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A review of SOHO/UVCS observations of sungrazing comets

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Abstract

In the last 10 years more than 1000 sungrazing comets have been discovered by the LASCO coronagraphs aboard SOHO the spacecraft; from this huge amount of data it has been possible to study the common origin of these comets and to explain some of the main peculiarities observed in their lightcurves. Moreover, the UV Coronagraph Spectrometer (UVCS) aboard SOHO allowed EUV spectroscopy of sungrazers in the final stage of their trajectory (i.e. between 1.4 and 10 solar radii), but a few sungrazers have been observed with this instrument. In this paper we review the main results from the UVCS observation of sungrazers C/1996 Y1, C/2000 C6 and C/2001 C2, discussing also the first possible detection of two fragments and the determination of the pyroxene dust grain number density in the latter one. Preliminary results on the UVCS data interpretation of a sungrazer observed in 2002 (C/2002 S2) are also presented here.
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1. The SOHO/LASCO contribution to the sungrazer observations

The SOHO (*Solar & Heliospheric Observatory*) spacecraft was launched on December 1995 and was originally planned only as a solar and heliospheric mission. After the achievements of the coronagraphs aboard the P78-1 satellite and the SMM (*Solar Maximum Mission*) spacecraft that discovered in the decade 1979–1989, respectively, 6 and 10 sungrazers, it was hoped that the three SOHO/LASCO coronagraphs (the *Large Angle Spectrometric COronagraph*, see later) might increase the number of discovered comets. Only one month later, on January 1996, the first Kreutz sungrazer was discovered in the LASCO/C3 coronagraph images and in the following months several more comets have been found revealing the potential of the SOHO mission as a comet discoverer. Then, in the following years, many amateur and professional astronomers started to search comets in the SOHO images. Less than 10 years later, on August 2005, SOHO/LASCO detected its 1000th comet[1] (more than 700 of these comets belong to the Kreutz sungrazer group), revealing that sungrazing comets are a much more common phenomenon than ever thought. A success that none of the LASCO scientists could have ever foreseen.

The sudden increase in the number of discovered sungrazers is due to the many advantages introduced by the LASCO coronagraphs. The LASCO instrument (see Brueckner et al., 1995) includes three coronagraphs C1, C2 and C3 with circular fields of view, respectively, between 1.1 and 3.0 $R_\odot$ (C1), 2.0 and 6.0 $R_\odot$ (C2) and 3.7 and 32 $R_\odot$ (C3) (C1 is internally occulted, while C2 and C3 are externally occulted coronagraphs). LASCO data consist typically of a sequence of images (1024 × 1024 pixels) taken at a rate of about 3 h^{-1} and viewed as "movies". The projected pixel size corresponds to 11.4 and 56.0 in, respectively, for C2 and C3 coronagraphs. These time and spatial resolutions, together with the very large field of view (FOV) of the C3 coronagraph and the higher

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[1]See http://ares.nrl.navy.mil/sungrazer/.

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photometric accuracy ($\sim\pm 0.1$ mag) with respect to the previous missions, allowed for automatic searches of comets and the detection also of faint, small bodies.

Such a huge amount of data gave the possibility to study in depth, from a comparison between the orbital parameters of different comets, the problem of the sungrazer origin. In particular, it has been demonstrated that many sungrazers arriving in pairs or triplets even with a difference of months in their perihelion passage originated via fragmentation events from a single sungrazer at distances of many tens of AU from the Sun (see e.g. Sekanina, 2002). A very small separation speed ($\sim 5\,\mathrm{m\,s^{-1}}$ near aphelion) between fragments is enough to produce a difference of more than nine months in the subsequent perihelion passage time (Sekanina, 2002). Recently the generation of the observed sungrazers has been explained with a runway fragmentation model involving cometary splitting both close and far to the Sun: starting from the breakup of a progenitor comet (that occurred less than 1700 years ago at about 50 AU) into two superfragments, it is possible to explain the origin of all eight sungrazers observed between 1843 and 1970 with a hierarchy of fragmentation processes (see Sekanina and Chodas, 2004). Close to the Sun, tidal stresses (in particular around the Roche limit of $\sim 3.2\,R_\odot$) and thermal stresses (diurnal and seasonal heating and cooling on the nucleus surface) may create cracks and fractures on the cometary nucleus and (helped also by the centrifugal forces of a spinning nucleus) cause its disruption into two or more parts. On the contrary, at large heliocentric distances, other processes (probably related to the low tensile strength of the cometary nucleus; see e.g. Greenberg et al., 1995) have to be considered in order to explain post-tidal break-up processes.

The very large number of comets detected by LASCO made it possible also to perform for the first time a statistical analysis and to explain some peculiarities of the observed sungrazer lightcurves. Typically, as a comet approaches the Sun, the observed white light intensity increases (because of the increasing solar flux); then, after a peak between 11 and 13 $R_\odot$ (Biesecker et al., 2002), it decreases (probably because the dust grains are produced at a rate lower than their sublimation rate) eventually showing secondary brightenings below $\sim 7\,R_\odot$. In particular, it has been demonstrated (Biesecker et al., 2002) that the lightcurves of some comets peak at 11.2 $R_\odot$, while others peak at 12.3 $R_\odot$, and that this difference is due, respectively, to a dominance of crystalline or amorphous olivine (which have different sublimation rates) in the submicron-sized particles of the cometary tails (Kimura et al., 2002). Moreover, including in a sungrazer erosion model one or more nearby subfragments traveling with the main nucleus at a distance unresolved by the LASCO coronagraphs, it has been demonstrated that the occasional secondary brightenings observed in some sungrazer lightcurves may be explained assuming that the subfragments have a lower erosion rate and survive longer than the main nucleus (Sekanina, 2003).

Spectroscopically, before the SOHO mission only one sungrazer (the Ikeya–Seki comet, see e.g. Slaughter, 1969) has been observed from the ground when it was at an heliocentric distance of $\sim 15\,R_\odot$. Another important SOHO contribution to the knowledge of the sungrazer properties—it has been the first observation of spectra from these comets close to the Sun. This has been possible using the SOHO/UVCS spectrometer aboard the SOHO satellite.

2. SOHO/UVCS observations

The *UltraViolet Coronagraph Spectrometer* (UVCS, Kohl et al., 1995) consists of two UV channels optimized for observations in the spectral range around the O VI $\lambda\lambda$ 1031.90–1037.63 Å doublet (namely the "O VI channel") and around the neutral Hydrogen Lyman α λ 1215.67 Å line (the "Lyα channel"). An additional mirror between the spectrometer grating and the detector allows H Lyα observation also in the O VI channel ("redundant channel"). Spectral ranges covered by the O VI and Lyα channels are, respectively, 937–1136 Å (469–563 Å for the second order) and 1145–1247 Å. The instantaneous FOV of the spectrometer slit, 42 in long and tangent to the limb of the Sun, may be rotated by 360° around an axis pointing to the Sun center and moved along the radial between 1.4 and 10 $R_\odot$. The detector pixel size corresponds to a resolution of 7 ft in the spatial direction and 0.0993 Å in the spectral direction (0.0915 Å $\mathrm{pixel^{-1}}$ for the redundant channel).

