

# MEx/ASPERA-3/IMA Archiving – Differential Flux and Moments for $H^+$ , $He^{++}$ , $O^+$ , and $O_2^+$

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Note: As of 2021-01-12 the archived data products include: All full scans of IMA from 2007-04-30 until 2020-12-31.

## Introduction

The Swedish Institute of Space Physics (IRF) have produced cleaned, mass-separated ion data with physical units for delivery to PSA. In this document the procedure for producing these files is described.

Section 1 lays out the procedure of the pipeline. The procedure follows three steps that will create three levels of data output: i) cleaned, mass-separated counts for internal use at IRF (section 1.1), ii) differential flux (section 1.2), and iii) ion moments (section 1.3). From these the differential flux and moments are to be generated for PSA.

In section 4, 5 and 6 further details on the calculations and procedures of the noise-removal method, the differential flux and the moments, respectively, are described. Finally, section 7 informs on the measures taken to ensure the quality of the data output through different quality flags and comparisons with other datasets.

The document “ASPERA-3 IMA Pipeline data verification” is attached to further inform on the verification of the data against other data products to ensure the validity of the output from this data pipeline.

## 1. How to use the scripts

1. For access to the software, please contact the ASPERA-3 PI, Mats Holmstrom, Swedish Institute of Space Physics, Kiruna, [matsh@irf.se](mailto:matsh@irf.se)
2. Copy `mexpath.py.sample` and rename to `mexpath.py`. Edit to put correct paths to data folders on local computer
3. Run project with the following command from terminal:
  - a. “`python mima_moments_on.py -v XX`”, replace XX with a number of days from today to run moment pipeline for
  - b. e.g. “`python mima_moments_on.py -v 10`” will run the moment pipeline for all the 10 days prior to the execution date.
  - c. See further description in “`mima_moments_on.py`” & “`mima_moments.py`” scripts

### 1.1 - Step 1: Mass separating the counts using MATLAB

There are several scripts needed to run through everything. For the mass separation matlab scripts are used. These are by far the most time consuming. For this part the “mfiles” folder contains the relevant scripts and the “tables” folder contain additional information needed to run the script, which is loaded from the mfiles scripts. Table 1 gives a short description of

each script used by the matlab program, and Figure 1 shows a flow chart of the calculations, where arrows show the path of the calculation, squares denote the scripts, ellipses denote the functionality that is the aim of the following scripts. The main matlab script is the overhead script that calls each other script and keeps track of everything.

The main matlab script is “batch\_matfiles2.m”. This script calls all other scripts and then stores the mass separated counts mat files. The files it uses is specified in the script “directories\_setup.m”, which has to be edited to make sure it is pointing to the correct directories on the computer used. All tables used by the script is located in the folder “tables”. The files downloaded by the script are stored in the folder “extrafiles”. The script downloads the latest version of the MEX ASPERA event file “EV\_ASPERA.MEX” and uses the information in there to find the changes in the modes of the instrument. The computed data is stored in folders located in the folder “processed\_data/Mars\_mat\_files6”. The data is stored in .mat files, which output is described in Table 2 and 3.

## 1.2 - Step 2: Calculate the differential flux using python

The differential flux is calculated after the mass separation is done. This is done using the script “differentialflux\_MExArchiving.py” located in the “moments” folder. Here, the mass separated counts are loaded, and converted into differential flux according to the simple equation

$$j(\varphi, \theta, E) = \frac{c}{G \cdot \tau \cdot E}, (1)$$

Where  $G$  is the geometric factor,  $\tau$  is the integration time for each step in the instrument and  $E$  is the energy. The calculation is further described in Section 2. The differential flux is then stored in .mat files identical to those of the mass separated counts, i.e. only the variable before containing the mass separated counts are changed and updated with the differential flux instead. This is done to make it easy with the transitioning. The data is stored in the “processed\_data/Mars\_flux\_files” folder. This calculation is very quick in comparison to the mass separation in step 1.

## 1.3 - Step 3: Calculate the moments from the differential flux

The last step is to calculate the moments from the differential flux. This is made by the script “moments\_MExArchiving.py” in the folder “moments”. This script takes the differential flux and transforms the data into 192 s 3D distributions from which the density, velocity and temperature is calculated using the 0<sup>th</sup>, 1<sup>st</sup> and 2<sup>nd</sup> moments, which calculation is further described in section 3. The output is stored in .dat files in the folder “processed\_data/Marsmoments7”, and is further described in Table 5. This is a quick calculation in comparison with the mass separation in step 1.

## 1.4 Data excluded from the archiving

Not all of the data from MEx/IMA is included in the archived data product. This is because there are some modes and settings of the instrument that needs some more careful examination before it is included, and is therefore left for a future work. The mode used in this project is “Mode 24”, which is the normal, most used, mode during the missions, which uses [M32, A16, E96, P16] bins. The solar wind mode should be implemented at a later stage.

There are several settings of the instrument, EEPROM, where the instrument uses different tables for energy and elevations. We have here excluded the EEPROM13 (fast mode) and

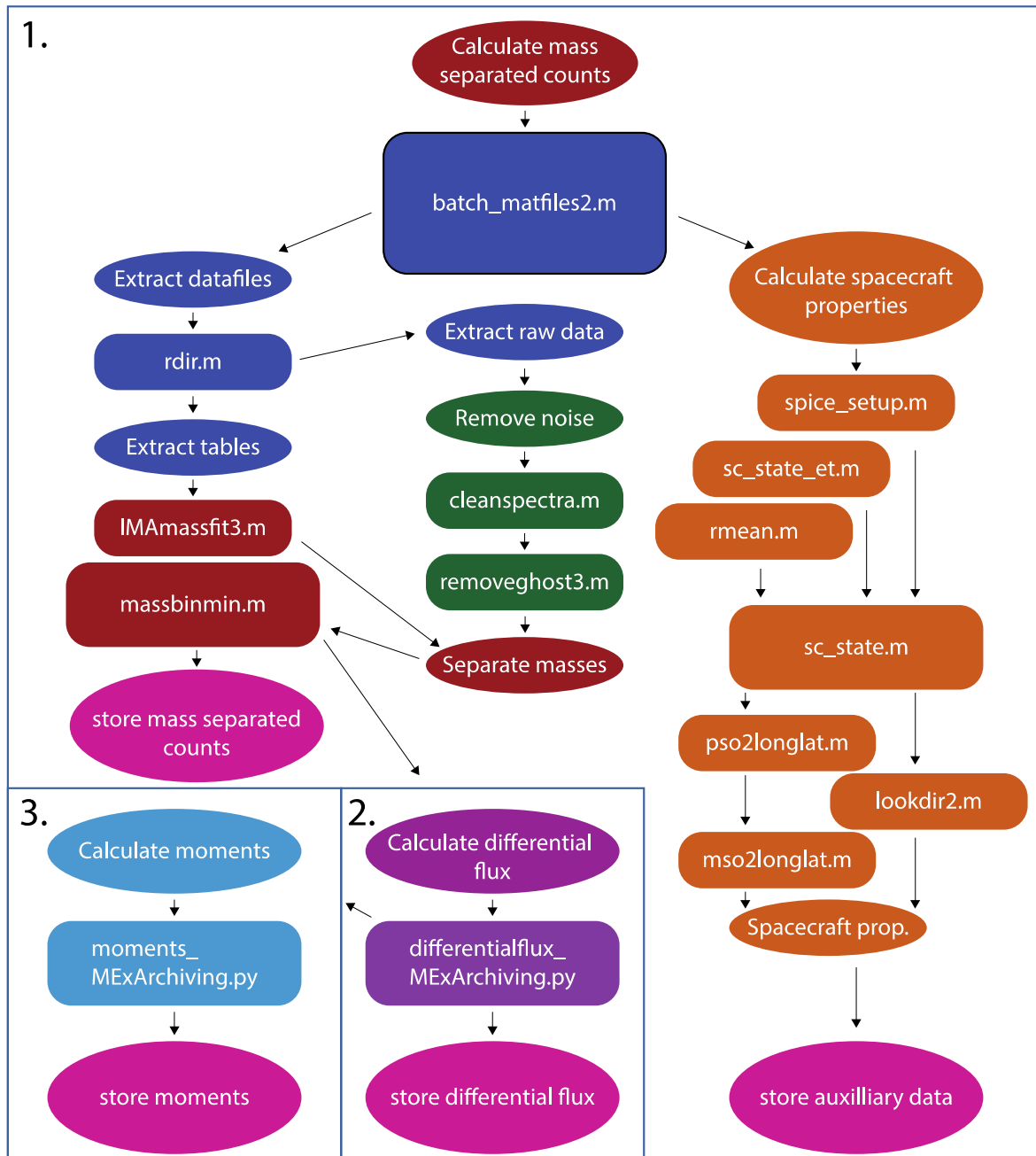
EEPROM14 (noise reduction) from the archiving. These settings were not used often, and to handle these fast and noise reduction modes will require some more careful analysis. They may be implemented at a later stage.

