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

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7 May 2010; Accepted for A&A Herschel Special Issue

**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 H₂O 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, CH₃OH, HCN, H₂S, 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 H₂O production rate ratio exceeds 220%. The dust to gas production rate ratio is on the order of 1.

**Key words.** Comets: individual: C/2006 W3 (Christensen); Techniques: photometric, spectroscopic; Radio lines: solar system; submillimeter

**1. Introduction**

Direct imaging shows that distant activity is a general property of cometary nuclei (e.g., Mazzotta Epifani et al. 2009). It is attributed to the sublimation of hypervolatile ices, such as CO or CO₂, or to the release of volatile species trapped in amorphous water ice during the amorphous-to-crystalline phase transition (Prälim et al. 2004). Indeed, at heliocentric distances r₂ 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. The best studied objects are the distant comet 29P/Schwassmann-Wachmann 1, where CO, CO₂, and CN were detected at 6 AU from the Sun, and C/1995 O1 (Hale-Bopp), whose exceptional activity allowed us to detect several molecules and radicals farther than 3 AU — including CO up to 14 AU (Biver et al. 2002; Rauer et al. 2003).

Comet C/2006 W3 (Christensen) was discovered in November 2006 at r₂ = 8.6 AU from the Sun with a total visual magnitude m_V ~18. This long-period comet passed perihelion on 9 July 2009 at r₂ = 3.3 AU. Because of its significant brightness (m_V ~ 8.5 at perihelion), it was an interesting target for the study of distant cometary activity. We report here on observations undertaken at r₂ = 3.3 AU post-perihelion with the PACS (Poelisch 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” (Hartogh et al. 2009). These observations are complemented by production rate measurements of several species using the Nançay radio telescope and the 30-m telescope of Institut de Radioastronomie millimétrique (IRAM) at 3.2–3.3 AU pre- and post-perihelion.

**2. Observations with Herschel**

Comet C/2006 W3 (Christensen) was observed with Herschel on 1–8 November, 2009 at r₂ ~ 3.3 AU and a distance from Herschel ∆ = 3.5–3.7 AU.

The PACS observations, acquired during the Herschel Science Demonstration phase, consisted of: 1) on November 1.83 UT, simultaneous acquisition of 8′x11′ coma images (Fig. 1) in Blue (60-85 µm) and Red (130–210 µm) bands using the scan map photometry mode with a scan speed of 10′/sec (Obsid #1342186621 and 1342186622 with orthogonal scanning, duration t_int = 565 s each), and 2) on November 8.74–8.82 UT, pointed source dedicated line spectroscopy over a 47″x47″ field of view (5x5 pixels of 9.4″) with a large (6′) chopper throw and a number (so-called line repetition l_rep) of ABBA nodding cycles (Obsid #1342186633, t_int = 6837 s). The water lines 2_1±1_0 (108.07 µm, l_rep=2), 3_1±2_0 (138.53 µm, l_rep=2), 3_0±2_1 (174.63 µm, l_rep=3), 2_2±1_0 (179.53 µm, l_rep=1) and 2_1±2_1 (180.49 µm, l_rep=1) were targeted at a spectral resolution ∆λ ~ 0.11–0.12 µm. PACS data were processed with the HIPE software version 2.3.1 which uses ground calibra-
Fig. 1. Blue (70 μm) and Red (160 μm) 1’×1’ 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. Contours levels are stepped by 0.1 in Log, up to 99% of maximum intensity, East is on the left, North is up. The Sun direction is indicated.

Fig. 2. Spectral Energy Distribution of C/2006 W3 (Christensen) combining SPIRE (SLW: red dots; SSW: green dots), PACS photometry (blue dots), and spectroscopy (cyan dots) data, scaled to a Half Power Beam Width of 18.7’’ and Δ=3.65 AU. SPIRE data were binned from ~ 0.02 to 0.4 cm⁻¹. Curves are models for amorphous carbon grains with $a_{max}=0.9$ mm, and size index $-3.6$ (solid), $-2.8$ (dashed), and $-3.85$ (dotted) (see text).