The large LASCO/C3 FOV allows for the discovery of sungrazers far from the Sun; after the detection, the orbit is computed immediately in order to set the position of the UVCS slit along the comet trajectory. Then, after the comet transit at a given heliocentric distance into the spectrometer FOV, the slit is moved, following the computed trajectory, in order to repeat the observations typically 4–5 times (see e.g. Fig. 1). Table 1 summarizes all the comets observed as of today by UVCS: despite the very large amount of LASCO Kreutz sungrazing comets, UVCS observed only 10 of these. Detailed study of sungrazers C/1996 Y1 (Raymond et al., 1998), C/2000 C6 (Uzzo et al., 2001) and C/2001 C2 (Bemporad et al., 2005) have appeared, while the analysis of the C/2002 S2 data is in progress. In the following sections we review the main results from these four observations.

3. The observed UV emission in sungrazing comets

For the UVCS observations of the C/1996 Y1 sungrazer the Lyα channel has been used, while C/2000 C6, C/2001 C2 and C/2002 S2 have been observed with the O VI channel. The selected spectral intervals include (besides the neutral H Lyα λ 1215.67 Å and Lyβ λ 1025.72 Å lines) resonance lines of important neutral and singly ionized elements (e.g. He I, N I, Al III, Si I, Si II, P II, O I, C II and Ar I) that in principle might be present in cometary spectra. However, UVCS detected so far sungrazer emission only in

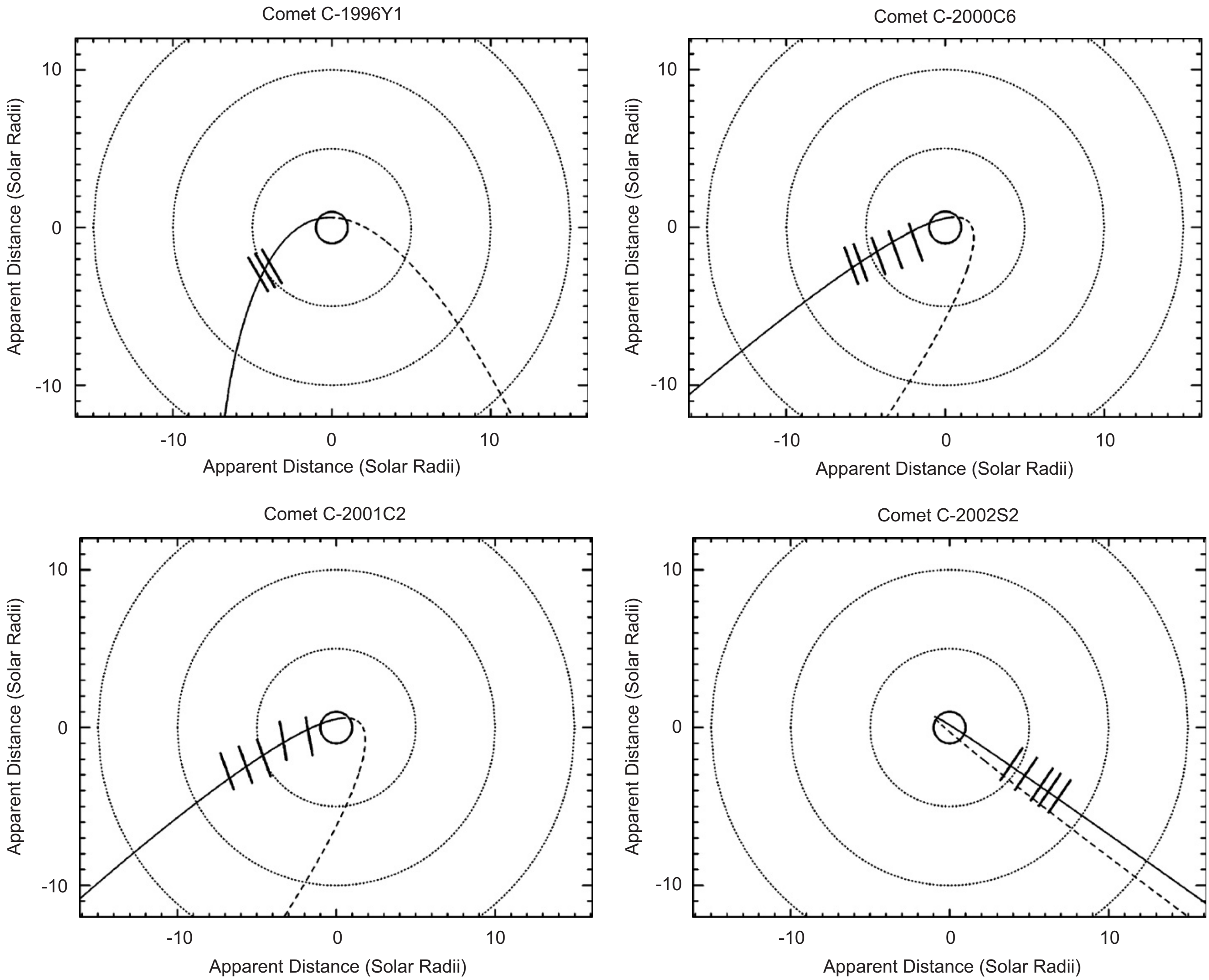

Fig. 1. Computed trajectories for the C/1996 Y1 (top left), C/2000 C6 (top right), C/2001 C2 (bottom left) and C/2002 S2 (bottom right) sungrazers; in each panel we show the pre-perihelion (solid lines) and expected post-perihelion (dashed lines) trajectories projected on the plane of the sky together with the UVCS slit positions for each observation. Dotted circles give the heliocentric distances of 5, 10 and 15 $R_{\odot}$. As it occurs typically for sungrazers, none of these comets survived after the perihelion passage.

the H Lyα line.[2] Hence, in the following we concentrate on the main properties of this line in sungrazer spectra.

The Lyα spectral line is present also in the solar corona and this background emission has to be removed in order to identify the cometary emission. For this reason, UVCS sungrazer observations begin at each heliocentric distance 15–20 min before the comet transit into the slit: the observed pre-comet line intensity along the slit is then subtracted from all the exposures. Once the cometary Lyα emission has been computed at different times along the UVCS slit, it is possible to reconstruct a "Lyα image" of the comet, by simply assuming that the pixel size perpendicular to the slit is equal to the exposure time multiplied by the estimated comet's velocity (projected on the plane of the sky). The results of this technique are shown in Fig. 2 for comets C/1996 Y1 (left),[3] C/2000 C6 (middle) and C/2001 C2 (right): these images demonstrate that sungrazing comets show a "Lyα tail" (instead of the "Lyα cloud" typical of non-sungrazing comets). As we will discuss in the next sections, the presence of this tail is mainly due to the interaction of the solar wind with neutral H atoms ejected by the comet.