**Table 1.** Functionality of each script used by the program. The numbers refer to Figure 1 groupings.

Script	Functionality
mima_moments_on.py	Script to use for running the entire pipeline. Execute as: python mima_moments_on.py -v XX (replace XX with number of days from now to execute)
mima_moments.py	Main script that executes the entire pipeline. Called by “mima_moments_on.py”. Will execute the mass separation, differential flux and moment calculation, and keep track of the folders to put all data in
(1.) batch_matfiles2.m	Main script for mass separation <ul style="list-style-type: none"> <li>• Starts up the program</li> <li>• Imports the raw data files</li> <li>• Loops through the data</li> <li>• Calls the other scripts</li> </ul> Called by mima_moments.py
massbinmin.m	Mass separation main script <ul style="list-style-type: none"> <li>• Removes the background</li> <li>• Calls “cleanspectra.m” for removing more background</li> <li>• Calls “removeghost3.m” to extract the H<sup>+</sup> ghosts from the spectra</li> <li>• Separates the masses using two different versions. Here we use the fitting version for the final output. The integration version is used to limit the fitting version when it gives unreasonable results.</li> </ul> Called by batch_matfiles2.m
calc_moments5.m	Main script for calculating the moments <ul style="list-style-type: none"> <li>• Calculates the density, velocity and temperature from the differential flux and directions for each bin</li> </ul> Called by batch_matfiles2.m
directories_setup.m	Main script for directories used in the program <ul style="list-style-type: none"> <li>• Need to make sure it is pointing to the correct data directories before running “batch_matfiles2.m”</li> </ul> Called by batch_matfiles2.m
IMAmassfit3.m	<ul style="list-style-type: none"> <li>• Initialises the mass tables for the</li> </ul>

	<p>fitting procedure</p> <ul style="list-style-type: none"> <li>Needs the correct tables before running</li> <li>Uses "MassTable.txt"</li> </ul> <p>Called by batch_matfiles2.m</p>
cleanspectra.m	<ul style="list-style-type: none"> <li>Spectra is cleaned from additional noise</li> <li>Uses the method of few-neighbour elimination</li> </ul> <p>Called by batch_matfiles2.m</p>
lookdir2.m	<ul style="list-style-type: none"> <li>Finds the direction vectors of the sectors, energy and elevation steps for the data</li> <li>Used by "calc_moments5.m" to calculate the moments</li> </ul>
mso2longlat.m	<ul style="list-style-type: none"> <li>Returns the planetocentric longitude and latitude of the spacecraft for each measurement</li> <li>Calls pso2longlat.m for calculation</li> <li>Used by main script (I364)</li> </ul> <p>Called by batch_matfiles2.m</p>
pso2longlat.m	<ul style="list-style-type: none"> <li>Calculates the longitude and latitude using spice kernels</li> </ul>
rdir.m	<ul style="list-style-type: none"> <li>Makes a list of the files in a directory and subdirectories</li> <li>Run by main script (I190) to extract all files to use for the script</li> </ul> <p>Called by batch_matfiles2.m</p>
removeghost3.m	<ul style="list-style-type: none"> <li>Extracts the ghosts</li> <li>Removes the ghosts from the original spectra that is later used for mass separation</li> <li>The extracted ghosts are later added to the protons differential flux in "massbinmin.m"</li> </ul> <p>Called by batch_matfiles2.m</p>
rmean.m	<ul style="list-style-type: none"> <li>Makes a running mean of the input array, over the defined number of points</li> <li>Used by main script (I368-I370) for fixing the calculated spacecraft velocity</li> </ul> <p>Called by batch_matfiles2.m</p>
sc_state.m	<ul style="list-style-type: none"> <li>Extract the position of the spacecraft in MSO vector</li> <li>Extract the SC's X and Z axis in MSO vector</li> </ul>

	<ul style="list-style-type: none"> <li>• Calls “sc_state_et.m” for the calculation</li> </ul> <p>Called by batch_matfiles2.m</p>
sc_state_et.m	<ul style="list-style-type: none"> <li>• Called by “state_et.m”</li> <li>• Calls the spice functions to extract the vectors for “sc_state.m”</li> </ul>
spice_setup.m	<ul style="list-style-type: none"> <li>• Setup spice folder to work for this project</li> <li>• Path needs to be adjusted for the computer it’s run on</li> </ul> <p>Called by batch_matfiles2.m</p>
addme.m	<ul style="list-style-type: none"> <li>• Adds all paths for the scripts used and the spice (mice) libraries</li> <li>• Run on matlab startup as “matlab -r addme”</li> </ul> <p>Called by batch_matfiles2.m</p>
(2.) differentialflux_MExArchiving.py	<ul style="list-style-type: none"> <li>• Calculates the differential flux from the mass separated counts from batch_matfiles2.m</li> </ul> <p>Called by mima_moments.py</p>
(3.) moments_MExArchiving.py	<ul style="list-style-type: none"> <li>• Calculates the moments from the differential flux from the differential flux python file</li> </ul> <p>Called by mima_moments.py</p>



**Figure 1.** Flow chart of the groups of scripts for calculation of 1. mass separated counts, 2. differential flux and 3. moments. Color coding follows the scheme of red: species separation, light blue: moment calculation, green: noise reduction, orange: auxiliary data, purple: differential flux calculation, dark blue: calculations or aim of the batch\_matfiles2.m script, and pink: storing of data.

**Table 2.** Variables in the output "fionYYYYMMDDHH00.mat" file which contain the mass separated counts. The output files are organised with one file per hour. The differential flux is identical, with the different file name "dfluxYYYYMMDDHH00.mat", with the exception of fH, fHepp, fO, and fO2 which for these files contain the differential flux in units of  $[\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{eV}^{-1}]$ .

Variable name	Dimensions	Description	Included in PSA?
E	[nE, 1]	Energy for each energy step	Yes

		[eV], where nE is either 55, 86 or 96 depending on the energy table settings (PROM)	
dE	[1, nE]	Delta energy for each energy step [eV]	No
fCO2	[A16, nE, nt]	Counts of CO <sub>2</sub> <sup>+</sup>	No
fH	[A16, nE, nt]	Counts of H <sup>+</sup>	Yes
fHe	[A16, nE, nt]	Counts of He <sup>+</sup>	No
fHepp	[A16, nE, nt]	Counts of He <sup>++</sup>	Yes
fHorig	[A16, nE, nt]	Original proton count	No
fHsp_orig	[A16, nE, nt]	Counts of Ghosts	Yes
fO	[A16, nE, nt]	Counts of O <sup>+</sup>	Yes
fO2	[A16, nE, nt]	Counts of O <sub>2</sub> <sup>+</sup>	Yes
fO2plus	[A16, nE, nt]	Counts of O <sup>++</sup>	No
mass	[50, nt]	Variable used for the mass separation	No
qualityflag_UV	[1, nt]	Indicates if there is UV contamination or not in the data [0, 1, 2]	Yes
qualityflag_marsis	[1, nt]	Indicates if MARSIS effect indicated in the data [0, 1, 0.5]	Yes
qualityflag_crosstalk	[1, nt]	Indicates if there is crosstalk between light and heavy species in the data [0, 1, 2]	Yes
qualityflag_SWcontamination	[A16, nE, nt]	Intermediate product for calculating quality flag, not intended to use as quality flag	No
sumions	[nE, M32, nt]	sum of all counts over azimuth after noise removal	No
sumorigions	[nE, M32, nt]	sum of all counts over azimuth before noise removal	No
tmptime	[1, nt]	Time of the differential flux [matlab time]	Yes

**Table 3.** The variables of the “auxYYYYMMDDHH00.mat” files. Contains the auxiliary data. Organised with one hour, same data for each file as for the mass separated counts and differential flux files.

Variable name	Dimension	Unit	Description	Included in PSA?
iPAref	[1, nt]	unitless	Pacc ref	No
promsection	[1, nt]	unitless	promsection for the data	No
elev	[1, nt]	unitless	elevation index for each time step	No
pacclevel	[1, nt]	unitless	Same as iPAref	No
curhvmask	[1, nt]	unitless	High voltage mask	No
curmode	[1, nt]	unitless	Mode of the data	No
curshadowmask	[1, nt]	unitless	Shadow mask	No
GI	[3, nE]		G-factor for heavy ions – AF definition	Yes
GH	[3, nE]		G-factor for H <sup>+</sup> – AF	Yes

			definition	
GHe	[3, nE]		G-factor for He+ and alphas – AF definition	Yes
Gghost	[3, nE]		G-factor for H+ ghosts – AF definition	Yes
imexx	[3, nt]	unitless	direction of mex X-axis in MSO	No
imexz	[3, nt]	unitless	direction of mex Z-axis in MSO	No
imexy	[3, nt]	unitless	direction of mex Y-axis in MSO	No
ixmso	[1, nt]	km	Spacecraft position MSO X	Yes
iyms0	[1, nt]	km	Spacecraft position MSO Y	Yes
izms0	[1, nt]	km	Spacecraft position MSO Z	Yes
ilon	[1, nt]	rad	Spacecraft Longitude on Mars	No
ilat	[1, nt]	rad	Spacecraft Latitude on Mars	No
scx	[1, nt]	km/s	spacecraft velocity X-MSO	Yes
scz	[1, nt]	km/s	spacecraft velocity Y-MSO	Yes
scy	[1, nt]	km/s	spacecraft velocity Z-MSO	Yes
x	[A16, nE, nt]	unitless	Vector direction of each angular bin in MSO X	No
y	[A16, nE, nt]	unitless	Vector direction of each angular bin in MSO Y	No
z	[A16, nE, nt]	unitless	Vector direction of each angular bin in MSO Z	No
azim_rad	[A16, 1]	rad	Azimuth table giving the angle for each sector in IMA coord. system	No
elev_rad	[P16, nE]	rad	Elevation table giving the angle for each elevation step for each energy step in IMA coord. system	No

**Table 4.** The variables of the local IRF files named “mima\_massepcounts\_YYYYMMDDHH00.mat” files. Contains the mass separated counts for H<sup>+</sup>, He<sup>++</sup>, O<sup>+</sup> and O<sub>2</sub><sup>+</sup>. Each one hour file is a subset of the fion and aux files of tables 2-3. To be used for internal IRF projects, not intended to use for PSA archiving.

