

# Short-term variability of inner-source pickup ions at 1 AU

## SOHO/CELIAS observations

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### ABSTRACT

**Context.** In 1995 a second extended source of pickup ions in the inner heliosphere was discovered. Since then this so-called inner source has been characterised in many studies, and various scenarios for its nature have been proposed. But to this day, the detailed nature of the inner source is still unknown.

**Aims.** Although it seems most likely that an interaction of solar wind and dust plays a key role in the production of the inner source pickup ions, available observations have not provided conclusive evidence for any proposed scenario. By analysing the short-term variability of the inner source, we determine a new observational constraint to address the nature of the inner source.

**Methods.** We used the data set of the charge time-of-flight instrument that operated in 1996 on-board the solar and heliospheric observatory at the first Lagrangian point to analyse inner source  $O^+$  and  $C^+$ . The unmatched combination of mass per charge resolution, which is sufficient to definitely resolve  $O^+$  and  $C^+$ , and typical high count rates of about 150 counts per day allowed us to address the short-term variability of the inner source for the first time.

**Results.** The comparison of the variability of inner-source and solar-wind ions shows that the flux of inner source pickup oxygen and carbon is directly correlated with the flux of solar wind oxygen, and carbon, respectively.

**Conclusions.** Among the scenarios for the nature of the inner source alone, the scenario of solar-wind neutralisation agrees with this new observational constraint.

**Key words.** solar wind – interplanetary medium

## 1. Introduction

Observations in the inner heliosphere have shown that there are two extended sources for the production of pickup ions (PUIs). The first source has been unambiguously identified as interstellar neutral atoms that can penetrate deep into the heliosphere unimpeded by electro-magnetic forces. In fact the existence and the nature of this interstellar source was predicted (Fahr 1974) prior to its first observation (Moebius et al. 1985). The advent of the idea of a second so-called inner source had been marked ten years after the first observation of interstellar pickup  $He^+$  by the discovery of one-fold ionised carbon that could not be attributed to the interstellar source (Geiss et al. 1995).

The inner source has been analysed in many subsequent studies and several characteristics have been inferred from the results. Direct observed characteristics are that it resembles the solar wind composition (Gloeckler et al. 2000), is randomly distributed (Geiss et al. 1996), produces a large continuous flux (Geiss et al. 1996), and is stable over the solar cycle (Allegrini et al. 2005). There is also evidence of a correlation of solar-wind  $H^+$  and inner-source PUI flux (Allegrini et al. 2005).

Another characteristic, a peak production close to the Sun within 10 to 30 solar radii, has been deduced from the shape of observed velocity spectra (Schwadron et al. 2000). However, this last characteristic depends on assumptions about the nature of the inner source, for which various scenarios have been proposed (Gloeckler et al. 2000; Schwadron et al. 2000; Wimmer-Schweingruber & Bochsler 2003; Bzowski & Krolkowska 2005; Mann & Czechowski 2005). All settings

assume that dust is important for generating the inner-source pickup ions, but so far none agrees with all observational constraints (Allegrini et al. 2005). Nevertheless, the observations are suggestive of a direct involvement of solar wind ions in the inner-source PUI production mechanism. Among them all, the two scenarios assuming an interaction of solar wind and dust are the most likely ones. The first proposed mechanism is called solar-wind recycling. Solar wind is implanted in and subsequently released by large  $\mu m$  dust grains close to the Sun (Gloeckler et al. 2000; Schwadron et al. 2000). In the second mechanism, called solar-wind neutralisation, solar wind is neutralised on penetration of small nm size dust grains (Wimmer-Schweingruber & Bochsler 2003). This scenario does not require a peak of production close to the Sun (Bochsler et al. 2006, 2007).

Despite the progress that has been made in the past two decades, existing dust and pickup ion measurements have not been sufficient to pinpoint the nature of the inner source conclusively (Allegrini et al. 2005). Inner source PUIs are hard to observe, because their flux is several orders of magnitude lower than the bulk solar wind flux. Previous studies using the Solar Wind Ion Composition Spectrometer (SWICS) on *Ulysses* measured approximately a single  $C^+$  ion per day. For example, the study of the stability over the solar cycle by Allegrini et al. (2005), comparing three periods of about 64 days each, was based on a total of  $\sim 200 C^+$  counts. Consequently, the short-term behaviour of the inner source has not been accessible and is unknown to this day.

For this reason, the Charge Time Of Flight instrument (CTOF) which operated in 1996 as part of the Charge, Element,

