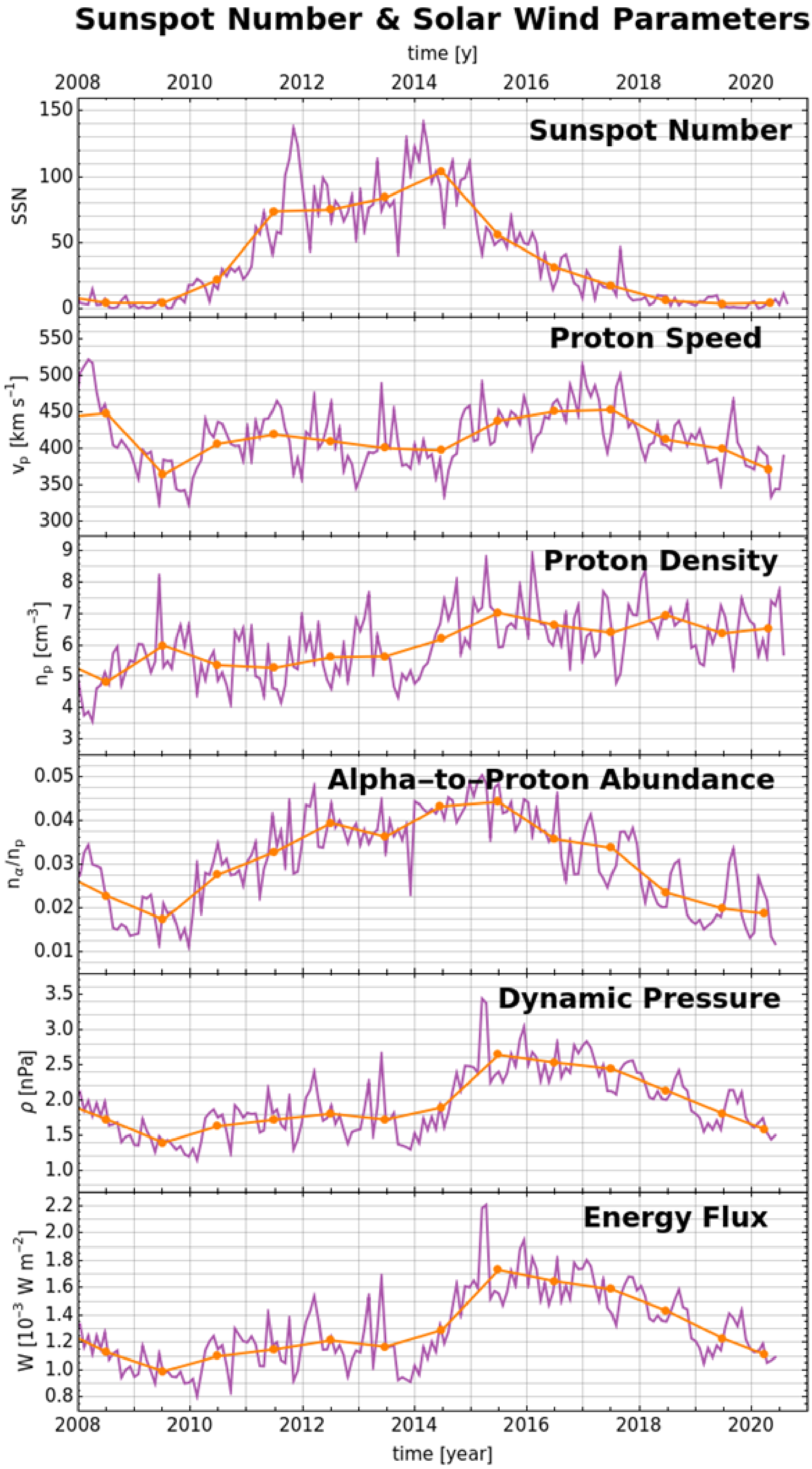


Figure 1 Time series of sunspot number (http://www.sidc.be/silso/home) and in-ecliptic solar wind parameters at 1 au during SC 24. Purple lines present Carrington rotation averages and orange lines yearly averaged data.

The solar wind latitudinal structure

was bimodal, with slow and dense solar wind around the solar equator, and with fast and less dense flows at higher latitudes at the beginning of SC 24 (see Figures 2 and 3). As the activity increased, the slow and dense solar wind flows were present at all latitudes. After the solar maximum, which lasted longer in the northern hemisphere than in the southern, the latitudinal structure returned to the bimodal configuration.