3. Observations with ground-based telescopes

Fig. 3. Sample of ground-based spectra of comet C/2006 W3 (Christensen): OH spectrum (average of 1665 and 1667 MHz lines) observed at Nançay on Feb. 2 to Apr. 19, and HCN (Sept. 13-14), CO (Oct. 29), and CH$_3$OH (Oct. 14) spectra observed at the IRAM-30m.

The OH lines at 18 cm were observed in comet C/2006 W3 (Christensen) with the Nançay radio telescope (Fig. 4 Table 1). The methods of observation and analysis are described in Crovisier et al. (2002). The observations were done pre-perihelion from February 10 to April 19 2009 when the
comet was at an average heliocentric distance similar to that of the Herschel post-perihelion observations. An average OH production rate \(Q_{\text{OH}} = 3.8 \pm 0.9 \times 10^{28} \text{ s}^{-1}\) is derived, which corresponds to a water production rate \(Q_{\text{H}_2\text{O}} = 1.1 \times Q_{\text{OH}} = 4.2 \pm 1.0 \times 10^{28} \text{ s}^{-1}\), assuming that water is the main source of OH radicals.

Observations with the IRAM 30-m were made on September 12–14 2009 with the recently installed EMIR receiver, completed by a short observation on October 29 just before the Herschel observations (Fig. 3 and online Fig. 5 Table I). CO, HCN (two rotational transitions), CH\(_3\)OH (six lines around 157 GHz) and H\(_2\)S were detected. Beam sizes are between 10 and 27\(^\prime\), similar to PACS and SPIRE fields of view.

### 4. Analysis and discussion

The observed water rotational lines are optically thick (e.g., [Biver et al. 2007; Hartogh et al. 2010]). To derive upper limits for the water production rate, we use an excitation model which considers radiation trapping, excitation by collisions with neutrals (here CO) and electrons, and solar IR pumping ([Biver et al. 1997; Biver et al. 1999]). A H\(_2\)O-CO total cross-section for de-excitation of 2 \(\times 10^{-14}\) cm\(^2\) is assumed ([Biver et al. 1999]). The same excitation processes are considered in CO models used to analyze the molecular lines observed at the IRAM 30-m. We used a gas kinetic temperature of 18 K, derived from the relative intensities of the CH\(_3\)OH lines, and a gas expansion velocity of 0.47 km s\(^{-1}\), consistent with the widths of lines detected at IRAM. The largest model uncertainty is in the electron density profile. We used the profile derived from the 1P/Halley in situ measurements and scaled it to the heliocentric distance and activity of comet Christensen, as detailed in, e.g., [Bensch & Bergin 2004]. The electron density was then multiplied by a factor \(n_{\text{e}} = 0.2\), constrained from observations of the 557 GHz water line in other comets ([Biver et al. 2007; Hartogh et al. 2010]). Upper limits on the water production rate obtained from the 2\(\text{J}_{2}-1\text{J}_{1}\) line observed with PACS, and from the 1\(\text{J}_{1}-0\text{J}_{0}\) line observed with SPIRE, are given in Table I. Other observed H\(_2\)O lines, either with PACS or with SPIRE, do not improve these limits. The higher water production rate measured pre-perihelion at Nançay may suggest a seasonal effect. As the field of view of the Nançay telescope is large (3.5\(^\circ\)\times19\(^\circ\)), another interpretation is the detection of water vapor sublimating from icy grains. The \(Q(H_2O)\) measured at Nançay corresponds to a sublimation cross-section of 400 km\(^2\), or a sublimating sphere of pure ice of 8 km radius.

