Coordinated observation of local interstellar helium in the Heliosphere

Solar cycle dependence of the helium focusing cone from SOHO/UVCS observations

Electron impact rates and associated pickup ions

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Abstract. The Ultraviolet Coronagraph on board SOHO (UVCS) has observed the 58.4 nm glow of the interplanetary He focusing cone at regular intervals since 1996. The intensity decrease with time already observed during the first two years (Michels et al. 2002) has dramatically amplified during the solar activity increase. Intensities seem to reach a plateau in 2001. Using a model of the cone emission which takes into account both photoionization and electron impact ionization of neutral helium we show that the photoionization increase alone cannot explain the observed intensity drop. Data can be fitted if at minimum activity the electron impact ionization rate is the solar cycle average rate predicted by Rucinski & Fahr (1989), and if this rate is increased by a factor of about 3.5 between 1996 and 2001. Assuming the Rucinski and Fahr radial dependence, such high electron impact rates create averaged He⁺ pickup ion (PUI) fluxes which may reach 50% of the fluxes of ions born after photoionization, or 35% of PUI total fluxes, as far as 1 AU from the Sun. In slow and dense solar wind enhancements, in particular in the presence of strong suprathermal tails, PUIs from electron impact could be the dominant species. This could explain a fraction of the observed correlation between He⁺ and H⁺ pickups and anticorrelation of He⁺ fluxes with solar wind velocity.

Key words. interplanetary medium – Sun: solar wind – Sun: general – plasmas

1. Introduction

The Sun is presently embedded and moving in a partially ionized and tenuous diffuse cloud (the LIC or Local Interstellar Cloud). This motion creates a permanent flow of interstellar neutral atoms, essentially hydrogen and helium, in the heliosphere. H and He atoms scatter the solar H-Lyman-alpha (121.6 nm) and He-Lyman-alpha (58.4 nm) radiation lines by resonance, creating the so-called hydrogen and helium interstellar glows. In the case of helium, the radiation pressure associated with the scattering is too weak to counterbalance solar gravitation, and as a result helium atom trajectories converge on the downwind side, forming the “helium focusing cone”. Since the relative motion of the Sun with respect to the local interstellar cloud is from $\lambda, \beta = 254, +6$ deg, the cone is only slightly inclined with respect to the ecliptic and the earth crosses the cone on the downwind side in early December (5th, or 6th). For about 15 years after the first detections of the

resonance emission of interstellar helium and of the focusing cone, kinetic models of the neutral helium flow have been applied to data and used to determine the temperature and the velocity of the flow prior to solar focusing and ionization by EUV photons and solar wind particles. Values of the order of 16 000 K and 25 km s⁻¹ were found (Ajello 1978; Weller & Meier 1981; Dalaudier et al. 1984). More recently, direct detections of helium atoms by the GAS experiment on board Ulysses have brought different results. Witte et al. (1993, 1996) and Witte (2004) found a much lower temperature of about 7000 K, identical to the interstellar cloud temperature (Lallement & Bertin 1992; Bertin et al. 1993). Pickup ion data also favour a low temperature (Möbius et al. 1995). Possible reasons for the discrepancies between glow and particle results have been investigated for many years, and they are now attributed to background contamination (Lallement et al. 2003).

The use of the SOHO UV coronagraph (UVCS) for helium glow observations was first proposed by J. L. Bertaux in 1996. The main advantage is that lines-of-sight through the outer corona probe the helium distribution and thus the

* This work is dedicated to the memory of Daniel, deceased in November 2001.

Fig. 1. Viewing geometry in June and December. UVCS lines of sight $7 R_s$ below the Sun (solar angle = 1.75°) intersect the focusing cone at $d1 = 0.20$ and $d2 = 0.33$ AU in June and December respectively.

ionization processes much closer to the Sun than in other methods, and bring new information. Michels et al. (2002) presented UVCS measurements of the He I $\lambda 584$ brightness of the focusing cone from 1996 through June 1998. They describe the observation parameters and radiometric calibration in detail. Here we briefly summarize the discussion and present the observations through June 2002.

