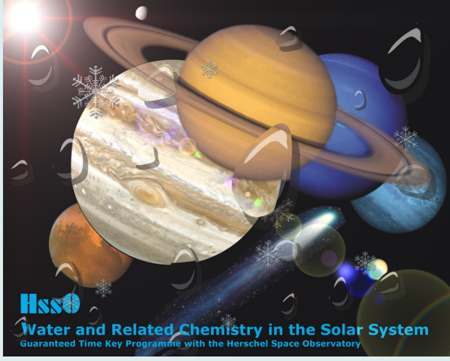
A study of the distant activity of comet C/2006 W3 (Christensen) using Herschel and ground-based telescopes



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Abstract. Comet C/2006 W3 (Christensen) was observed in November 2009 at 3.3 AU from the Sun with Herschel. The PACS instrument acquired images of the dust coma in 70-µm and 160-µm filters, and spectra covering several H_2O rotational lines. Spectra in the range 450-1550 GHz were acquired with SPIRE. The comet emission continuum from 70 to 672 µm was measured, but no lines were detected. The spectral energy distribution indicates thermal emission from large particles and provides a measure of the size distribution index and dust production rate. The upper limit to the water production rate is compared to the production rates of other species (CO, CH_3OH, HCN, H_2S, OH) measured with the IRAM 30-m and Nançay telescopes. The coma is found to be strongly enriched in species more volatile than water, in comparison to comets observed closer to the Sun. The CO to H_2O production rate ratio exceeds 220%. The dust to gas production rate ratio is on the order of 1.

Introduction

Distant activity is a general property of cometary nuclei, which is attributed to the sublimation of volatile ices such as CO or CO_2, or to the release of volatile species trapped in amorphous water ice during the amorphous-to-crystalline phase transition. Indeed, at heliocentric distances larger than 3-4 AU, the sublimation of water, the major volatile in cometary nuclei, is inefficient. Characterizing the processes responsible for distant activity is important for understanding the structure and composition of cometary nuclei, their thermal properties and their evolution upon solar heating. However, detailed investigations of distant nuclei are sparse.

We report here on observations of the distant comet C/2006 W3 (Christensen) undertaken in November 2009 at an heliocentric distance of 3.3 AU with the PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) instruments on Herschel (Pilbratt et al. 2010), in the framework of the Herschel Guaranteed Time Key Project called "Water and related chemistry in the Solar System" - also called HssO (Hartogh et al. 2009). These observations are complemented by production rate measurements of several species using the Nançay radio telescope and the IRAM 30-m telescope at 3.2-3.3 AU pre- and post-perihelion. The results of this poster are described in detail in the A&A special issue (Bockelée-Morvan et al., 2010).

Comet C/2006 W3 (Christensen)

This long-period comet was discovered in Nov. 2006 at 8.6 AU from the Sun. It passed perihelion on 9 July 2009 at 3.13 AU from the Sun. Because of its significant brightness (mv = 8.5 at perihelion), it was an interesting target for the study of distant cometary activity.

Herschel Observations

- ❖ PACS photometry (8'x11') in B and R bands
- ❖ PACS spectroscopy targetting 5 water lines
- ❖ SPIRE spectroscopy covering 450-1550 GHz (1 to 8 Nov. 2009)

Ground-based observations

- ❖ OH 18-cm lines with the Nançay radio telescope (2 Feb. to 19 Apr. 2009)
- ❖ HCN, CO, CH_3OH, H_2CO, H_2S, CS lines with the IRAM 30-m telescope (Sept. and Oct. 2009)

The composition of the gaseous coma

Water lines were not detected with PACS or SPIRE. Using a radiative transfer code, we derived an upper limit on the water production rate from the 2_{12}-1_{01} line (179.53 µm or 1669.9 GHz)) observed with PACS of 1.4 10^{28} molec.s^{-1}. From the 1_{11}-0_{00} line (1113 GHz) observed with SPIRE, we get Q(H_2O) < 4 10 10^{28} molec.s^{-1}. The higher water production rate measured pre-perihelion at Nançay (4 10^{28} molec. s^{-1}) may suggest a seasonal effect. As the field of view of the Nançay telescope is large (3.5'x19'), another interpretation is the detection of water sublimating from icy grains.

