10 years of ISN Hydrogen measurements by IBEX-Lo

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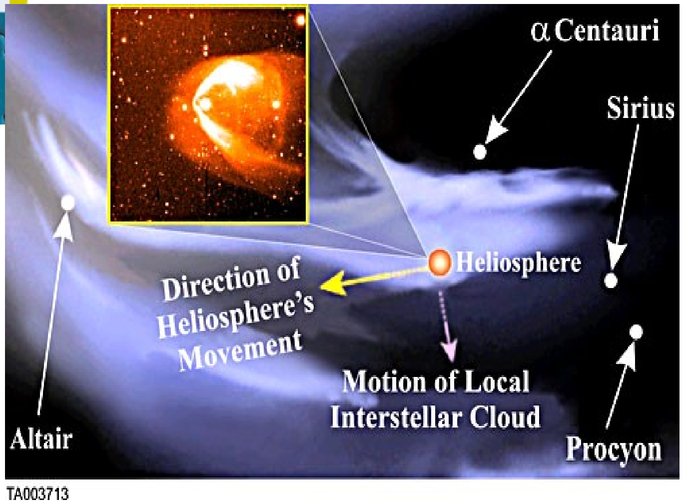
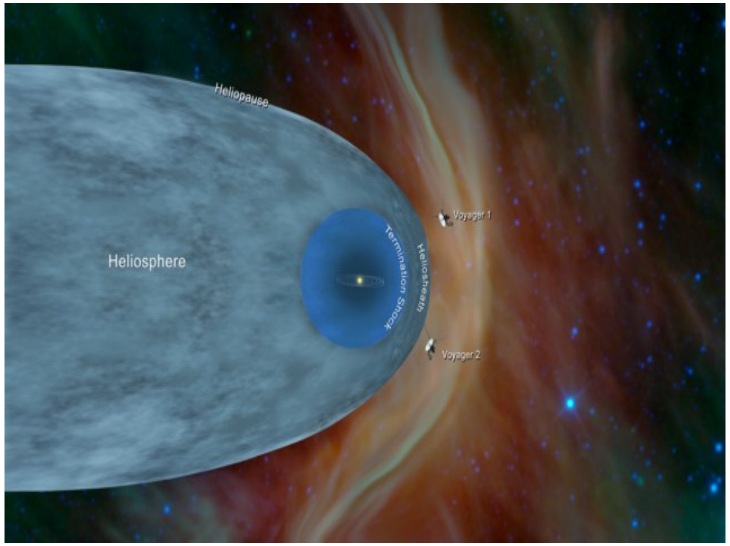
The Heliospheric puzzle





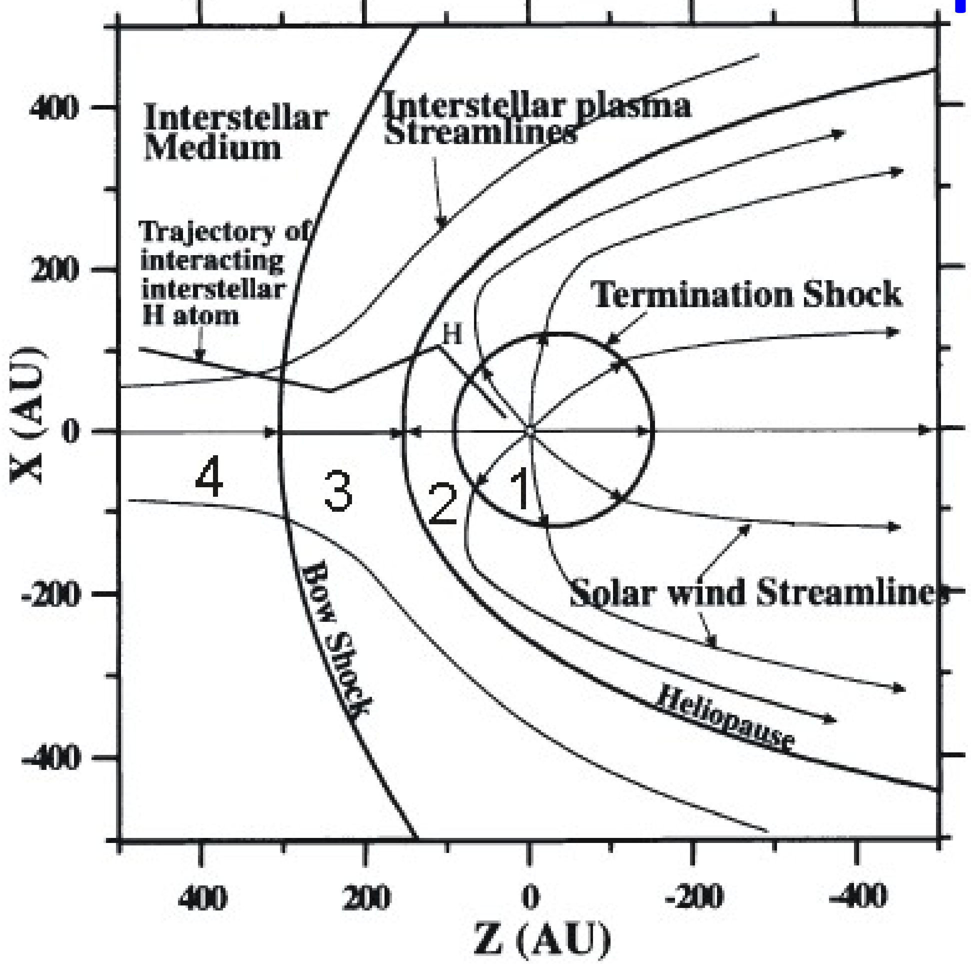
Local interstellar cloud: partially ionized hydrogen plasma (H, e, p, He etc.) with typical parameters:

T ~ 6700 K
$n_p \sim 0.02 - 0.1\ cm^{-3}$, $n_H \sim 0.1 - 0.2\ cm^{-3}$
V ~ 23-26 km/s =>
«interstellar wind»

Multi-component nature of the heliosphere:

- electrons and protons;
- interstellar neutrals (H, He, O); direct measurements by IBEX
- energetic particles (ACR, GCR, ENA);
- magnetic fields (heliospheric and interstellar);
- time-depended and 3D nature of the problem due to solar cycle and heliolatitudinal variations of the solar wind;

Interstellar hydrogen atoms inside the heliosphere



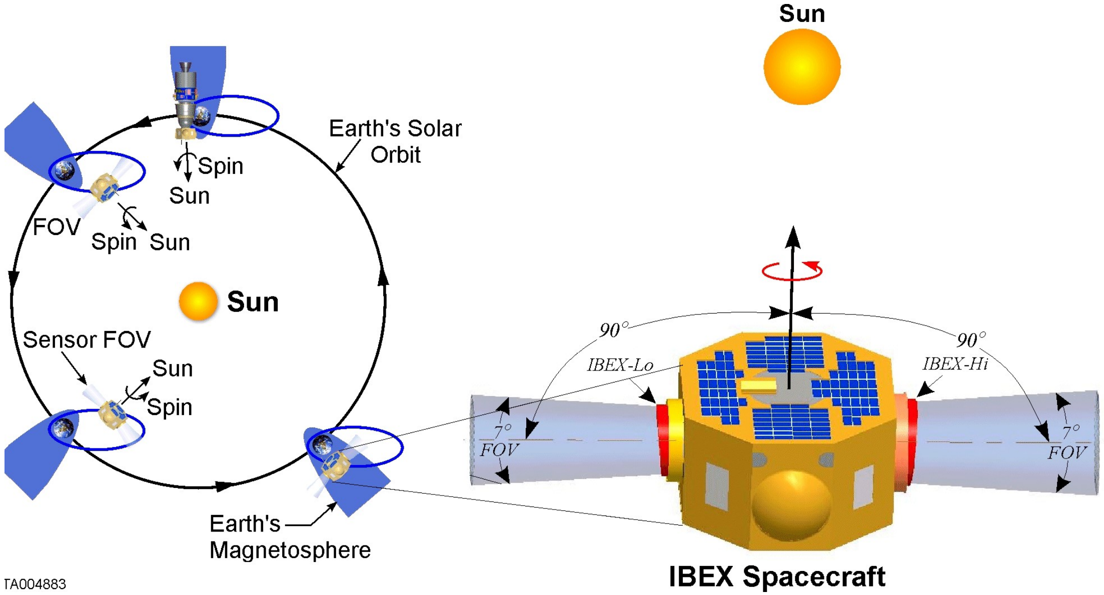
- ➢ Due to large mean free path H atoms penetrate deeply to the heliosphere, where they can be measured directly or indirectly.
- ➢The hydrogen atoms provide us information on the parameters of the LISM as well as on the properties of the heliospheric interface region.
- ➢ Detailed kinetic model of the velocity distribution function of hydrogen atoms is necessary to analyze the experimental data.