Variable name	Dimensions	Description
file_version	[unitless]	Version of data file created
processing_date	Time [YYYY-MM-DD]	Date of creation of this data file



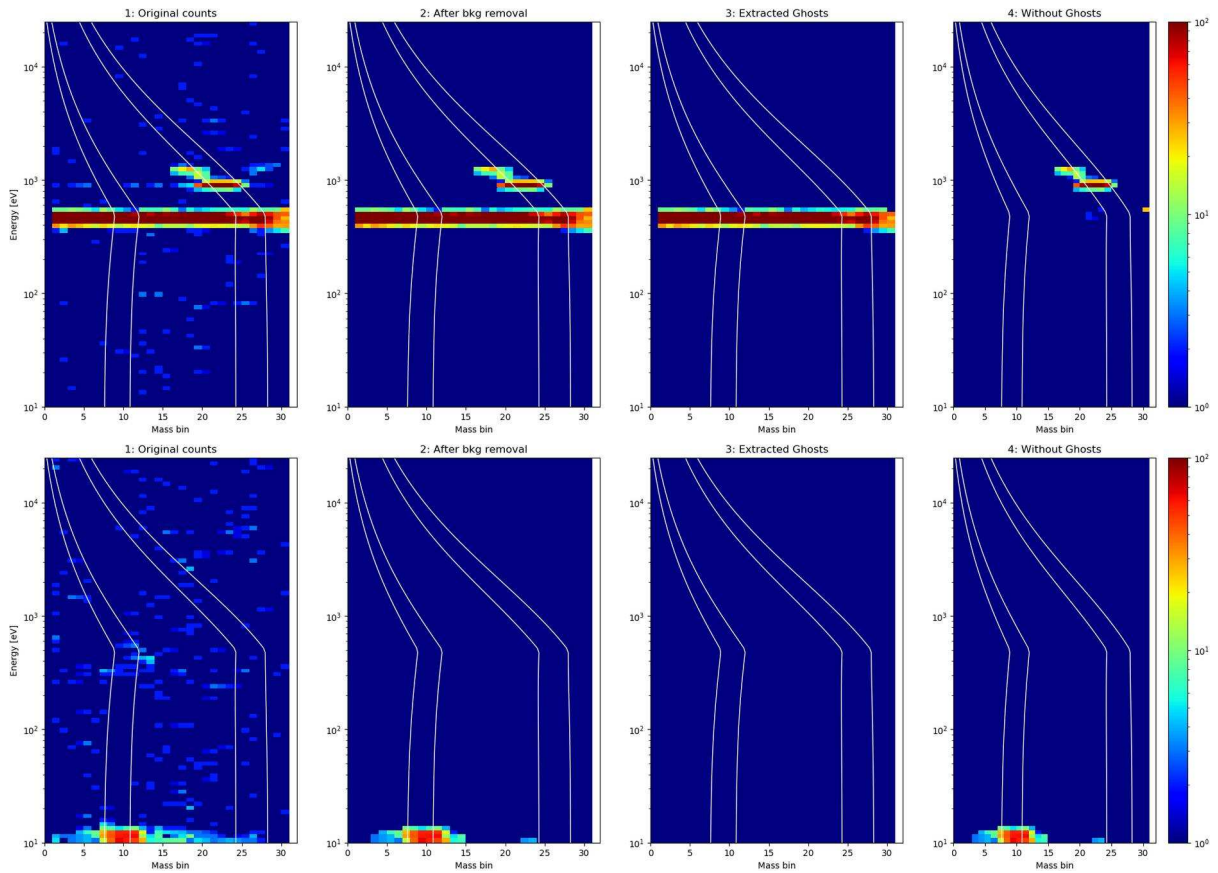
program_name_to_create_this_file	[unitless]	Name of the script used to produce this data file
Mode	[P16, nT]	Mode used by the instrument, (nT = number of full instrument scans, P16 = number of elevation scans)
promsection	[P16, nT]	Promsection value
pacc	[P16, nT]	Post acceleration value
time	[P16, nT]	Time (matlab time, start time for each measurement)
H	[A16, nE, P16, nT]	Counts of H <sup>+</sup> (nE = number of energy steps, depends on promsection. Will be either 55, 86, or 96, A16 = number of azimuth scans)
Hepp	[A16, nE, P16, nT]	Counts of He <sup>++</sup>
O	[A16, nE, P16, nT]	Counts of O <sup>+</sup>
O2	[A16, nE, P16, nT]	Counts of O <sub>2</sub> <sup>+</sup>
HGhost	[A16, nE, P16, nT]	Counts of proton ghosts
qualityflag_UV	[P16, nT]	Indicates if there is UV contamination (large noise level) or not in the data [0, 1, 2]
qualityflag_marsis	[P16, nT]	Indicates if MARSIS effect appears in the data [0, 1, 0.5]
qualityflag_crosstalk	[P16, nT]	Indicates if there is crosstalk between light and heavy species in the data [0, 1, 2]

## 4. From raw count data to mass separated counts

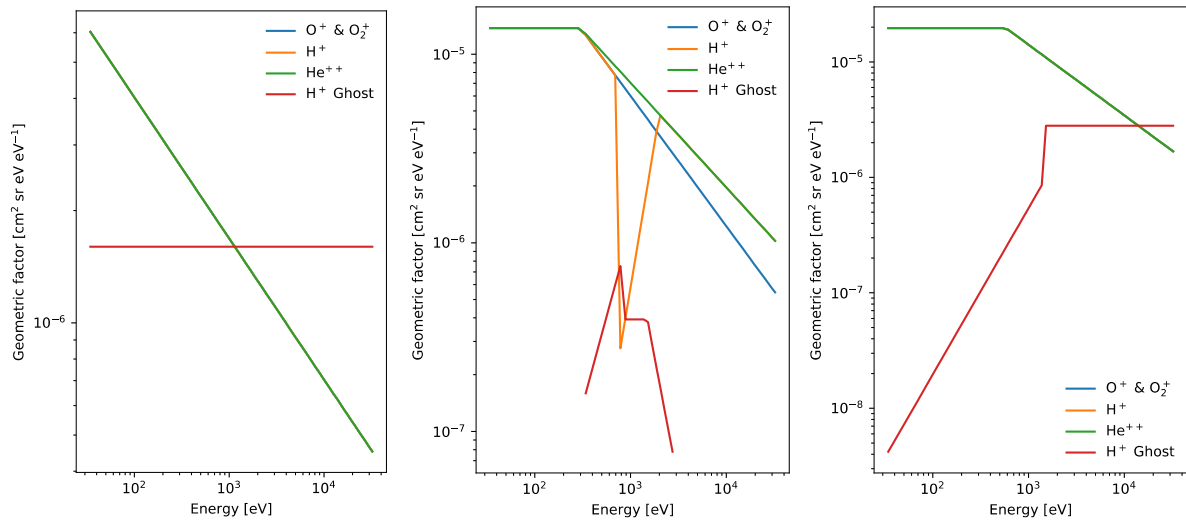
To calculate the species separated counts from the raw count data of the instrument, several steps are taken. First, the noise is handled. An average noise profile is computed for each mass-energy matrix by calculating the median counts over all 16 sectors. The average noise profile is subtracted from each raw mass-energy matrix, making sure it is above 0 counts, to reduce the noise in the computed differential flux. Additional noise is removed through few-neighbour elimination. Here, a count is regarded as noise, and removed from the mass-energy matrix, if the count is 0 in both neighbouring energy levels (for the same mass channel) and mass channels (for the same energy level). See Figure 2 for examples of the noise reduction.

The next step is to take care of the ghost signatures. At high energies, the proton population will have two components in the instrument MCPs. One component that strike the MCP directly and one component that strike the outer wall of the mass-separation chamber. A fraction of the protons striking the outer wall of the chamber is reflected and scattered onto the MCP. The signature of the scatter depends on the PACC setting. These protons, denoted “ghosts”, are accounted for by using several schemas for detection and extraction. By comparing the signal in the mass channels that should contain heavy ions with those that should not, the probability of ghosts in the signal can be found and extracted, where one example is shown in Figure 2. The method works very well on a statistical basis, but some errors still exist that may need to be handled by a case-by-case method. This is left as a future work and is very important to note when using the dataset to work on case studies.