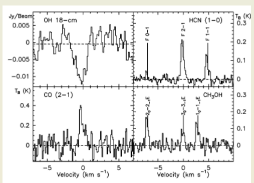

Fig. 1 : Sample of spectra observed at the Nançay and IRAM 30-m telescopes

CO, HCN, CH_3OH and H_2S were detected at IRAM. With a CO production rate of 3x10^{28} s^{-1}, comet Christensen is only four times less productive than comet Hale-Bopp at 3.3 AU from the Sun (Biver et al. 2002). The post-perihelion measurements show that the CO to H_2O production rate ratio in comet Christensen exceeds 220%, indicating a CO-driven activity. For comparison, CO/H_2O was 120% in comet Hale-Bopp at 3.3 AU from the Sun. When normalized to HCN, abundance ratios HCN:CO:CH_3OH:H_2S:CS are 1:240:9:6:0.3 and 1:150:10:9:0.3 for comets Christensen and Hale-Bopp, respectively. Therefore, besides being depleted in H_2O, comet Christensen is enriched in CO relative to HCN, while other molecules have similar abundances (Fig.2).

Both the HCN and CO spectral asymmetries and the images of dust emission (Fig. 3) indicate preferentially dayside outgassing of the nucleus. The enhanced CO production towards the Sun implies sub-surface production at depths not exceeding the thermal skin depth (< 1 cm). The distant CO production in comet Christensen may result from the crystallization of amorphous water ice immediately below the surface .

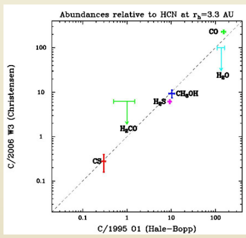

Fig. 2 : Comparaison of the composition of Hale-Bopp and Christensen's atmospheres.

Images of the dust thermal emission

The dust coma is highly condensed but clearly resolved in both blue (B) and red (R) PACS images (Fig. 3). The width at half maximum of the radial profiles is 9.0" and 18.1" in B and R, respectively, a factor 1.64 larger than the PSF (5.5" in B, 11" in R). The B and R images are extended Westward towards the Sun direction. The nucleus does not contribute significantly to the signal in the central pixels.

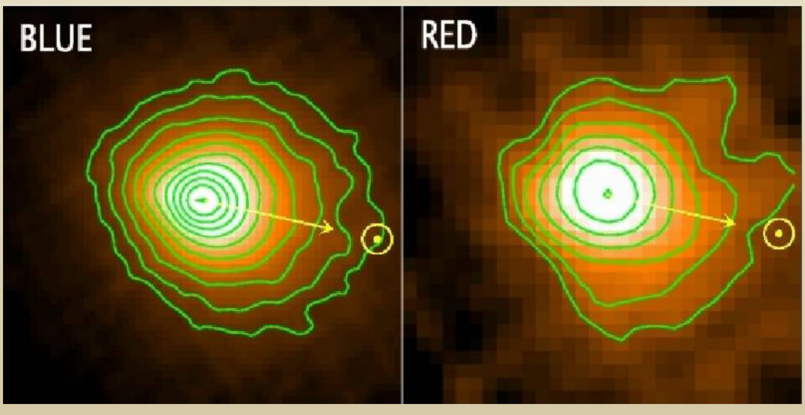

Fig. 3 : Blue (70 µm) and Red (160 µm) 1-arcmin maps of C/2006 W3 (Christensen) observed with PACS on 1 November 2009 UT. Pixel size is 1" in the Blue map and 2" in the Red map. The Sun direction is indicated. Contour levels are stepped by 0.1 in Log, up to 99% of maximum intensity.

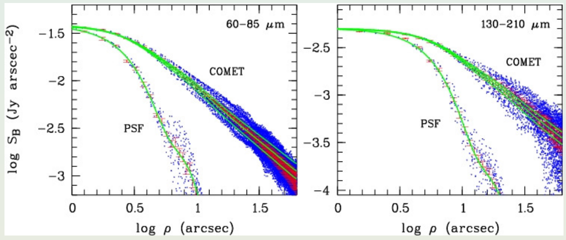

Fig. 4 : Comet surface brightness and re-scaled PSF (Vesta) in B (left box) and R (right box) bands. Blue dots: surface brightness for each pixel. Red dots: mean values in 0.5" (B) or 1.0" (R) wide annuli, with error bars. For the comet, the continuous green lines are radial profiles obtained by convolving a ρ^{-x} law with the PSF with, from top to bottom, x = 1.0, 1.05, 1.1 (B) and x = 0.95, 1.0, 1.05 (R).The green line superimposed on Vesta data is the PSF model.