Charge exchange : $H + H^{+} = H^{+} + H$ - the main process of interaction between the neutral and charged components

Tools for diagnostic of H distribution inside the heliosphere are measurements of backscattered solar Lyman-alpha radiation and direct measurements by IBEX-Lo.

The Interstellar Boundary Explorer (IBEX)

is a NASA satellite in Earth orbit



<u>Launch</u>: 2008;

<u>Data:</u> from 2009 till now;

IBEX is dedicated to observe fluxes of the interstellar and energetic neutrals: H, O, Ne, He.

Geometry of IBEX measurements allows to obtain one full sky map during 0.5 year.

<u>The main goal of the mision:</u> remote sensing of the heliospheric boundary.

<u>Two detectors:</u>
IBEX-Hi (300 eV – 6 keV) - ENA;
IBEX-Lo (10 eV – 2 keV) – interstellar low energetic neutrals.

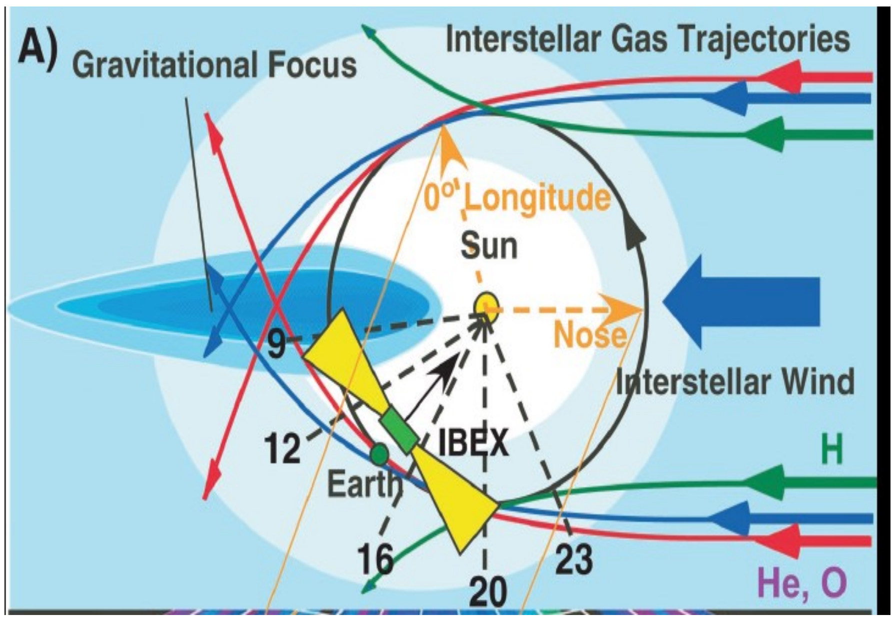
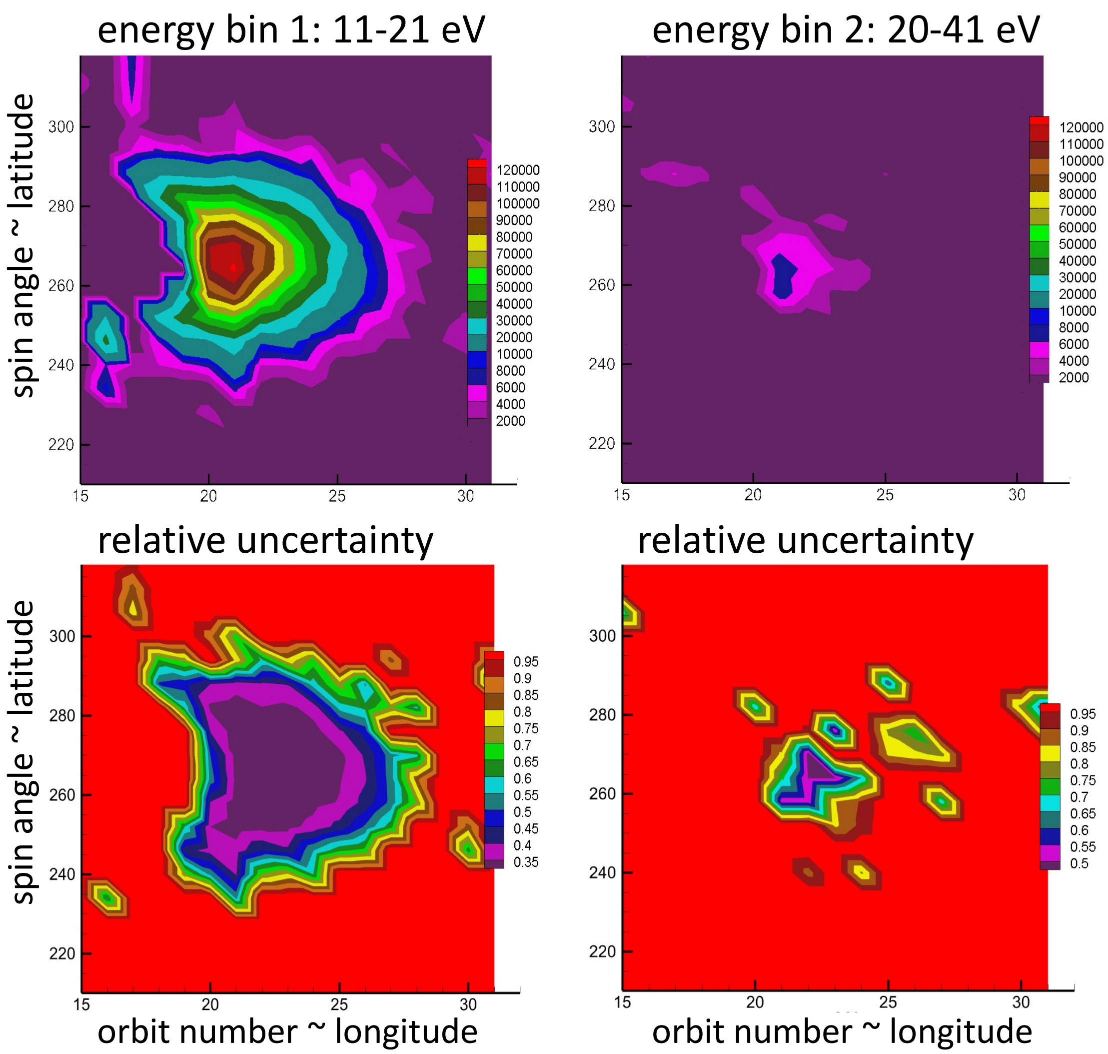


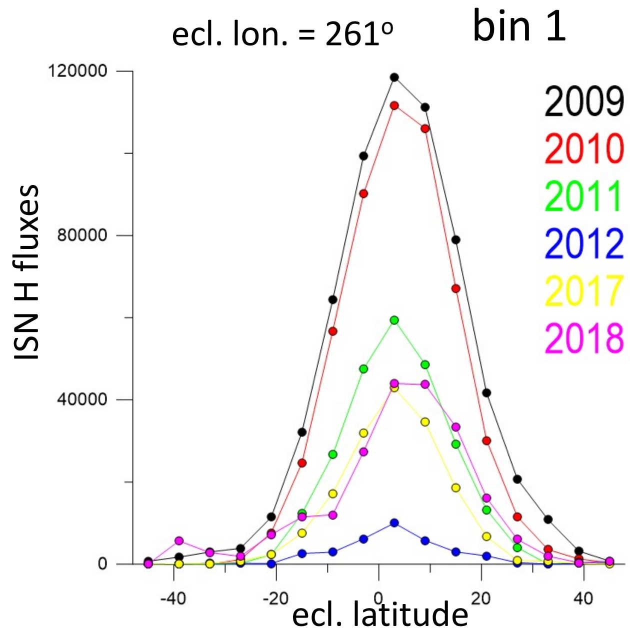
Fig. from Moebius et al., Science, 2009

Example of the IBEX-Lo data: ISN hydrogen fluxes at 1 AU [1/(cm2 sr s)] in 2009



- The ISN H data are cleaned from the signal of the ISN He atoms.
- The all data are presented and described by Galli et al., ApJ, 2019.