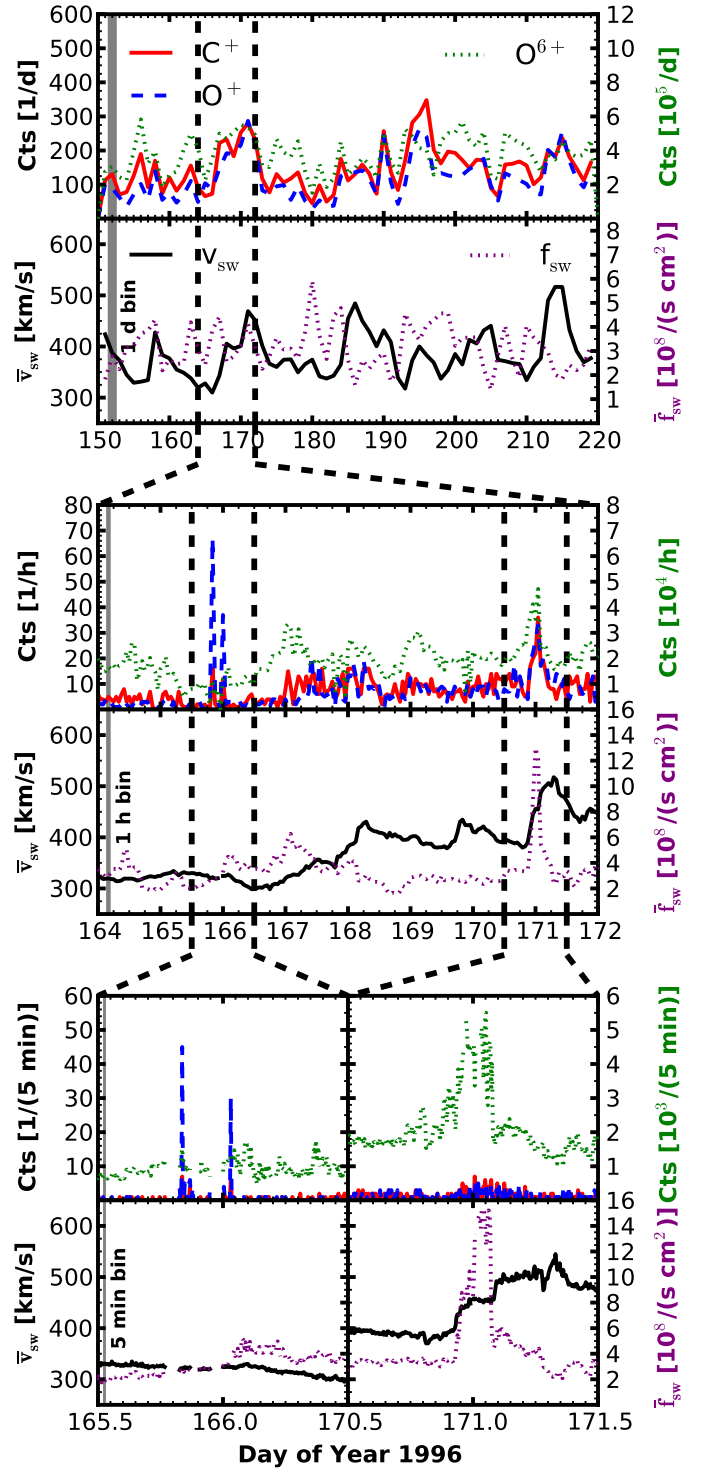
and Isotope Analysis System (CELIAS; Hovestadt et al. 1995) on the Solar Heliospheric Observatory (SOHO) is perfectly suited to studying inner-source PUIs (Berger et al. 2012).  $O^+$  and  $C^+$  are clearly resolved, and the count rates exceed previous studies by more than two orders of magnitude. Surprisingly, the data, with one exception of Venus tail ray  $O^+$  observations (Grünwaldt et al. 1997), has never been used to study inner source PUIs, although CTOFs active phase coincides with the discovery of the inner source. In this work and a companion paper (Taut et al. 2015) we investigate inner source PUIs using CTOF data. Here, we address the short-term variability of inner source  $O^+$  and  $C^+$  while the companion paper addresses the composition of the inner source.

## 2. Method

The difference in the two production mechanisms of solar-wind recycling and solar-wind neutralisation is likely to affect the in-situ short-term behaviour of the inner source. Thus, it provides an additional observational constraint for distinguishing between the two scenarios. Arising from the two-step nature of the production mechanism in the solar-wind recycling scenario, there should be a phase shift between solar-wind heavy-ion flux and inner-source PUI flux. An implanted ion remains in the grain for a certain time  $\tau$  until it is released by grain sputtering caused by the total solar-wind flux. This time can be estimated as  $\tau(r) = \lambda/S(r)$  (Wimmer-Schweingruber & Bochsler 2003). Using a typical implantation depth  $\lambda \geq 100 \text{ \AA}$  and a grain sputtering rate  $S(1 \text{ AU}) = 1 \text{ \AA yr}^{-1}$ , we get  $\tau(0.05 \text{ AU}) \geq 0.25 \text{ yr}$  for the expected position of the peak production at  $r = 0.05 \text{ AU}$ . In the case of the solar-wind neutralisation scenario, the production is nearly instantaneous, so for neutralisation, we expect the variability of an inner source PUI species to correlate with the corresponding solar wind flux of its element; for example, the variability of  $O^+$  should be correlated with the variability of the total solar wind oxygen flux. For the recycling scenario, with  $\tau(0.05 \text{ AU}) \geq 0.25 \text{ yr}$ , even slow solar wind with  $v_{sw} = 300 \text{ km s}^{-1}$  has covered a distance of more than 15 AU, and the in-situ flux of inner source PUIs should be uncorrelated with the solar-wind flux of the same element. Instead we expect a correlation of the variability of all inner source PUI species with the solar-wind proton flux that is the main driver for grain sputtering. Investigating the correlation of inner-source and solar-wind ions allows us to identify the most likely candidate for the production scenario of the inner source.

