Evidence for pyroxene dust grains in C/2001 C2 sungrazing comet

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ABSTRACT

In this paper we analyze SOHO/UVCS data of the sungrazing comet C/2001 C2, a member of the Kreutz family, observed on February 7, 2001, at the heliocentric distances of 4.94 and 3.44 solar radii. As confirmed also by LASCO/C3 images, this comet splits in a main nucleus and a fragment which have been identified in our UV data. A study of the cometary Hydrogen Lyα emission from these two objects showed a different behaviour: the Lyα signal from the fragment decays exponentially with time, while the signal from the main object consists of an exponentially decaying term plus a constant background. This secondary component has been ascribed to the sublimation of pyroxene dust grains, whose end products neutralize coronal protons via charge exchange processes. With this hypothesis we derive for the first time an estimate of the pyroxene dust grains number density in a sungrazing comet.

1. INTRODUCTION

The composition of cometary dust is far from being fully understood, but many remote observations of the cometary dust thermal emission revealed the presence of amorphous and crystalline silicates like olivine ([Mg, Fe]$_2$ SiO_4) and pyroxene ([Mg, Fe]$_2$ Si_2O_6). Nevertheless in the literature there are no measurements for the dust grain number density N_d in sungrazing comets: the only estimate refers to the dust density derived by Vega 1, Vega 2 and Giotto spacecraft measurements during the comet P/Halley flyby. At a reference distance of 1000 *Km* from the nucleus, when the comet was at an heliocentric distance between ~ 0.8 and 0.9 AU, it turns out that the grains with a mass of ~ 10^{-14}*g* have N_d ~ 1–2 $\cdot 10^{-5}$ cm^{-3} (Vaisberg *et al.*, 1986; Mazets *et al.*, 1987; McDonnell *et al.*, 1987). In this work we derived, from UV data, the first order of magnitude estimate for the silicate grains number density in sungrazing comets.

2. UVCS OBSERVATIONS

On February 7, 2001 the sungrazing comet C/2001 C2 (SOHO-294, a member of the Kreutz sungrazer family) approached the Sun from the South-East quadrant at a latitude angle of about 30°S, projected onto the plane of the sky: the *UltraViolet Coronagraph Spectrometer* instrument (UVCS, see Kohl *et al.*, 1985) observed this comet at 5 different heights: 7.41, 6.17, 4.94, 3.44 and 1.78 $R_\odot$.

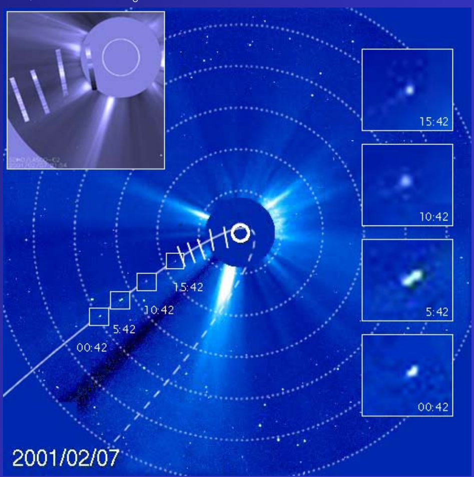

FIGURE 1: *the C/2001 C2 comet motion as observed by LASCO/C3: in this panel we superposed onto the 7 February 2001, 10:42 UT LASCO/C3 frame the cometary LASCO/C3 images at 00:42, 05.42 ,10:42 and 15.42 UT; the different UVCS observation heights are also shown. The dotted circles correspond to the observation heights of 5, 10, 15, 20, 25 and 30* $R_\odot$. *In order to compare the cometary motion with the positions of the UVCS slit we plotted also the pre-perihelion (solid line) and expected post-perihelion (dashed line) C/2001 C2 trajectory as computed from the orbital parameters. Moreover, in order to show the coronal morphology at lower levels, we superpose onto the LASCO/C2, 21:54 UT image (upper left panel) the UVCS Lyα coronal intensity at 1.78, 3.44, 4.94 and 6.17* $R_\odot$.

A study of the orbit from the cometary orbital parameters shows that the comet moved primarily on the plane of the sky with a projected speed which varied from ~210 to ~420 *Km/s* between the 5 UVCS observation heights. In this work we focus on data acquired by the O VI channel: the slit center was set at a solar latitude of 20°S and 10°S respectively for the three higher and the two lower heights in order to follow the comet motion (see Fig. 1). At each height we acquired a series of 200 *s* exposures for a total observing time of about 70 minutes; the observations started 4–5 exposures before the comet arrival on the slit. The slit width was set to 150 *μm*: the data have been acquired with a spectral resolution of 0.183 Å and a spatial resolution of 21".