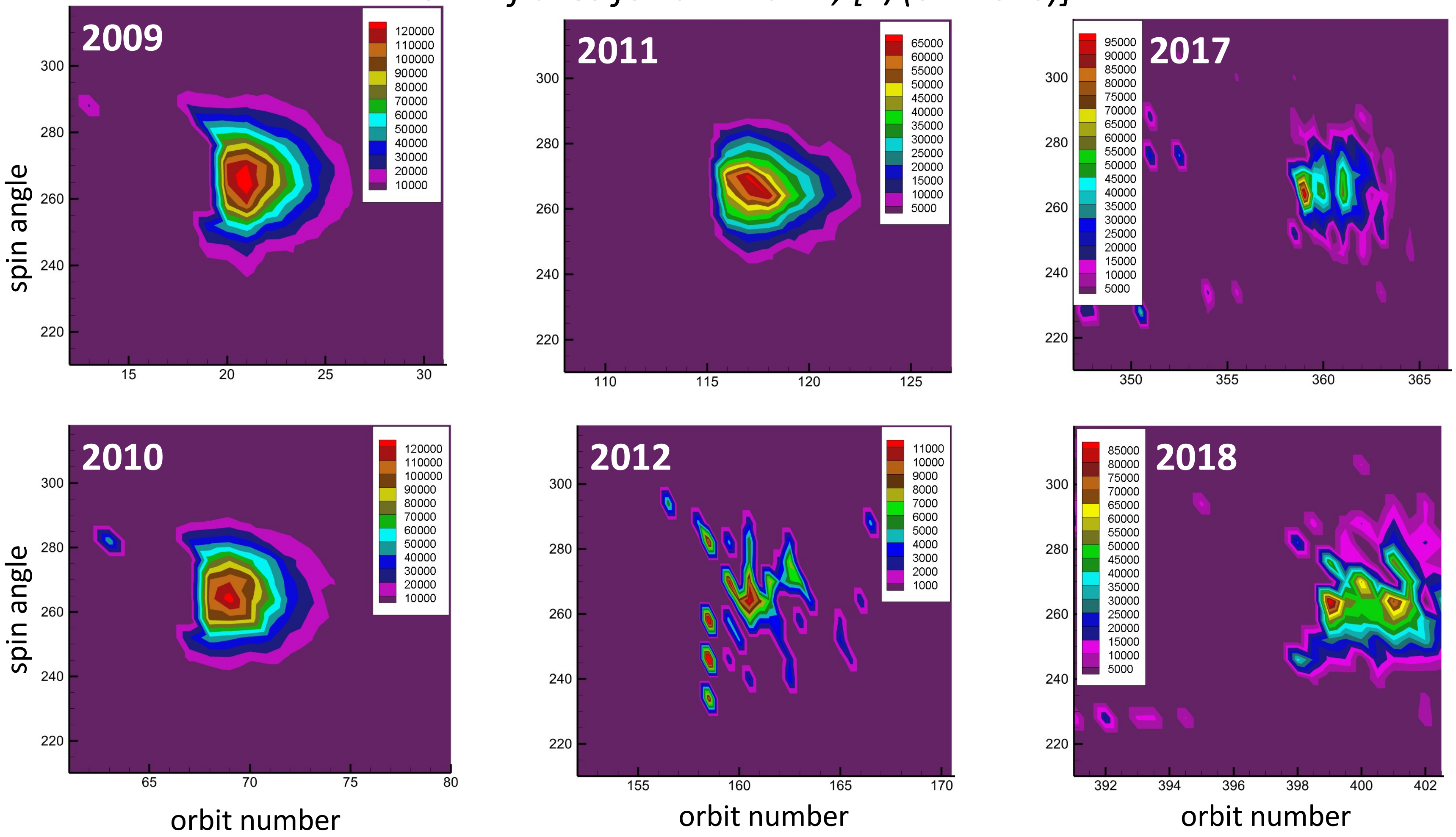
Temporal variations during solar cycle:



The considered data: 2009-2012 + 2017-2018

- We decided to consider the ISN H fluxes measured in energy bin 1 + bin 2 together (i.e. integrated over 11-41 eV);
- We consider only the directions where the relative uncertainty of the fluxes is less than 0.9;
- Mostly we consider the data in the primary format of orbit number and the spin angle, but sometimes for a better representation we consider the data rebinned to the format of ecliptic maps.

ISN H fluxes for bin1+bin2, [1/(cm2 sr s)]



3D time-dependent kinetic model of the H atoms distribution inside the heliosphere

Kinetic equation:

$$\boxed{\frac{\partial f(\mathbf{r},\mathbf{w},t)}{\partial t} + \mathbf{w}\cdot\frac{\partial f(\mathbf{r},\mathbf{w},t)}{\partial \mathbf{r}} + \mathbf{F}(r,\lambda,v_r,t)\cdot\frac{\partial f(\mathbf{r},\mathbf{w},t)}{\partial \mathbf{w}} = -\beta(r,\lambda,t)\cdot f(\mathbf{r},\mathbf{w},t)}$$

$$\boldsymbol{F} = \boldsymbol{F}_g + \boldsymbol{F}_{rad} = -\frac{G\cdot M_s\cdot(1-\mu)}{r^2}\cdot\frac{\boldsymbol{r}}{r} \qquad \mu = |\mathbf{F}_{rad}|/|\mathbf{F}_g|$$

$\mu=\mu(t,\lambda,v_r)$

$$\beta(r,\lambda,t) = (\beta_{ex,E}(\lambda,t)+\beta_{ph,E}(\lambda,t))\left(\frac{r_E}{r}\right)^2 = \beta_E(\lambda,t)\left(\frac{r_E}{r}\right)^2$$

λ – heliolatitude
v_r – radial velocity of atom
r_E=1 AU

Hydrogen distribution in the heliosphere is affected by:

*1. local effects that are important near the Sun (solar gravitation F_g, radiation F_{rad} and ionization β_E): **model is 3D and time-depended** due to detailed description of these effects;*

2. Kinetic effects of the heliospheric interface: boundary conditions at 70 AU: H distribution function at 70 AU is not Maxwellian and is taken from results of the self consistent kinetic-MHD model by Izmodenov & Alexashov, 2020.

Input parameters of the model

- **Charge exchange ionization rate: $\beta_{ex,E}$ (t,λ),** λ – heliolatitude;

  In the ecliptic plane $\beta_{ex,E}(t,\lambda=0)$ is calculated based on parameters of the solar wind that are known from OMNI database. Dependence on heliolatitude is derived from the SOHO/SWAN data (by Eric Quemerais & Dimitra Koutroumpa);

$$\beta_{ex,E}(t,0) = n_{p,E}(t) \cdot w_{sw,E}(t) \cdot \sigma(w_{sw,E})$$

$$\beta_{tot,E}(t,\lambda) = \beta_{tot,E}(t,0) \cdot \frac{\beta_{tot,SWAN}(t,\lambda)}{\beta_{tot,SWAN}(t,0)}.$$

$$\beta_{tot,E}(t,\lambda=0) = \\ = \beta_{ex,E}(t,0) + \beta_{ph,E}(t,0)$$

- **Photoionization rate: $\beta_{ph,E}$(t,λ)**;

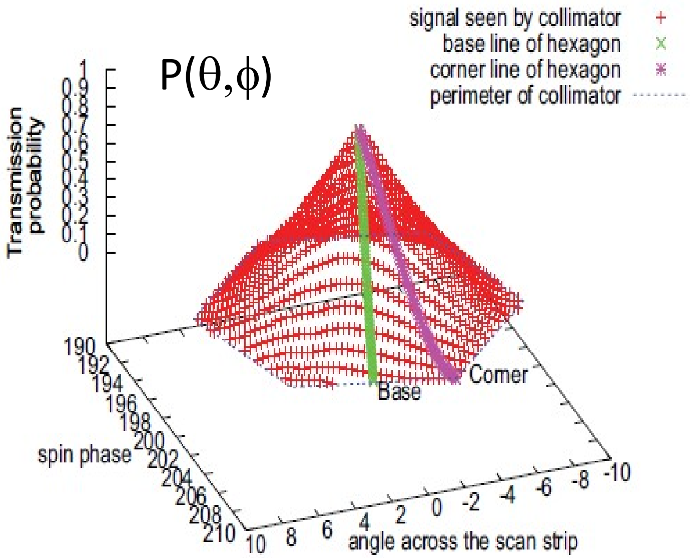
  dependence on time is based on data from the database SOLAR2000; dependence on λ is the same as for the charge-exchange rate;

- **Solar gravitation and radiation pressure: μ(t,λ,v_r);**

  $\mu(t,\lambda,v_r)$ is calculated from the solar Lyman-alpha flux (LASP Lyman-α composite, version 4, Machol et al., 2019) by using a formula proposed by Kowalska-Leszczynska et al. (2020);