The first interesting result from the C/2000 C6, C/2001 C2 and C/2002 S2 observations arises from the Gaussian fits of the Lyα line profiles: those ascribed to a superposition of cometary and coronal emission show no

[2]The UVCS detection of O I, C II and C III in spectra of non-sungrazing comets (Povich et al., 2003) is probably related to the higher brightness of these objects.

[3]Even if in order to reconstruct the Lyα image of this comet it has been necessary to take into account also that the slit height has been changed during the observations (see Raymond et al., 1998).

Table 1
Comets observed by UVCS

Year	Obs. date	Comet name	Comet group	Published
1996	December 23	C/1996 Y1 (SOHO-6)	Kreutz	Yes[a]
1997	May 1–2	C/1997 H2 (SOHO-8)	None	No
1998	June 1	C/1998 K10 (SOHO-54)	Kreutz	No
1999	May 20	C/1999 K1 (SOHO-63)	Kreutz	No
	September 17	C/1999 S1 (SOHO-86)	Kreutz	No
2000	February 10	C/2000 C6 (SOHO-104)	Kreutz	Yes[b]
	February 29	C/2000 D1 (SOHO-106)	Kreutz	No
	September 9–11	2P/Encke	None	Yes[c]
	October 11	C/2000 T1 (SOHO-204)	Kreutz	No
2001	February 6–7	C/2001 C2 (SOHO-194)	Kreutz	Yes[d]
2002	May 14	C/2002 J8 (SOHO-442)	Kreutz	No
	September 18	C/2002 S2 (SOHO-517)	Kreutz	No
2003	January 27–29	C/2002 X5 (Kudo-Fujikawa)	None	Yes[e]

[a] Raymond et al. (1998).
[b] Uzzo et al. (2001).
[c] Raymond et al. (2002).
[d] Bemporad et al. (2005).
[e] Povich et al. (2003).

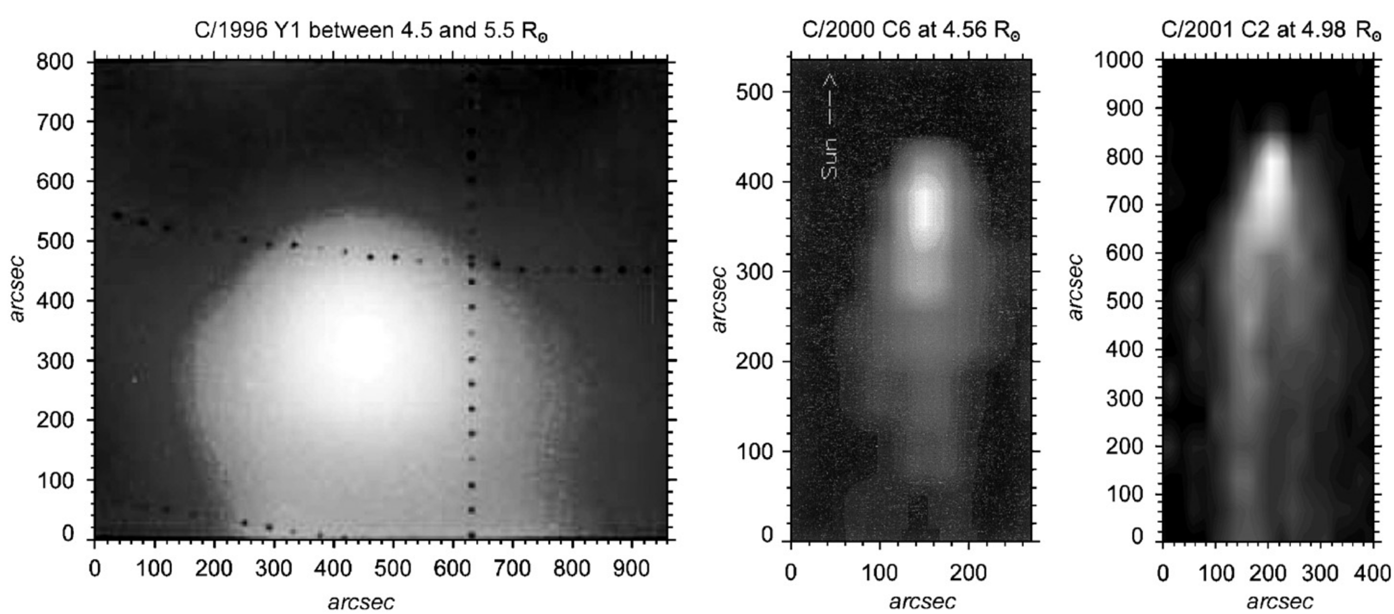

Fig. 2. Composite Lyα image of the C/1996 Y1 (left, adapted from Raymond et al., 1998), C/2000 C6 (middle, adapted from Uzzo et al., 2001) and C/2001 C2 (right, adapted from Bemporad et al., 2005) sungrazers as reconstructed from UVCS observations after the subtraction of the coronal background. In these images the pixel size along the x axis corresponds to the spatial resolution along the UVCS slit, while the pixel size along the y axis corresponds to the comet's radial velocity multiplied by the exposure time.

significant Doppler line shift with respect to the coronal background spectral line (contrary to what we could expect from the cometary speed along the LOS). Moreover, cometary and coronal profiles have about the same line width (see Fig. 3, middle and right panels). These results imply that the H atoms responsible for the observed sungrazer emission close to the Sun have both the bulk velocity and the kinetic temperature of the ambient coronal atoms. On the contrary, Lyα profiles in the C/1996 Y1 data (Fig. 3, left panel) were Doppler shifted and broader than the coronal profiles. As we discuss in the next section, this was related to a different origin of the C/1996 Y1 Lyα emission with respect to the sungrazers mentioned above.