## 3. Observations and analysis technique

To study the short-term variability of inner-source pickup ions we used observations from SOHO/CELIAS that were obtained in the period from days 150 to 220 in 1996. For this period data from CTOF and the Proton Monitor (PM), which are both part of CELIAS, are available, and fluxes of solar-wind protons and  $O^{6+}$  can be compared to pickup  $He^+$ ,  $O^+$ , and  $C^+$ . Solar wind (proton) velocity,  $v_{sw}$ , and proton density,  $n_{sw}$ , and thus proton flux,  $f_{sw}$ , are routinely measured by the PM and provided via the SOHO archive in five-minute resolution. The remaining ions have been observed by CTOF. In the case of solar wind  $O^{6+}$ , CTOF matrix rate data were analysed according to Hefti (1997) to determine five-minute count rates. For the pickup ions, we analysed CTOF pulse-height analysis data and extracted velocity spectra with a five-minute cadence according to Berger et al. (2012).



**Fig. 1.** Time series of CTOF count rates for inner-source  $C^+$  and  $O^+$ , and solar-wind  $O^{6+}$  (upper sub-panels) and PM solar-wind speed and flux  $v_{sw}$  and  $f_{sw}$  (lower sub-panels) are shown for daily, hourly, and 5-min cadences (top, middle, bottom panel).

Figure 1 shows a time series of the data products in daily, hourly, and five-minute cadences. We set limits in  $w = v_{ion}/v_{sw}$  to select inner-source PUIs. The lower limits  $w_{O^+} > 0.8$  for  $O^+$  and  $w_{C^+} > 1.0$  for  $C^+$  have been set to avoid the background caused by solar wind iron and pickup helium. Upper limits for  $O^+$  and  $C^+$  have been set to separate inner from interstellar source contributions. While  $C^+$  is attributed solely to the inner source,  $O^+$  has a significant contribution from interstellar PUIs at  $w_{O^+} > 1.4$

(Berger et al. 2012). Thus the upper limits for  $C^+$  and  $O^+$  have been set to maximum  $w_{C^+}$ , which can be observed with CTOF, and  $w_{O^+} < 1.4$ , respectively. Although the count rates of  $O^+$  and  $C^+$  are more than three orders of magnitude lower than of solar wind  $O^{6+}$ , they are much higher than in previous investigations, where a single count per day is typically observed. A strong variability can be seen even in the highest cadence of five minutes.

The period around day of year (DoY) 166, which is shown in the bottom left-hand panel shows significant spikes in the  $O^+$  count rates rising from less than one count per five minutes up to 45 counts per five minutes. These spikes are accompanied by small spikes in  $C^+$  but without any distinctive features in  $v_{sw}$ ,  $f_{sw}$ , and  $O^{6+}$ . A previous study (Grünwaldt et al. 1997) has identified these spikes as Venus tail rays. The bottom right-hand panel shows a second period around DoY 171 in closeup. A clear signature of a compression region in  $f_{sw}$  and  $O^{6+}$  is observed. Interestingly,  $O^+$  and  $C^+$  also show an increase that roughly coincides with the solar-wind compression. The features in the two closeup periods are also visible in the middle panel in a one-hour cadence. In a one-day cadence displayed in the upper panel, the features that happen on time scales of five minutes up to a few hours are hardly visible. But the daily fluxes of solar wind ions, as well as pickup ions, also show strong variability. In the following we address the short-term variability of  $O^+$  and  $C^+$ .

### 3.1. Variability

As stated above, a correlation of inner-source PUI and solar-wind proton flux would point towards the solar-wind recycling scenario, while a correlation of inner-source PUI, and the corresponding solar-wind heavy ion flux would favour the solar-wind neutralisation scenario.

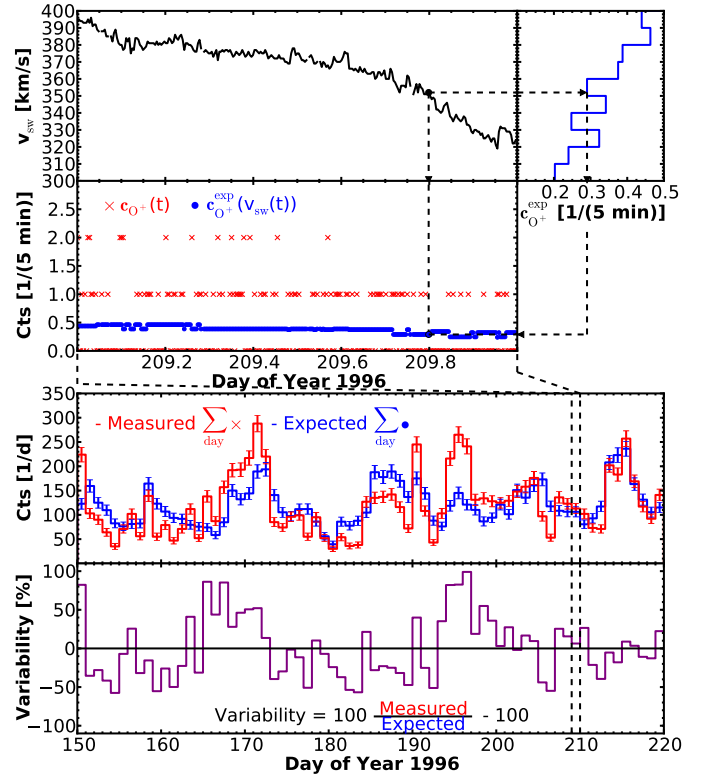
We now use the CELIAS data to search for correlations between the fluxes of  $H^+$ ,  $O^{6+}$ ,  $O^+$ , and  $C^+$ . For that we have to account for instrumental influences. The detection efficiency may vary strongly depending on the ion species and within one species on the ion velocity. In general, the detection efficiency increases with ion velocity. In addition, the highest velocity that can be measured with CTOF depends on the mass per charge of the observed ion species. While  $O^{6+}$  can be measured up to  $v_{max} = 1580 \text{ km s}^{-1}$ , the maximum velocity for  $O^+$  is  $v_{max} = 645 \text{ km s}^{-1}$ . Thus, the phase-space coverage in terms of  $w$  depends on the ion species and solar-wind speed. To calculate the variability of the different species, we have chosen an approach that implicitly accounts for these effects. For a given solar wind speed,  $v_{sw}(t) = V_{SW}$ , and ion species, the phase space coverage in terms of  $w$  and, especially, the detection efficiency for each  $w$  is constant and independent of time. Thus, we can calculate solar wind speed  $V_{SW}$  and ion species-dependent mean five-minute count rates and use them as expectation values. If  $\mathbf{T}_{V_{SW}}$  is the set of periods in which  $v_{sw}(t) = V_{SW}$  and  $c_{ion}(t)$  are five-minute ion count rates, the expected count rate in five minutes is given by

