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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, that was observed on February 7, 2001, at the heliocentric distances of 4.98 and 3.60 solar radii. This comet splits in a main nucleus and a fragment which have been identified in UV data. A study of the cometary Hydrogen Lyα emission from these two objects revealed that the Lyα signal from the fragment decays exponentially with time, while the signal from the main object consists of an exponentially decaying term superposed onto a constant background. The latter emission has been ascribed to the sublimation of pyroxene dust grains, whose end products neutralize coronal protons via charge exchange processes. This interpretation allowed us to estimate, for the first time, the number density of pyroxene dust grains in a sungrazing comet.

Keywords: Comets, general; Comets, individual (C/2001 C2); Spectroscopy, EUV

1. Introduction

Knowledge of the cometary dust density and composition is crucial for the interpretation of the cometary light-curves and to derive informations on the nucleus composition. Many remote observations of the thermal emission from cometary dust 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 number density N_d (cm^{-3}) of dust grains in sungrazing comets: the cumulative number density of dust has been derived only from 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 a heliocentric distance between ≃0.8 and 0.9 AU, it turns out that the grains with a mass up to 10^{-14} g have $N_d \sim 1$–2×10^{-5} cm^{-3} (see, e.g., Lamy et al., 1987).

In this work we derived, from UV data, the first order of magnitude estimate of the number density of silicate grains in sungrazing comets. Section 2 describes the UVCS dataset; in Section 3 we briefly explain the origin of the observed cometary signal introducing the technique we use to find cometary parameters; in Section 4 we show how an unexpected background emission can be attributed to pyroxene grains. A short summary of our results concludes the paper.

2. UVCS observations

On February 7, 2001 the sungrazing comet C/2001 C2 (SOHO-294) approached the Sun from the South-East quadrant at a latitude, projected onto the plane of the sky, of about 30°S. The *UltraViolet Coronagraph Spectrometer* (UVCS, see Kohl et al., 1995) experiment on SOHO tried observing this comet at 5 heliocentric distances: 7.42, 6.17, 4.98, 3.60 and 2.20 $R_\odot$. In order to follow the comet motion, the center of the UVCS slit was

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set at a latitude of 20°S when the comet was at distances $\geqslant 4.98\ R_\odot$, and at 10°S when the comet was closer to the Sun. At each height we took a series of 200 s exposures for a total observing time of about 70 min; observations started 4–5 exposures before the expected time for the comet detection. The slit width was set to 150 μm: data have been acquired with a spectral resolution of 0.183 Å and a spatial resolution of 21'' (corresponding to ≃15,200 km).

After subtracting the average coronal intensity (derived from the pre-comet observations), the comet turned out to be visible mainly in the Hydrogen Lyα line and only at 4.98 and 3.60 $R_\odot$. A small emission in the Lyβ line has been used to verify, from the ratio I(Lyα)/I(Lyβ), that the observed Lyα counts originate only from radiative excitation, while a transient weak emission observed at about 1206 Å has been ascribed to the Si III 1206.5 Å line. In the following we focus on the cometary Lyα emission.

In the top panels of Fig. 1, we show the cometary Lyα emission at both heights from all the available exposures: 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 (scaled to *arcsec* by taking into account the component of the cometary velocity perpendicular to the slit and the exposure time). As shown in Fig. 1, while the 3.60 $R_\odot$ image shows emission from only one tail, emission at 4.98 $R_\odot$ appears to originate from two distinct features, hereafter referred to as "tail 1" (the brighter structure) and "tail 2". In this work we interpreted the two Lyα tails as a signature, respectively, of the main nucleus and of an accompanying subfragment. We notice that (see Fig. 1) the Lyα intensity of tail 1 seems to decrease more slowly with time than it happens for tail 2. This shows up more clearly in the bottom panels, where we plot the Lyα intensity profiles vs. time obtained by summing, in each exposure, over all the cometary counts observed along the slit. As we show in the following sections, the very slow decrease of the Lyα intensity in tail 1 cannot be explained in the classical picture of emission from H atoms originating from the photodissociation of H_2O molecules.

3. The cometary Lyα emission

Before discussing the N_d determination, we need to 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.

Because the observed Lyα is due to radiative excitation, there are two possible sources for this emission: H atoms created from the photodissociation of the H_2O molecules ejected by the sublimating nucleus, or by charge exchange between the above and coronal protons. In order to choose