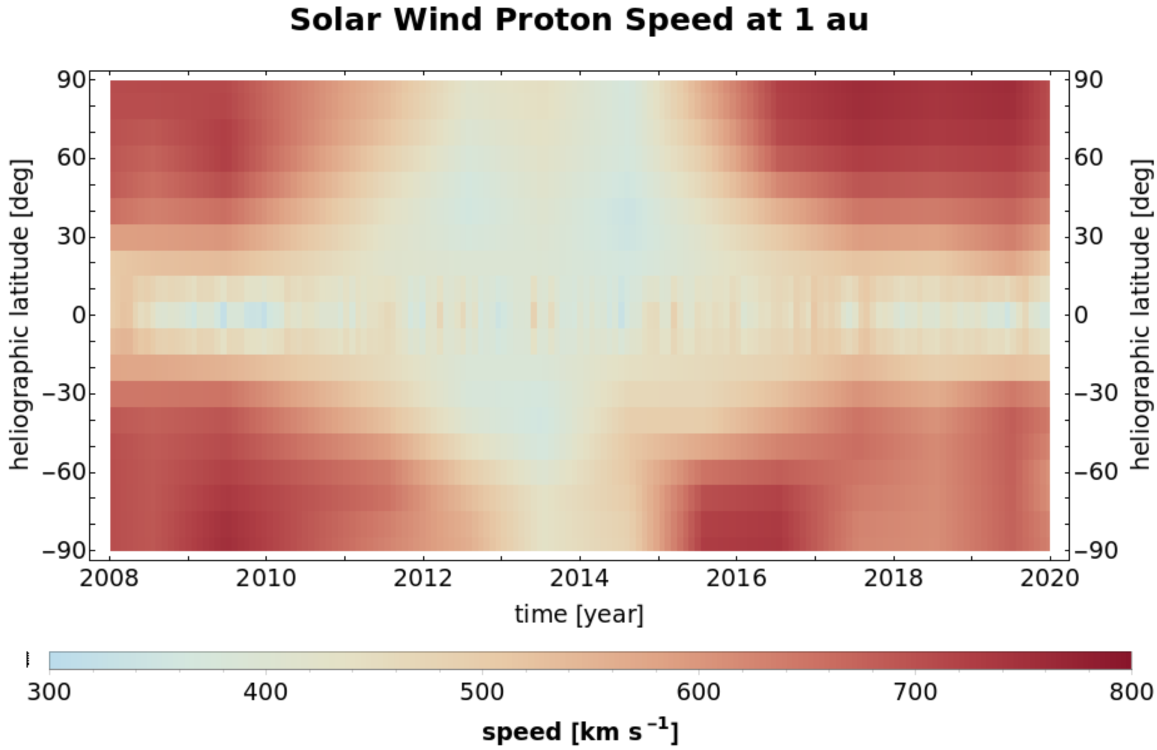


Figure 2 Solar wind proton speed variations in latitude and time at 1 au in SC 24.