With a CO production rate of 3\(\times 10^{28}\) s\(^{-1}\), comet Christensen is only four times less productive than comet Hale-Bopp at \(r_h = 3.3\) AU ([Biver et al. 2002]). The post-perihelion measurements show that the CO to H\(_2\)O production rate ratio in comet Christensen exceeds 220\%, indicating a CO-driven activity (Table I). For comparison, CO/H\(_2\)O was \(\sim 120\%\) in comet Hale-Bopp at 3.3 AU from the Sun. When normalized to HCN, abundance ratios HCN:CO:CH\(_3\)OH:H\(_2\)S:CS are 1:240:9:6.3:0.1 and 1:150:10:9:0.3 for comets Christensen and Hale-Bopp, respectively (online Fig. 6 [Biver et al. 2002]). Therefore, besides being depleted in H\(_2\)O, comet Christensen is enriched in CO relative to HCN, while other molecules have similar abundances. The dust coma is highly condensed but clearly resolved in both blue (B) and red (R) PACS images (Fig. I). The width at half maximum of the radial profiles is 9.0\(^\prime\) and 18.1\(^\prime\) in B and R, respectively, a factor 1.64 larger than the PSF (\(\sim 5.5\)\(^\prime\) in B, 11\(^\prime\) in R). The B image is extended Westward towards the Sun direction at PA = 257.5\(^\circ\) (phase angle = 16\(^\circ\)). This asymmetry is also seen in the R image. HCN and CO spectral lines are similarly blue-shifted (Table I), which indicates preferentially daytime emission of these molecules from the nucleus, and is consistent with the dust coma morphology. Since CO is likely the main escaping gas (CO\(_2\) has been observed to be less abundant than CO in comets [Bockelée-Morvan et al. 2004]), dust-loading by CO gas is suggested. 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 ([Prialnik et al. 2004]).

Radial profiles in the B and R bands are presented in Fig. 7 for both the comet and the PSF (from Vesta data). Although highly structured, the background has been estimated as best as

| Line | Velocity shift | Prod. rate |
|------|---------------|------------|
| PACS | < 2.2 \times 10^{-16} | < 1.4 \times 10^{28} |
| SPIRE | < 8 \times 10^{-15} | < 4 \times 10^{28} |

\(n_{\text{e}}\) is assumed (Biver et al., 1999). The water coma immediately below the surface (Prialnik et al., 2004).
possible and subtracted. The PSF has a complex shape which has been 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 $S_B \propto \rho^{-x}$. One finds that the full range of radial profiles can be reproduced with $0.8 < x < 1.2$. Most of the dispersion is likely due to the PSF structure and more specifically to its extended tri-lobe pattern (Lutz, 2010). The average surface brightness profiles can be fitted with $x = 1.05 \pm 0.05$ in the B band and $x = 1.00 \pm 0.05$ in the R band. The radial dependence of the surface brightness is then compatible with the steady-state $\rho^{-1}$ law in the full 60–210 µm spectral range.

There is then no evidence for a significant contribution of nuclear thermal emission in the central pixels. Assuming that the CO production rate scales proportionally to the nuclear 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 (see Altenhoff et al., 1999, for Hale-Bopp’s nucleus size). From the Standard Thermal Model (Lebofsky & Spence, 1989) with the nucleus albedo set to 4% and the emissivity and beaming factor taken as unity, a 20 km diameter body would contribute to 4.5% of the flux measured in the central 1′′ pixel of the B image ($F_B = 38.4$ mJy/pixel), and still less (2%) in the R image where the measured peak intensity is $F_R = 19.5$ mJy/pixel (2′′-pixel). From the B image, we estimated that $D < 26$ km.