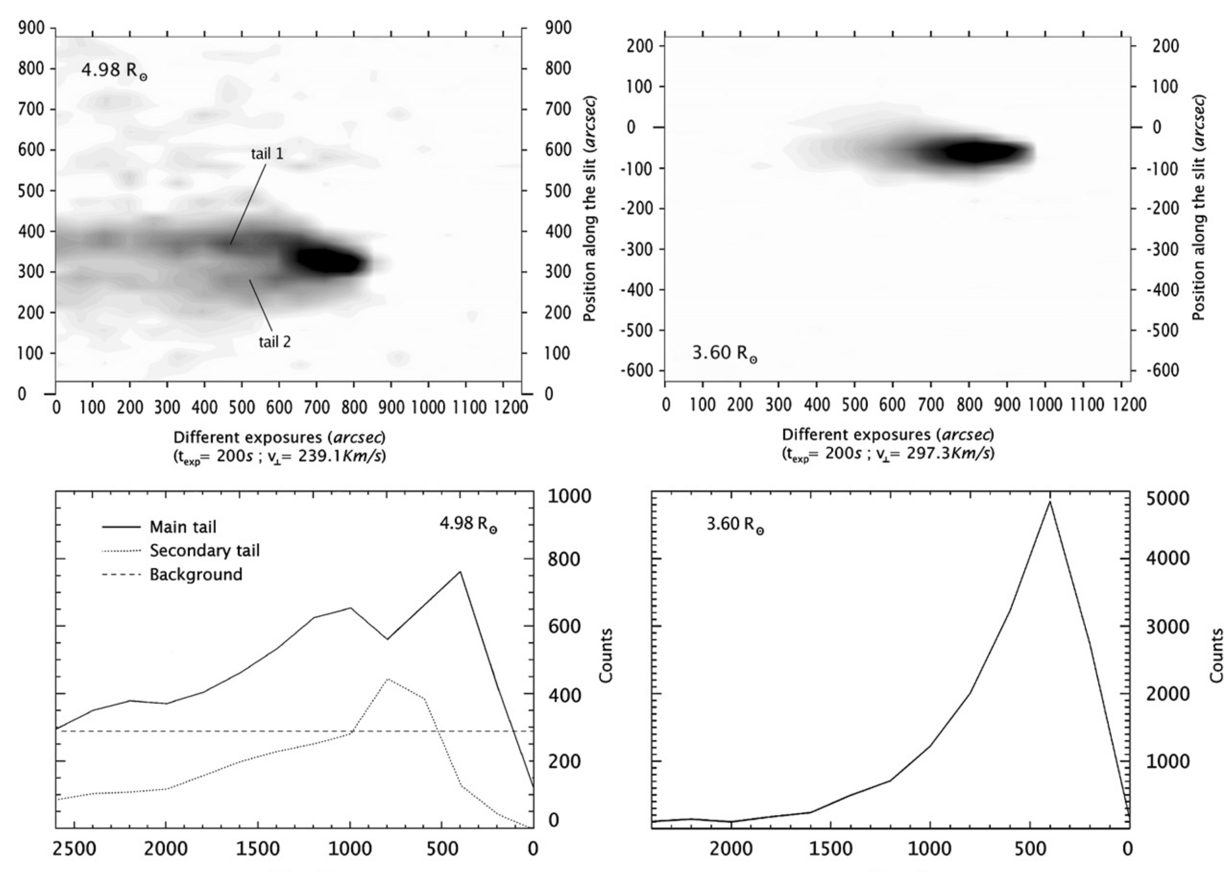

Fig. 1. Top: composite Lyα images of C/2001 C2 at 4.98 (left) and 3.60 $R_\odot$ (coronal background subtracted). In the *y*-axis 0 marks the UVCS slit center position; North is up. Bottom: profile of the observed cometary Lyα counts vs. time at both heights summed along the slit.

between these two possibilities we notice that in the charge exchange process $p^+_{cor} + H_{H_2O} \rightarrow H_{cor} + p^+$ between coronal protons p^+_{cor} and neutral atoms H_{H_2O} that are secondary products from the ejected H_2O, the momentum transfer is very small (McClure, 1996). The approximate equivalence between the FWHM of the coronal and cometary Lyα profiles indicate that nearly all the H atoms responsible for the cometary emission are formed by the above process.

Once the H_{cor} atoms have been created, the local number density N_H of H atoms that the comet leaves along its path exponentially decays with a lifetime τ_{ion} until the cometary Lyα signal disappears. This decay is well visible at 3.60 $R_\odot$ in Fig. 1 and we would expect to see it both in tail 1 and tail 2 at 4.98 $R_\odot$. The observed profiles for the cometary Lyα counts vs. time depend also on the charge exchange rate τ^{-1}_{cx}, the cometary outgassing rate $\dot{N}$ and some parameters of the comet motion. As described by Uzzo et al. (2001), provided enough data points are available, it is possible to fit the observed curve and identify the 3 unknown parameters τ^{-1}_{ion}, τ^{-1}_{cx} and $\dot{N}$. Knowing τ^{-1}_{ion}, the coronal electron density N_e encountered by the comet can be derived (because $\tau_{ion} \propto 1/N_e$, see Scholz and Walters, 1991), while from the $\dot{N}$ value, the radius and mass of the cometary nucleus can be estimated.

4. Pyroxene dust grain density

Fitting the Lyα decay with time at 3.60 $R_\odot$ (Fig. 1, bottom right), we find from the τ_{ion} value a coronal electron density $N_e = 7.21 \times 10^4$ cm^{-3}, consistent with values given in the literature (see, e.g., Gibson et al., 1999) at this height.