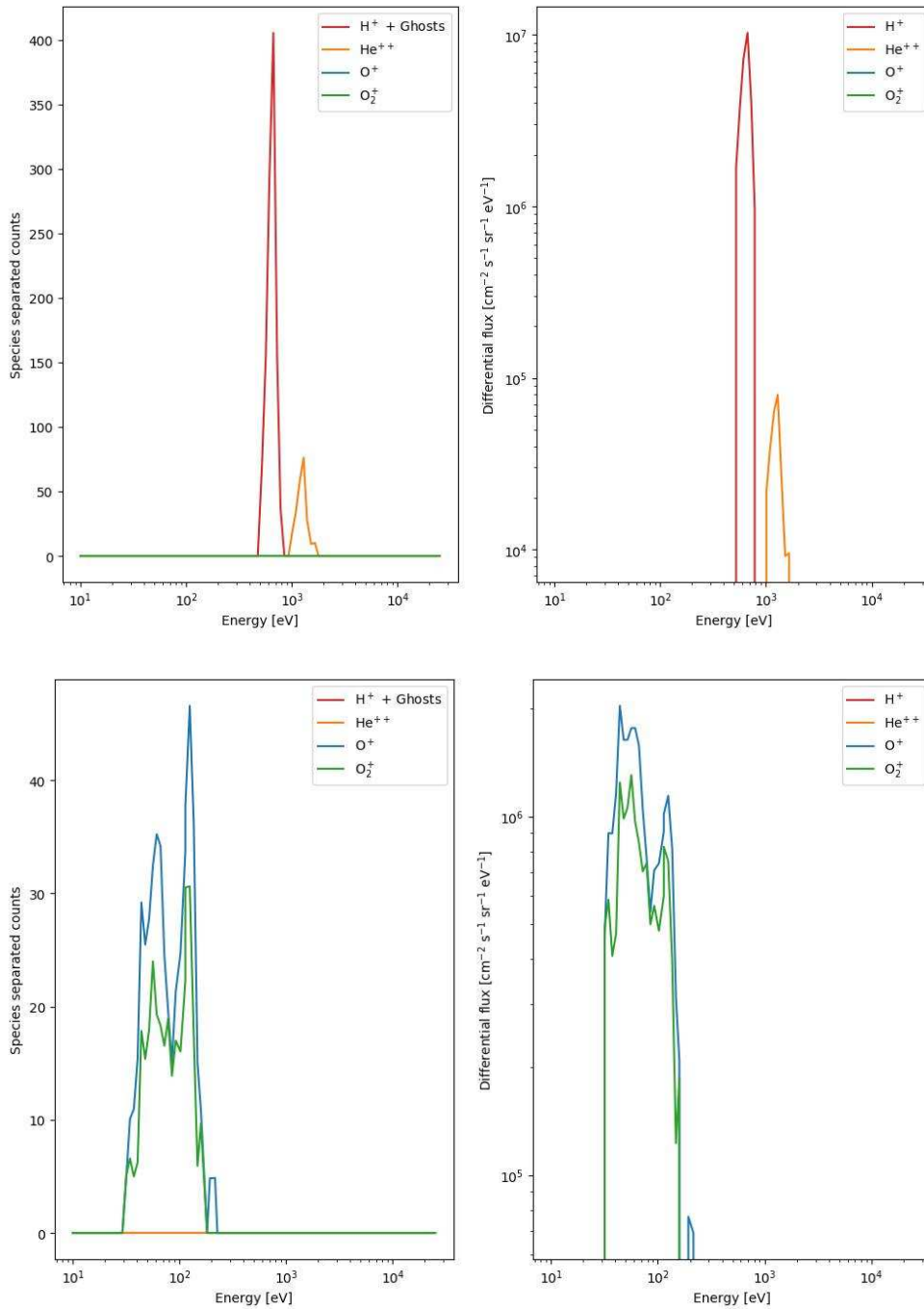
Thereafter, the data is separated for the different species. The mass separation is done through fitting a Gaussian distribution function for each species of  $H^+$ ,  $He^+$ ,  $O^+$ ,  $O_2^+$ , which shape and position was established from calibration. These mass separated counts are then stored in the .mat files.



**Figure 2.** Example of noise cleaning and ghost extraction for two cases. Top row: large ghost component, and noise cleaning, bottom row: low energy heavy ion component, and noise cleaning. For each row the first panel shows original raw counts from the instrument, second panel shows the spectra after noise cleaning, third panel shows the extracted “ghosts” in the data and the third panel shows the raw spectra without the noise and the extracted “ghosts”. The white lines in each panel represents the theoretical positions of the species (from right to left)  $H^+$ ,  $He^+$ ,  $O^+$  and  $O_2^+$ , determined from calibration. The colour bar represents raw counts.



**Figure 3.** G-factors for the different species. The panels from left to right correspond to the three different PACC settings of increasing order.



**Figure 4.** Progression from species separated counts to differential flux using the geometric factors in Figure 3. Top row shows an example from the solar wind at 2009-01-04 08:23, and the bottom row shows an example containing ionospheric heavy ions at 2007-05-05 06:22.

## 5. From mass separated counts to differential flux

The differential flux,  $j$ , of each species is calculated from the mass separated counts using the different geometrical factors for each species. The conversion for protons is

$$j_{H^{+},i}(\varphi, \theta, E) = \frac{c_{H^{+},i}}{\tau \cdot G_{H^{+},E} + \frac{c_{H^{+},i}}{\tau \cdot G_{H^{+},E} \cdot 2}}$$

where  $c_{H^{+},i}$  is the counts of protons for energy step  $i$ ,  $c_{H^{+},i}$  is the counts for the extracted ghosts,  $G_{H^{+},E}$  is the geometric factor for  $H^{+}$ ,  $\tau$  is the integration time of 0.125 s, and  $\varphi, \theta$  is the angles for each angular bin used. The same procedure, but without the ghosts, is valid for the  $He^{++}$  (alpha) particles and the heavy ions  $O^{+}$  and  $O_2^{+}$ . Geometric factors used are shown in Figure 3 and an example of a calculation from species separated data to the differential flux in Figure 4.

An important factor is that the instrument has three levels of post-acceleration. The levels will provide slightly different responses for the species and energy levels. The calibration has provided the positions and widths of the Gaussian distribution functions for the species. However, the ghosts will give different responses depending on the post-acceleration. Therefore, the method has been modified to take into account these differences, in for example the ghost extraction and the g-factor response.

## 6. From differential flux to moments

After the differential flux is calculated from the raw count data for each species, the next step is quite straightforward. The moments are calculated through the integration of the counts over energy and direction. The density is calculated from the 0<sup>th</sup> moment as

$$n = \sum_{k,l,m} \sqrt{\frac{Mm_p}{2qQE_m}} j(\varphi_k, \theta_l, E_m) \cos \theta_l \Delta E_m \Delta \theta_l \Delta \varphi, (3)$$

where  $M$  is the mass per charge of the species,  $m_p$  is the mass of the proton,  $q$  is the electron charge,  $Q$  is the charge of the ions,  $E$  is the energy, and  $\varphi$  and  $\theta$  are the azimuth and elevation angles respectively. The 1<sup>st</sup> order moment gives the flux as

$$F_x = n v_x = \sum_{k,l,m} j(\varphi_k, \theta_l, E_m) \cos^2 \theta_l \cos \varphi_k \Delta E_m \Delta \theta_l \Delta \varphi, (4 a)$$

$$F_y = n v_y = \sum_{k,l,m} j(\varphi_k, \theta_l, E_m) \cos^2 \theta_l \sin \varphi_k \Delta E_m \Delta \theta_l \Delta \varphi, (4 b)$$

$$F_z = n v_z = \sum_{k,l,m} j(\varphi_k, \theta_l, E_m) \sin \theta_l \cos \theta_l \Delta E_m \Delta \theta_l \Delta \varphi. (4 c)$$

Which is used to calculate the ion velocity. Note that the archived ion velocities have been corrected for the spacecraft velocity, but not the spacecraft potential. The temperature of the distribution is calculated from the 2<sup>nd</sup> moment which gives the thermal pressure

$$p = \int m(v - u)^2 f(v) dv, (5 a)$$

which gives the temperature as  $p = nkT$

$$T = \frac{\int m(v-u)^2 f(v) dv}{nk}, (5b)$$

In IMAs spherical coordinate system calculating from differential flux, the 1D temperature is calculated using Equation 5b as

$$nT = \sum_E \left( \left( \sqrt{\frac{2qQE_m}{Mm_p}} - u \right)^2 \left( \sum_{\theta} \sum_{\varphi} j(\varphi_k, \theta_l, E_m) \sqrt{\frac{(Mm_p)^3}{2qQE_m}} \cos \theta_l \right) \Delta E_m \right). (6)$$

The temperature is converted from eV to K by a multiplication with the electron charge and division with the Boltzmann's constant.

Here, the lowest energies (which does not have a full FOV scan) are not included in the calculation of the moments. This will mainly affect the heavy ions. A quality flag is added to denote when a possible large effect of this is apparent in the data (see section 5.2.2).

**Table 5.** The variables of the “moments\_YYYYMMDDHH00.dat” files. Each file contains one hour of data, similar to the previous files.

Nr.	Name	Unit	Description	Included in PSA?
1	t1	YYYYMMDDTHHMMSS.f	time start for this full integration	Yes
2	t2	YYYYMMDDTHHMMSS.f	time stop for this full integration	Yes
3	avposx	km	average spacecraft position X MSO	Yes
4	avposy	km	average spacecraft position Y MSO	Yes
5	avposz	km	average spacecraft position Z MSO	Yes
8	nH	cm-3	density H+	Yes
9	VHx	km/s	velocity H+ MSO x (corrected for sc vel.)	Yes
10	VHy	km/s	velocity H+ MSO y (corrected for sc vel.)	Yes
11	VHz	km/s	velocity H+ MSO z (corrected for sc vel.)	Yes
12	THx	eV	Temperature H+ MSO x	No
13	THy	eV	Temperature H+ MSO y	No
14	THz	eV	Temperature H+ MSO z	No
15	speed_1D_H	km/s	Average speed H+	No
16	Temp_1D_H	eV	Average temperature in 1D H+	Yes