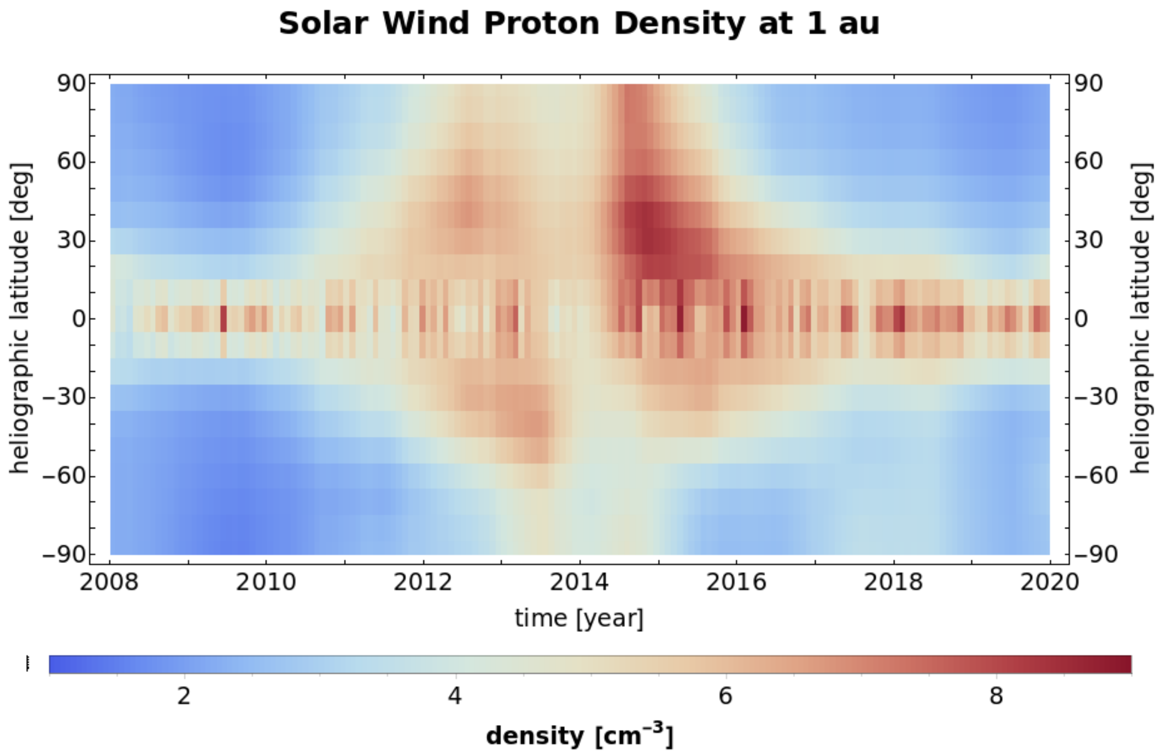
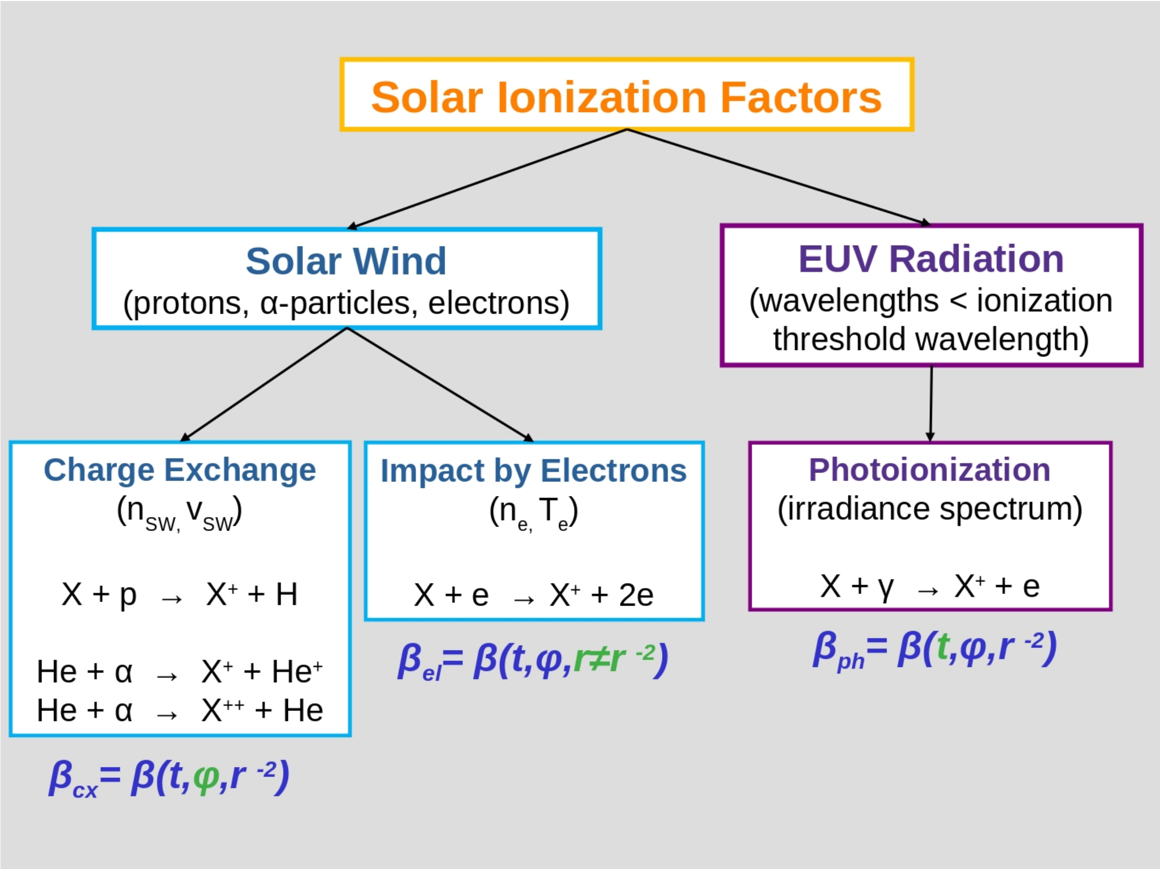