The identification of the cometary signal over the underlying coronal emission has been performed subtracting the average coronal intensity before the comet arrival from the following exposures. This procedure showed that, in the observed spectral windows, the comet is visible only in the Lyα 1216 Å line. A small emission in the Lyβ 1025 Å line has been used only to estimate the Lyα radiative and collisional component percentage (see below), while a transient weak emission observed at about 1206 Å has been ascribed to the Si III 1206.5 Å line. The comet give a signal only at 4.94 and 3.44 $R_\odot$: in the following we focus on the cometary Lyα emission at these two heights.

In Fig. 2 we show the cometary emission in Lyα at both heights from all the available exposures before (left panels) and after (right panels) the subtraction of the coronal intensity. Along the *y* axis we scaled the different bins along the UVCS slit to *arcsec*, while along the *x* axis we plotted the intensity measured in different exposures; the *x* axis has been scaled in *arcsec* from the cometary velocity component perpendicular to the slit and the exposure time. A comparison between the two panels reveals some interesting differences: while the 3.44 $R_\odot$ image shows only one tail, in the 4.94 $R_\odot$ two tails are clearly visible. Moreover, the northernmost and brighter tail (hereafter tail 1) seems to decrease more slowly with time than the weaker structure (in the following tail 2). As we show in the next sections, this very slow decrease in the tail 1 Lyα intensity can't be explained in the classical picture of emitting H atoms coming from the photodissociation of H_2O molecules; in this work we ascribe this effect to a background emission due to the presence of pyroxene dust grains.

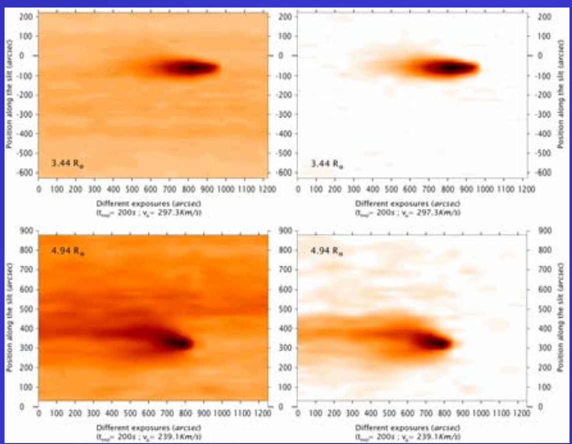

FIGURE 2: *composite Lyα images of C/2001 C2 observed at 3.44 (top panels) and 4.94* $R_\odot$ *(bottom panels). At both heights we give the Lyα images before (left) and after (right) the subtraction of the background Lyα. Notice at 4.94* $R_\odot$ *the presence of two tails and the longer Lyα signal persistence after the comet passage in respect to the 3.44* $R_\odot$ *observation. In the y axis 0 marks the UVCS slit center position; North is up. These images have not been corrected for the cometary motion along the slit and the solar wind speed.*

In order to separate the contribution of the two tails, we assumed that the cometary Lyα intensity distribution along the slit is symmetric around the peak, as suggested by the image at 3.44 $R_\odot$. After correcting the Lyα image for the cometary motion in the direction parallel to the slit (using the computed cometary velocity component along the UVCS slit), we assumed that tail 1 intensities northward of their peak values are, at each time, unaffected by tail 2 and we built the intensity distribution of tail 1 by simply mirroring its northern isophotes. The secondary tail isophotes have been obtained by subtracting from the original Lyα image the contribution of tail 1: the curves we obtained with this method for the tail 1 and tail 2 Lyα counts are discussed in the next sections.

3. THE COMETARY LYα EMISSION

Before discussing the N_d determination, we briefly outline the physics of the cometary Lyα emission; the reader is referred to Uzzo *et al.* (2001) and Raymond *et al.* (1998) for a more detailed treatment of the problem.