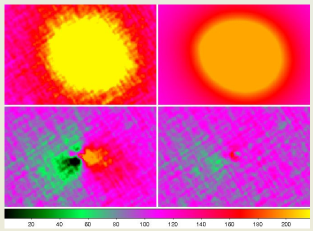

Fig. 5 : The top left figure shows the observed B image of the comet. The bottom left image shows the residuals after subtracting the azimuthal average. The rather strong residuals can be eliminated by convolving the 2D PSF with a model of radial profile $S_B \sim \rho^{-x}$ and an ad-hoc asymmetry, i.e., x(θ) = 1.15 to 0.95 for θ = 0 to 180°, where θ is the angle from the sunward to antisun direction. The resulting synthetic image is shown top right in the figure and the residuals of the subtraction bottom right. A much better agreement with the observations is obtained. Using this model, we put an upper limit of 100 mJy on the contribution of the nucleus to the observed B image. Similar results were obtained for the R image.

Dust radial distribution and nucleus size

Radial profiles in the B and R bands are presented in Fig. 4 for both the comet and the PSF (from Vesta data). The PSF was fitted radially with two gaussian profiles centered at ρ = 0 and ρ = 6" (resp. 12") for the B (resp. R) bands. A symmetric 2D PSF has then been constructed and convolved with theoretical cometary surface brightness profiles $S_B \propto \rho^{-x}$. The average surface brightness profiles can be fitted with x =1.05 ± 0.05 in the B band and x = 1.00 ± 0.05 in the R band. The radial dependence is thus close to the steady state 1/ρ law.

There is no evidence for a significant contribution of nucleus thermal emission in the central pixels (Fig. 5). From the B image, we estimated that the nucleus diameter is < 26 km. Assuming that the CO production rate scales proportionally to the nucleus surface area, the size of Christensen's nucleus is estimated to be a factor of two smaller than Hale-Bopp's nucleus size, i.e. D ~ 20 km for comet Christensen.

Dust size distribution and production rate

The spectral index (=1.8) of the Spectral energy distribution (SED, Fig. 6) indicates the presence of large grains, consistent with the maximum ejectable dust size loaded by the CO gas (0.9 mm for a D = 20 km nucleus).

We modelled the thermal emission of the dust coma using absorption cross-sections calculated with the Mie theory to compute both the temperature of the grains, solving the equation of radiative equilibrium, and their thermal emission. We considered a differential dust production Q_d(a) varying as $a^{-\alpha}$ as a function of size, with sizes between 0.1 µm and 0.9 mm. The best fit to the PACS data is obtained for a size index α = - 3.6(+0.25/-0.8) assuming amorphous carbon grains. The size-dependent grain velocities were computed following Crifo et al. (1997) and vary from 6 to 224 m s^{-1}. The derived dust production rate corresponds to a dust to gas ratio on the order of 1, assuming that CO is the main escaping gas from the nucleus.

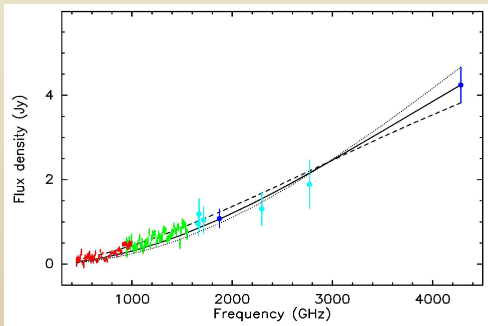

Fig. 6 : SED of C/2006 W3 (Christensen) combining SPIRE (red-SLW and green-SSW dots), PACS photometry (blue dots), and spectroscopy (cyan dots) data, scaled to a FOV of 18.7". Curves are models for amorphous carbon grains with a differential production Q_{dust}(a) varying as $a^{-\alpha}$, with a_{max}= 0.9 mm, and α = -3.6 (solid), -2.8 (dashed), and -3.85 (dotted).

Conclusion

The observations of comet C/2006 W3 (Christensen) performed with PACS and SPIRE, together with HIFI observations of comet C/2008 Q3 (Garradd) and 81P/Wild 2 (Hartogh et al. 2010a, b) show that Herschel provides unique capabilities for the study of comet nuclei, and their dusty gaseous atmospheres.

References: Biver et al. 2002, EMP, 90, 5; Bockelée-Morvan et al. 2010, A&A, in press; Crifo, J.F.& Rodionov, A.V.1997, Icarus, 127, 319; Griffin et al., 2010, A&A, in press; Hartogh, P. et al. 2009, P&SS, 57, 1596; Hartogh et al. 2010a, A&A, in press, Hartogh et al. 2010b, this conference; Pilbratt, G. et al. 2010, A&A, in press; Poglitsch, A. et al., 2010, A&A, in press;.

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