4. Origin of the Lyα emission

In this section we discuss the origin of the neutral H atoms responsible for the observed sungrazer Lyα emission. However, we notice that, independently of their origin, a first question is whether this emission arises from

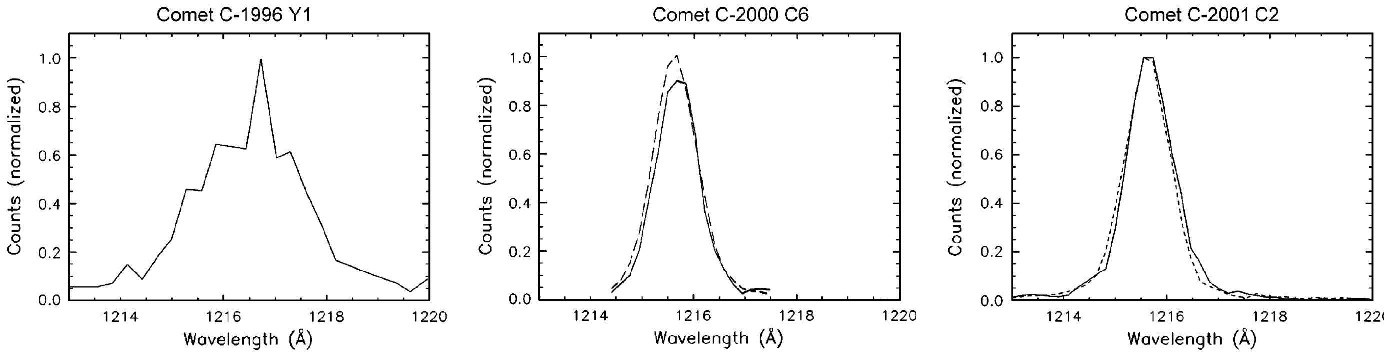

Fig. 3. Normalized cometary Lyα profiles for the C/1996 Y1 (left panel, adapted from Raymond et al., 1998), C/2000 C6 (middle panel, adapted from Uzzo et al., 2001) and C/2001 C2 (right panel, adapted from Bemporad et al., 2005) sungrazers as observed in the exposure and the position along the slit where the signal maximizes. In the middle and right panels the cometary profile (solid) is compared to the average coronal profile.

collisional excitation with thermal electrons and/or from the resonant scattering of the chromospheric radiation. The answer can be found in the observed ratio between the Lyβ and Lyα spectral lines: at typical coronal temperatures ($T\sim10^6$ K), collisional excitation would give a ratio on the order of $\sim0.13-0.14$ (Raymond et al., 1998), while for resonant scattering a much lower ratio ($\sim0.001-0.002$, Raymond et al., 1998) is expected. UVCS observations gave the same result for all the four sungrazers mentioned above: the Lyβ cometary emission was very faint or absent, hence (as is usually the case in the solar corona Raymond et al., 1997) we concluded that the observed cometary Lyα emission arises almost entirely from radiative excitation.

This conclusion gives a first indirect information about the H atoms scattering the observed Lyα: because the radial component of the sungrazers speed below 10 $R_\odot$ is typically above 200–250 km/s, the absorption profile of the H atoms traveling with the comet is Doppler shifted (by more than 0.8–1.0 Å) with respect to the chromospheric emission profile. This shift reduces the ability of these atoms to scatter the chromospheric radiation, leading to a Doppler dimming in the resonantly scattered Lyα intensity ("Swing effect") by more than a factor 2.5–5.0 for a 10^6 K corona (see Kohl et al., 1997). This implies that H atoms traveling with the comet may be responsible only for a small fraction of the observed cometary emission. Moreover, there is another important consequence of the Swing effect in sungrazers. In general, as a comet approaches the Sun, the nucleus surface, heated by the increasing solar radiation, starts outgassing dust and water: the H_2O and OH molecules are then photodissociated creating a "first generation" of neutral H atoms. In non-sungrazing comets far from the Sun ($\sim$1 AU) these H atoms are responsible for most of the Lyα emission; the balance between the attracting gravitational force and the repelling radiation pressure "pushes" the H atoms in the anti-sunward direction creating the typical aspherical shape of the cometary Lyα cloud which may extend up to $2-3\times10^6$ km away from the comet nucleus. On the contrary, in sungrazing comets close to the Sun the effect of the radiation pressure on the H atoms trajectories is strongly reduced (by more than an order of magnitude) by the Swing effect and the elongated shape of the Lyα tail shown in Fig. 2 has to be ascribed to other processes.

The "first generation" of H atoms from the photodissociation of water in principle may be ionized at a rate $\tau_{\rm ion}^{-1}$ or undergo a charge exchange process with the ambient coronal protons at a rate $\tau_{\rm cx}^{-1}$. In typical coronal conditions of low electron density ($n_{\rm e}\sim10^6-10^7\,{\rm cm}^{-3}$) but very high electron temperature ($T_{\rm e}\sim10^6$ K), the collisional ionization (occurring at a rate (Scholz and Walters, 1991) $\tau_{\rm col}^{-1}=n_{\rm e}\times(3.21\times10^{-8})\,{\rm s}^{-1}$) dominates over the photoionization ($\tau_{\rm ion}^{-1}\simeq\tau_{\rm col}^{-1}$). For a relative speed of about $v_{\rm rel}=250\,{\rm km\,s}^{-1}$ between the coronal protons and the cometary neutrals, the charge exchange rate is (McClure, 1966) $\tau_{\rm cx}^{-1}=\sigma_{\rm cx}v_{\rm rel}=n_{\rm e}\times(3.25\times10^{-8})\,{\rm s}^{-1}$. Then $\tau_{\rm cx}^{-1}\simeq\tau_{\rm col}^{-1}$ and we may assume that a half of the cometary neutrals undergo charge transfer with coronal protons. Because of the small momentum transfer in the latter process (McClure, 1966), these "secondary" H atoms have the same kinetic temperature as the ambient coronal atoms and move away from the Sun with the same bulk speed. The observed similarities (see Fig. 3, middle and right panels) between the cometary (for C/2000 C6, C/2001 C2 and C/2002 S2 sungrazers) and coronal Lyα line profiles, together with the above discussion on the Swing effect, led us to conclude that the H atoms responsible for the main observed Lyα emission are those formed via charge exchange between neutrals from the photodissociation of water and coronal protons, while emission from the "first generation" of H atoms is negligible (Swing effect).