$$c_{ion}^{exp}(V_{SW}) = \sum_{t \in \mathbf{T}_{V_{SW}}} \frac{c_{ion}(t)}{|\mathbf{T}_{V_{SW}}|}. \quad (1)$$

Then the relative variability in percent can be calculated by

$$\text{Variability}(t) = 100 \cdot \frac{c_{ion}(t)}{c_{ion}^{exp}(v_{sw}(t))} - 100. \quad (2)$$

Figure 2 illustrates how the variability of  $O^+$  is derived. The upper panels demonstrate how  $v_{sw}(t)$  translates into  $c_{O^+}^{exp}(v_{sw}(t))$ . To



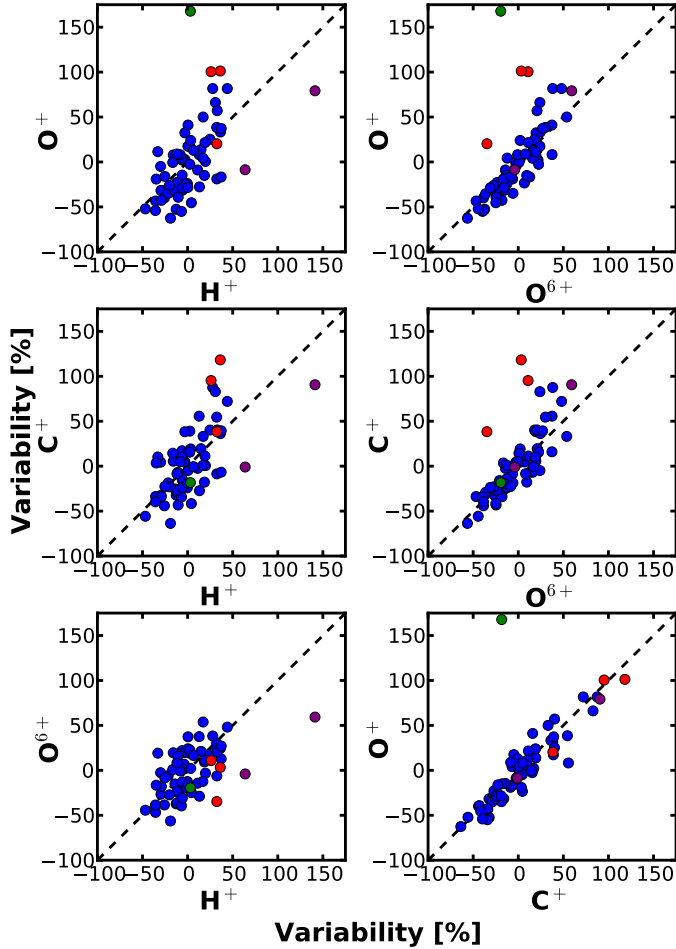
**Fig. 2.** Illustration how  $O^+$  daily variabilities are derived. *Top main panel:* 5-min solar-wind speeds  $v_{sw}(t)$  (top, left) and expectation values  $c_{O^+}^{exp}(V_{SW})$  (top, right) are used to construct a time series of expected counts (blue, bottom). Together with the time series of observed counts (red, bottom), observed and expected daily values can be derived. *Bottom main panel:* time series of observed (red) and expected (blue) daily counts (top). Error bars denote the uncertainty due to counting statistic. Finally the time series of the resulting daily variability is displayed (bottom).

get good statistics, the mean values  $c_{O^+}^{exp}(V_{SW})$  have been calculated for the whole analysed period from days 150 to 220 and  $V_{SW}$  intervals with widths of  $10 \text{ km s}^{-1}$ . Because five-minute count rates and expectation values are too low to get reasonable variabilities using Eq. (2), a temporal binning is applied, and variabilities are derived. The results for a daily binning are displayed in the lower panels. It can especially be seen that the deviation between measured and expected counts is typically much greater than the expected deviations if only counting statistic is assumed (error bars). Therefore, the derived variability can be attributed to a definite temporal variation.

### 3.2. Correlations

The calculated variabilities for  $H^+$ ,  $O^{6+}$ ,  $O^+$ , and  $C^+$  can be compared to search for possible correlations. In the top four panels of Fig. 3 the resulting variabilities for one day temporal binning of  $C^+$  and  $O^+$  are plotted versus  $H^+$  and  $O^{6+}$ . It can be seen that inner-source pickup  $O^+$  and  $C^+$  correlate rather with solar wind  $O^{6+}$  than with solar wind  $H^+$ . The two bottom panels show the results for  $O^{6+}$  versus  $H^+$  and  $O^+$  versus  $C^+$ .