The Spectral Energy Distribution (SED) of the dust thermal emission can constrain important properties of cometary dust. In particular the dust size distribution and production rate (Jewitt & Lutz, 1990). The flux density in the SPIRE spectrum (Fig. 3) varies as $v^{-1.78}$. The spectral index, close to $\alpha = 2$, indicates the presence of large grains, consistent with the maximum ejectable dust size loaded by the CO gas ($a_{\text{max}} \sim 0.9$ mm for a $D = 20$ km body of density $\rho_N = 500$ kg m$^{-3}$, with the dust density $\rho_d = \rho_N \cdot a_{\text{max}} \propto D^{-5}$. Crifo et al. (2005). We modelled the thermal emission of the dust coma following Jewitt & Lutz (1990). Absorption cross-sections calculated with the Mie theory were used to compute both the temperature of the grains, solving the equation of radiative equilibrium, and their thermal emission. Complex refractive indices of amorphous carbon and olivine (Mg:Fe = 50:50) (Edoh, 1983; Dorschner et al., 1995) were taken as broadly representative of cometary dust. We considered a differential dust production $Q_d(a)$ as a function of size, with sizes between 0.1 µm and 0.9 mm. The size-dependent grain velocities $v_g(a)$ were computed following Crifo & Rodionov (1997) assuming $D = 20$ km, and vary from 6 to 224 m s$^{-1}$ ($\sim a^{-0.5}$ at large sizes). We assumed a local dust density $\rho \propto r^{-2}$, where $r$ is the distance to the nucleus, consistent with the maps. The best fit to the flux ratio $F_B/F_R$ in R and B bands is obtained for $Q_d(a) \propto a^{(-3.0 \pm 0.5)}$, which yields a dust opacity (the ratio between the effective emitting dust cross-section and dust mass), of $6.8 \pm 2.8$ and $5.7 \pm 1.3$ m$^{-2}$ kg$^{-1}$ at 450 GHz, and dust production rates of $850^{+1100}_{-800}$ and $920^{+730}_{-110}$ kg s$^{-1}$, for carbon and olivine grains, respectively. The whole SED between 450 and 4300 GHz is consistently explained (Fig. 3). Assuming that CO is the main gas escaping from the nucleus, the inferred dust to gas mass production ratio is then 0.5 to 1.4.

5. Conclusions

Comet Christensen was a distant comet. Nevertheless, the comet was clearly detected by PACS and SPIRE, providing useful constraints on the properties of the cometary dust. Although water emission was not detected in this object, the limits obtained are significant. The prospects for future comet studies with Herschel are thus very good.

Acknowledgements. PACS has been developed by a consortium of institutes led by MPE (Germany) and including UKATC, Univ. Sussex (UK); and Caltech, JPL, NHSC, Univ. Colorado (USA). This development has been supported by national funding agencies: CSA (Canada); NAOC (China); CEA, LAN (France); IFSI, Univ. Padua (Italy); IAC (Spain); Stockholm Observatory (Sweden); Imperial College London, RAL, UCL-MSSL, UKATC, Univ. Sussex (UK); and Caltech, JPL, NHSC, Univ. Colorado (USA). This development has been supported by national funding agencies: ESA (Spain); Imperial College London, RAL, UCL-MSSL, UKATC, Univ. Sussex (UK); and Caltech, JPL, NHSC, Univ. Colorado (USA). Additional funding support for some instrument activities has been provided by ESA: HCCS/HSp/HEPIE are joint developments by the Herschel Science Ground Segment Consortium, consisting of ESA, the NASA Herschel Science Center, and the HIIF, PACS and SPIRE consortia. IRAM is an international institute co-funded by CNRS, France, MPG, Germany, and IGN, Spain. The Nançay radio observatory is cofunded by CNRS, Observatoire de Paris, and the Région Centre (France). D.B.-M. thanks M.A.T. Groenewegen and D. Ladjal for support in PACS data analysis and V. Zakharov for useful discussions on gas and dust dynamics.

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Fig. 7. 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 $\rho^{-x}$ 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 (see text).
Fig. 2. Spectra of C/2006 W3 (Christensen) obtained with PACS on 8 November, 2009 (central pixel pointed on the comet nucleus). The pixel size is $9.4'' \times 9.4''$. The wavelengths of water lines are indicated by vertical dashed lines.
Fig. 5. Spectra of C/2006 W3 (Christensen) observed with the IRAM 30-m telescope.
Fig. 6. Comparison of measured abundances relative to HCN in comets C/2006 W3 (Christensen) and C/1995 O1 (Hale-Bopp) at 3.3 AU from the Sun.