A different origin has to be invoked to explain the broader, red-shifted Lyα line profiles observed in the C/1996 Y1 sungrazer spectra (Fig. 3, left panel). As it is well known, once the cometary neutrals (immersed into the interplanetary magnetic field) are ionized, they are subject to the Lorentz force leading to a mass loading of the solar wind. For a comet moving in a supersonic solar wind flow this induces the formation of a bow shock (upstream of the comet) which both slows down the wind speed and heats the plasma leading to a broadening of the observed spectral lines. When the magnetic field and the solar wind speed are both radial ($h\geqslant2-3\,R_\odot$), the effective shock velocity is given by the sum of the cometary (inward) and the wind (outward) velocities: this means that the formation of the bow shock for sungrazers depends on whether the coronal region crossed by the comet is a fast or a slow wind region. As shown by the LASCO images, the C/1996 Y1 sungrazer was observed at the solar minimum well outside of the equatorial streamer belts, hence it was probably immersed in the fast wind. On the contrary, C/2000 C6, C/2001 C2 and C/2002 S2 were observed closer to the equatorial plane (see Fig. 1) around the solar maximum, when fast and slow winds are mixed at all latitudes. Then the cometary bow shock formed only for the C/1996 Y1 sungrazer (leading to the observed broadening in the Lyα profiles), and did not form for the other three comets. The authors concluded that neutrals responsible for the C/1996 Y1 Lyα emission were H atoms formed via charge exchange at the bow shock; these atoms, because of the thermal broadening of their absorption profile, were still capable of intercepting the chromospheric Lyα photons. During the UVCS observations, the C/1996 Y1 sungrazer had a LOS velocity of $186\,\mathrm{km\,s^{-1}}$ away from the observer, as computed from the orbital parameters, while the fast wind encountered by the comet had a LOS velocity toward the observer. Then, the observed strong Lyα shift (Fig. 3, left panel) may be interpreted as the "LOS component of the speed of the partially decelerated solar wind" (Raymond et al., 1998) in the post-shock flow. From the estimated range of the cometary shock velocity and the observed proton kinetic temperature ($T_\mathrm{k} = (9.1 \pm 0.8) \times 10^6\,\mathrm{K}$), the authors (Raymond et al., 1998) inferred a wind speed of $v_\mathrm{w} \leqslant 620\,\mathrm{km\,s^{-1}}$.

5. Determination of sungrazer properties

The H atoms responsible for the Lyα emission are deposited by charge exchange along the comet path through the solar corona and this process locally increases the number density of neutrals with respect to the pre-comet density. After the comet transit, the collisional ionization starts to progressively reduce the number of H atoms and the Lyα emission decays as $\exp(-t/\tau_\mathrm{ion})$ until the cometary signal disappears. Hence, the observed shape of the Lyα tails shown in Fig. 2 is produced by an exponential decay which depends only on the unknown cometary outgassing rate $\dot{N}$ (i.e. the number of neutrals per second produced by outgassing in $H\,\mathrm{s}^{-1}$), the ionization rate τ_ion^{-1} (related to n_e as previously described) and other known observational parameters (Uzzo et al., 2001; Bemporad et al., 2005). An example of the observed exponential decay for the C/2001 C2 sungrazer is shown in Fig. 4. The general expression for the Lyα counts expected in each UVCS exposure depends, besides the parameters mentioned above, also on the unknown time t_st at which the comet first entered the slit (Uzzo et al., 2001). By fitting the observed exponential decay with this curve it is possible to estimate the pair of τ_ion and t_st values for which the χ^2 value is minimum and evaluate the outgassing rate $\dot{N}$ as a normalization parameter. From the outgassing rate, assuming that each water molecule gives rise to two neutral H atoms, we may estimate the mass loss rate $Q_{\mathrm{H_2O}}$ ($\mathrm{kg\,s^{-1}}$). Approximating the cometary nucleus as a sphere with active surface S_act (probably the whole surface for sungrazers), and assuming a balance between the energy supplied by the solar radiation over S_act and the energy required to sublimate the quantity of ice derived from $\dot{N}$, we have

$$S_\mathrm{act} = \frac{\dot{N}L}{F_\odot(1-A)N_A}, \quad (1)$$

where $L = 4.81 \times 10^{11}\,\mathrm{erg\,mol^{-1}}$ is the ice latent heat of sublimation, $A = 0.06$ is the cometary albedo, $F_\odot = 1.37 \times 10^6 (215.21\,\mathrm{R_\odot\,r^{-1}})^2\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ is the solar flux scaled to the cometary heliocentric distance h ($\mathrm{R_\odot}$) and N_A ($\mathrm{molec\,mol^{-1}}$) is the Avogadro number. From the S_act value it is possible to estimate the equivalent radius for the cometary nucleus $r = \sqrt{S_\mathrm{act}/4\pi}$. This relationship holds only in absence of unobserved fragmentation events. Table 2 gives the results obtained at different heliocentric distances h from the observations of the first three comets (the C/2002 S2 analysis is still in progress). An important result in this table is the UVCS detection of a significant mass below $\sim 6\,\mathrm{R_\odot}$, where these small comets are normally unobserved by white light coronagraphs. This apparent inconsistency may be removed with the same argument used to explain the secondary brightenings in the sungrazer lightcurves, i.e. introducing in the sungrazer erosion model one or more small subfragments traveling with the main nucleus and assuming that these subfragments survive closer to the Sun because of their lower erosion rate (Uzzo et al., 2001).

Another important result from Table 2 is the sudden increase in the Q_H2O value observed for the C/2000 C6 between 5.71 and $4.56\,\mathrm{R_\odot}$. This can be interpreted in terms of a nucleus fragmentation which suddenly increased the total surface exposed to the Sun and, as a consequence, the outgassing rate. It is the first time that a sungrazer fragmentation has been inferred from observations. However, as outlined by the authors (Uzzo et al., 2001), other explanations are possible such as a sudden increase in the local density n_e (even if in a denser region the increase in τ_cx^{-1} may be balanced by an increase in the τ_ion^{-1}) or an outburst of gas and dust from the nucleus (but close to the Sun probably the whole nucleus surface is active and there are no inert crusts candidate for the outburst).

The third result shown in Table 2 is the first direct identification of a subfragment traveling at $4.98\,\mathrm{R_\odot}$ with the C/2001 C2 main nucleus. The presence of two fragments has been inferred from the observation of two separate tails in the reconstructed Lyα image (see Fig. 2, right panel). From the observation of only a single Lyα tail later at $3.60\,\mathrm{R_\odot}$, the authors concluded that the sub-fragment responsible for the secondary tail at $4.98\,\mathrm{R_\odot}$ completely sublimates between these two heliocentric distances, as verified from the estimated radius at $4.98\,\mathrm{R_\odot}$ and the estimated rate of change in radius