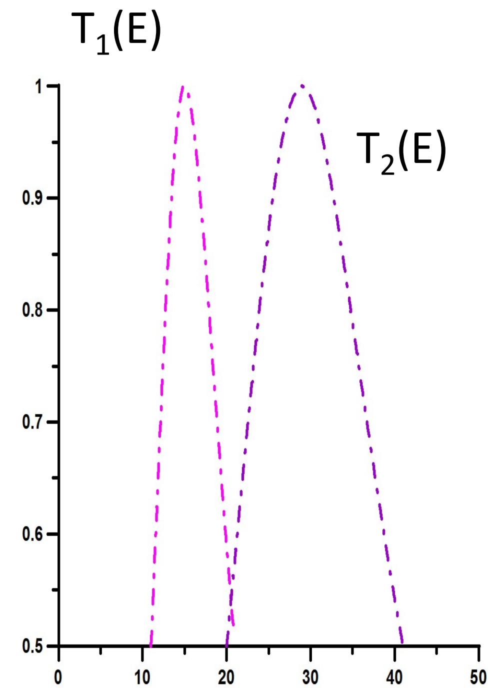
What do we need to take into account for modelling of the IBEX-Lo data

- real position and velocity of IBEX;
- real spin-axis orientation;
- collimator: point spread function: $P(\theta,\phi)$;
- energy transmission function: $T_{1,2}(E)$;
- spatial and temporal averaging of H fluxes by the same way as it is done for IBEX data (over 6-degree spin angle bin and over 7-8 days of orbit);



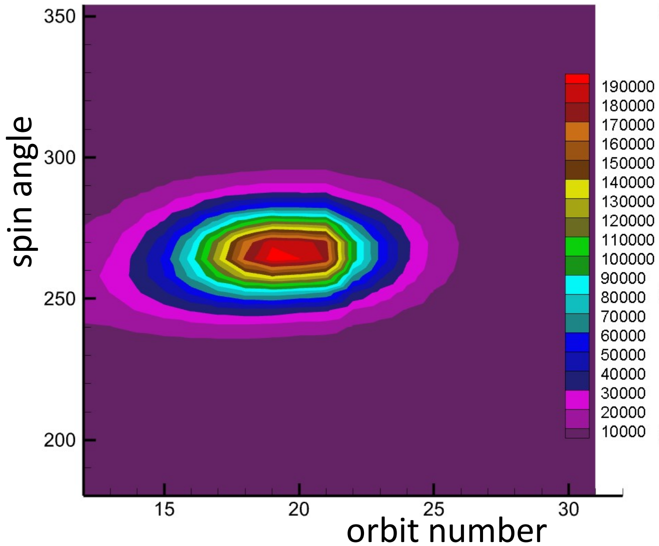
Calculation of the ISN H fluxes for energy bin i along the line-of-sight characterized by a spin angle α_j:

$$F_{i,j} = \frac{1}{\Delta t}\int_{t_0}^{t_1} dt\, \frac{1}{\Delta\alpha}\int_{\alpha_j-\Delta\alpha/2}^{\alpha_j+\Delta\alpha/2} d\alpha \quad \times$$
$$\times \int\int \hat{P}(\theta,\varphi)\, sin(\theta) d\theta\, d\varphi \quad \times$$
$$\times \int_{V_{i,1}}^{V_{i,2}} f_H(\mathbf{w}_H)\, |w_{rel}|^3\, E_{rel}\, \hat{T}_i(E_{rel})\, dw_{rel}.$$

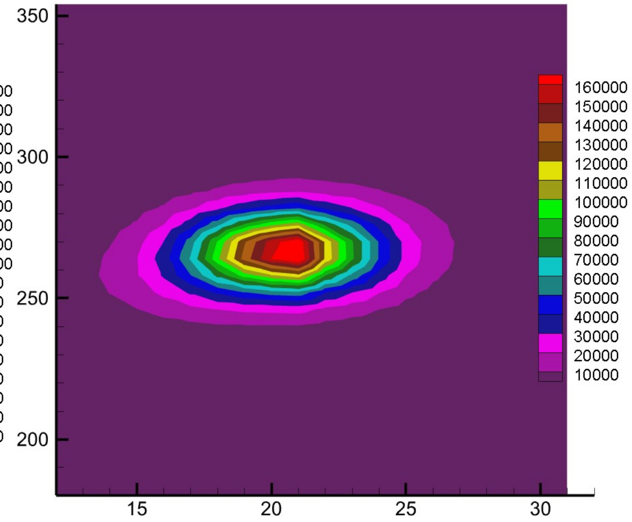


Model results: effect of μ on the ISN H flux maps (bin1+bin2, 11-41 eV)