At 4.98 $R_\odot$ (Fig. 1, bottom left) we derived a value of $N_e = 1.60 \times 10^4$ cm^{-3} from the tail 2 curve fit (in agreement with values from Gibson et al., 1999) and a lower ($\leqslant 1.55 \times 10^4$ cm^{-3}) N_e value for the tail 1 curve because of its very slow decrease in time and the high τ_{ion} value from the fit. However, this is opposite to what we expect, because tail 1 lies at the edge of a coronal streamer where N_e should be higher.

This inconsistency leads us to hypothesize that the observed tail 1 curve in Fig. 1 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 (see Fig. 1) and fitting the resulting curve, we derive $N_e = 3.0 \times 10^4$ cm^{-3}, higher than the N_e value estimated from tail 2, as expected.

Let us now examine how to interpret the constant Lyα background emission. A Lyα intensity of about $I(\text{Ly}\alpha) \simeq 280$ counts $= 3.93 \times 10^9$ phot cm^{-2} s^{-1} sr^{-1} corresponds to an additional number $\bar{N}_H \simeq 3.0$ H cm^{-3} of H atoms. Now the question is: where do these additional H atoms originate 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. These authors, finding that pyroxene aggregates in sungrazer comae have their sublimation zone at $h \sim 5R_\odot$ – which corresponds exactly to our observation height – suggest that the sublimating grains act as "(...) agent to neutralize protons in the solar corona.". Following this scenario, we ascribe the number $\bar{N}_H$ of additional H atoms to a charge transfer process between products from pyroxene grains sublimation and coronal protons. We further hypothesize 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 then photodissociated by the solar radiation 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 in the coronal plasma interacting with the comet ($T \simeq 7.2 \times^5$ K from the Lyα FWHM and $N_e = 3.0 \times 10^4$ 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:

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

where $m_d(SiO_2)$ is the SiO_2 mass of the grain and $m(SiO_2) = 9.98 \times 10^{-23}$ g is the mass of a SiO_2 molecule. Assuming that the pyroxene composition formula is $Mg_{1.8}Fe_{0.2}Si_2O_6$ (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 $m_d(SiO_2) = 6.42 \times 10^{-14}$ g. 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 N_d. Equating this number to the $\bar{N}_H$ number estimated above we find:

$$\mathrm{N_d} = \bar{\mathrm{N}}_\mathrm{H}\left[\mathrm{N_p}\frac{m_d(\mathrm{SiO_2})}{m(\mathrm{SiO_2})} v_p \left(\frac{\sigma_{cx}(\mathrm{Si})}{2} + 2\sigma_{cx}(\mathrm{O})\right)\tau_{ion}\right]^{-1} = 6.2 \times 10^{-10}\ \mathrm{cm^{-3}},$$

where $N_p \simeq N_e$ is the coronal proton density and $v_p \simeq 420$ km/s is the proton velocity with respect to the colliding neutrals which move in first approximation with the comet. To compare the present value with values in the literature, we may assume N_d to decrease as $1/d^2$ with the increasing distance d 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.

5. Conclusions

In this work, we report on the identification of pyroxene dust grains in the sungrazing comet C/2001 C2 observed by SOHO/UVCS at 4.98 and 3.60 $R_{\odot}$. The slow H Lyα intensity decrease in time at 4.98 $R_{\odot}$ has been interpreted as a consequence of the charge exchange between coronal protons and the products of 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. Analysis of this background emission allowed us to derive for the first time an order of magnitude estimate for the number density of pyroxene dust grains in sungrazers.

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References

Gibson, S.E. et al. Solar minimum streamer densities and temperatures using whole sun month coordinated data sets. JGR 104, 9691, 1999.

Kimura, H. et al. Dust grains in the comae and tails of sungrazing comets: modeling of their mineralogical and morphological properties. Icarus 159, 529, 2002.

Kimura, M. et al. Inelastic processes in collisions of H^+ ions with C, N, O, and Si atoms below 1 keV. Phys. Rev. A 55, 2778, 1997.

Kohl, J.L. et al. The ultraviolet coronagraph spectrometer for the solar and heliospheric observatory. SP 162, 313, 1995.

Lamy, P.L. et al. Comet P/Halley: implications of the mass distribution function for the photopolarimetric properties of the dust coma. A& A 187, 767, 1987.

McClure, G.W. Electron transfer in proton–hydrogen–atom collisions: 2–117 keV. Phys. Rev. 148, 47, 1996.

Raymond, J.C. et al. Solar wind at 6.8 solar radii from UVCS observation of comet C/1996Y1. ApJ 508, 410, 1998.

Scholz, T.T., Walters, H.R.J. Collisional rates and cooling within atomic hydrogen plasmas. ApJ 380, 302, 1991.

Uzzo, M. et al. Results from UVCS and LASCO observation of the sungrazing comet C/2000 C6. ApJ 558, 403, 2001.

Wooden, D.H. et al. Silicate mineralogy of the dust in the inner coma of comet C/1995 01 (Hale–Bopp) pre- and postperihelion. ApJ 517 (2), 1034, 1999.