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Letter to the Editor

Imaging and spectroscopy of comet C/2001 Q4 (NEAT) at 8.6 AU from the Sun*

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Abstract. Comet C/2001 Q4 (NEAT) was observed inbound at an heliocentric distance of 8.6 AU. Broadband filter images in the visible and long slit spectroscopy in the 3500–7000 Å range was recorded. No sign of CN emission was detected and an upper limit for CN production rate of 1.4×10^{25} molecules s^{-1} is estimated. The color of the dust in the inner coma is very red with a spectral index of 29%/1000 Å. The radial profile of the dust coma displays steep gradients of 1.7 (inner part) to 2.4 (outer part). The *afρ* value, a proxy for the dust production, is measured to be 1500 cm. The coma shows a weak and short conic structure in the northern hemisphere that is interpreted as dust fan produced by an active region on the nuclear surface.

Key words. comets – C/2001 Q4 (NEAT) – distant activity

1. Introduction

Comet C/2001 Q4 (NEAT) (hereafter C/Q4) was discovered on 24 August 2001 with the Palomar 1.2 m Schmidt telescope by the Near-Earth Asteroid Tracking project NEAT of NASA's Jet Propulsion Laboratory (Pravdo et al. 2001). Orbital elements determined by Marsden (2002) suggest that this object may have come from the Oort Cloud and may be on one of its first visits to the inner solar system (Marsden, private communication). C/Q4 was found at 10 AU inbound surrounded by an 8′ wide coma (Pravdo et al. 2001), i.e. it was discovered as an active comet at a larger distance than comet Hale-Bopp in 1995 (found at 7.2 AU from the Sun). Comet C/Q4 is expected to become a naked-eye object, possibly of significant brightness (0–1 mag), during its perihelion passage at about 0.96 AU in May 2004.

For the three reasons mentioned above, 1) Oort Cloud comet, 2) activity at large solar distance, and 3) having a perihelion passage near 1 AU as bright object, comet C/Q4 is a very suitable and interesting target for a long-term monitoring project. Such a project could serve to determine the solar distance dependence of activity, to study the nuclear activity of a dynamically "new" comet over the widest possible distance range, and to compare it with the only other comet measured over a similar distance range, C/1995 O1 (Hale-Bopp), a dynamically evolved object, the nuclear activity of which is well documented in literature (Rauer et al. 1998, 2003).

Here, we present the results from first imaging and spectroscopic observations in the visible wavelength range of our monitoring project of comet C/Q4.

2. Observations and data reduction

Observations: The observations of C/Q4 reported here were performed on 13, 14 and 15 March 2002 with the 3.6 m telescope at the European Southern Observatory ESO in La Silla/Chile. The EFOSC2 focal reducer instrument was used for both the broadband filter imaging and the spectroscopy of the comet in the visible wavelength range. The 2048 × 2048 pixels CCD (ESO N. 40) was binned at readout to 2× 2 pixels. This yields an equivalent pixel size of 0.314″ on the sky in imaging mode and along the slit in the spectroscopic one. A 300 gr/mm grism was used, giving a dispersion of 4.1 Å/pixel. At the time of our observations comet C/Q4 was 8.6 AU from the Sun and 9.2 AU from Earth. The pixel scale on the comet was then ≈2100 km/pixel. Table 1 summarizes the details of the observations, the observing geometry of the comet and the atmospheric conditions.

The daily observing window was less than forty minutes since the comet was placed low at the western horizon. For broadband imaging Bessell V and R as well as Gunn i filters were used; the spectra covered the UV to red

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* Based on observations collected at the European Southern Observatory, Chile.

Table 1. Observing log, observing geometry and atmospheric conditions for C/2001 Q4 (NEAT).