The UVCS experiment (Kohl et al. 1995, 1997) has a $42'$ slit that can be between 1.5 and $10 R_{\text{SUN}}$ tangent to a circle concentric with the solar limb. The He I measurements make use of the “redundant” optical path of the O VI channel of UVCS, in which a convex mirror focuses light in the $1160\text{--}1260 \text{ \AA}$ range ($580\text{--}630 \text{ \AA}$ in second order) on the O VI detector. The He I measurements require extreme positions of the diffraction grating and internal occulter, as well as the redundant path in second order. Therefore, the radiometric calibration is known much less accurately than for the more standard observing parameters. As discussed by Michels et al. (2002), the estimated uncertainty for the He I intensity is 50%, as opposed to 20% for first order lines. (Gardner et al. 2000).

The sensitivity is very stable, however. A number of bright stars are observed every year, and the count rates remain constant to within a few percent. For observations that use a large fraction of the mirror area, such as those presented here, the sensitivity has remained constant to within 5% (Valcu et al. 2003).

Most of the He I observations were obtained in early December or early June, with the UVCS entrance slit at a position angle of 180° at heliocentric distances of 5, 7 or $9 R_{\text{SUN}}$. This provides lines of sight that intersect the axis of the cone at 0.15, 0.20 and 0.24 AU (December) or 0.21, 0.33 and 0.48 AU (June), as shown schematically in Fig. 1. The December observations sample high emissivity regions close to the Sun, but the June observations intersect the cone at a smaller angle, giving a longer path length through the cone. A position angle of 180° also places the line of sight in the southern coronal hole, reducing the background due to scattered Ly α photons. Other observations include crosswind measurements and observations east, west and north of the Sun made to map the brightness distribution on June 1999.

Figure 2 shows sample spectra. In December 1996 the line was well above background, while the line is much weaker in the most recent observations. The grating ghost at $1170 \text{ \AA}$ is far enough from the He I line that it only presents problems when Ly α intensity is high. This occurred for many of the observations near solar maximum and for some observations outside the southern coronal hole.

Fig. 2. A sample of UVCS spectra. The 58.4 nm signal is well above the background in 1996–1997, which is no longer true in 2000.

Fig. 3. UVCS measured intensities in Rayleighs as a function of time. The marker size is a function of the offset angle from the interstellar wind axis. The direction of sight was $7 R_s$ below the Sun for most data points (see Table 1).

The measured intensities in Rayleighs are presented in Table 1, which also includes H-Ly β intensities for each observation. Here we model He 58.4 nm fluxes only. The data are displayed in Fig. 3. The new entire set of data points shows that the intensity decrease observed between 1996 and 1998 continued after 1998, to reach a total decrease by a factor of 10 between the first period of observations and 2000. After 2000, there seems to be a stabilization, and a slight increase is visible in 2002.

The factor of ten decline in brightness since December 1996, coupled with a general increase in the Ly α background toward solar maximum, leads to an increase in the random measurement error from less than 10% in 1996 and 1997 to perhaps 30% in 1999 and beyond.

Table 1. UVCS measurements since 1996. Data from 1996 to 1998 (Michels et al. 2002) have been recalibrated. PA is the position angle and r is the impact parameter.