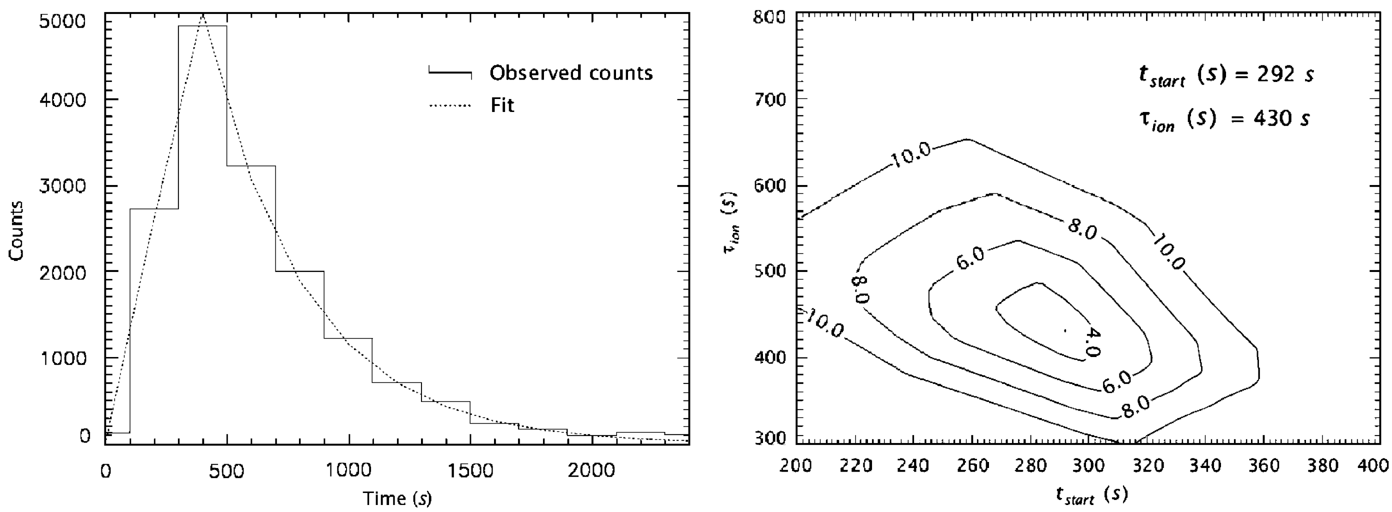

Fig. 4. Left: the C/2001 C2 Lyα counts (summed over the slit length) vs time curve as observed at 3.6 $R_\odot$ (solid line) and the curve fit (dotted line). Right: the iso-χ^2 curves for the determination of the (τ_{ion}, t_{st}) values at which the χ^2 value is minimum (see text).

Table 2
Derived sungrazer parameters (see text)

Comet name	Q_{H2O} (kg s^{-1})	r (m)	h ($R_\odot$)
C/1996 Y1	20.0	3.4	6.80
C/2000 C6	10.5	2.5	6.36
	34.6	3.4	5.71
	140.	5.8	4.56
	71.8	3.0	3.26
C/2001 C2	58.9[a]	7.8	4.98
	28.5[b]	5.4	4.98
	820.[a]	20.3	3.60

[a]Main nucleus.
[b]Subfragment.

(Bemporad et al., 2005). However, the authors point out that other possible interpretations may be invoked: e.g. two Lyα tails can be generated from a single object by a further outburst of gas (even if this process—as mentioned above—seems unlikely for a sungrazer because of the strong solar flux impinging on a self-rotating nucleus) or can be created by interaction between H atoms and the dust tail or there may be two dust tails. In the following we discuss some of these scenarios.

We like first to address the problem of the orientation of the tails: in Fig. 5 we show the "real" orientation of the C/2000 C6 Lyα tail at 4.56 $R_\odot$ (a) and of the C/2001 C2 Lyα tails at 4.98 (b) and 3.60 $R_\odot$ (c) after the correction for the comet motion along the UVCS slit. This figure demonstrates that the Lyα tails of sungrazing comets are not aligned with the radial from the Sun, but with the cometary path, even if, as mentioned before, the H atoms responsible for the cometary emission move with the bulk velocity of the ambient protons. This result may be explained by considering the values for the charge transfer and collisional ionization times. The velocity, relative to the comet, of the H atoms from outgassing (Delsemme, 1982) and photodissociation processes (Huebner et al., 1992) is less than about 40 km s^{-1}, much smaller than the typical sungrazer speed close to the Sun (Raymond et al., 1998; Uzzo et al., 2001; Bemporad et al., 2005) (~250–300 km s^{-1}). The charge transfer times between the outgassed neutral atoms and the coronal plasma, τ_{cx}, estimated from the curve fit of the C/2001 C2 Lyα decays at 4.98 and 3.60 $R_\odot$ are, respectively, ~1500 s and ~400 s. As a consequence, the H atoms from the outgassing cover a distance of ⩽80 arcsec and ⩽20 arcsec from the nucleus, before they undergo charge transfer. As revealed by the distribution along the slit of the Lyα emission before the comet arrival (and confirmed also by the LASCO images), at 4.98 $R_\odot$ this comet crossed a region very close to the boundaries of a coronal streamer, while at 3.60 $R_\odot$ the comet was immersed into the streamer. Hence, assuming (Poletto et al., 2002) a coronal outflow speed of, respectively, $\simeq$ 170 km s^{-1} and $\simeq$ 35 km s^{-1} and taking into account the angle (~13° and ~16°) between the orbital path and the radial from the Sun at both heights, it turns out that, because $\tau_{cx} \simeq \tau_{ion}$, the H atoms from the charge exchange cover ⩽20 arcsec and ⩽5 arcsec before being ionized. Then, the expected spread from the orbital path of the observed Lyα cometary emission should not exceed ~100 arcsec and ~25 arcsec, respectively, at 4.98 and 3.60 $R_\odot$. The above distances are comparable with the extension of the Lyα tails shown in Fig. 5. This explains the orbital orientation of these tails: the short lifetime of the H atoms from the charge exchange does not allow tails to align with the local outflow velocity.

Considering now the origin of one or both the observed Lyα tails, we have to take into account that H atoms may originate from the interaction of the hydrogen tail and the dust tail or from the interaction with two dust tails if particles were ejected at two different times. Also, neutral H atoms may be created by the interaction of coronal protons with the products from the sublimation of dust grains.