Figure 3 SHOIR-reconstructed solar wind proton density variations in latitude and time at 1 au in SC 24.

IONIZATION RATES



We consider two sources of ionization reactions for the interstellar atoms inside the heliosphere:

1) interaction with the solar wind particles, and 2) ionization by the extreme ultraviolet (EUV) flux (β_{ph}). Solar wind protons and α-particles charge exchange (β_{cx}) with the interstellar atom, while solar wind electrons knock out the electron from it (β_{el}).

Thus Heliospheric Ionization Rates = $\beta_{cx} + \beta_{ph} + \beta_{el}$

The ionization rates change with the solar activity,

resulting in variations in time (t). These variations result from a changing distribution of active regions on the solar surface and thus lead to variations in heliographic latitude (φ). Watch Figure 4 to compare changes of the solar surface with the latitudinal variations of the solar wind speed. As the solar wind and solar EUV fluxes move away from the Sun, the ionization rates decrease with the distance (r). The SHOIR model reconstructs the modulation of the charge exchange rates in heliographic latitude by tracking variations of the solar wind speed and density.

Movie

Figure 4 Variations of the solar surface visible in 304Å compared with latitudinal variations of the solar wind speed during SC 24. ***Please note that this is an exemplary animation, for a comprehensive discussion of the relation of solar wind changes with the solar activity, a magnetic field needs to be included.***

Different species of interstellar atoms are prone to different ionization processes.

Charge exchange with solar wind protons is dominant ionization reaction for hydrogen; photoionization is the most effective ionization process for helium and neon. Oxygen is prone to both charge exchange and photoionization. Figure 5 presents fractional contribution of individual ionization processes to the total ionization rates for H, O, Ne, and He in SC 24.