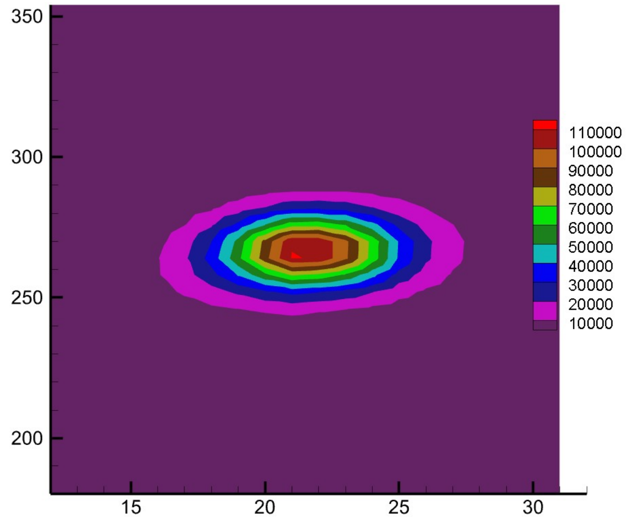
μ=0.8, β=4.d-7



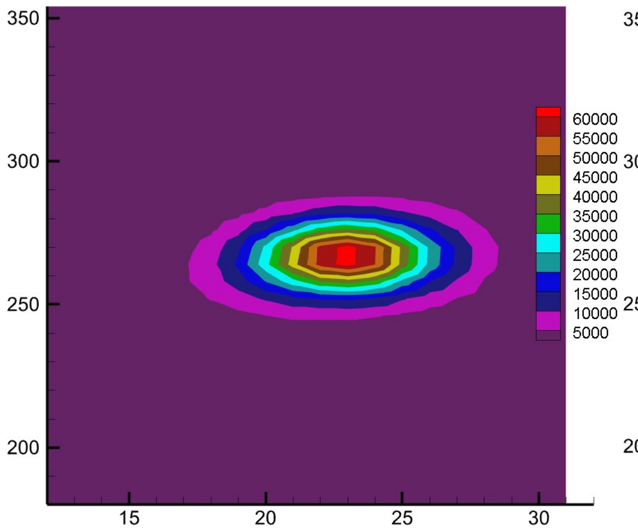
μ=0.999, β=4.d-7



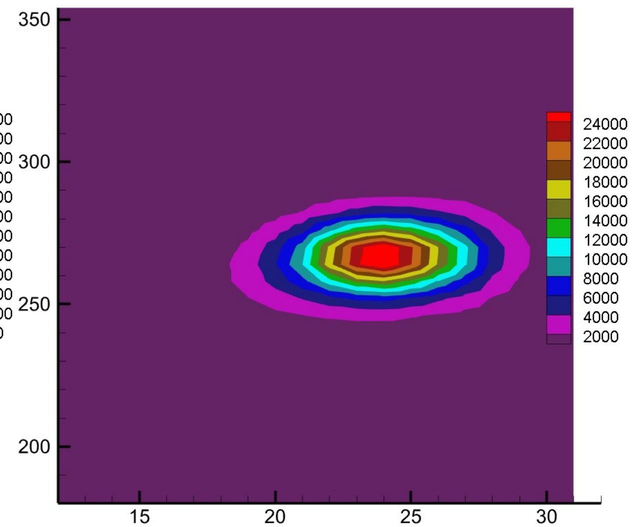
μ=1.2, β=4.d-7



μ=1.4, β=4.d-7



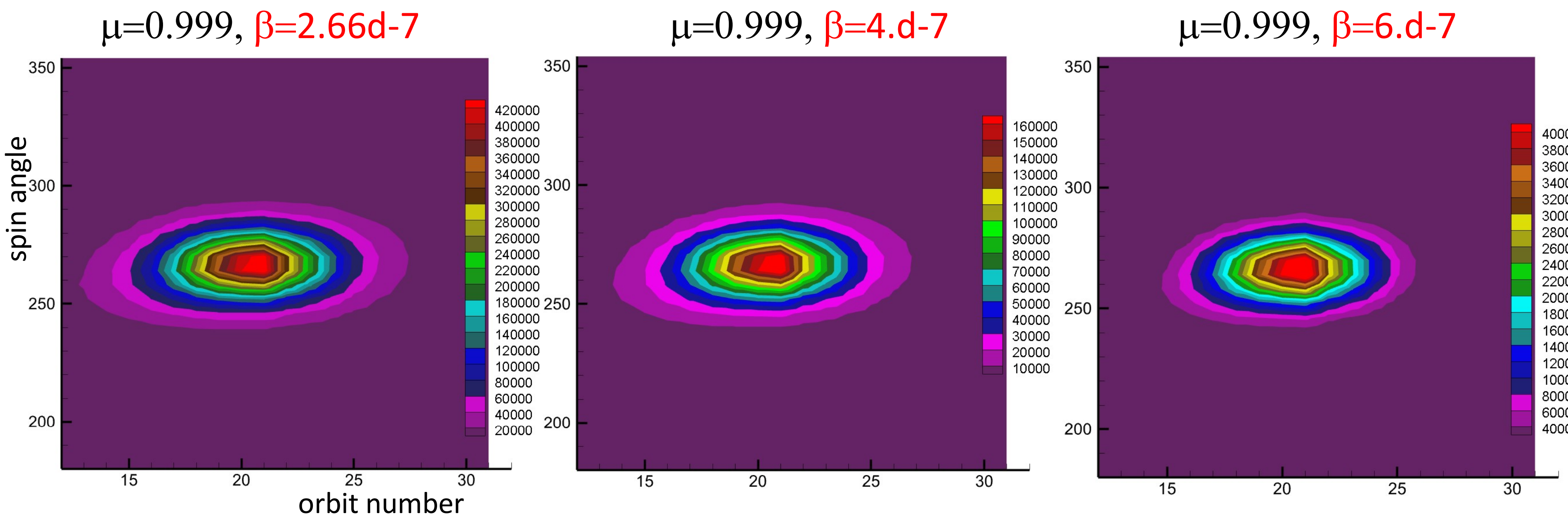
μ=1.6, β=4.d-7



<u>Increase of μ leads to:</u>

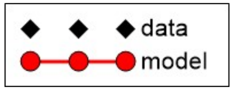
- shift of maximum to the right;
- decrease of the fluxes;
- shape of the map is about the same and does not depend on μ;

Model results: effect of β on the ISN H flux maps (bin1+bin2, 11-41 eV)

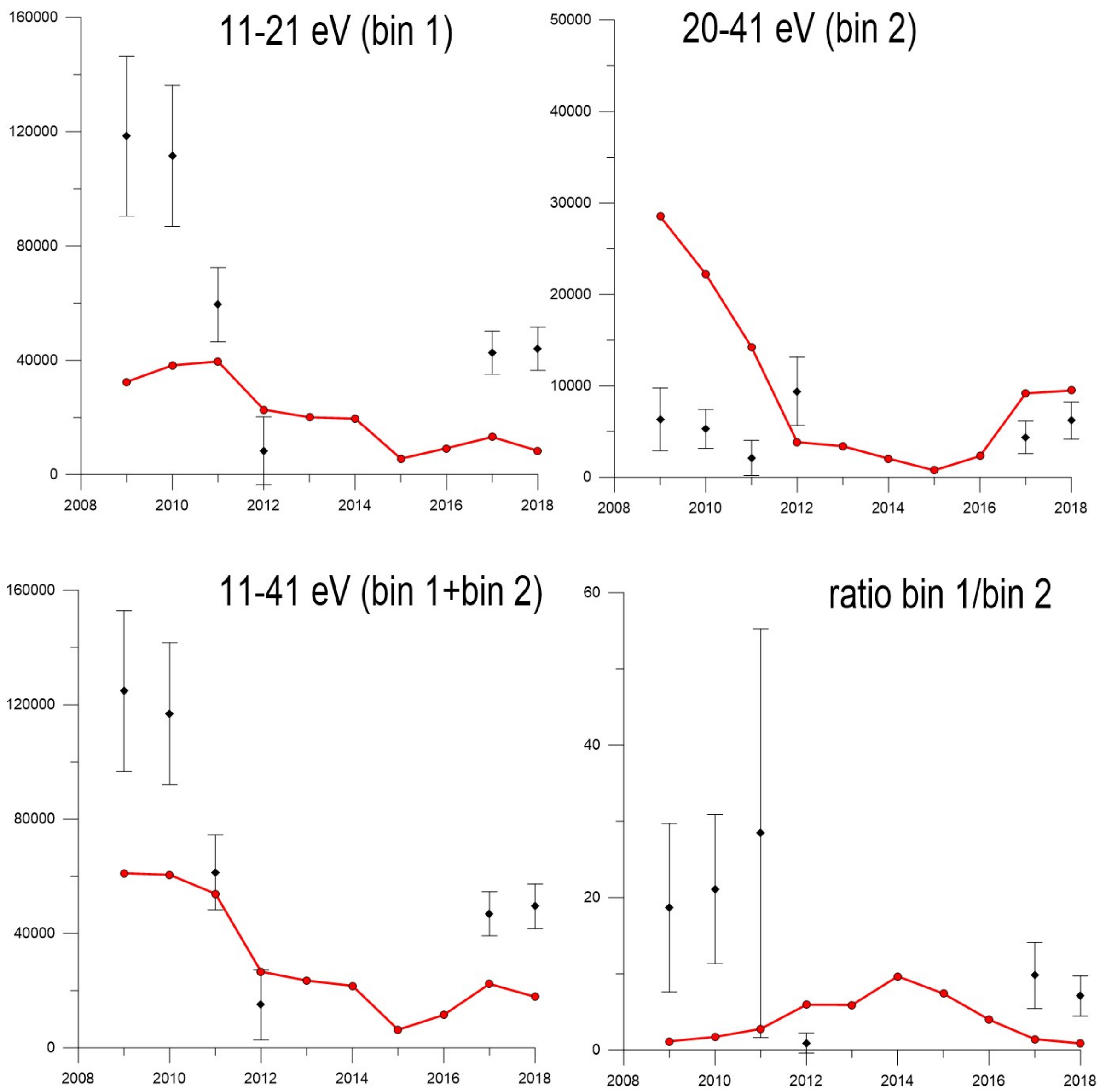


- increase of β by a factor of 2.25 leads to decrease of the fluxes by a factor of 10.5;
- increase of β does not change a shape of the map as well as position of the maximum;

Temporal variations of the ISN H fluxes



ISN H fluxes at the same direction (ecl. lon = 261°, ecl. Lat. = 3°) in 2009-2018:

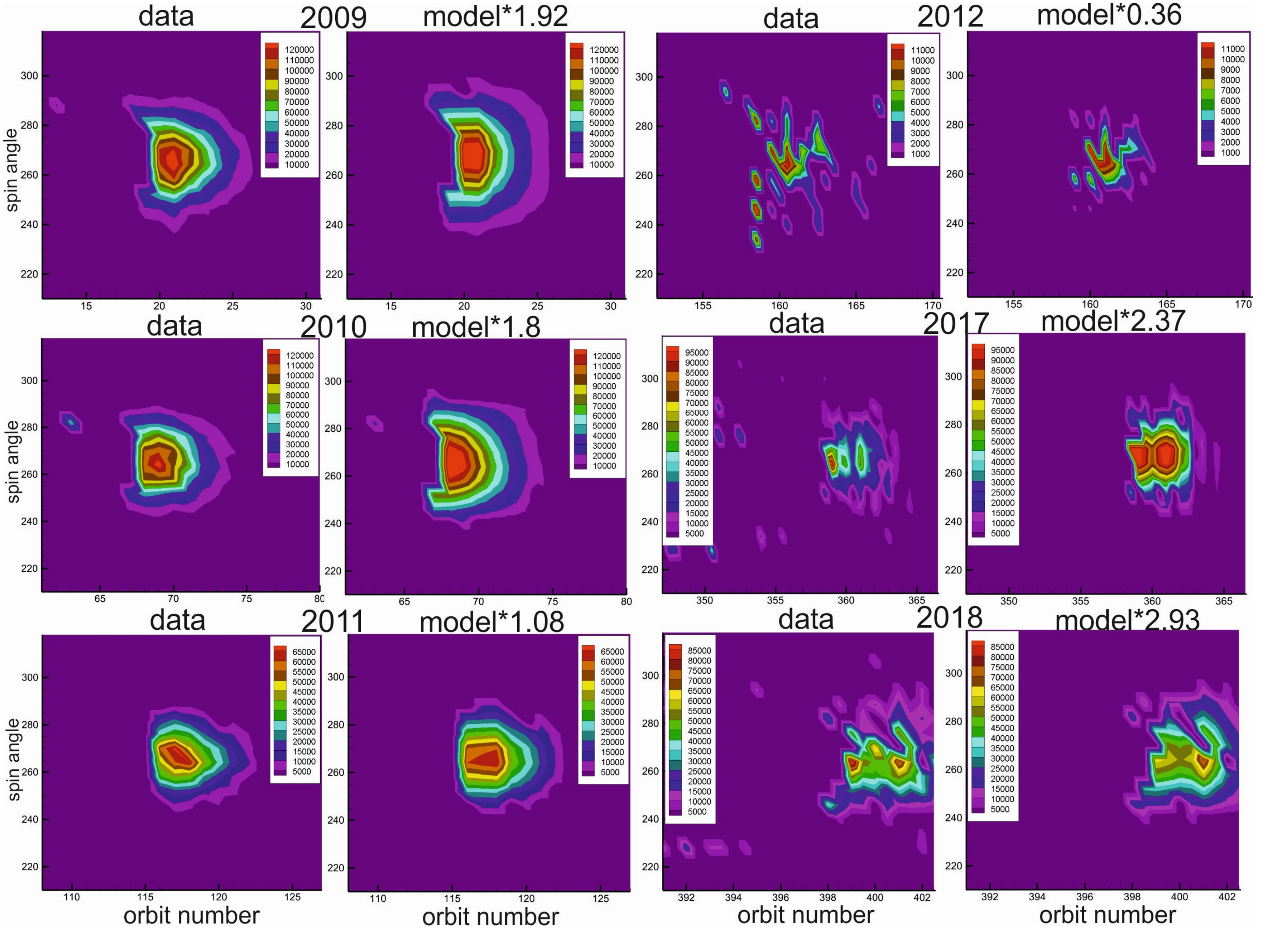


- ratio of fluxes in energy bin 1 to fluxes in energy bin 2 in the data is systematically larger than in the model (for 2009-2011 and 2017-2018) => probably there is a technical issue of dividing the fluxes between energy bins in the data. Therefore we decided to consider the mixture of fluxes in energy bin 1 and 2;

- for bin1+bin2 temporal variations of the fluxes are qualitatively the same in the data and in the model, but quantitative difference is a factor of 2-3.

Comparison between the data and the model results

The model results are multiplied by a factor of flux_max_data / flux_max_model for each year:

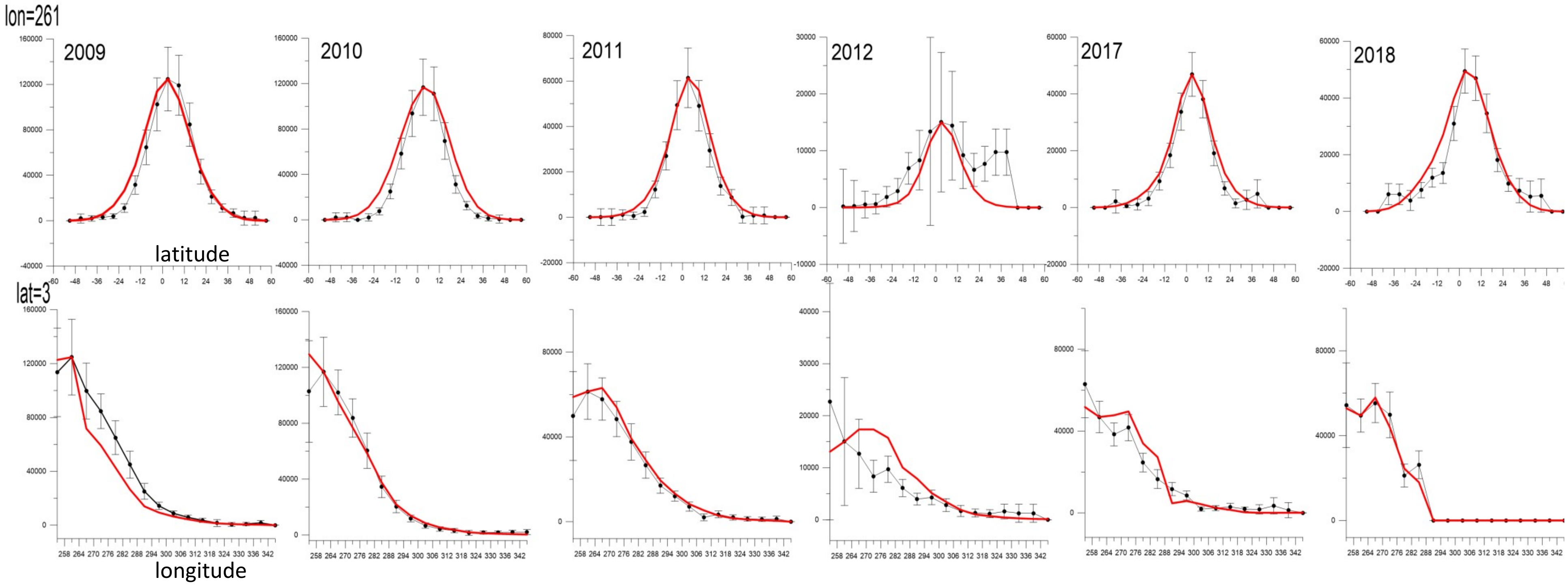


1D slices in ecliptic coordinates

(longitude = 261^{o} and latitude = 3^{o})

Data

Model (multiplied by the same factor as in previous slide)



Fitting of the data by varying μ_0 and β_0 in the model

- $\mu(t,v_r,\lambda)=\mu_0*F_{kow}(t,v_r,\lambda)/F_{kow}(t,v_r=0,\lambda)$, F_{kow} is a function from Kowalska-Leszczynska et al. (2020);

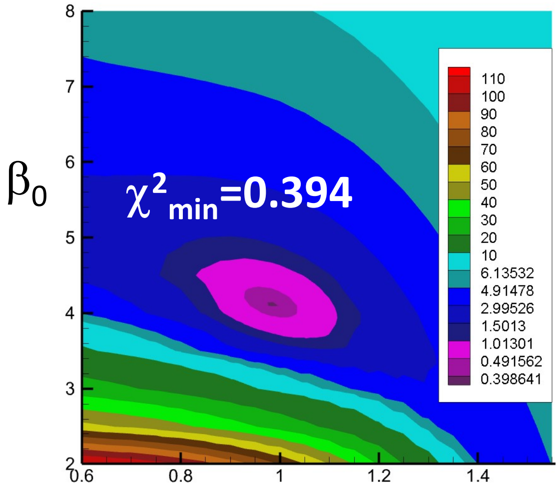
- $\beta(\lambda)=\beta_0*\beta_{model}(\lambda)/\beta_{model}(\lambda=0)$, β_{model} is the total ionization rate averaged over the considered time period for one IBEX map;

- by minimization of χ^2 we fit the IBEX-Lo ISN H flux maps (separately for each year) and find the best fitting parameters μ_0 and $\beta_{0;}$

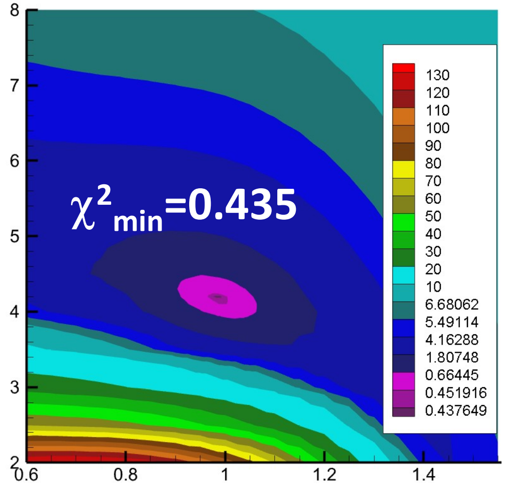
- for the fitting we chose those directions on the maps where relative uncertainty of the data is less than 0.9.