Date (UT)	r_h (AU)	Δ (AU)	ϕ (deg)	Image/Spectra	Exp.Time (min)	Sky
2002 March 13.008–13.024	8.59	9.28	4.58	Images $R/V/i$	$3 \times 2/3 \times 2/3 \times 2$	clear, partially in twilight, airmass >2
2002 March 14.012–14.027	8.58	9.28	4.54	Spectra (3500–7000 Å)	2×10	clear, partially in twilight, airmass >2
2002 March 15.006–15.020	8.57	9.28	4.51	Spectra (3500–7000 Å)	2×10	clear, partially in twilight, airmass >2

Abbreviations: r_h = heliocentric distance (AU), Δ = geocentric distance (AU), ϕ = comet phase angle, Exp.Time = exposure time.

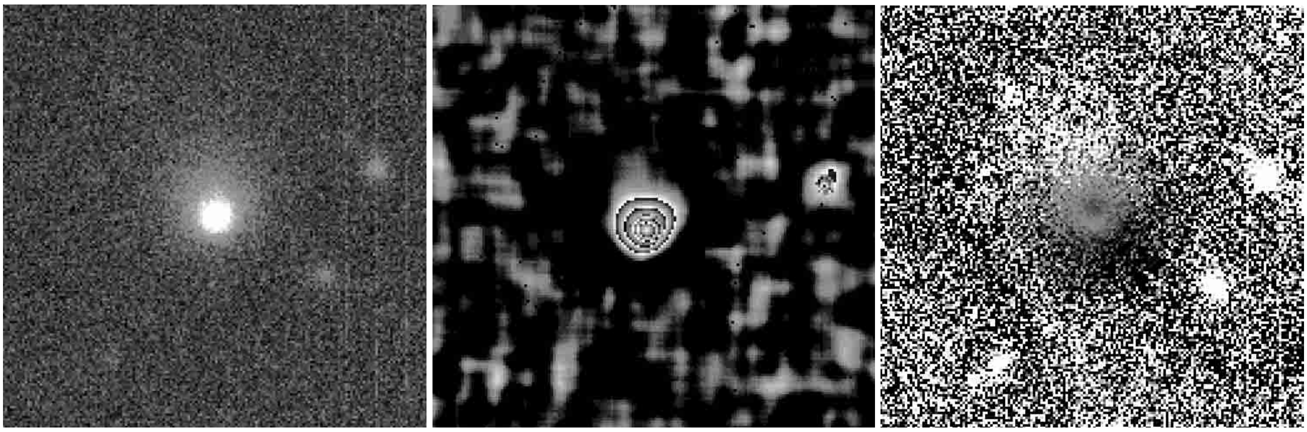

Fig. 1. The Coma of comet C/2001 Q4 (NEAT): original image (left), adaptive Laplace filtered version (middle), radially normalized version (right). Details of the original image: co-added 3×2 min exposures in Bessell R filter obtained on 13 March 2002; North is up, East to the left; Position Angle of the extended Sun-comet radius is ≈115°; field of view is ∼55 000 × 55 000 km; nucleus is in the center of the field of view. In the middle image a fan-like structure is visible in the northern direction (see text).

wavelength range (for details on the instrument equipment see `http://www.ls.eso.org/lasilla/Telescopes/360cat/efosc`). Apart from the comet exposures the usual set of photometric and spectrophotometric standard stars, sky and dome flatfields, arc lamps as well as bias exposures were taken. The 2″ wide and 5′ long slit was oriented across the coma in the direction of the parallactic angle, which was just 25° away from the position angle of the projected extended radius vector of the comet. Non-sidereal tracking at the speed of the comet and autoguiding with combined offsets was applied for the moving target.

Basic data reduction: After bias and sky flatfield corrections the comet images were flux calibrated using the photometric standard star fields of the observing night for the zero points together with tabulated extinction coefficients of the site and instrument color corrections as given by the EFOSC2 instrument calibration plan (`http://www.ls.eso.org/lasilla/Telescopes/360cat/efosc/docs/Perf_ZeroPtSummary.html`).