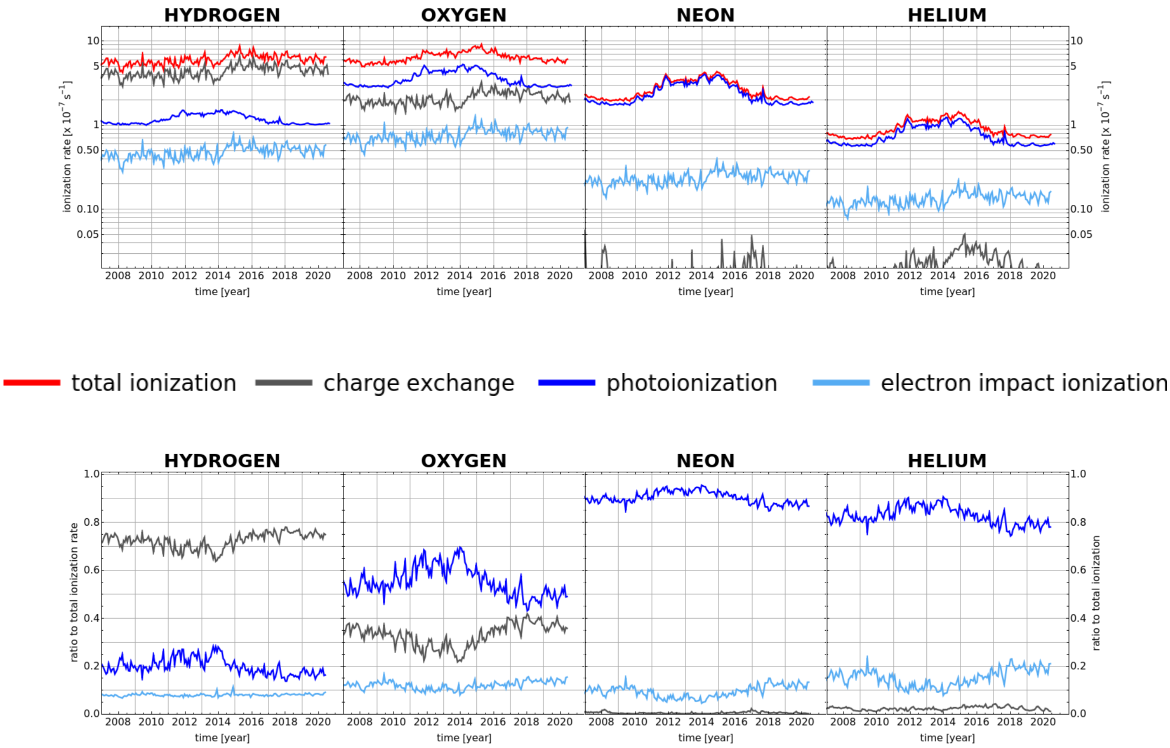


Figure 5 Top: SHOIR-calculated individual and total ionization rates for H, O, Ne, and He in the ecliptic plane at 1 au in SC 24. Bottom: Fractional contribution of different ionization processes to the total ionization rates for a given species.

See Sokół et al. 2019 (https://doi.org/10.3847/1538-4357/aafdaf) to find out more about the heliospheric ionization rates and get helpful references, and also check the recent revision by Sokół et al. 2020 (https://doi.org/10.3847/1538-4357/ab99a4).

KEY RESULTS

Regular monitoring of solar wind and solar EUV flux data assures accurate estimation of heliospheric ionization rates.

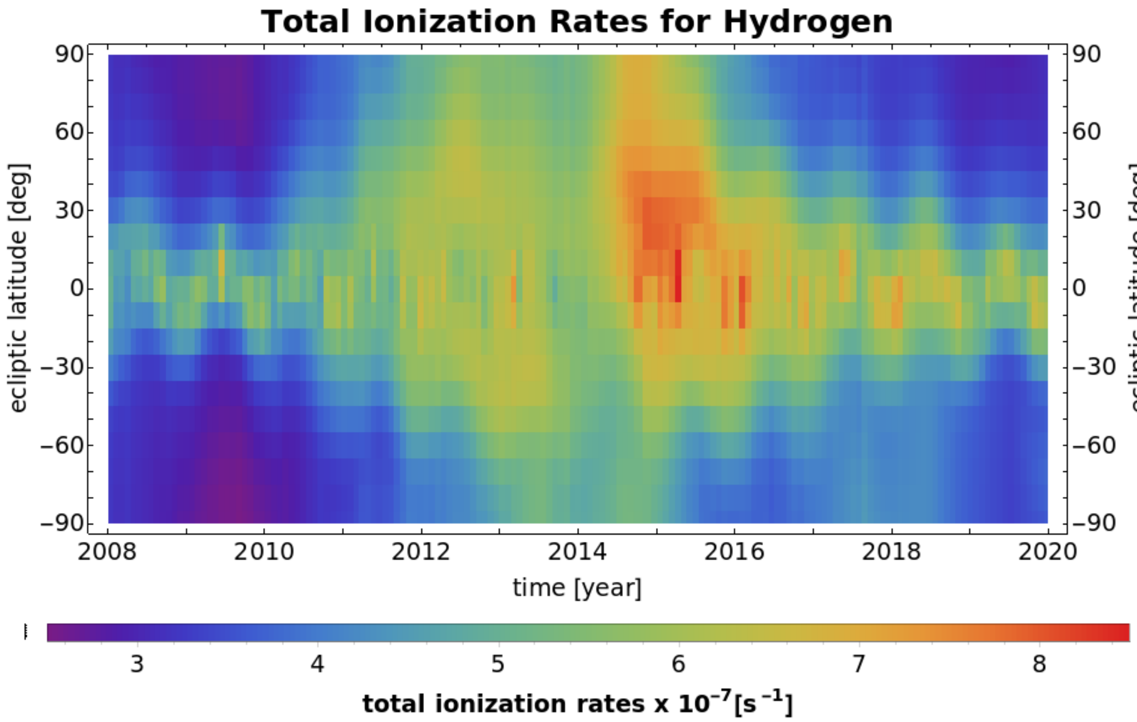


Figure 6 SHOIR-calculated latitudinal variation of the total ionization rates for H at 1 au in SC 24.