Results of the fitting: χ2 maps

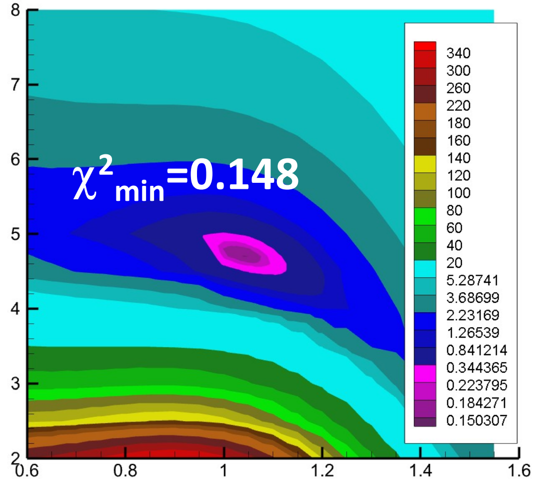
2009: μ_0=0.989, β_0=4.d-7



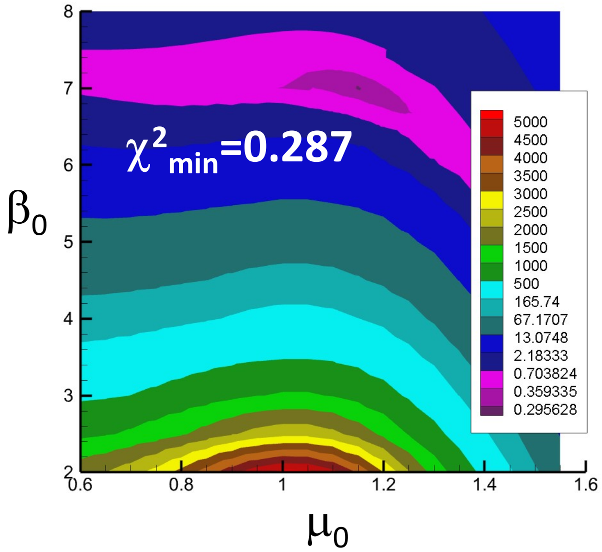
2010: μ_0=0.98, β_0=4.2d-7



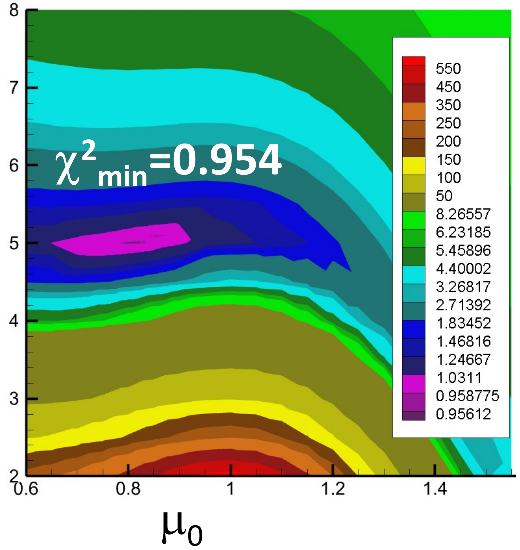
2011: μ_0=1.039, β_0=4.7d-7



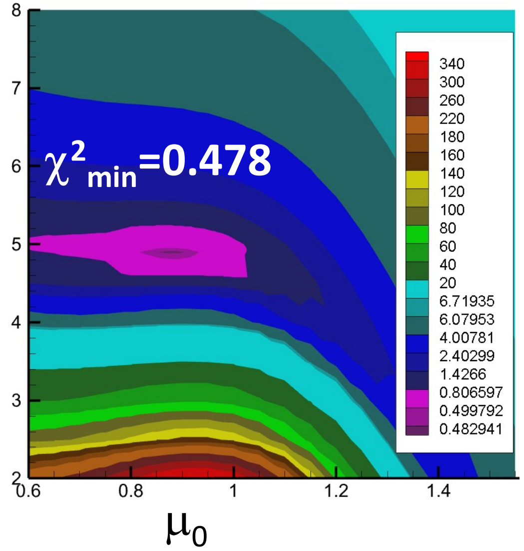
2012: μ_0=1.15, β_0=7.d-7



2017: μ_0=0.81, β_0=5.d-7

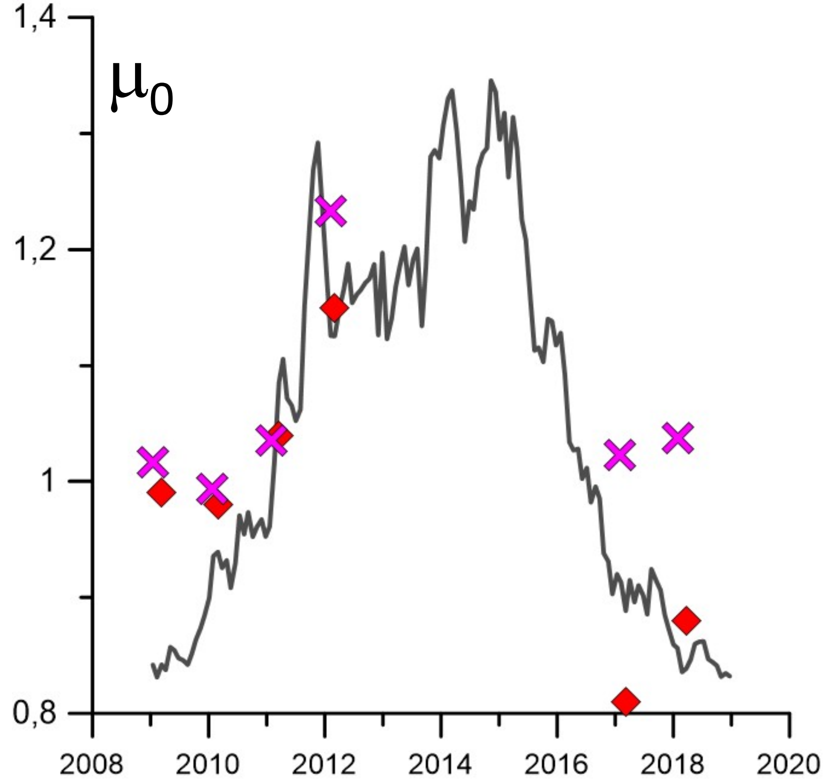


2018: μ_0=0.88, β_0=4.9d-7

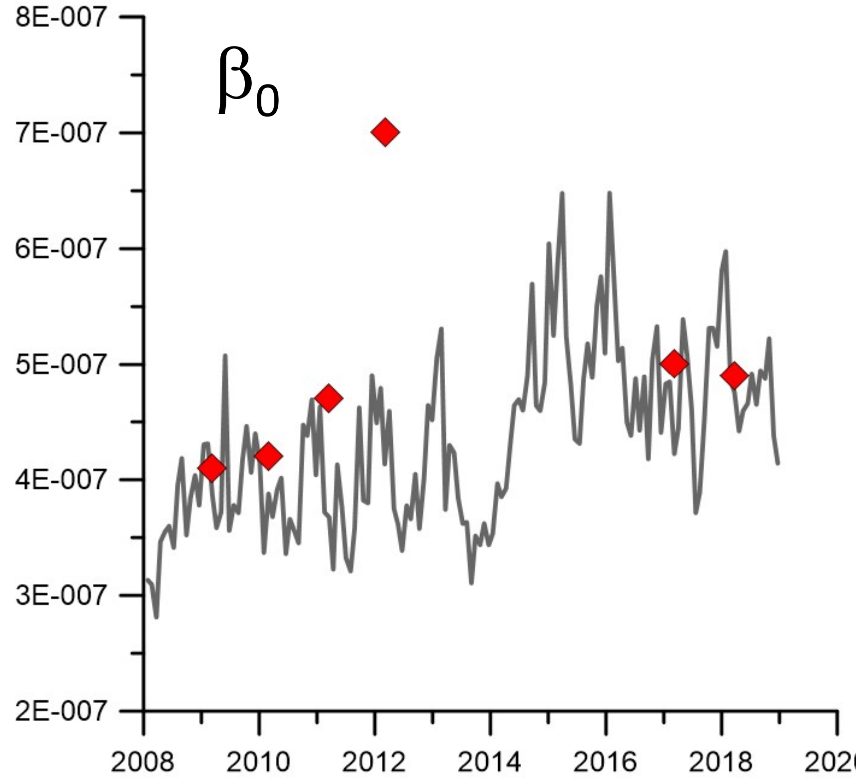


Comparison of the fitting results with the initial model parameters

μ_0 obtained from the IBEX-Lo data
μ_0 obtained from the solar Ly-a flux
(by Kowalska-Leszczynska et al.,2020 for v_r=0)
μ_0 obtained by Rahmanifard et al. (2020) based on IBEX-Lo data