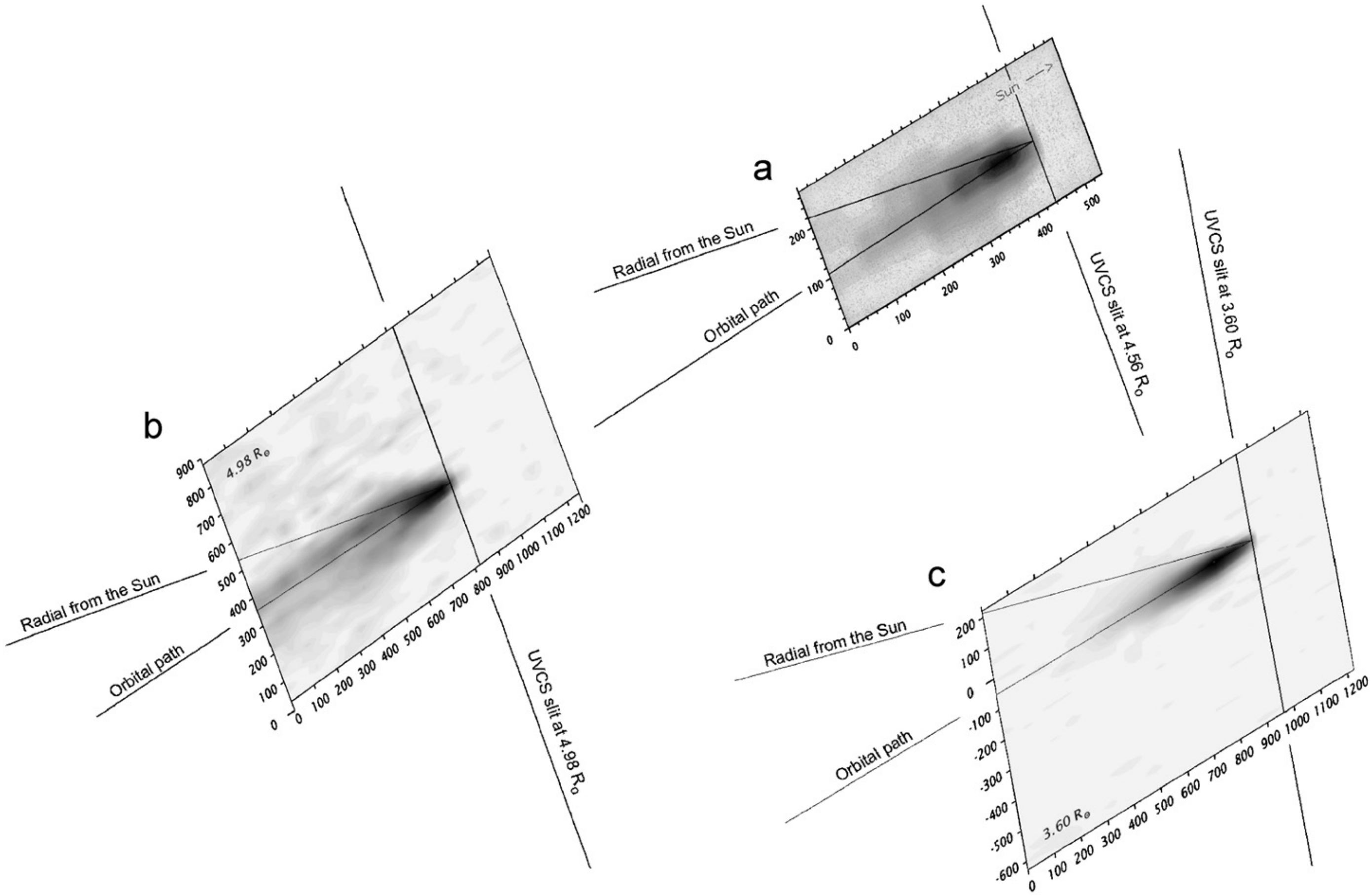

Fig. 5. The Lyα images of (a) the C/2000 C6 sungrazer at 4.56 $R_\odot$, (b) the C/2001 C2 sungrazer at 4.98 and (c) 3.60 $R_\odot$ corrected for the comet motion along the UVCS slit and aligned with the slit inclination (see Fig. 1).

In particular, an association has been made between the heliocentric distance of 4–5 $R_\odot$ at which the cometary Lyα emission peaks and the sublimation rate of pyroxene dust grains which peaks at about the same height (Kimura et al., 2002). In this scenario, a mixing between the "genuine" Lyα tail and the "secondary" Lyα tail by the interaction of coronal protons with products from the sublimation of pyroxene grains is expected. Moreover, the orbital orientation of the Lyα tails shown in Fig. 5 is similar to the non-radial orientation of the sungrazer dust tail observed in the white light coronagraphs (Sekanina, 2000).

We point out that a preliminary analysis of UVCS data shows also in comet C/2002 S2 the presence of two Lyα tails (Fig. 6), very similar to those we observed in the C/2001 C2 sungrazer. As shown in Fig. 1, the orbital plane of C/2002 S2 (unlike C/2001 C2) was observed edge on. Because in general the ion and dust tails lie on the orbital plane, in this case we can no longer explain the presence of two tails invoking an ion and a dust tail or two different dust tails superposed along the line of sight. This is demonstrated also by the presence in the white light images for this comet of a single dust tail lying in between the two Lyα tails (Fig. 6, top right panel).

A further problem in the data interpretation is that, while the emission from the main tail is red-shifted by more than 60 km s^{-1}, the Lyα profiles of the secondary tail are blue-shifted by more than 120 km s^{-1} (Fig. 6, bottom right panel). The resulting Doppler shift image of the comet is puzzling and the two observed Lyα tails cannot be easily interpreted as the signature of two fragments as we did for the C/2001 C2 sungrazer. Moreover, because the white light images show only a single tail, the presence of two Lyα tails cannot be the signature of two jets from the nucleus, which should be visible also in LASCO images. We conclude that a more thorough discussion about these issues (beyond the purpose of this paper) is needed to explain the comet behavior (Giordano et al., in preparation).

6. An estimate of the C/2001 C2 pyroxene grain number density

The presence of amorphous and/or crystalline silicates like olivine ($[Mg, Fe]_2 SiO_4$) and pyroxene ($[Mg, Fe]_2 Si_2O_6$) has been revealed by many remote observations of the cometary dust thermal emission (Hanner et al., 1994; Harker et al., 1999). As anticipated in Section 1, different features observed in the sungrazer lightcurves have been explained as a "superposition of two distinct lightcurves originating from olivine and pyroxene grains" (Kimura