There are two possible sources for this emission: H atoms originating from the photodissociation of the H_2O molecules ejected by the sublimating nucleus, or H atoms created by charge exchange between the above and coronal protons. However, these two different generations of H atoms give rise to Lyα emission only via radiative excitation: for this spectral line this is usually the case in the solar corona (see *e.g.* Raymond *et al.*, 1997) and has been verified both in the two works cited above and also in our data from the observed ratio $R^{obs}_{\beta\alpha}$= I(Lyα) / I(Lyβ). The expected ratios between the radiative components $R_{\beta\alpha\,r}$ and bewtween the collisional components $R_{\beta\alpha\,c}$ in our case are respectively ~0.0021 and ~0.14, while the average $R^{obs}_{\beta\alpha}$ at 3.44 and 4.94 $R_\odot$ are respectively 0.0041 and 0.0020, leading us to the above conclusion. Moreover the gaussian fit of the Lyα profiles indicate that nearly all the H atoms responsible for the Lyα sungrazer emission are formed by the charge exchange process p^+_{cor} + H_{H2O} ⟶ H_{cor} + p^+ between coronal protons p^+_{cor} and neutral atoms H_{H2O} that are secondary products from the ejected H_2O. Because the momentum transfer in this process is very small (McClure, 1966), the newly formed H_{cor} atoms have about the coronal proton velocity distribution as confirmed in our data by the approximate equivalence between the FWHM of the coronal and cometary Lyα profiles.

Once the H_{cor} atoms have been created by the process described above, the local H atoms number density along the comet path exceeds the preceeding coronal value determined at the equilibrium by the coronal ionization rate τ^{-1}_{ion} : then the number N_H of H atoms that the comet left along its path exponentially decays with a lifetime τ_{ion} until the cometary Lyα signal disappears and the H ionization equilibrium is reestablished. This decay is well visible at 3.44 $R_\odot$ in Fig. 3 and we would expect to see it both in tail 1 and tail 2 at 4.94 $R_\odot$. The observed curves for the cometary Lyα counts will depend also on the charge exchange rate τ^{-1}_{cx}, the cometary outgassing rate $\dot{N}$ and some parameters of the comet motion. With the model introduced by Uzzo *et al.* (2001) it is possible to fit the observed curve finding the 3 unknown parameters τ^{-1}_{ion}, τ^{-1}_{cx} and $\dot{N}$. The knowledge of τ^{-1}_{ion} gives an estimate for the coronal electron density N_e encountered by the comet (because $\tau^{-1}_{ion} \propto 1/N_e$, see Scholz & Walters, 1991), while from the $\dot{N}$ value, the radius and mass of the cometary nucleus can be estimated.

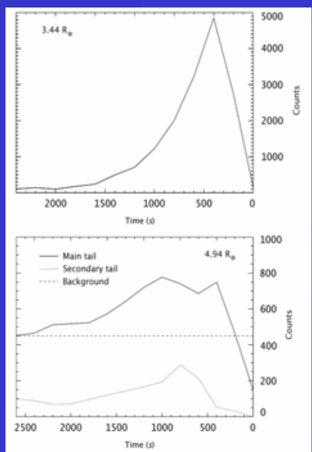

FIGURE 3: *observed cometary Lyα counts vs time in the single tail at 3.44* $R_\odot$ *(top panel) and in the two tails at 4.94* $R_\odot$ *(bottom panel); the curves show the Lyα counts in each exposure summed along the UVCS slit.*

4. PYROXENE DUST GRAIN DENSITY

Fitting with the model described above the 3.44 $R_\odot$ curve (Fig. 3, top panel), we find from the τ_{ion} value N_e = 7.21 $\cdot 10^4$ cm^{-3}, consistent with values given in the literature (Gibson *et al.*, 1999; Strachan *et al.*, 2002) at this height.

At 4.94 $R_\odot$ the model gives us a value of N_e = 1.67 $\cdot 10^4$ cm^{-3} from the tail 2 curve fit (in agreement with measurements in the literature) and a lower (<1.55 $\cdot 10^4$ cm^{-3}) N_e value for the tail 1 curve (Fig. 3, bottom panel) because of the very slow decrease in time and the high τ_{ion} value from the fit. This is not in agreement with the appearance of the ambient corona crossed by the comet, because (see Fig. 1 and Fig. 2) at this height a small coronal streamer lies about 100 *arcsec* Northward from tail 1. Hence we would expect from the tail 1 fit a N_e value higher than that derived from tail 2, *i.e.* a faster exponential decay with time.

This inconsistency leads us to hypothesize that the observed tail 1 curve in Fig. 3 consists of an exponential decay plus a constant background, (that we justify later on in this section): subtracting from all the exposures following the main intensity peak a constant background of 450 *counts* (see Fig. 3) and fitting the resulting curve, we compute N_e = 4.31 $\cdot 10^4$ cm^{-3}, higher than the N_e value estimated from tail 2, as expected. A Lyα intensity of I(Lyα)≈ 450 *counts* = 6.31 $\cdot 10^9$ *phot* cm^{-2} s^{-1} sr^{-1} corresponds to an additional number $\overline{N}_H \approx$ 4.78 H cm^{-3} of H atoms. Now the question is: where do these additional H atoms come from?