<i>mo</i>	day	yr	$r(R_s)$	PA(deg)	$Ly\beta(R)$	HeI(R)
12	5	96	9	180	1.3	48.1
12	6	96	9	180	1.4	44.7
12	7	96	9	180	1.5	40.0
12	23	96	9	180	1.3	20.8
2	18	97	9	180	1.1	5.5
6	5	97	9	180	0.6	38.6
6	5	97	7	180	1.0	36.7
6	13	97	6.6	147	0.7	26.0
8	27	97	6.3	85	5.4	7.2
12	2	97	9	180	1.3	25.8
12	2	97	7	180	1.1	22.0
12	4	97	9	180	1.4	23.7
12	4	97	7	180	1.5	20.2
12	4	97	5.1	180	1.5	19.6
12	6	97	9	180	1.7	24.6
12	6	97	7	180	1.6	24.6
12	6	97	5.1	180	1.8	20.3
12	7	97	9	180	1.3	20.7
12	7	97	7	180	1.6	19.9
12	7	97	5.1	180	1.5	24.4
12	9	97	9	180	1.1	26.6
6	8	98	9	180	0.9	13.3
11	10	98	9	180	1.5	4.0
11	23	98	9	180	1.6	8.7
11	25	98	9	180	1.2	10.2
11	26	98	7	180	1.2	9.6
11	27	98	5.1	180	2.2	5.9
11	28	98	9	180	1.6	9.6
12	2	98	9	180	1.8	11.9
12	7	98	9	180	1.8	7.2
12	8	98	7	180	1.6	9.1
12	10	98	9	180	1.9	9.8
12	12	98	5.1	180	3.1	6.2
6	10	99	5.1	230	2.3	11.7
6	10	99	9	230	0.7	14.8
6	11	99	5.1	230	4.8	7.9
6	11	99	9	230	0.7	11.5
6	12	99	5.1	230	5.3	10.4
6	12	99	9	230	0.7	13.8
6	13	99	9	310	2.4	10.5
6	19	99	5.1	200	2.9	6.6
6	19	99	9	200	0.8	12.7
6	20	99	9	129	0.7	7.7
12	12	99	9	180	1.8	6.3
12	14	99	9	180	2.0	5.5
12	15	99	9	180	2.1	4.7
12	16	99	9	180	1.8	3.4
6	9	00	9	180	1.4	6.6
11	25	00	7	180	2.3	3.9
11	28	00	7	180	3.0	2.9
12	5	00	7	180	3.1	3.9
12	8	00	7	180	2.3	5.5
12	13	00	7	180	4.7	4.1
12	17	00	7	180	4.6	5.1
12	21	00	7	180	3.2	4.7

Table 1. continued.

<i>mo</i>	day	yr	$r(R_s)$	PA(deg)	$Ly\beta(R)$	HeI(R)
12	26	00	7	180	2.9	4.1
1	7	01	7	180	3.5	3.4
1	14	01	7	180	3.0	3.6
1	22	01	7	180	4.0	2.3
6	3	01	7	180	1.5	10.5
12	2	01	7	180		5.4
6	6	02	7	180		7.4

2. Modelling

The model we use is a classical kinetic model of the flow, updated to include electron impact (or any ionizing phenomenon whose dependence on solar distance differs from r^{-2} and cannot be treated in a simple analytical way). Helium atom trajectories are conics, defined by the atom velocity at large distance from the Sun and the initial impact parameter (Dalaudier et al. 1984). The velocity and temperature “at infinity”, i.e. far enough from the Sun for a total absence of effects on the velocity and density distribution, are here taken to be 25.4 km s^{-1} and 7000 K , very close to neutral atom measurements of $26.3 \pm 0.4 \text{ km s}^{-1}$ and $6300 \pm 430 \text{ K}$ (Witte 2004), and the mean values between neutral gas and EUVE observations $26.2 \pm 0.75 \text{ km s}^{-1}$ and $6320 \pm 730 \text{ K}$ (Möbius et al. 2004). These parameters are identical to the velocity and temperature before entry in the heliosphere, because there is no or negligible coupling of helium with the plasma. We use for the direction of the flow $\lambda, \beta = 74, -6 \text{ deg}$, (ecliptic coordinates) according to UV measurements which are very appropriate to locate the conspicuous focusing cone (Dalaudier et al. 1984; Weller & Meier 1981). Those values are similar, within error bars, to those deduced from in situ data ($\lambda = 74.43 \pm 0.33 \text{ deg}$, see Gloeckler et al. 2004; $\lambda, \beta = 74.7, -5.3 \text{ deg}$, see Witte 2004). The helium flow density is taken here to be 0.015 cm^{-3} , according to its most precise measurements from pickup ion data analyses (Gloeckler et al. 2004) and neutral gas data analyses (Witte 2004). The continuous density decrease due to ionization processes is computed along all individual trajectories. Losses are the result of photoionization, here assumed to be isotropic and to vary with r^{-2} , and of impact with solar wind electrons. There is a small contribution to the ionization processes due to charge-exchange with solar protons, and solar alphas, as discussed by Ratkiewicz et al. (1990) and recalculated in detail by McMullin et al. (2004). Here we neglect the contribution from charge exchange, because it adds only a few percent to the total rate (Rucinski et al. 1996). Expected contributions to the ionization from all interactions with solar wind particles have been estimated to be small compared to photoionization beyond 1 AU, but closer to the Sun their relative importance increases.