The spectra were corrected through bias and dome flatfield exposures and wavelength calibrated through the available HeAr arc lamp exposures. The spectral response of the telescope/instrument configuration used, was obtained from the spectrophotometric standard star exposures and, thereafter, the cometary spectra were flux calibrated.

In order to improve the signal-to-noise ratio, all flux calibrated data of the same kind (for instance all available R filter exposures) were co-added after careful alignment to the position of the photometric nucleus which is assumed to coincide with the central brightness peak in the coma. Thereafter, sky subtraction is applied to the coadded frames. For imaging a sky background level was determined from ring aperture measurements at a distance from the nucleus at which no coma light was found. For the spectra the skylines were subtracted using the line fluxes at a "safe" distance (∼60″) on both sides of the comet spectrum where no coma light was present.

3. Analysis and results

Here we present the analysis and results on the colors, the radial profile, the content and the geometric structure of the cometary dust coma obtained from the images of C/Q4 as well as the conclusion on the gas production of the comet.

– *Coma structures*: The cometary images were analyzed for the presence of coma structures applying two different numerical enhancement procedures to the flux calibrated data, 1) adaptive Laplace filtering (Richter 1978, 1991; Boehnhardt & Birkle 1994) and 2) radial renormalization (A'Hearn et al. 1986). The former method is sensitive to gradient changes on different scales depending on the width of the spatial filter applied. The latter method uses the azimuthally averaged, radial profile of the coma flux to create a 2-dimensional image of the average coma flux level and divides it – after centering to the central coma peak – through the original image of the comet.

Figure 1 shows the coma of the comet and enhanced structures therein. A short and wide conic structure is visible in the northern coma hemisphere: approximate position angle of central axis ∼10°, opening angle ∼90° at the nucleus,

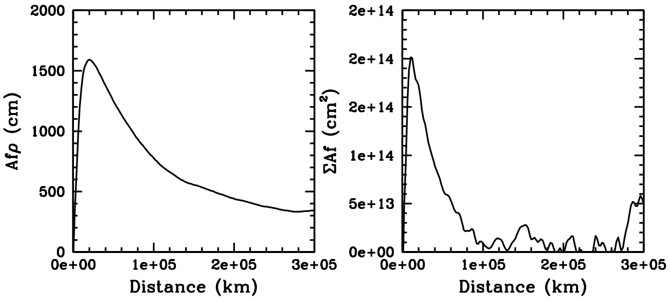

Fig. 2. The *afρ* and Σaf profiles.

maximum extension >65 000 km. It is detectable in all three filters used, though less pronounced in the *V* and *i* filter exposures of the comet. The position angle of its main axis is more than 90° away from the expected tail direction (at ∼115°). Based upon our own dust tail calculations for the comet (Beisser & Boehnhardt 1987; Beisser & Drechsel 1992) using solar radiation pressure parameters β of 0.0001–2.0 and zero dust emission velocities, we conclude that this structure is not due to the dust tail in the background of the coma which is viewed almost face on from Earth (viewing angle ≈4.5°). Only very old and heavy grains (release time more than 2 years before observations and with $\beta < 0.01$) would fall in the eastern edge of the observed coma structure. Therefore, we suggest that it is a fan-like structure in the coma of the comet produced by an active region on the rotating nucleus, resembling the northern fan seen in comet Hale-Bopp at large heliocentric distances pre- and post-perihelion (Boehnhardt et al. 2002).