To quantify the correlation for different pairs of ion species the sample correlation coefficient,  $r_{ion1}^{ion2}$ , can be calculated. As transient events can strongly influence the obtained variabilities, especially the derived expectation values  $c_{ion}^{exp}(V_{SW})$ , we removed such periods from our analysis. First the period around DoY 166 in which venus tail ray  $O^+$  is observed (Grünwaldt et al. 1997)



**Fig. 3.** Daily variabilities of various pairs of ions are plotted against each other. The colour indicates values that correspond to certain periods (see Sect. 3.2).

must be removed. The strong enhancement of  $O^+$  with respect to all other ions, can be seen in the bottom left panel of Fig. 1, and the corresponding variability is marked in green in Fig. 3. Furthermore, the periods DoY 150 to 151 and 183.5 to 184.5, showed an increased proton flux, which is indicated by purple in Fig. 3. Both periods can be attributed to interplanetary coronal mass ejections (ICMEs; Cane & Richardson 2003). Finally the continuous period from DoY 194.5 to 197.5 showed increased fluxes of  $O^+$  and  $C^+$ , indicated by red in Fig. 3. For this period no signature of an ICME has been observed but at approximately DoY 191.5 the Large Angle and Spectrometric COronagraph experiment (LASCO) on SOHO observed a Coronal Mass Ejection (CME) SOHO LASCO CME CATALOG<sup>1</sup> (2014) with a large angular extend of  $86^\circ$  and a speed of about  $430 \text{ km s}^{-1}$ . Because LASCO observations only resolve the CME motion perpendicular to the line of sight, it can not be ruled out that parts of the CME have moved towards SOHO's position at the first lagrangian point. If so, its time of arrival would have been in the interval from DoY 194.5 to 197.5. In situ measured  $v_{\text{sw}}$  around DoY 194.5 rises from  $\approx 315 \text{ km s}^{-1}$  to the derived CME speed of  $\approx 430 \text{ km s}^{-1}$  and stays at velocities above  $370 \text{ km s}^{-1}$  until approximately DoY 197.5. Thus, the increased fluxes of  $O^+$  and  $C^+$  might be related to this CME, although no ICME signatures have been observed in situ. With this

<sup>1</sup> [http://cdaw.gsfc.nasa.gov/CME\\_list/](http://cdaw.gsfc.nasa.gov/CME_list/)

**Table 1.** Mean correlation coefficients  $r_{\text{ion1}}^{\text{ion2}}$  (ion2 = row, ion1 = column), and their standard deviations for the two periods  $T_1$  and  $T_2$  are given.

	$T_1$		$T_2$	
	$H^+$	$O^{6+}$	$H^+$	$O^{6+}$
$O^+$	$0.61 \pm 0.04$	$0.76 \pm 0.04$	$0.65 \pm 0.05$	$0.86 \pm 0.02$
$C^+$	$0.64 \pm 0.03$	$0.74 \pm 0.04$	$0.66 \pm 0.05$	$0.86 \pm 0.02$
$He^+$	$0.70 \pm 0.07$	$0.26 \pm 0.12$	$0.63 \pm 0.07$	$0.23 \pm 0.14$
$O^{6+}$	$0.53 \pm 0.07$	–	$0.63 \pm 0.04$	–
	$O^+, T_1$		$O^+, T_2$	
$C^+$	$0.95 \pm 0.04$		$0.94 \pm 0.05$	

we have calculated  $r_{\text{ion1}}^{\text{ion2}}$  for two periods,  $T_1$  and  $T_2$ . In  $T_1$  only the interval of Venus Tail Ray observations (green) has been neglected, whereas in  $T_2$  also the periods marked in purple and red have been excluded. Variabilities were calculated for various cadences from 0.1 to 3.0 days in 0.1 steps. The results for  $T_2$  are displayed in Fig. 4. In Table 1 the mean value and the standard deviation of  $r_{\text{ion1}}^{\text{ion2}}$  for  $T_1$  and  $T_2$  are given.

Because  $H^+$  measurements come from the PM while the remaining ions are measured by CTOF we used CTOF measurements of interstellar pickup  $He^+$  in the range  $1.5 < w_{He^+} < 2.0$  to check whether the good correlation among  $O^{6+}$  and  $O^+$ ,  $O^{6+}$  and  $C^+$ , and  $O^+$  and  $C^+$  respectively, might be produced by instrumental effects that have not been considered correctly in our analysis. Therefore, CTOF pulse height analysis data have been analysed and  $He^+$  variabilities have been determined similarly as described for  $C^+$  and  $O^+$ . Because  $r_{O^{6+}}^{He^+}$  is significantly smaller than  $r_{H^+}^{He^+}$  we can rule out that high values of  $r_{O^{6+}}^{O^+}$ ,  $r_{O^{6+}}^{C^+}$ , and  $r_{C^+}^{O^+}$  are due to instrumental biases.