The solar modulation is an essential factor in interpreting measurements of interstellar gas (e.g., Galli et al. 2019 (https://doi.org/10.3847/1538-4357/aaf737)), energetic neutral atoms (e.g., McComas et al. 2020 (https://doi.org/10.3847/1538-4365/ab8dc2)), pickup ions (e.g., Sokół et al. 2016 (http://dx.doi.org/10.1093/mnras/stw515), Sokół et al. 2019 (https://doi.org/10.3847/1538-4357/ab21c4)) and the studies of the heliosphere and its interaction with the local interstellar medium (e.g.,Swaczyna et al. 2016 (http://dx.doi.org/10.3847/0004-637X/827/1/71), Zirnstein et al. 2020 (https://doi.org/10.3847/1538-4357/ab8470)). We can follow the solar modulation calculating the ionization rates with available in situ and remote measurements of the solar factors.

Interstellar hydrogen is the most affected by the solar environment inside the heliosphere.

In Figure 6 we present the total ionization rates for H as a function of time and ecliptic latitude in SC 24. The highest ionization rates are during the solar maximum in 2015 in the northern hemisphere. This asymmetry reflects the North-South asymmetry of the solar wind structure (see Figures 2 and 3).

As illustrated in the top panel of Figure 7, the total ionization rates for H in the northern hemisphere were almost equal to the in-ecliptic values for nearly three years while in the souther hemisphere for less than a year. The smallest ionization rates are in the higher latitudes during the solar minimum. The polar ionization rates were smaller at the beginning of the SC 24 than at the end.

In Figure 7 you can also see a comparison of the total ionization rates for H, O, Ne, and He at 1 au during SC 24 for two polar directions and in the ecliptic plane.