– *afρ*: *afρ*, as first defined by A'Hearn et al. (1984), is considered a measure of the dust production rate of a comet. For comet C/Q4 it was calculated for each filter image by integrating the flux in concentric full apertures around the central brightness peak in the coma. The differential radial *afρ* profile, called here Σaf, (equivalent to the albedo multiplied by the total surface area covered by the dust that is present in concentric rings centered at the nucleus) is thus determined as function of the nucleocentric distance. Figure 2 shows that *afρ* is not constant through-out the coma, as it would be the case for dust production with constant outflow. The value of *afρ* in *R* band is 1500 cm for an aperture size of 20 000 km. This value is a factor of ≈40 below the amount around the time of discovery of Hale-Bopp, which was 63 000 cm at 7.1 AU from the Sun (Schleicher et al. 1997). The steepness of the azimuthally averaged coma surface brightness, calculated from linear least-square fits of a power law function over the aperture radius increases from ∼1.7–1.8 in the inner coma (fitting range: 12 000–41 000 km) to ∼2.2–2.4 in the outer part (fitting range: 41 000–105 000 km). Note that the inner ∼12 000 km (equivalent to ≈2″) are excluded from this fit since they are subject to smearing effects due to atmospheric seeing and they do not show the real brightness distribution of the very inner part of the coma. Since the measured slope parameters deviate significantly from unity which is characteristic of a steady state coma of isotropic dust outflow with constant velocity, we conclude that the radial profile of the dust coma is modified by solar radiation pressure effects that tend to "pile-up" the dust in the viewing direction as seen from Earth at a phase angle of only ≈4.5°. The maximum extension of the dust coma determined from the Σaf plots is of the order of 100 000 km.

– *Gas production*: All the spectra are carefully realigned along the slit to the optocentric center and co-added. Since we discarded one spectrum because of its low quality, the total exposure time of the coadded spectrum is 30 min. To obtain the possible emission gas features (CN, C_2, C_3 ...), a monodimensional synthetic dust spectrum was created using a high resolution solar spectrum convolved with the instrumental point spread function and adjusted to account for the intrinsic dust color of the comet. The latter is deduced from the slope of the cometary spectrum measured in wavelength regions without known gas emissions. From this, a two dimensional synthetic cometary dust spectra was created using the cometary dust profiles along the slit, extracted from wavelength regions without gas contamination. Finally, the difference between the cometary and synthetic spectrum gives the cometary gas spectrum. The result can be checked in Fig. 3, where the monodimensional original cometary spectrum of the inner coma is overplotted with the synthetic one for the 3600–4500 Å region. Apart from the difference in noise, the two spectra are virtually identical and no trace of the CN feature at about 3880 Å is visible. This feature, which is the most prominent gas feature in cometary spectra, is not detectable in the two-dimensional spectrum, either.

The standard deviation of the flux in the CN band range and within a slit area of ±10 000 km around the optocenter in the coma is 6×10^{-8} erg cm^{-2} ster^{-1} s^{-1}. Assuming a 3σ upper limit for CN intensity and a g-factor of $2.8\times10^{-13}\times r_{\rm h}^{-2}$ erg s^{-1} mol^{-1} (Schleicher 1983), we estimate an upper limit of the average column density equal to 6×10^{8} cm^{-2}. This in turn results in an upper limit for the CN gas production rate, Q(CN), of 1.4×10^{25} molecules s^{-1}. This value is computed with the Vectorial Model (Festou 1981) using a parent scalelength equal to $5.4\times10^{4}\times r_{\rm h}^{2}$ km (Rauer et al. 2003), a parent velocity function equal to $1.12\times r_{\rm h}^{-0.41}$ km s^{-1} (Biver et al. 1999), a daughter scalelength of $2.2\times10^{5}\times r_{\rm h}^{2}$ (A'Hearn et al. 1995) and a daughter velocity equal to 1.06 km s^{-1}, independent on the heliocentric distance (Bockelée-Morvan & Crovisier 1985). For the g-factor and scalelengths a $r_{\rm h}^{-2}$ and $r_{\rm h}^{2}$ dependences are assumed, that may not be valid for such a large heliocentric distance. However we believe that these dependences are good enough for a simple upper limit determination.

The main error source in Q(CN) is uncertainty in the extinction correction applied to the standard star and the comet spectra that are taken at different airmasses (1.5 versus >2, respectively). Since the nights were photometric, we estimate that the error in Q(CN) is not more than 0.5×10^{25} mol/s (equivalent to 30%).