17	qf_lowcounts	unitless	Quality flag for low counts for H <sup>+</sup>	Yes
18	qf_lowEcountratio	unitless	Quality flag for high counts below energy threshold for H <sup>+</sup>	Yes
19	nHepp	cm <sup>-3</sup>	density He <sup>++</sup>	Yes
20	VHeppx	km/s	velocity He <sup>++</sup> MSO x (corrected for sc vel.)	Yes
21	VHeppy	km/s	velocity He <sup>++</sup> MSO y (corrected for sc vel.)	Yes
22	VHeppz	km/s	velocity He <sup>++</sup> MSO z (corrected for sc vel.)	Yes
23	THeppx	eV	Temperature He <sup>++</sup> MSO x	No
24	THeppy	eV	Temperature He <sup>++</sup> MSO y	No
25	THeppz	eV	Temperature He <sup>++</sup> MSO z	No
26	speed_1D_Hepp	km/s	Average speed He <sup>++</sup>	No
27	Temp_1D_Hepp	eV	Average temperature in 1D He <sup>++</sup>	Yes
28	qf_lowcounts	unitless	Quality flag for low counts for He <sup>++</sup>	Yes
29	qf_lowEcountratio	unitless	Quality flag for high counts below energy threshold for He <sup>++</sup>	Yes
30	nO	cm <sup>-3</sup>	density O <sup>+</sup>	Yes
31	VOx	km/s	velocity O <sup>+</sup> MSO x (corrected for sc vel.)	Yes
32	VOy	km/s	velocity O <sup>+</sup> MSO y (corrected for sc vel.)	Yes
33	VOz	km/s	velocity O <sup>+</sup> MSO z (corrected for sc vel.)	Yes
34	TOx	eV	Temperature O <sup>+</sup> MSO x	No
35	TOy	eV	Temperature O <sup>+</sup> MSO y	No
36	TOz	eV	Temperature O <sup>+</sup> MSO z	No
37	speed_1D_O	km/s	Average speed O <sup>+</sup>	No
38	Temp_1D_O	eV	Average temperature in 1D O <sup>+</sup>	Yes
39	qf_lowcounts	unitless	Quality flag for low counts for O <sup>+</sup>	Yes
40	qf_lowEcountratio	unitless	Quality flag for high counts below energy	Yes

			threshold for O+	
41	nO2	cm-3	density O2+	Yes
42	VO2x	km/s	velocity O2+ MSO x (corrected for sc vel.)	Yes
43	VO2y	km/s	velocity O2+ MSO y (corrected for sc vel.)	Yes
44	VO2z	km/s	velocity O2+ MSO z (corrected for sc vel.)	Yes
45	TO2x	eV	Temperature O2+ MSO x	No
46	TO2y	eV	Temperature O2+ MSO y	No
47	TO2z	eV	Temperature O2+ MSO z	No
48	speed_1D_O2	km/s	Average speed O2+	No
49	Temp_1D_O2	eV	Average temperature in 1D O2+	Yes
50	qf_lowcounts	unitless	Quality flag for low counts for O2+	Yes
51	qf_lowEcountratio	unitless	Quality flag for high counts below energy threshold for O2+	Yes

## 7. Quality check

To make sure the processed data is correct, several measures have been taken. First, a set of three quality flags are included for the differential flux, and two for the moments. Second, the data products are compared with published results and other computed data sets.

### 7.1 Quality flags for differential flux

#### 7.1.1 Quality flag - UV contamination

The first quality flag checks the UV contamination of the data product ('qualityflag\_UV'). The quality flag is calculated from the sum of the counts removed by the noise cleaning method. If there are a lot of noise due to the UV contamination, the noise handling will remove a significant portion of the counts, which means that it might remove valid counts as well. Therefore, the flag is raised to 1 if the removed number of counts exceeds 400 counts, and is set to 2 if the removed counts exceeds 1000 counts. We do not recommend to use data with anything other than 0 on this flag. Figure 5 shows example statistics of the number of counts removed by the noise cleaning and the lines show the limits for the flag. There is one value for each time step of 12 s (each elevation scan).

#### 7.1.2 Quality flag - MARSIS

The second quality flag ('qualityflag\_marsis') indicates whether we have identified the "MARSIS effect" in the data (for details on the MARSIS effect see Voshchepynets et al., 2018). Times identified by A. Voshchepynets (personal communication, 2019-11-08) that incorporate accelerated ions from the MARSIS effect is indicated by a 1 in the flag. The flag is only valid until the end of 2017, as it has not been checked after this. Therefore, the flag is set to 0.5 after end of 2017. There is one value for each time step of 12 s (each elevation scan).



### 7.1.3 Quality flag - crosstalk

The third quality flag ('qualityflag\_crosstalk') handles the potential crosstalk from the solar wind. Here we have checked the simultaneous measurement of solar wind protons and heavy ions. If we have both contributions and one is larger than the other, a flag is raised to indicate potential cross talk in the instrument. The flag is given a 1 if the counts of lighter species is higher than the heavier, while a 2 is given when the heavier species is higher than the lighter. This way the user can choose if they want to include the data with a flag. We recommend to not use data with flag 1, but if flag 2 is given the user is recommended to analyse the data themselves to check if there is significant crosstalk with the lighter species or if the data is okay. There is one value for each azimuth sector and time step of 12 s (each elevation scan).

## 7.2 Quality flags for moments

### 7.2.1 Quality flag - low total counts

The fourth quality flag ('qualityflag\_lowcounts') handles if the data used to calculate the moments is statistically viable or not. If there is not enough counts in the full scan, the moments is likely not accurate. However, since there are many steps taken to ensure a good noise removal from the raw data, we do not expect a large noise content in the moment calculations. Therefore, the threshold is put at 10 counts. If there is less than 10 counts in the full 192 s scan, the flag is raised (value = 1). An example of the total statistics for 2007-2009 for  $O^+$  is shown in Figure 6. Here we see that the peak is located above 10 counts, and that there is a peak of low counts near 1. The lowest peak is a sign of measurements with only noise or too little statistics, and is therefore excluded when using this quality flag.

### 7.2.2 Quality flag - high counts below energy threshold

The fifth quality flag ('qualityflag\_lowEcountratio') takes into account that there is no elevation sweep for the lowest energies. Below the threshold, the instrument will only provide one elevation angle bin, and therefore these energies are excluded from the moment calculations as it will not give a proper moment. In order to check how valid the moments are, with respect to this threshold, a ratio between the number of counts measured below the threshold and the number of counts above the threshold is calculated. If the ratio is larger than 1.0 this flag is raised (value = 1). As we do not measure the full elevation sweep for low energies, this value does not state that there is 50 % more counts in the lowest energy bins, but is set as an indicator that somewhere here the data need to start being taken care of in more detail. Around here the distribution will be affected by more or less than a factor 2, and an interpolation procedure might be needed to provide better results. An example of the ratio for  $He^{++}$  and  $O^+$  for 2007-2009 is shown in Figure 7. For  $O^+$  there is a significant amount of data products that has a ratio above 1, which is a consequence of low altitude measurements where the low energy  $O^+$  ions are located. Therefore, the  $O^+$  and  $O_2^+$  moments are highly affected by the usage of data only above the energy threshold. This is important to take into account when analysing the data. The  $He^{++}$  product also contains a large portion of ions below the energy threshold. Presumably, these low energy  $He^{++}$  ions are not solar wind alpha particles inside the ionosphere, but is more likely a signature of another species with mass per charge 2, i.e.  $H_2^+$ . A discussion of this is made in Lundin et al. (2009). This separation have not been included in this data product, but need to be taken into account by the user when analysing the archived  $He^{++}$  data.

For the fourth and fifth quality flag, there is one value for each time step of 192 s (full scan of the instrument). In addition, the moments are only calculated for the data with a flag set to 0

(except for the MARSIS flag which also incorporates 0.5, and the SW contamination flag which also incorporates 2) on the above three quality flags (UV, MARSIS and crosstalk).

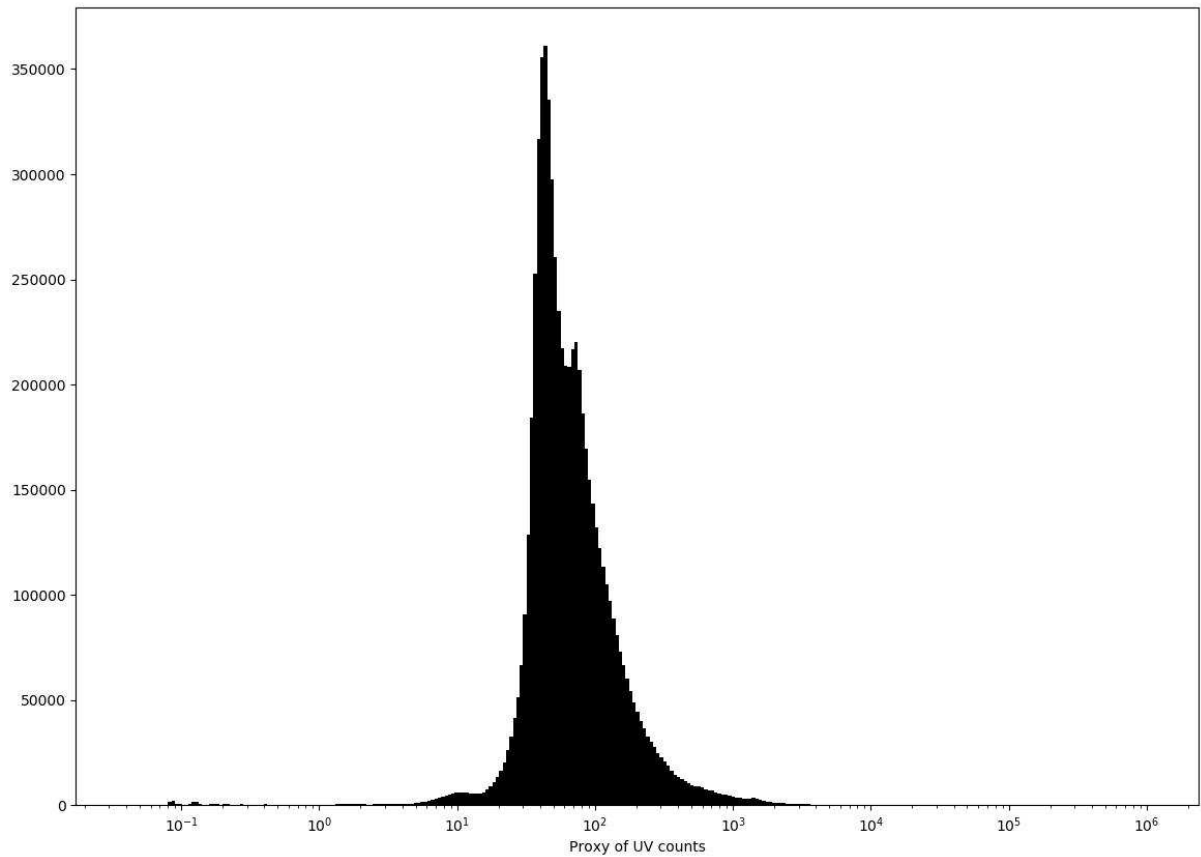
### 7.3 Comparison with published data products

The second measure to check the quality is to compare the calculated products with published results. Our aim is to make sure that the data is correct and usable on a statistical basis.