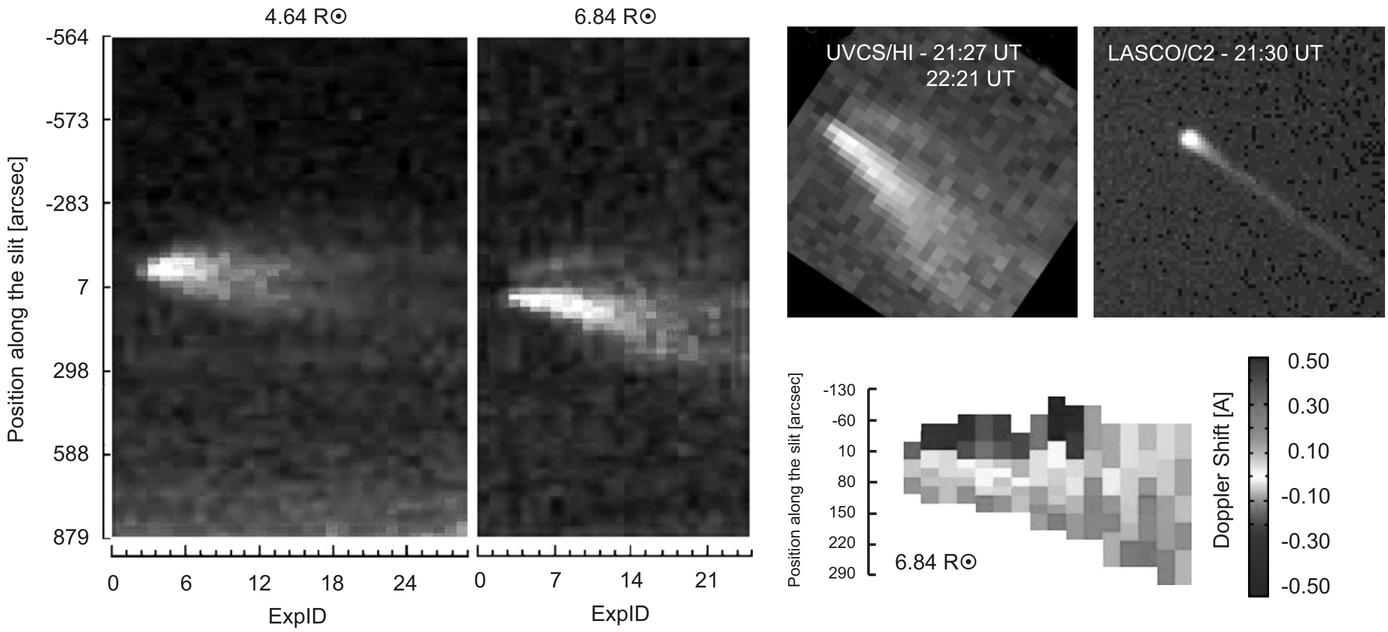

Fig. 6. Left panels: the Lyα images (coronal background emission not subtracted) of the C/2002 S2 sungrazer at 4.64 (left) and 6.84 $R_\odot$ (right); because of the orientation of the orbital plane, the correction for the comet motion along the UVCS slit is negligible. Top right panel: a comparison between the Lyα tail at 6.84 $R_\odot$ from UVCS data and the dust tail in the LASCO/C2 white light image. Bottom right panel: the puzzling Lyα Doppler image at 6.84 $R_\odot$ (see text).

et al., 2002). Moreover, it has been pointed out (Sekanina, 2000) that in the sungrazer dust tails the β parameter (i.e. the ratio of radiative to gravitational pressure acting over the dust grains) has a maximum value $\beta_{max} \leqslant 0.6$, equal to the upper limit of β for cometary silicate grains, implying that grains in the sungrazer tails consist mainly of dielectric materials such as silicates. Nevertheless, in the literature there are no measurements of the number density N_d (cm^{-3}) of dust grains in sungrazing comets (the cumulative number density of dust has been measured in situ only from Vega 1, Vega 2 and Giotto spacecraft instruments during the comet P/Halley flyby, McDonnell et al., 1987; Lamy et al., 1987).

A tentative estimate for the pyroxene dust grain number density N_d has been derived from the C/2001 C2 UVCS data (Bemporad et al., 2005). As mentioned in the last section, this comet showed two Lyα tails at 4.98 $R_\odot$: after the separation of the Lyα counts vs time curves from the two tails, we applied the technique described in Section 5 to evaluate the outgassing of the two fragments. From the fit we derived an estimate for the outgassing rate $\dot{N}$, the ionization rate τ_{ion} and (from the latter) the local n_e. As revealed by the distribution along the slit of the Lyα emission before the comet arrival (and confirmed also by the LASCO images), at 4.98 $R_\odot$ this comet was traveling in a region very close to the boundaries of a coronal streamer. As we said, the brighter tail (in the following "tail 1") was at the edge of this streamer, while the secondary tail ("tail 2") lay in an outer region: hence, we expect to derive from the tail 1 fit a higher n_e value than for tail 2. On the contrary, the slower decrease, in time, of the Lyα counts of tail 1, leads to higher τ_{ion}, and a lower n_e value, than for tail 2. This inconsistency leads us to hypothesize that the observed decay in time of tail 1, given in Fig. 2, consists of an exponentially decaying signal superposed onto a constant background. Subtracting from all the exposures after the main intensity peak a constant background of 280 counts and fitting the resulting curve, we derived an n_e value higher than estimated from tail 2, as expected.

The explanation for these background additional Lyα counts can be found in the interaction between coronal protons and the dust grains. As anticipated in the previous section, the pyroxene grains in sungrazer comae have their sublimation zone around $\sim 5\,R_\odot$, which corresponds exactly to our observation height. Products from their sublimation (mainly SiO_2 molecules, Kimura et al., 2002) may undergo a charge transfer with the ambient coronal protons. Given the cross sections σ for the charge transfer processes between protons and O or Si atoms from the photodissociation of SiO_2 molecules and assuming a typical bulk density and radius for the pyroxene grains (Kimura et al., 2002), we derive, as a function of the unknown N_d, an expression for the expected number of H neutrals produced by the charge transfer. Because this value should match that of the additional H atoms $\bar{N}_H$ estimated from the observed constant background of the Lyα counts, we have a means to evaluate the pyroxene dust grain number density needed to reproduce our observations. It turns out that $N_d \simeq 6.2 \times 10^{-10}\,cm^{-3}$. To compare the present value with values in the literature, we may assume N_d to decrease as $1/d^2$ where d is the distance from the cometary nucleus. Then, in comet Halley, a N_d value of $\simeq 6.2 \times 10^{-10}\,cm^{-3}$, would be met at $d \simeq 1.3 \times 10^5$ km. Obviously conditions in sungrazers are completely different from those in comets at $\simeq 1$ AU.

7. Conclusions

UVCS observations in the Lyα spectral line of sungrazers provided a wealth of new information about these comets. Namely:

- The presence of "hidden mass" below $\sim 6\,R_{\odot}$, undetected by the LASCO white light coronagraphs, has been ascribed to the presence of slowly eroding subfragments traveling with the main nucleus. From the observed exponential decay with time of the Lyα intensity after the comet transit, an (model-dependent) estimate for the cometary outgassing rate and the nucleus radius has been made.
- The occurrence of a fragmentation event has been inferred from the observation of an increase of the C/2000 C6 Lyα emission at $\approx 5\,R_{\odot}$ and from the observation, at about the same heliocentric distance, of two tails in the C/2001 C2 sungrazer. It was the first time that UVCS observed two Lyα tails; however, we remind the reader that alternative explanations for the C/2001 C2 observations cannot be ruled out.
- An order of magnitude estimate for the density of pyroxene dust grains has been made, for the first time, from the detection of a constant background Lyα emission in the C/2001 C2 data.

Additional exciting results are expected from the analysis of the C/2002 S2 UVCS observations. UVCS data revealed once more the presence of two Lyα tails; however, because of the orientation of the orbital plane of the comet, of its Doppler shift image and of the comparison with white light images, it seems that previous interpretations do not hold. In order to find an alternative explanation, Giordano and collaborators (Giordano et al., in preparation) are working now on a comet simulation code based on the Monte Carlo technique. The code aims at understanding the relationships between the observed shape of the Lyα image and the cometary and coronal parameters such as the comet speed and outgassing rate, the wind speed, coronal kinetic temperature, electron temperature and density. In conclusion, the UVCS spectrograph turned out to represent a crucial means to derive unknown parameters of sungrazers before their final plunge into the Sun.

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