$$\beta_{\text{el}} = 8 \times 10^{-14} \text{ A} \left[-\frac{C_c}{\alpha_c} Ei(-\alpha_c) + \frac{G_c}{\varphi_c} Ei(-\varphi_c) - \frac{C_h}{\alpha_h} Ei(-\alpha_h) + \frac{G_h}{\varphi_h} Ei(-\varphi_h) \right]$$

Fig. 4. Electron impact rate as a function of distance to Sun for average solar wind conditions (from Rucinski & Fahr 1989), and the same rate multiplied by 3.5. Superimposed are the photoionization rates at solar minimum and maximum (McMullin et al. 2004).

$$\text{where } Ei(-a) = -a \int_0^\infty \exp(-ax) \ln(x) dx$$

$$A = \frac{8\pi}{m_e^3}; C_{c,h} = n_{c,h} \left[\frac{m_e}{2\pi k T_{c,h}} \right]^{3/2}$$

$$G_{c,h} = 0.75 \exp(0.46) C_{c,h}; \alpha_{c,h} = \frac{P_{c,h}}{k T_{c,h}}$$

$$\varphi_{c,h} = \alpha_{c,h} + 0.46.$$

In our updated model the impact rate is evaluated numerically along the individual trajectories at any solar distance by interpolation using precalculated tables ($r, \beta_{el}(r)$). For those tables we assume that the density and the temperature of the core and halo electrons vary with distance as:

$$n_{c,h}(r) = n_{c,h}^0 r^{-2}; T_{c,h}(r) = T_{c,h}^0 r^{-\gamma_{c,h}}$$

and we use at each distance the above formulation of Rucinski & Fahr (1989) for their standard parameters: $n_c = 6.72 \text{ cm}^{-3}$, $n_h = 0.28 \text{ cm}^{-3}$, $\gamma_c = \gamma_h = 0.33$

At each date t , we allow for an adjustable scaling factor $\alpha_e(t)$ to the impact rate. $\alpha_e(t)$ is thus independent of the distance. The impact rate for $\alpha_e(t) = 1$ is displayed in Fig. 4, as well as the photoionization rate for solar minimum and solar maximum conditions. It is clear from Fig. 4 that electron impact ionization exceeds photoionization within 0.06–0.15 AU (13–30 R_s), depending on the activity.

The emissivity and the emission line profile at each point vary as a function of the local velocity distribution of helium atoms and of the solar line shape. Emissions and spectral profiles are computed by integrating the backscattered emission and the corresponding profile along the LOS from the location of SOHO to 100 AU. Radiative transfer effects are assumed to be negligible, which has been shown to be a valid assumption for lines-of-sight which do not exactly coincide with the cone axis (Dalaudier et al. 1984). Because measurements are done from the earth orbit, and the sightlines are within 2 degrees from the ecliptic, this is never achieved.