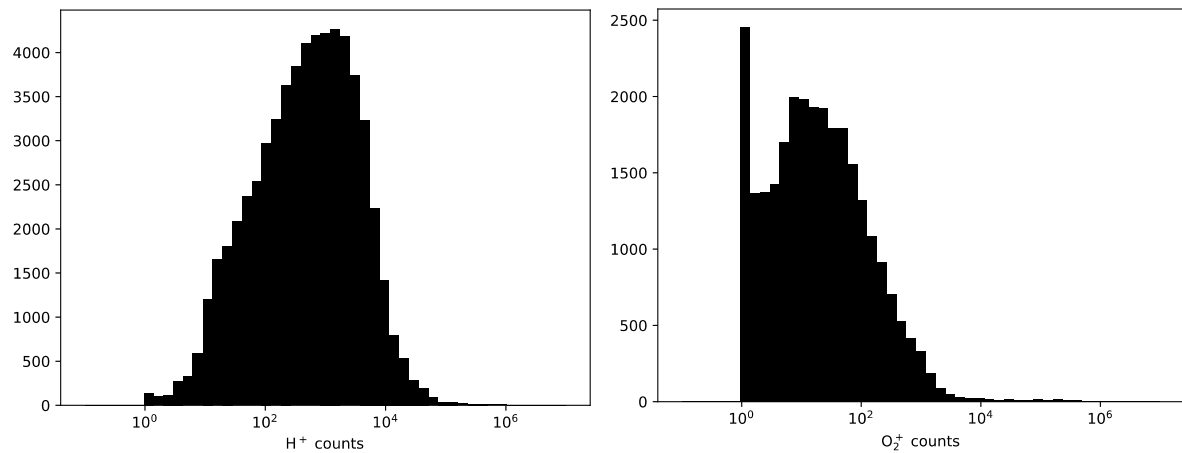
The differential flux data from May 2007 until February 2011 was included in the statistical study of Nilsson et al. (2012), which made average energy distributions in different regions in the Martian plasma environment. The results are reasonable and compares well to other studies made using the MAVEN mission later. The results also compare well with other studies, using different methods for the same parts explained above. For example, we may compare the flux maps of Nilsson et al. (2012) to those of Ramstad et al. (2015), which show clear agreement on a statistical basis. It is important to remember that average numbers differ, depending on the methods used, and the data used on each study, as shown for similar studies made in the Venusian plasma environment (Nordström et al., 2013). Even so, the results are similar and comparable on a statistical basis. Note that for detailed case studies we recommend to always confirm with the raw count data.

Figure 8 shows an example of two orbits with comparison between the archived density and velocity moments and the moments from AMDA, which has another version of calculated moments from ASPERA-3/IMA, for  $H^+$  and  $O^+$  on 4 Nov 2014. The AMDA moments have been used in several publications already and is a good dataset to compare with. Statistically, the AMDA and archived datasets agree. The small differences that appear between them comes from differences in the handling of the data, such as noise and ghost, as well as the handling of missing parts of a distribution. AMDA might use interpolations or fitting procedures to handle the data, while in the archived data here we have only integrated the data as it is, with no interpolation. We have also not included the low energies, as we do not have a full FOV measurement in this energy range (see section 5.1). This means that populations that have a large part below this energy threshold will not show the correct density and velocity in the archived data. This part is challenging to handle, and we have included a quality flag to indicate when this is important. A deeper study is needed in order to properly handle these data, and has not been done in the archived moments.

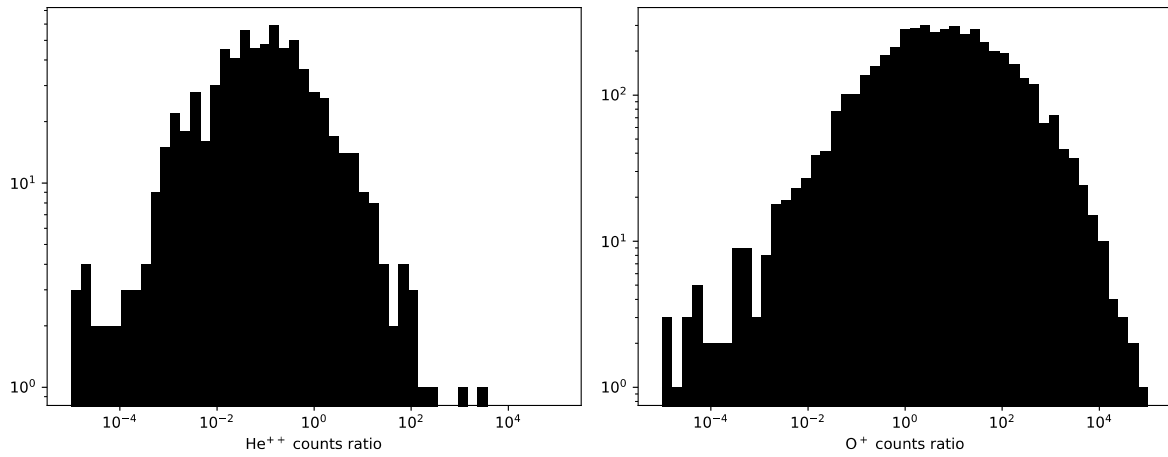
Figure 9 shows an example date of a comparison between the AMDA and archived temperatures. The data shows differences between the values, but a general similar magnitude. The difference between specific data is presumably caused by a difference in approach of calculating the temperatures. Here, an integration of the 2<sup>nd</sup> moment has been implemented on a 1D approach (see Equation 6).



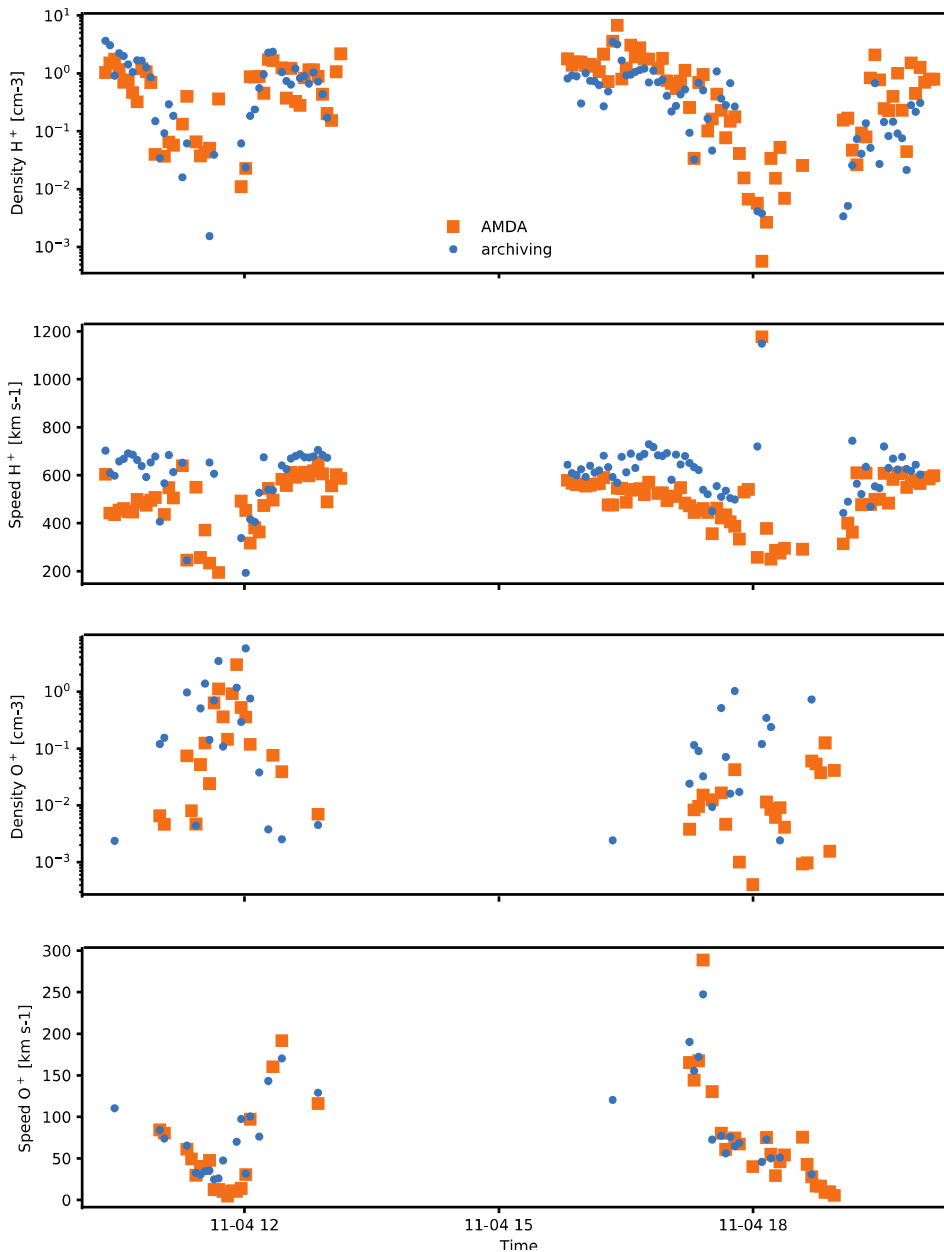
**Figure 5.** Proxy of UV counts from a few months of data from how many counts were removed in the noise cleaning. If more than 400, or more than 1000, a flag is raised. The flag indicates that there was a lot of noise and probably a problem of either UV contamination or penetration of high energy particles.