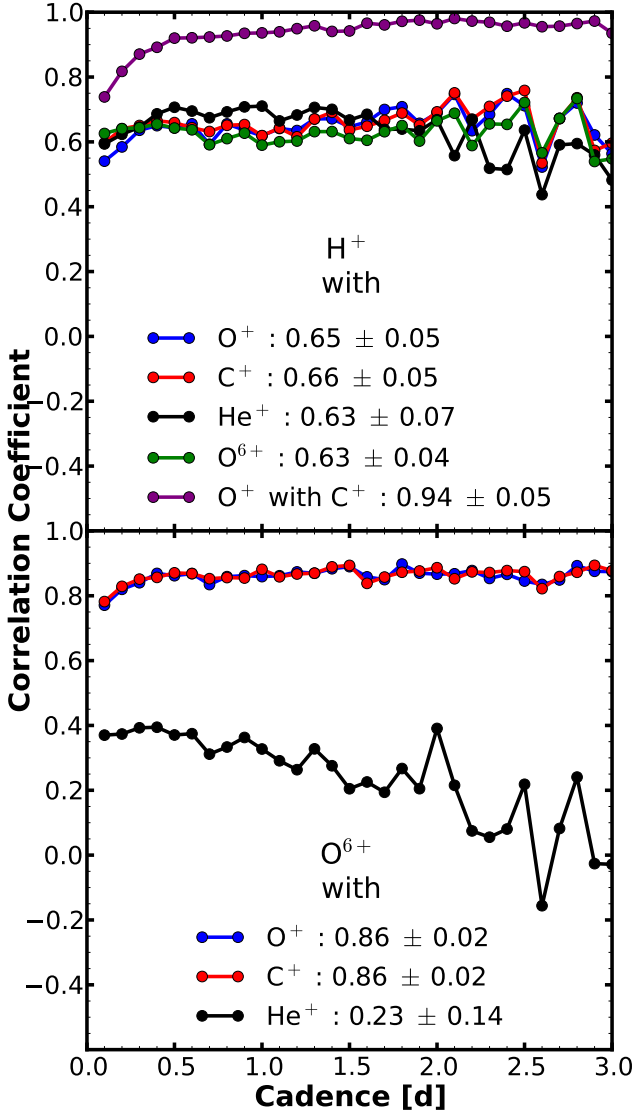
## 4. Discussion

Although the correlation coefficient cannot provide definite proof of a causal relationship of the correlated quantities, our results can be interpreted in the context of the two discussed scenarios for the production of inner-source PUIs. In Sect. 2 it was pointed out that a correlation of  $O^+$  and solar-wind oxygen would be expected for the solar-wind neutralisation scenario, while a correlation of  $O^+$  and solar-wind  $H^+$  would be expected in the case of the solar-wind recycling scenario.

For both periods  $T_1$  and  $T_2$ , the correlation coefficient between  $O^+$  and  $O^{6+}$ ,  $r_{O^{6+}}^{O^+}$ , is significantly larger than between  $O^+$  and solar-wind  $H^+$ ,  $r_{H^+}^{O^+}$ . This result indicates that the flux of inner-source pickup  $O^+$  is directly correlated with the flux of solar-wind  $O^{6+}$ . We argue that this correlation can be interpreted as a direct correlation of inner-source and total solar-wind oxygen flux, for the following reasons. First,  $O^{6+}$  is the dominant charge state of oxygen in the solar wind and therefore already a good indicator of the total solar-wind oxygen flux. Second, the variability of the charge state distribution of oxygen depends on  $v_{\text{sw}}$  (Zurbuchen et al. 1999). Using solar-wind speed-dependent expectation values,  $c_{O^{6+}}^{\text{exp}}(v_{\text{sw}})$ , to determine the variability of  $O^{6+}$  assures that the variability of  $O^{6+}$  directly reflects the variability of solar-wind oxygen. Consequently, our results strongly imply that inner-source PUIs are produced by solar-wind neutralisation instead of solar-wind implantation.

Now we discuss whether the remaining correlation coefficients,  $r_{\text{ion1}}^{\text{ion2}}$ , are also consistent with this scenario. From observations (von Steiger et al. 2000), it is known that the fraction





**Fig. 4.** Correlation coefficients for various pairs of ions obtained for period  $T_2$  plotted versus cadence. Additionally, the average correlation coefficient of all cadences with respective standard deviation are given.

of heavy ions in the solar wind is variable. Thus, the solar-wind elemental flux can be described as

$$f_{\text{elm}}^{\text{sw}} \propto f_{\text{H}^+}^{\text{sw}} \cdot \eta_{\text{elm}} \quad (3)$$

with solar-wind proton flux,  $f_{\text{H}^+}^{\text{sw}}$  and elemental fractionation,  $\eta_{\text{elm}}$ . In the neutralisation scenario, the production of neutrals is proportional to the solar-wind elemental flux and dust cross section. Inner-source pickup ions are born from these neutrals by ionisation, so that we get, for the elemental inner-source flux,

$$f_{\text{elm}}^{\text{is}} \propto f_{\text{elm}}^{\text{sw}} \cdot \sigma_{\text{dust}} \cdot \beta_{\text{elm}} \quad (4)$$

with elemental solar-wind flux,  $f_{\text{elm}}^{\text{sw}}$ , dust cross section  $\sigma_{\text{dust}}$ , and total ionisation rate  $\beta_{\text{elm}}$ . Total ionisation rates  $\beta_{\text{elm}}$  are governed by photoionisation,  $\beta_{\text{elm}}^{\text{pi}}$ , electron-impact ionisation,  $\beta_{\text{elm}}^{\text{el}}$ , and charge exchange with solar wind protons,  $\beta_{\text{elm}}^{\text{ce}}$ ,

$$\beta_{\text{elm}} = \beta_{\text{elm}}^{\text{pi}} + \beta_{\text{elm}}^{\text{el}} + \beta_{\text{elm}}^{\text{ce}} \quad (5)$$