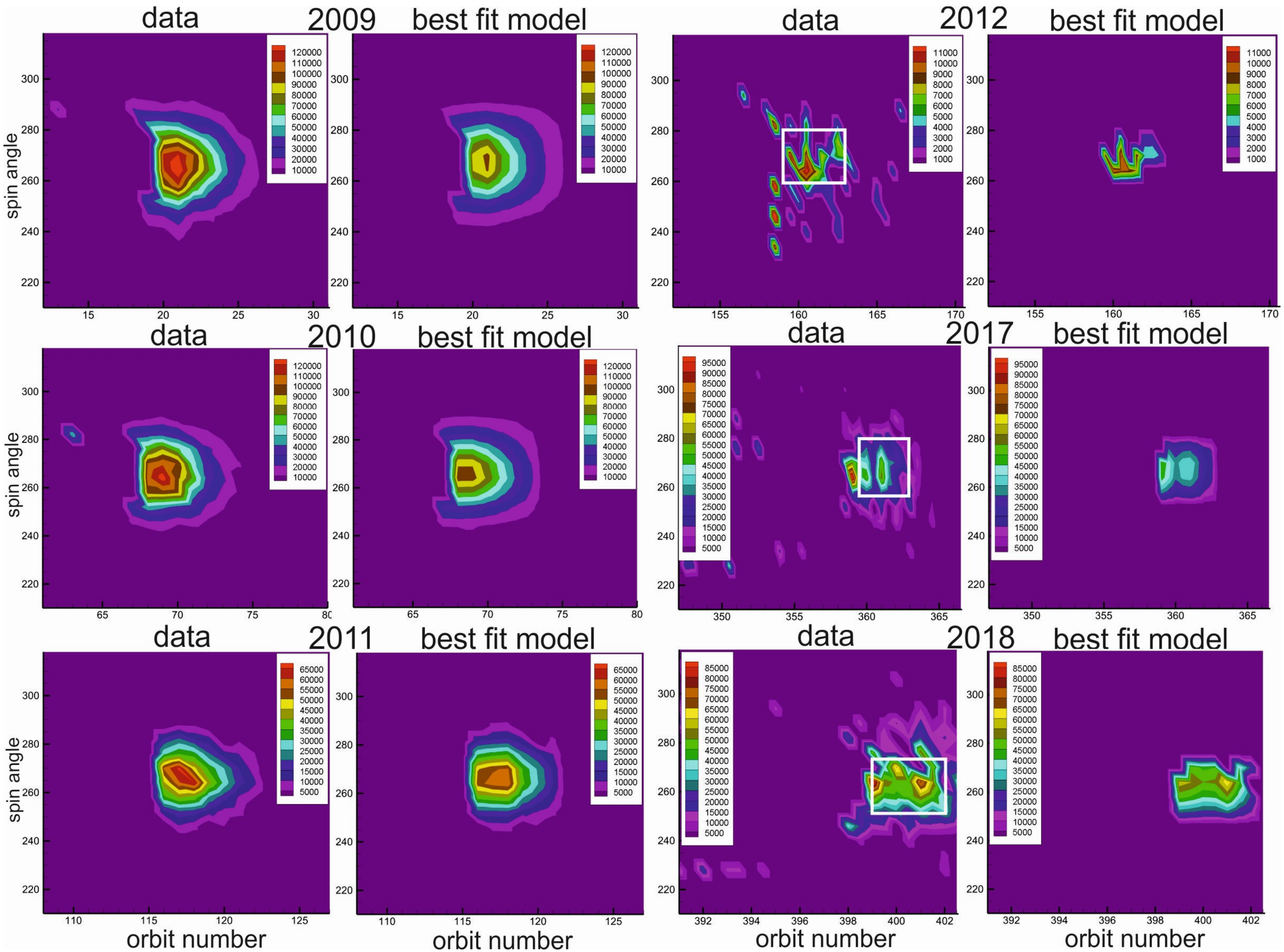


β_0 obtained from the IBEX-Lo data
β_0 obtained from the OMNI database in the ecliptic plane



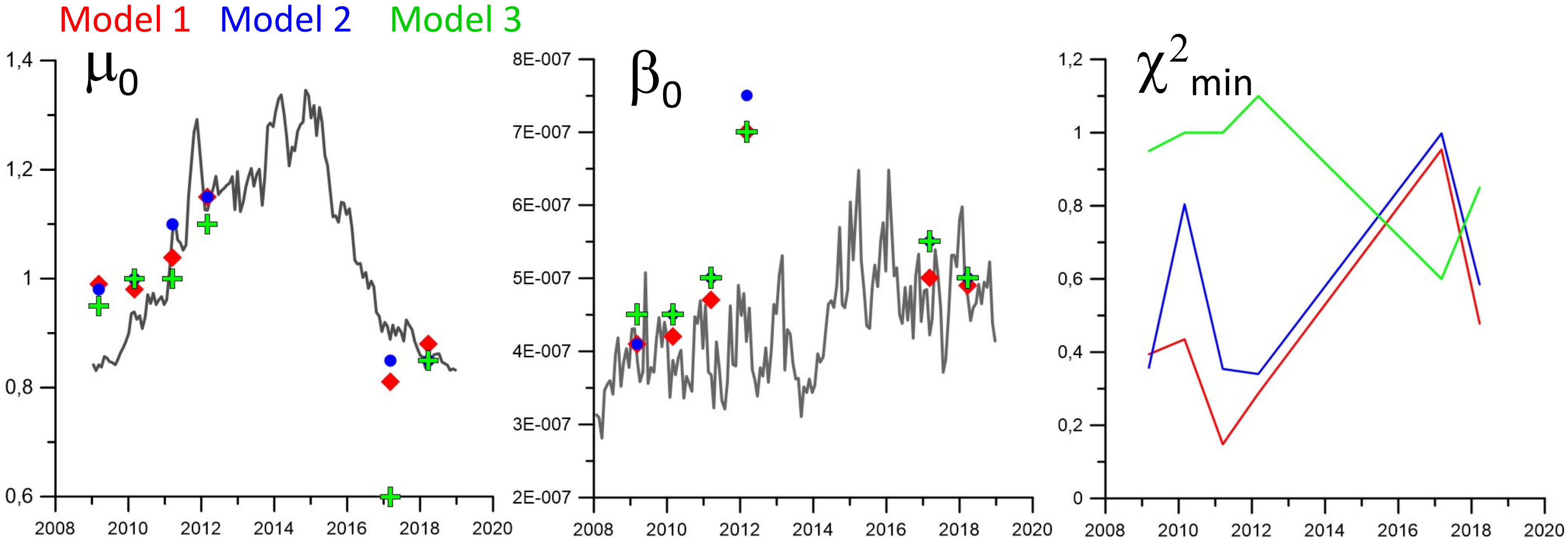
- For μ_0: the most difference is in 2009 when the IBEX-Lo data predict larger μ then it was thought before;
- For β_0: an agreement is quite good besides 2012 when the IBEX-Lo data show very low ISN H fluxes and therefore quite large β_0 is obtained by our fitting procedure; probably there is some technical problem with a calibration factor of IBEX-Lo in 2012 or just statistic is not enough;
- Our results for μ_0 are close to those obtained by Rahmanifard et al. (2020) – for the fitting they use only position of maximum fluxes and did not use maps of the fluxes;

Comparison of the data with the best fit model results



Results of the fitting procedure by using of 3 different models of the ISN H distribution

- Model 1 is the initial 3D quasi-stationary model with non-maxwellian boundary conditions at 70 AU due to distribution of the ISN H flow at the heliospheric boundary;
- Model 2 is the same as the Model 1, but without heliolatitudinal variations of the ionization rate, i.e. β=const=β_0;
- Model 3 is the same as the Model 1 but with simple maxwellian boundary conditions at 70 AU;



- In general, it is seen that results of different models are close to each other => determination of μ_0 and β_0 from the IBEX-Lo data could be considered as model independent.
- But, the Model 3 provides systematically larger χ^2_{min} (besides 2017) compared to the Models 1 and 2.

Summary

- ratio of the fluxes measured in energy bins 1 and 2 is systematically larger in the data compared to the model, we expect possible technical problems with the separation of energy channels. Therefore, it is better to consider a sum of the fluxes measured in 1-2 energy bins together;
- the fluxes in bin1+bin2 decrease from 2009 to 2012, disappear in 2013-2016 and appear again in 2017-2018, this temporal evolution is confirmed by the model results;
- The model fluxes are systematically smaller than the measured ones for all years besides 2012, where the measured fluxes are extremely low (smaller than the modelled one by a factor of 2.7). This suggests that there may be technical problems with calibration in 2012;
- The model calculations show that the solar radiation pressure (μ) influences both position of the maximum fluxes and absolute value of the fluxes, while the ionization rate (β) influences only the absolute value of the fluxes;
- Fitting of the IBEX-Lo data by the model results allows to obtain the best fit parameters μ_0 and β_0 for each year separately (by minimization of χ^2). It is shown that the obtained best fit parameters are about the same for using of different models of the ISN H distribution;
- Results o the fitting are the following:

  - In 2009 and 2010 the IBEX-Lo data predict larger μ_0 than it was known before from the solar Lyman-alpha flux;

  - In 2017 the IBEX-Lo data shows a bit smaller μ_0;

  - In 2011, 2012, and 2018 an agreement in the obtained and known μ_0 is quite good;

  - for all years besides 2012 an agreement of the obtained β_0 with the total ionization rate known before is very good; difference in 2012 could be due to some calibration issue;
- For the future perspective we hope that the IMAP measurements of the ISN H fluxes will provide more accurate and clear data to obtain advanced scientific results.