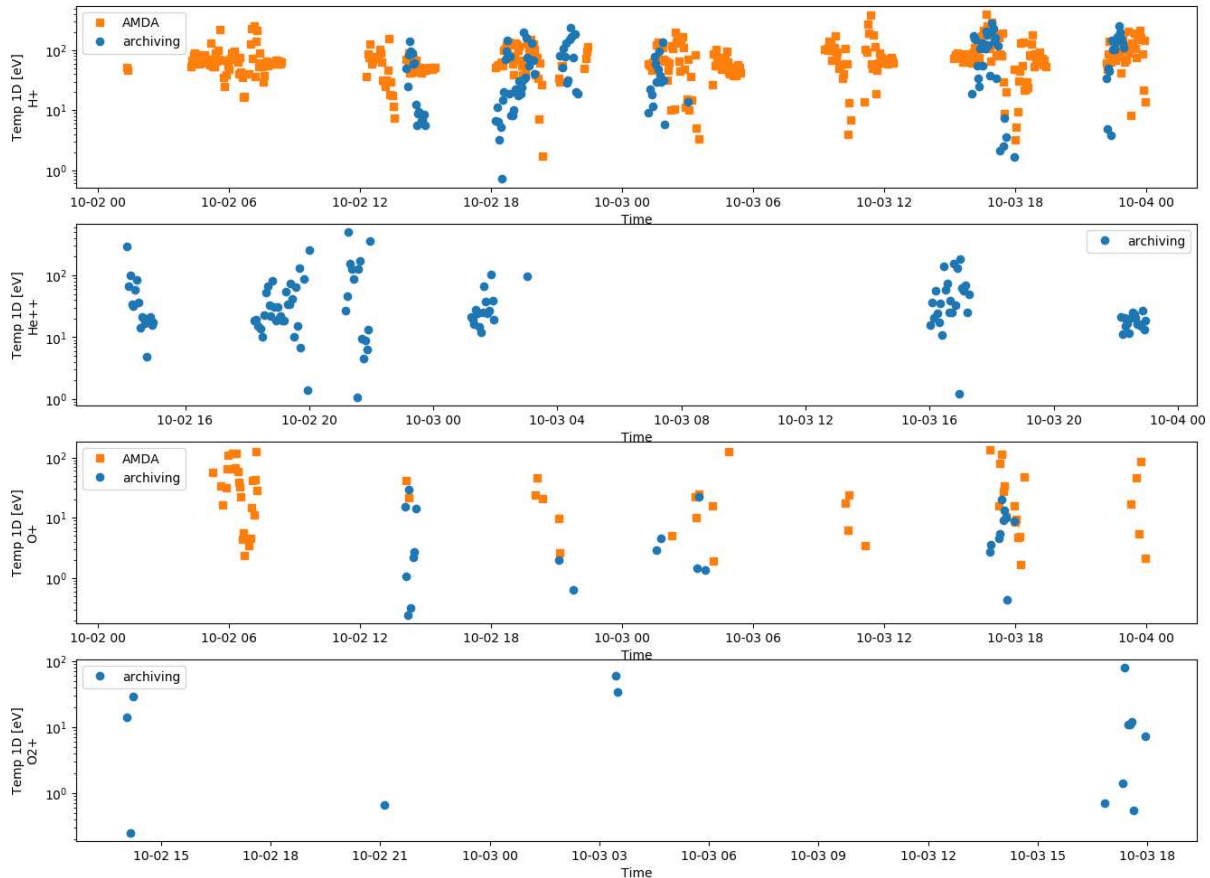
**Figure 6.** Number of counts integrated over a 192 s scan for  $H^+$  (left) and  $O_2^+$  (right). The threshold for calculating moments is set at 10 counts (see discussion on fourth quality flag in text for more details).



**Figure 7.** Ratio of counts below and above the energy threshold for elevation sweeping for  $\text{He}^{++}$  (left) and  $\text{O}^+$  (right). Threshold for calculating moments is set at a ratio equal to 1. (see discussion on fifth quality flag in text for more details).



**Figure 8.** Comparison between the moments stored in AMDA (orange squares) and the archived moments (blue dots) for  $H^+$  and  $O^+$ . In general, the two datasets agree. The small differences is due to differences in the methods. In this project we have only integrated the counts as is, with no interpolation or fitting of the data, while in AMDA there is a difference in the handling of the proton ghosts, and they likely include an interpolation to the low energies that does not contain a full FOV for  $O^+$ .



**Figure 9.** Comparison between temperature moments stored in AMDA (orange squares,  $T = (T_x + T_y + T_z) / 3$ ) and the archived 1D temperatures calculated from the integrated moments for  $H^+$ ,  $He^{++}$ ,  $O^+$  and  $O_2^+$  (blue dots, Eq. 6). In general the two datasets agree. The small differences is due to differences in methods. In this project we have only integrated the counts as is, with no interpolation or fitting of the data, while in AMDA there is a difference in the handling of the proton ghosts, and they likely include an interpolation to the low energies that does not contain a full FOV for  $O^+$ .

## References

Lundin, R., Barabash, S., Holmström, M., Nilsson, H., Yamauchi, M., Dubinin, E. M., and Fraenz, M. (2009), Atmospheric origin of cold ion escape from Mars, *Geophys. Res. Lett.*, 36, L17202, doi:[10.1029/2009GL039341](https://doi.org/10.1029/2009GL039341).

Nilsson, H., G. Stenberg, Y. Futaana, M. Holmström, S. Barabash, R. Lundin, N. J. T. Edberg, and A. Fedorov (2012). Ion distributions in the vicinity of Mars: Signatures of heating and acceleration processes. *Earth, Planets and Space*, 64(2):9. Doi: 10.5047/eps.2011.04.011

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Ramstad, R., S. Barabash, Y. Futaana, H. Nilsson, X.-D. Wang, and M. Holmström. (2015). The Martian atmospheric ion escape rate dependence on solar wind and solar EUV conditions: 1. seven years of Mars Express observations. *Journal of Geophysical Research: Planets*, 120:1298–1309.

Voshchepynets, A., Barabash, S., Ramstad, R., Hölmstrom, M., Andrews, D., Nicolaou, G., et al. (2018). Ions accelerated by sounder-plasma interaction as observed by Mars Express. *Journal of Geophysical Research: Space Physics*, 123, 9802–9814. <https://doi.org/10.1029/2018JA025889>

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# ASPERA-3 IMA

## Pipeline data verification

	<b>Name and function</b>	<b>Signature &amp; Date</b>
<b>Prepared by:</b>	Hans Nilsson	Hans Nilsson hane@irf.se  Digitally signed by Hans Nilsson hane@irf.se Date: 2022.11.09 09:25:05 +01'00'
<b>Verified by:</b>	Moa Persson	Moa Persson  Digitally signed by Moa Persson Date: 2022.11.14 13:15:27 +09'00'
<b>Approved by:</b>	Mats Holmström	

**CHANGE RECORD**

Version		Date	Changed Paragraphs	Remarks
Issue	Rev			
1	0	2022-11-08		New document



**TABLE OF CONTENT**

**1 INTRODUCTION.....4**

1.1 Summary .....4

1.2 Scope of this document .....4

1.3 Applicable Documents .....4

1.4 Reference Documents .....4

1.5 Abbreviations and acronyms .....4

**2 COMPARISON OF THE OLD DATA SET AND THE NEW PIPELINE DATA .....4**

2.1 Description .....4

2.2 Results for O<sup>+</sup> and O<sub>2</sub><sup>+</sup> .....5

2.3 Results for H<sup>+</sup> .....6

2.4 Results for He<sup>2+</sup> .....6

**3 CONCLUSION .....7**

**4 LIST OF SELECTED TIME PERIODS.....7**

			<b>Mars Express</b>	Reference : <b>MARS-IRF-IMA-TN-001</b> Issue : <b>1</b> Rev. : <b>0</b> Date : <b>2022-11-08</b> Volume : <b>-</b> Page: <b>4</b>
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## 1 INTRODUCTION

### 1.1 Summary

The Swedish Institute of Space Physics (IRF) has been producing cleaned, mass-separated data in physical units for internal use throughout the Mars Express mission. The software used was made ad hoc according to the needs of the scientists and improved over the years as a better understanding of the instrument emerged. In order to deliver user friendly data in physical units to the PSA a pipeline was set up under a contract with ESA. The new pipeline was based on the old data processing software, but cleaned up and rewritten to be better documented and maintainable. When the new pipeline was tested the results were compared to the old data set and it was initially concluded that the two data sets agreed. At a later stage a bug in the new pipeline was still found, giving incorrect results from the new pipeline. This was corrected, and with this technical note we compare some samples from the new pipeline with the old data set. It is found that the two data set agree. There are some differences, but these are due to the evolution of the data processing over the years which has been fully applied to the data from the new pipeline. This is mostly seen in the proton data, whereas for heavy ions the difference is very slight.

### 1.2 Scope of this document

This document presents a comparison of the data from the new pipeline and the old data set used at IRF for a number of one hour intervals in 2009 and 2010. These were chosen as this covers one Martian year and two different energy tables, with a change of energy table taking place in 16 November 2009.