The relative importance of the three constituents of  $\beta_{\text{elm}}$  have been estimated for energetic neutral oxygen atoms by

Bzowski et al. (2013). They find that charge exchange and photoionisation are equally important and that electron impact is negligible in the analysed period. Considering cross sections for charge exchange from Lindsay & Stebbings (2005) and low differential velocities  $v_{\text{O}} - v_{\text{sw}}$ , as expected from solar-wind neutralisation, charge exchange is much less important for inner-source neutral compared to energetic neutral oxygen. Consequently, we argue that  $\beta_{\text{O}}$  is determined by  $\beta_{\text{O}}^{\text{pi}}$ . To our knowledge there are no comparable calculations for carbon, but in general charge exchange is expected to be even less important for carbon (Ruciński et al. 1996) owing to the quasi resonance of oxygen and protons. Comparing photoionisation and electron impact ionisation cross sections for carbon and oxygen (NIST 2014), one finds that  $\beta_{\text{O}}^{\text{pi}}/\beta_{\text{O}}^{\text{el}} \approx \beta_{\text{C}}^{\text{pi}}/\beta_{\text{C}}^{\text{el}}$ , and thus  $\beta_{\text{C}}$  is also determined by  $\beta_{\text{C}}^{\text{pi}}$ . With  $\beta_{\text{elm}} \approx \beta_{\text{elm}}^{\text{pi}}$  for carbon and oxygen, we obtain from Eq. (4),

$$f_{\text{elm}}^{\text{is}} \propto f_{\text{elm}}^{\text{sw}} \cdot \sigma_{\text{dust}} \cdot \beta_{\text{elm}}^{\text{pi}} \quad (6)$$

Combining Eqs. (3) and (6), we get

$$f_{\text{elm}}^{\text{is}} \propto f_{\text{H}^+}^{\text{sw}} \cdot \eta_{\text{elm}} \cdot \sigma_{\text{dust}} \cdot \beta_{\text{elm}}^{\text{pi}} \quad (7)$$

Considering that  $r_{\text{H}^+}^{\text{O}^{6+}}$  is very similar to  $r_{\text{H}^+}^{\text{O}^+}$  we argue due to Eq. (7) that the variability of the product,  $\sigma_{\text{dust}} \cdot \beta_{\text{elm}}^{\text{pi}}$ , is small compared to  $\eta_{\text{elm}}$ . Because measurements of the solar-wind carbon-to-oxygen ratio show only a small variability (von Steiger et al. 2000), i.e.  $\eta_{\text{C}} \approx \eta_{\text{O}}$ , we expect that  $r_{\text{O}^{6+}}^{\text{O}^+}$  is very similar to  $r_{\text{O}^{6+}}^{\text{C}^+}$ , in accordance with our observations. In particular, our results are compatible with the idea that solar-wind carbon correlates with inner-source pickup C<sup>+</sup>. That the strongest correlation is found between C<sup>+</sup> and O<sup>+</sup> additionally supports this conclusion. Consider that  $\eta_{\text{C}} \approx \eta_{\text{O}}$  and that  $\sigma_{\text{dust}}$  is the same for carbon and oxygen, it follows from Eq. (7) that C<sup>+</sup>/O<sup>+</sup> would only vary like  $\beta_{\text{C}}/\beta_{\text{O}}$ . Thus, the strong correlation,  $r_{\text{O}^+}^{\text{C}^+} = 0.94 \pm 0.05$ , indicates only a minor variability of  $\beta_{\text{C}}/\beta_{\text{O}}$ .

The correlation coefficients for different cadences as shown in Fig. 4 clearly show that the correlations exist on all timescales, reaching from 2.5 h up to 3 days. A systematic decrease in sub-day cadences in all  $r_{\text{ion1}}^{\text{O}^+}$  and  $r_{\text{ion1}}^{\text{C}^+}$  could be explained by spatial diffusion of PUIs. Diffusion would inherently weaken the observed correlations. But we would like to point out that the observed decrease is most likely attributed to the low counting statistics of both ions, leading to a discretisation in the variability calculated according to Eq. (2). This interpretation is supported by the fact that this decrease is strongest in  $r_{\text{O}^+}^{\text{C}^+}$ . Furthermore our results, i.e. the overall strong correlation coefficients, indicate that spatial diffusion is weak for inner-source PUIs.

Table 1 shows the correlation coefficients for two different time periods  $T_1$  and  $T_2$  as defined in Sect. 3.2. A comparison between  $T_1$  and  $T_2$  reveals a significant increase in  $r_{\text{O}^{6+}}^{\text{O}^+}$  and  $r_{\text{O}^{6+}}^{\text{C}^+}$  that is not visible for  $r_{\text{H}^+}^{\text{O}^+}$  and  $r_{\text{H}^+}^{\text{C}^+}$ . The significant increase in  $r_{\text{O}^{6+}}^{\text{O}^+}$  and  $r_{\text{O}^{6+}}^{\text{C}^+}$  is attributed to the period from DoY 194.5 to 197.5, which is marked in red in Fig. 3 and which have been removed for  $T_2$ . In this period, both O<sup>+</sup> and C<sup>+</sup> are equally enriched compared to O<sup>6+</sup>,  $r_{\text{O}^+}^{\text{C}^+}$  are consistently very similar for  $T_1$  and  $T_2$ . Consideration of Eq. (4) as either the dust cross section  $\sigma_{\text{dust}}$ , the ionisation rates  $\beta_{\text{elm}}^{\text{pi}}$ , or both is significantly increased for this period. As mentioned in the previous section, this period might be influenced by a CME, although no signature of an ICME has been observed. On the other hand, measurements of the Solar Extreme ultraviolet Monitor, which is also part of CELIAS show only minor changes of  $\pm 5\%$  in the UV flux for the analysed period. Thus, we do not expect a significant change in the ionisation rates. What can be seen, however, is a small spike that