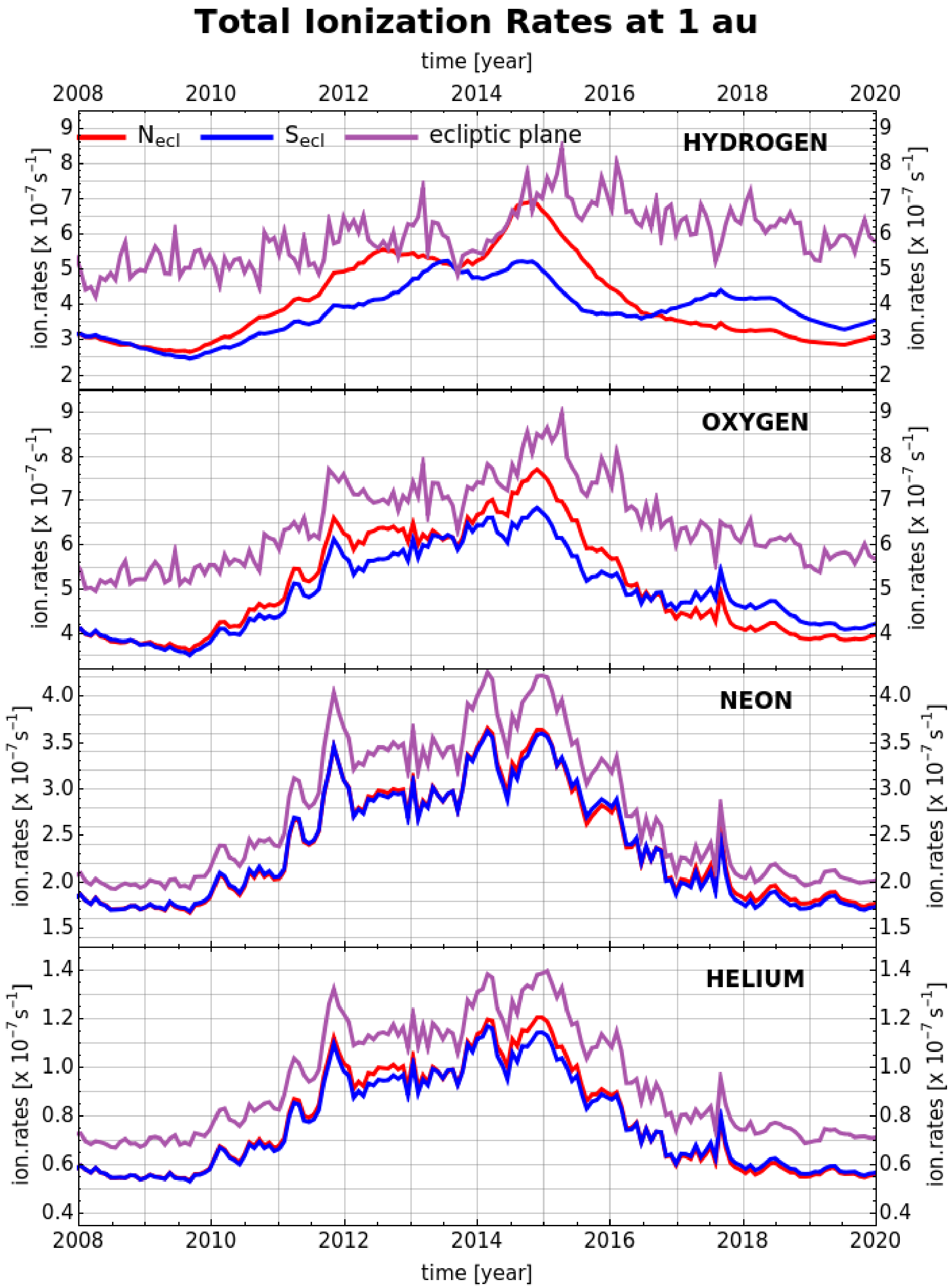


Figure 7 SHOIR-calculated total ionization rates for H, O, Ne, and He at 1 au during SC 24 for three directions (see legend in the top panel).

COMPARISON WITH PREVIOUS MODEL

The revision of the solar source data changed the heliospheric ionization rates in and out of the ecliptic plane for less than 10% in case of helium to over 40% in case of hydrogen.

In consequence, H, Ne, and O were stronger ionized by the solar environment during SC 24 than we previously thought.