Model emissivities and line intensities have been shown by Michels et al. (2000), for photoionization only and no electron impact ionization. For average conditions of ionization, i.e. of solar activity, the maximum emissivity region is on the downwind side on the cone axis at a distance of the order

of 0.1 AU. As viewed from SOHO in early December, the maximum LOS intensity is at about 0.25 degrees (1 R_s) below the Sun, and the intensity decreases very rapidly when the pointing direction moves away from this direction both longitudinally and latitudinally. Introduction of electron impact decreases the emissivity everywhere, especially at small solar distances, and moves the maximum emissivity region away from the Sun.

Concerning solar parameters, the linewidth of the 58.4 nm solar line is 42 km s^{-1} or 136 mÅ in all the calculations, whatever the solar cycle phase (see below). The photoionization rate, the electron impact rate and the illuminating flux are studied further here.

The following (at least) four parameters may be significantly influenced by the solar activity level: i) the solar flux at 58.4 nm is known to increase with activity; ii) the EUV flux shortward of 30.4 nm, and thus the helium photoionization rate, also increases with activity. iii) The solar wind particle flux, its composition and its temperature change, which in turn modifies the electron impact rate and charge-exchange rate. iv) The 58.4 nm solar line width may change with the activity, which would impact on the number of resonant atoms able to absorb and scatter the radiation.

We discuss first the solar line width (iv): it has been measured with SOHO/SUMER and shown to be between 92 and 155 mÅ FWHM in quiet regions of the disk, with a favored value of 118 mÅ FWHM , and no observed trend for line width variation from minimum to maximum (McMullin et al. 2004). The disk integrated linewidth has been also measured using off-limb observations of the straylight and found to be between 135 and 125 mÅ FWHM in 1996 and 2000, with an error on both measurements of 10% (Wilhelm 2002, private communication; Lemaire 2002, private communication). A solar cycle variation for this disk-averaged value is thus not precluded, but remains within measurement errors. We have used in the model a constant value of 42 km s^{-1} (half-width at e^{-1}) or 136 mÅ FWHM .

The solar flux (i) at 58.4 nm increases strongly with activity. Figure 5 shows the results of a MgII index fit to the SOHO/CDS 584 full-disk raster scans (see McMullin et al. 2004, for details). There is a simple proportionality of the backscattered signal to this illuminating flux at first order, i.e. if the solar line shape does not vary substantially. We have used in the model the McMullin et al. values from Fig. 5 as illumination levels appropriate to each data point. The error on the absolute flux is due to the CDS uncertainty on the flux, which is 21%. However, the uncertainty on the relative change over time is only 10% (Lang et al. 2002).

The photoionization rate (ii) strongly increases too, as shown by SOHO-SEM data. We have applied to each data point the photoionization rate predicted by McMullin et al. (2002, 2004), derived from SOHO-SEM data. The corresponding rates are displayed in Fig. 6. The estimated error on the rate is about 10%.

Both the 58.4 nm flux and the photoionization rate have inverse effects, i.e. when activity increases helium is more illuminated, but its density decreases as it suffers stronger losses due to stronger photoionization. Simulations are thus needed to model the intensity decrease between 1996 and 2001 due to solar EUV variation.

Fig. 5. 58.4 nm solar flux of the Mg-II proxy fit to SOHO/CDS 584 full disk raster scans. Fluxes at the dates of UVCS measurements are shown by crosses.

Fig. 6. The neutral helium photoionization rate at 1 AU derived from SOHO/SEM data. Filled circles correspond to the dates of UVCS measurements and values used in the modelling.

Figure 7 shows the data/model ratio calculated for the fluxes and rates of Figs. 5 and 6, assuming the electron impact rate at each distance is exactly as predicted by Rucinski & Fahr (1989) for average solar wind conditions, that is for $\alpha_e = 1$ throughout the period of measurements. It is clear from Fig. 7 that the relative decrease of the ratio, by a factor of 5, is smaller than the relative decrease of the measured intensity (a factor of 10). This means that the ionization increase overcomes the effect of the illuminating flux increase, but the intensity decline is not at all reproduced. If we assume that all the intervening phenomena are included in the modeling, this means that either the increase of one of the two ionization process has been underestimated, or the increase of the illuminating flux is not as strong as predicted. This latter explanation does not hold, because as said above, the uncertainty on the relative change over time of the solar 58.4 nm emission is only 10%, well below the factor of two required to account for the observed result.