coincides with the expected CME injection time deduced from LASCO observations. Given that CMEs are expected to pick up nm-size dust grains [Allegrini et al. \(2005\)](#), it is possible that the dust cross section has been temporarily increased, if the outer boundaries of the CME have grazed SOHO. This dust pickup process has been discussed as the main argument against the neutralisation scenario [Allegrini et al. \(2005\)](#), because the resulting solar-cycle dependence of the inner source has not been observed. However, this finding is based on fewer than 200 counts of  $C^+$  and  $O^+$ , respectively, while the increased fluxes observed by CTOF from DoY 194.5 to 197.5 are based on a total of 918 and 719 counts for  $C^+$  and  $O^+$ , respectively. In addition, the study of the solar-cycle dependence was based on observations at  $\sim 70^\circ$  heliographic latitude. [Gopalswamy et al. \(2003\)](#) found a north-south asymmetry of CMEs during that period of solar-maximum condition. In fact, in the northern hemisphere where the *Ulysses* observations have been obtained, no CME above  $60^\circ$  has been observed. Thus, the conclusion that the inner source is stable over the solar cycle is not necessarily true on global scales.

## 5. Conclusions

Previous findings by [Allegrini et al. \(2005\)](#) have pointed towards a correlation of solar wind  $H^+$  flux with the count rates of inner-source  $O^+$  and  $C^+$ . The  $C^+$  and  $O^+$  count rates obtained by *Ulysses*/SWICS at  $\sim 2$  AU and roughly  $\pm 70^\circ$  heliographic latitude were increased for solar-wind  $H^+$  fluxes above  $2 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$  compared to fluxes below this value. This has been interpreted as a hint towards a possible correlation of the solar-wind proton and inner-source PUI flux. In this study we have addressed this possible correlation using SOHO/CELIAS observations.

The unrivalled counting statistic of the CTOF instrument allowed us to show that the flux of inner-source  $O^+$  and  $C^+$  is highly variable. Daily fluxes show a strong variability roughly in the range  $\pm 50\%$  compared to the mean flux observed in the analysed period from DoY 150 to 220 in 1996. We calculated the variability for various cadences from  $\sim 2.5$  h up to 3 days and found that  $O^+$  and  $C^+$  correlate with the flux of solar-wind  $O^{6+}$  with  $r_{O^{6+}}^{O^+} = 0.86 \pm 0.02$ , and  $r_{O^{6+}}^{C^+} = 0.86 \pm 0.02$ , respectively. This correlation, which is significantly stronger than  $r_{H^+}^{O^+} = 0.65 \pm 0.05$  and  $r_{H^+}^{C^+} = 0.66 \pm 0.05$ , can be interpreted as a direct correlation of inner-source and solar-wind elemental flux. A decrease in the obtained correlation coefficients for sub-day cadences is most probably due to the low counting statistic of  $O^+$  and  $C^+$ , but we cannot rule out the possibility that this decrease is partly real. A physical explanation for this decrease could be weak spatial diffusion of inner-source PUIs. However, even the highest cadence of  $\sim 2.5$  h shows a strong correlation, and the overall strong correlation coefficients indicate that spatial dispersion of inner-source PUIs is globally weak.

Regarding the scenarios for the nature of the inner source for pickup ions, our results clearly point towards the solar-wind neutralisation scenario, because of its instantaneous production mechanism. Owing to the long delay between implantation in and re-emitting from dust grains, the solar-wind recycling scenario is not expected to show the observed correlation but rather the opposite result of a strong correlation with the solar-wind  $H^+$  flux. The found correlations among all analysed ions,  $H^+$ ,  $O^{6+}$ ,  $O^+$ , and  $C^+$ , agree with the expectations from solar-wind neutralisation. Especially the moderate correlation of  $O^+$  and  $H^+$ , which has been indicated by previous findings, is not due to a direct causal relationship but rather a consequence of a moderate correlation of  $O^{6+}$  and  $H^+$ . Although the main driver

for the observed variability of inner-source oxygen is the variability of solar-wind oxygen with  $r_{O^{6+}}^{O^+} = 0.86 \pm 0.02$ , the even stronger correlation of inner-source carbon and oxygen with  $r_{O^+}^{C^+} = 0.94 \pm 0.05$  points towards a small variability of the dust cross section, the ionisation rates, or both.

In the analysed period from DoY 150 to 220, the continuous interval from DoY 194.5 to 197.5 showed increased inner-source fluxes that might be related to a CME-related increase in the dust cross section. This possible CME-dust interaction, which has previously been the main argument against the solar-wind neutralisation scenario, requires further investigation. Especially the stability of the inner-source over the solar cycle, which has only been observed at high solar latitudes, should be investigated in the ecliptic.

In summary, our results clearly suggest that the solar wind is directly involved in the production of inner-source pickup ions, confirming and adding to previous studies that found a solar-wind-related composition of the inner source. Among the two proposed scenarios for the nature of the inner source that directly incorporate the solar wind, previous findings, and the findings presented in this study can be explained solely by the solar-wind neutralisation scenario.

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