### 1.3 Applicable Documents

CCN 1 for ESA Contract 4000115355 (Production and Archiving of solar wind moments from Mars and Venus Express observations- Ion Fluxes by MEX/ASPERA)

### 1.4 Reference Documents

MEx/ASPERA-3/IMA Archiving – Differential Flux and Moments for H<sup>+</sup>, He<sup>++</sup>, O<sup>+</sup>, and O<sub>2</sub><sup>+</sup>, Moa Persson, Hans Nilsson, Mats Holmström, Yoshifumi Futaana

### 1.5 Abbreviations and acronyms

IRF Institutet för rymdfysik (Swedish Institute of Space Physics)  
 ESA European Space Agency  
 PSA Planetary Science Archive  
 IMA Ion Mass Analyzer – part of the ASPERA-3 instrument suite on Mars Express

## 2 COMPARISON OF THE OLD DATA SET AND THE NEW PIPELINE DATA

### 2.1 Description

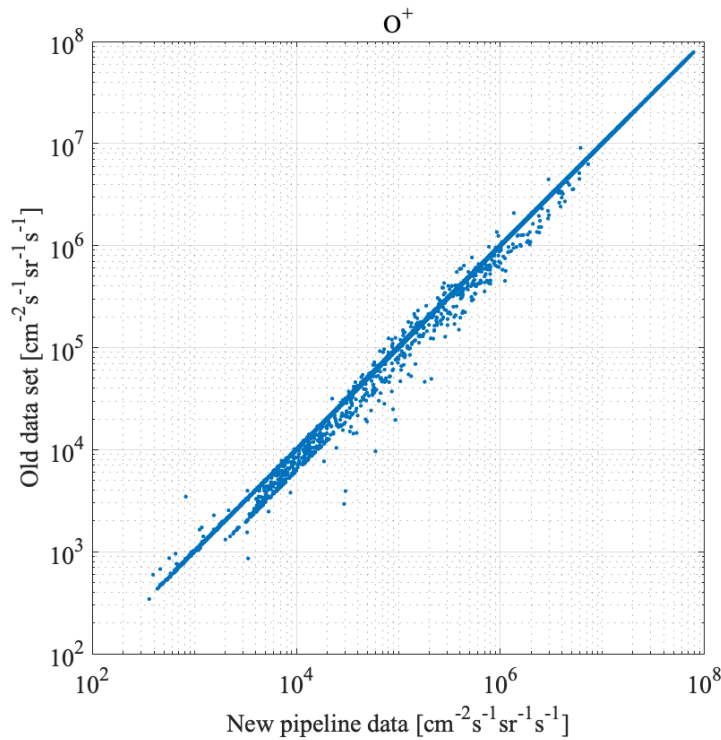
Data in both data sets are stored in one hour intervals. In the oldest data, these were cut according to time, sometimes cutting the data in the middle of a the acquisition of a full ion distribution function. Later data adjusted this to contain only full distributions. Therefore the exact times in the one hour data files are not necessarily the same for the two data sets. The comparison was done for the times that overlapped in the two data sets. Using quick-look plots one hour intervals were selected for most months in 2009 and 2010 when data was available from IMA. The times are listed in section 4.

IMA data is obtained for a range of energies and angles. A one-dimensional data set was produced, comparing the differential flux from the two data sets for each data point. The values from the two data sets were plotted against each other. It is expected that the two data sets essentially follow each other with only small deviations from a straight line with coefficient 1.

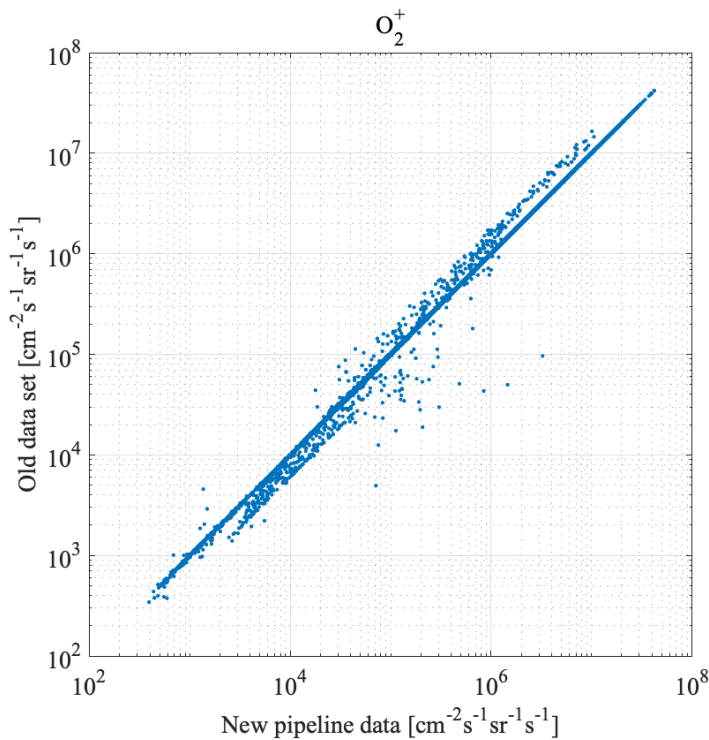


## 2.2 Results for $O^+$ and $O_2^+$

Agreement between the two data sets is very good for the main heavy planetary ions,  $O^+$  and  $O_2^+$  as shown in figures 1 and 2. The small deviations are due to changes in the noise and cross-talk reduction. The vast majority of all points fall on the line with equal values.



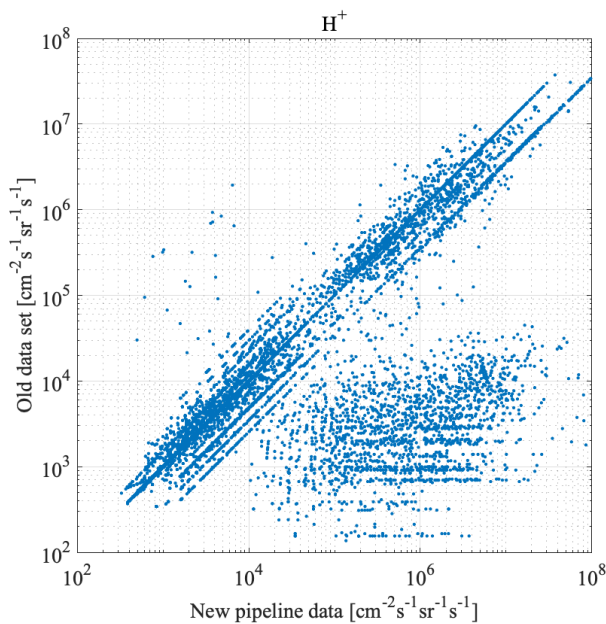
**Figure 1** Comparison of the new pipeline data (X) and the old data set (Y)



**Figure 2** Comparison of the new pipeline data (X) and the old data set (Y)

### 2.3 Results for H<sup>+</sup>

The result for H<sup>+</sup> shows a much larger scatter than for the heavier ions. There are two reasons for this. The data is processed to remove a scattered proton signal from the heavy ion mass channels, and this has improved over the years. The removed data is used to assess the H<sup>+</sup> signal, so this process affects the estimated H<sup>+</sup> signal much more than it affects the counts of O<sup>+</sup> and O<sub>2</sub><sup>+</sup>. The second reason for the discrepancy is that the geometric factor, i.e. the conversion from instrument counts to physical units, has been updated for the protons during the mission. This update has not been applied to the old data set.



**Figure 3** Comparison of the new pipeline data (X) and the old data set (Y)

### 2.4 Results for He<sup>2+</sup>

The results for He<sup>2+</sup> are fairly similar to those for O<sup>+</sup> and O<sub>2</sub><sup>+</sup>. Agreement is generally good and there is no systematic difference.

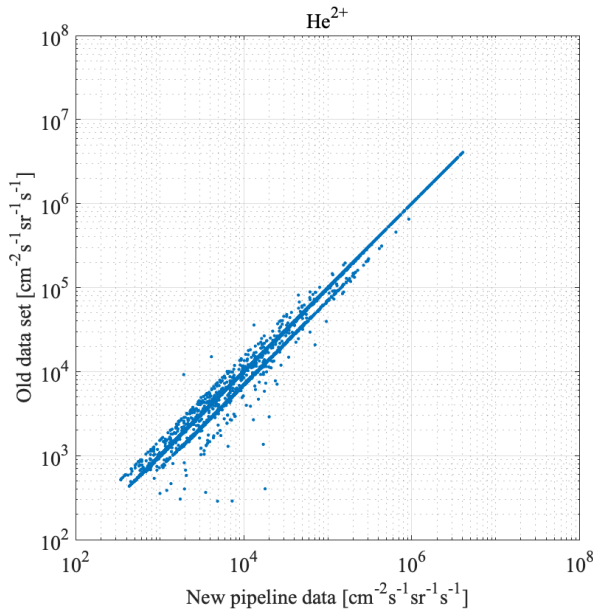


Figure 4 Comparison of the new pipeline data (X) and the old data set (Y)

### 3 CONCLUSION

The new pipeline can now be considered verified against the old data set. We can see that the data about to be delivered to PSA is consistent with the old data set and thus the data used in previous ASPERA-3 IMA publications. A further cross calibration with MAVEN is still most worthwhile for the heavy ions O<sup>+</sup> and O<sub>2</sub><sup>+</sup> but that is a large undertaking requiring significant resources.

### 4 LIST OF SELECTED TIME PERIODS

The list of used times pasted in from the code is showed below in yyymmddHHMM.format.

```

datelist = [...
'200902130400' ;...
'200903101100' ;...
'200904192200' ;...
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'200906062200' ;...
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