We then explore an underestimate of the photoionization change as the source of the discrepancy. Keeping the electron impact constant, we allow the photoionization rate, this time in units of the rate of Fig. 6 derived from SOHO/SEM, to vary with time as a polynomial function of order 2. The coefficients of the polynomial function have been adjusted to fit the

Fig. 7. Data to model ratio for time varying ionization rate and illuminating flux as in Figs. 5 and 6 resp., assuming a constant electron impact ionization rate, from Rucinski & Fahr (1989). Strong departures appear at increasing activity.

Fig. 8. Temporal variation of the photoionization rate β_{ph} required to fit the data assuming a constant electron impact rate and the solar 58.4 nm flux from Fig. 5. β_{ph} is assumed to be a polynomial function of time of order 2. For comparison, a polynomial fit of order 2 to the proxy (Fig. 6) is superimposed. The difference between the two rates is much larger than the estimated error on the photoionization rate.

observations. Figure 8 shows which time dependent photoionization rate is needed to obtain the best fit to the data: the required increase of the rate is by about a factor of 4, while the photoionization rate calculated by McMullin et al. increases by about 2.5 only. The difference is well above the error on the measured rate which is of the order of 10%, and the explanation in terms of underestimated photoionization increase appears very unlikely.

The other very likely explanation for the data-model discrepancy of Fig. 7 is the assumed constancy of the electron impact rate. Indeed, solar wind changes linked to increasing activity must be followed by ionization variation. This was already predicted by Rucinski & Fahr (1989). It is not easy however to model such changes, because the average relative importance of the “halo” electrons and their average temperature is not precisely known. Such a study is beyond the scope of this paper, and we restrict our study here to an estimate of the amplitude of the increase rate required to explain UVCS data.

Fig. 9. *Top:* data and model values for the adjusted electron impact rate. *Bottom:* the best-fit electron impact ionizing rate, in units of the Rucinski et al. rate (i.e. the factor α_e) required to fit the data assuming solar fluxes and ionization rates from Figs. 5 and 6. An increase of α_e by a factor ≈ 3.5 is necessary between 1996 and 2001.

To estimate the importance of the electron impact time dependence, we assumed that for each UVCS data point (i.e. at each solar cycle phase), the electron impact rate has the same dependence on the distance to the Sun (shown in Fig. 4, for average conditions), but is amplified by a factor $\alpha_e(t)$. This scaling factor $\alpha_e(t)$ is assumed to follow a polynomial law of order 2 with respect to time t . We have adjusted the coefficients of the polynomial to obtain the best fit of the model to the data. During this exercise, the solar flux and the photoionization rate are the 58.4 nm proxy of Fig. 5 and the SOHO/SEM derived rate of Fig. 6 respectively.

The adjustment of the model to the data by fitting of $\alpha_e(t)$ to a second order polynomial is shown in Fig. 9. Both α_e and model values, superimposed on the data, are displayed. A very satisfactory fit is found if $\alpha_e(t)$ increases from about 1 at solar minimum up to a maximum of 3.5 in 2001.

Is such an increase of the electron impact rate realistic? There are a number of reasons which suggest it could be. Electron impact rate estimates are uncertain and the model results cover a very broad range of values (see Rucinski & Fahr 1989). The temperature and the temperature dependence with distance of solar wind electrons are poorly known in the corona. The temperature has a large influence, because the electron impact cross-section depends on the electron velocity, i.e. on the solar wind electron temperature structure. We know now that the higher the activity, the most ubiquitous the slow solar wind, which is characterized by a higher electron temperature than the fast wind, and thus likely by an enhanced electron impact rate. On the other hand, the electron suprathermal tail (the “halo”, or “strahl”) may play a major role. It is well known that the relative importance of the core and of the suprathermal tail depends on the wind type and thus on the activity level.