Kimura *et al.* (2002) interpreted the observed sungrazer lightcurves in terms of the different characteristic timescales for sublimation of olivine and pyroxene dust grains. In particular, finding that pyroxene aggregates in sungrazer comae have their sublimation zone at *h* ~ 5 $R_\odot$, which corresponds to our observation height, they hypothesized that the sublimating grains may act as "(...) agent to neutralize protons in the solar corona.". Following this suggestion we ascribe the number $\overline{N}_H$ of additional H atoms to a charge transfer process between products from pyroxene grains sublimation and coronal protons. We hypotesize that the mass loss of pyroxene grains in the sublimation process occurs by ejection of SiO_2 molecules alone (see Kimura *et al.*, 2002). The ejected SiO_2 molecule is photodissociated by the solar flux and the O and Si atoms created by this process may ionize and/or undergo a charge transfer, depending on the ambient plasma conditions.

From a comparison between the experimental charge transfer process rates (Kimura *et al.*, 1997) and the estimated ionization rates at the conditions of our plasma (T_k = 7.2 $\cdot 10^5$ *K* from the Lyα FWHM and N_e = 4.31 $\cdot 10^4$ cm^{-3} from the tail 1 fit described above), it turns out that about half of the Si atoms from the photodissociation of SiO_2 undergoes charge transfer with coronal protons, while all the produced O atoms undergo charge transfer before being ionized. Hence we have that the number density *N*(Si) and *N*(O) of Si and O atoms available for charge exchange traveling with the comet are:

$$N(\mathrm{Si}) = \frac{1}{2} N_d \frac{m_d(\mathrm{SiO_2})}{m(\mathrm{SiO_2})} \quad ; \quad N(\mathrm{O}) = 2 N_d \frac{m_d(\mathrm{SiO_2})}{m(\mathrm{SiO_2})} = 4N(\mathrm{Si})$$

where $m_d(SiO_2)$ is the SiO_2 mass of the grain and $m(SiO_2)$ = 9.98 $\cdot 10^{-23}$*g* is the mass of a SiO_2 molecule. Assuming that the crystal composition formula is $Mg_{1.8}$ $Fe_{0.2}$ Si_2 O_6 (see *e.g.* Wooden *et al.*, 1999) and using typical bulk density and radius for the pyroxene grains estimated by Kimura *et al.* (2002), we have $m_d(SiO_2)$ = 6.42 $\cdot 10^{-14}$*g*. Hence, knowing *N*(Si) and *N*(O), from the cross sections σ_{cx}(Si) and σ_{cx}(O) for inelastic processes in collisions of H^+ ions with neutral Si and O atoms (Kimura *et al.*, 1997), we may derive the expected number of H neutrals produced by charge transfer as a function of the unknown grain number density N_d. Equating this number to the $\overline{N}_H$ number estimated from the observed bachground we find:

$$N_d = \overline{N}_H \left[N_p \frac{m_d(\mathrm{SiO_2})}{m(\mathrm{SiO_2})} v_p \left(\frac{\sigma_{cx}(\mathrm{Si})}{2} + 2\sigma_{cx}(\mathrm{O}) \right) \tau_{ion} \right]^{-1} = 1.0 \cdot 10^{-9}\, cm^{-3}$$

where N_p~N_e is the coronal proton density and $v_p \approx$ 420*Km/s* is the proton velocity with respect to the colliding neutrals which move in first approximation with the comet. In order to compare this value with measurement given in Sec. 1 for the Halley coma, we may suppose that N_d decreases like $\propto 1/d^2$ (where *d* is the distance from the cometary nucleus) and estimate that the value of N_d = 1.0 $\cdot 10^{-9}$ cm^{-3} would be found at a distance of ~ 10^5*Km* from the nucleus.

5. CONCLUSIONS

In this work we report on the first identification of pyroxene dust grains in a sungrazing comet which allows us to derive for the first time an order of magnitude estimate for the pyroxene dust grain number density in these comets. The slow Lyα intensity decrease in time at 4.94 $R_\odot$ has been interpreted as a consequence of the charge exchange between coronal protons and the products from the dissociation of cometary pyroxene dust grains. This process leads to the formation of an additional number of H atoms which shows up as a background in the cometary Lyα emission.

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