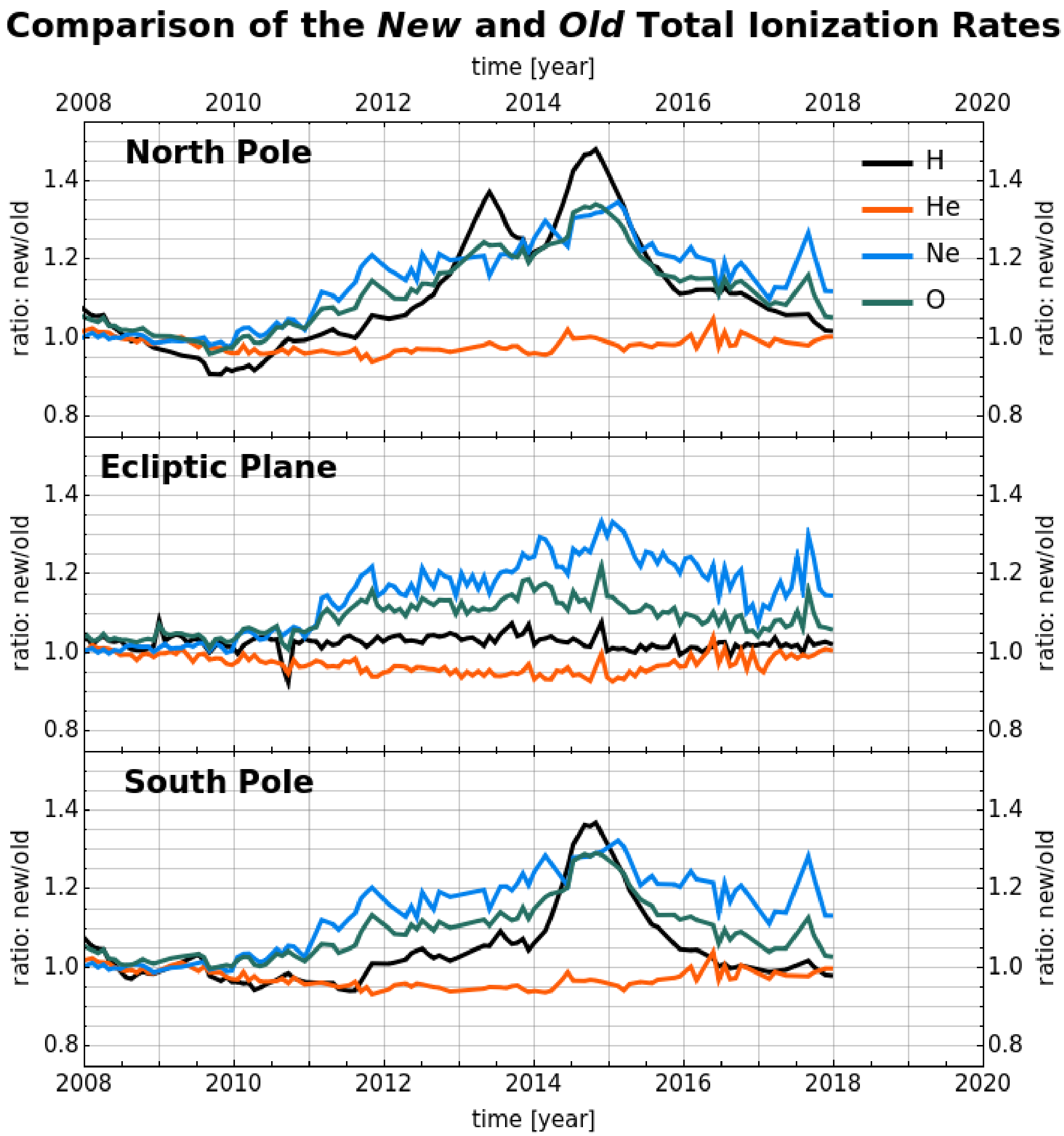


Figure 8 Time series of ratio of the total ionization rates at 1 au for various species, see legend in the upper right corner, after (the present version of SHOIR) and before the data revisions for SC 24. The directions are for the ecliptic coordinate system.

The current version of SHOIR includes:

– revised OMNI data collection released in 2019,

– revised IPS-derived solar wind speed latitudinal structure from 2010 onward,

– recent version of TIMED/SEE data (Version 12) to calculate the photoionization rates.

Figure 8 presents the ratio of the present, up-to-date, SHOIR-calculated total ionization rates to the ionization rates calculated with the previous model with solar data before the revisions. **The changes are the greatest in the high latitudes during the maximum of SC 24, the smallest during solar minimum are at the beginning of the cycle.** The newly estimated ionization rates are greater for all species in question but helium, for which the new rates are smaller than the previous ones.

CONCLUSIONS AND SUMMARY

Our study shows that **a change of the source data can significantly influence the estimation of the ionization rates**.

In SC 24, the data revision most affects the solar wind out of the ecliptic plane during the solar maximum and the estimate of the photoionization rates, the latter because of a change of the reference data. The changes are not constant and vary in time and in latitude.

In Sokół et al. 2020 (https://doi.org/10.3847/1538-4357/ab99a4) you can find out more about the best selection of the solar source data for calculation of the heliospheric ionization rates presently. The updates to the model are also available on the SHOIR website (https://jmsokol.helio.zone/SHOIR.html).

Thank you for your attention.

Feel free to ask questions, I will be happy to answer them.

DISCLOSURES

This study is a result of the project "Solar Cycle Modulation Of Pickup Ions And Energetic Neutral Atoms Throughout The Heliosphere" funded by the Polish National Agency for Academic Exchange (NAWA) Bekker Program Fellowship PPN/BEK/2018/1/00049 realized in the Department of Astrophysical Sciences at Princeton University.

ABSTRACT

Studying of solar ionizing environment for the interstellar plasma inside the heliosphere is an unavoidable aspect of the interpretation of the full solar cycle of IBEX observations. We present a recent revision of the observation-based model of the ionization rates inside the heliosphere discussed by Sokół et al. 2020 (ApJ 897:179). The solar wind (SW) and the extreme ultraviolet (EUV) radiation affect fluxes of interstellar atoms inside the heliosphere both in time and in space. We present a Sun–Heliosphere Observation-based Ionization Rates (SHOIR) model based on the SW and EUV data available in solar cycle 24. We revised the in-ecliptic variation of the SW parameters, the latitudinal structure of the SW speed and density, and the photoionization rates. The revision most affects the SW out of the ecliptic plane during solar maximum and the estimate of the photoionization rates, the latter because of a change of the reference data. The changes are not constant and vary in time and in latitude. Our study shows that the polar SW is slower and denser during the solar maximum of solar cycle 24, and that the current estimates of the total ionization rates are higher than the previous ones for H, O, and Ne, and lower for He. The changes for the in-ecliptic total ionization rates are less than 10% for H and He, up to 20% for O, and up to 35% for Ne compared to the previous estimates.

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