Moreover, recent analyses of the SOHO/LASCO C2 white-light data, over the same period of time as the UVCS data set, show an increase by a factor of about 3 to 4 of the electron density between 2 and 5 solar radii (Lamy et al. 2002). Because the solar wind particle flux does not increase by such a factor, this observed density increase must be accompanied by a systematic decrease of the expansion velocity at those distances (in order to keep the average value of the product nV about constant), i.e. the acceleration probably occurs higher in the corona. At larger distances where the solar wind velocity reaches its asymptotic speed one expects the average density to have much smaller systematic cyclic variations. However, most of the electron impact occurs within 20–30 solar radii, in a region which may have the same characteristics as those observed closer within the C2 FOV region, i.e. an activity-dependent density.

We believe that an enhanced ionization by the solar wind is very likely at the origin of the strong decrease of the HeI 58.4 nm intensity recorded by UVCS during the increasing phase of the solar cycle. We note that the adjustment to the data points seems to be equivalently good for observations made in June and December, as well as for those made from earth locations outside the plane of symmetry (see Fig. 7). This shows that the modeled density distribution is appropriate along the cone and on the sides.

3. Pickup ion fluxes

In view of the above results and the relative importance of solar wind impact on the helium atoms, we have used our stationary model to calculate the fluxes of pickup ions born after electron impact and after photoionization, respectively. Figure 10

Fig. 10. Total and electron-impact generated pickup ions fluxes at 1 AU as a function of the angle with the sun-wind axis, for minimum and maximum solar activity. The ratio between the electron-impact born ion flux and the total flux from photoionization + impact is shown on the right scale. The flux of PUIs born after electron impact is about 30% of the total flux on both the downwind and upwind sides. The average fractional dependence is not very different in solar minimum and maximum conditions. In the highly variable slow wind the ratio may strongly increase locally.

shows the fluxes of PUIs born from electron impact which are expected to be measured at 1 AU, as a function of the angle with the wind direction, at both solar minimum and maximum conditions. More specifically, the photoionization rate is 1.55×10^{-7} and $0.65 \times 10^{-7} \text{ s}^{-1}$, and the electron impact rate is 4 times and 1 time the standard Rucinski et al. value. We have used for maximum activity a factor of 4 instead of the UVCS-derived value of 3.5 for computational reasons. The ratio between the flux of He^+ ions born after electron impact and the total flux of He^+ ions has a very weak dependence on the direction. This ratio is of the order of 25% and 35% at 1 AU, at solar minimum and maximum conditions respectively. This shows that solar wind-generated PUIs at solar maximum are in about the same proportions as EUV-generated PUIs.

Figure 11 displays the PUI fluxes as a function of solar distance on both the upwind and downwind axes, for maximum solar activity conditions. The relative flux of solar wind-generated PUIs is decreasing with distance, as expected from the faster decrease of the impact rate as compared to photoionization.

Clearly these fluxes must strongly vary according to the solar wind characteristics. Because the slow wind is highly variable, is in average denser and contains hotter electrons, one expects in the slow wind a very large variability of the relative amount of impact PUIs, with high fluxes in the high density and hot solar wind, and low fluxes elsewhere. On the contrary, high speed wind is more homogeneous, has cooler electrons and a smaller flux, and as a result one expects solar wind PUIs to be in smaller and in less variable proportions.

These characteristics may partly explain a number of observations. First, in some cases, the fluxes of hydrogen PUIs and helium PUIs have been observed to be correlated (Gloeckler et al. 1994). This correlation has been attributed to transport effects, because the main fraction of the ions are generated by different processes, photoionization for helium and charge-exchange for hydrogen. We suggest here that in solar wind

Fig. 11. Solar maximum upwind and downwind pickup ion fluxes as a function of distance. The fraction of PUIs born after electron impact is shown on the right scale. Their contribution to the total flux is significant within 1 AU and is similar in both regions.

flux enhancements a large fraction of helium pickup ions may have been produced by electron impact (and charge-exchange). From Figs. 10 and 11, temporary solar wind flux enhancements by a factor of 5 are enough to bring the impact-born ion flux largely above the photoionization-born ion flux. Reciprocally, rarefied solar wind may be characterized by a low fraction of e-ionized helium ions. Because pickup proton fluxes are also enhanced or depleted in the same way in dense or rarefied solar wind, the proportionality may be explained partly in this way.

Second, according to SOHO/CELIAS observations helium pickup ion fluxes seem to be anticorrelated with the wind velocity, and are characterized by a very large variability in the slow wind (Litvinenko et al. 1995). Isenberg et al. (1999) have attempted to model these effects in terms of microscopic processes, but found the opposite trend. Later on, instrumental selection effects were invoked. We suggest that part of this behavior may reflect the strong increase of electron-impact ions in the high density regions which are frequently encountered in the slow wind. Because these regions are not only dense but also characterized by enhanced suprathermal electron fluxes, e-ionization is very efficient. On the contrary, high speed winds are homogeneous and have lower electron tails, thus in general helium ions born from electron impact will be in much smaller proportions.

Finally, refined analyses of both neutral atom and pickup ion data have shown that their fluxes are latitude dependent (see Gloeckler et al. 2004; Witte 2004), with significant gradients. Any latitude dependence linked to illuminating fluxes must be smooth, because those fluxes are disk-integrated. On the contrary, solar wind effects are truly directional and can have sharp latitudinal gradients. We suggest that those dependencies with latitude of neutral atoms and pickup ions may be also produced by electron impact in addition to photoionization.

The dependence of the total pickup ion fluxes observed at 1 AU on the ionization rates is highly non-linear, as ionization is responsible for the production of pickup ions and for the depletion of the source of neutrals in the inner heliosphere. In Fig. 10, the photoionization rate is divided by 2.3, and the impact rate by 4.0, when going from solar maximum to minimum

values. Therefore, one might expect naively a relative reduction of the electron impact-related pickup ion flux by a factor of about 1.7, while the reduction is only about 1.3. This has to do with the stronger increase of impact ionization close to the Sun as a function of distance and thus a faster depletion of the neutrals than solely through photoionization. In essence, pickup ion production and neutral gas depletion partially compensate each other in their effects on the observed integral pickup ion flux, and thus one has to be careful in evaluating the relative contributions of electron impact and photoionization and their temporal variations on pickup ions.

4. Conclusion

Measurements of the interstellar helium cone glow intensity have been routinely done with SOHO-UVCS since 1996, providing a new unprecedented diagnostic of the density distribution within 0.3 AU and its evolution with the solar cycle. We have modelled those data, taking advantage of the continuous measurements of the solar EUV fluxes by the SOHO-SEM monitor. The data can be well fitted over the cycle if an additional ionization mechanism, other than photoionization, is introduced. Assuming this mechanism is essentially electron impact ionization, as predicted by Rucinski & Fahr (1989), and using the dependence on solar distance calculated by these authors, we find that electron impact rates increase by a factor of about 3.5 from minimum to maximum, starting with their standard value at minimum. Such an increase is plausible, in view of the increase by about the same factor and over the same period of the coronal electron density between 2 and 5 solar radii deduced from SOHO-LASCO white light data (Lamy et al. 2002).

For such high electron impact rates, fluxes of helium pickup ions born after electron impact can reach average values of the order of 50% of the fluxes of pickup ions born after photoionization. We suggest that when the solar wind fluxes are above their average values (and especially in the highly variable slow wind), e-ionization PUI fluxes may be temporarily the dominant species, and that this could explain a part of the observed correlation between hydrogen and helium pickup ion fluxes, and of the anticorrelation of the He^+ fluxes (and increasing variability) with the solar wind velocity.

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