– *Colors*: From the comparison of the solar and the comet spectra in the inner coma (±10 000 km from the center) for wavelength regions free of gas emission bands, we obtain the color of the dust. The color of the comet is very red with an almost constant spectral index of 29%/1000 Å (±6%/1000 Å or 20%) in the spectral region between 4200 and 7000 Å. Again, the main error source is the difference in airmasses between standard star and comet. At wavelengths shorter than

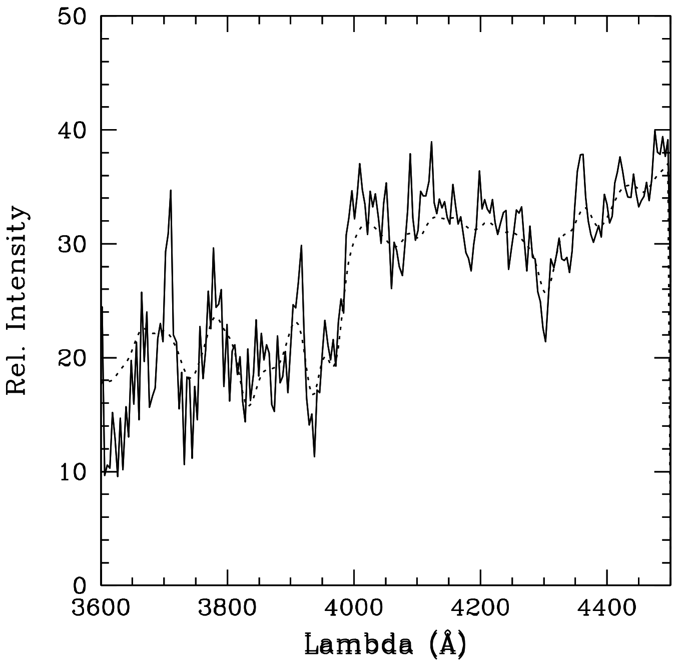

Fig. 3. Comparison of cometary spectra (full line) and synthetic cometary dust spectra (dotted line). The cometary spectra refer to the inner 20 000 km, centered on the photometric center

4200 Å the spectral index seems to decrease, but due to the above error source, it is difficult to assess if that is real.

By comparing the images taken in the V, R and i bands we found that the dust was a little bluer in the direction of the fan-like structure in the northern coma hemisphere described above. The change of color is of the order of the noise in the $i - R$ color map, because of the low S/N in the i images, but it is well above the noise in the $R - V$ color map. This change is of the order of 10% with respect to the photometric center, at a distance of 10 000–20 000 km (corresponding to $\approx$1.5–3″) in the northern part. We believe that the color difference of the coma fan is not artificial, since misalignment of the images, the most critical task of the data reduction process, is less than 0.1 pixels (i.e. <200 km at the distance of the comet). The measured color change may indicate a difference in the dust size distribution (with smaller grains more abundant) in the fan-like structure with respect to the "normal" dust in the rest of the coma. In the spectra this change of color is undetectable because of their lower S/N ratio with respect to the images.

4. Conclusions

Comet C/2001 Q4 (NEAT) showed a well developed dust coma of more than 100 000 km diameter at 8.6 AU from the Sun. No CN, C_2, or C_3 gas emission was detected at this distance which places an upper limit of 1.4×10^{25} molecules s^{-1} for the CN production of the nucleus. The amount of dust in the coma has an *afρ* value of 1500 cm. Applying simple linear scaling laws to Hale-Bopp *afρ* data at 7.1 AU inbound (Schleicher et al. 1997) – which may not be valid, because C/Q4 seems to be a "new" object while Hale-Bopp was an evolved one and the percentage of surface covered by the active region may be significantly different –, a $\approx$6 times smaller nucleus size (order of 5–10 km) is likely for comet C/Q4. The light distribution in the dust coma seems to be slightly anisotropic suggesting the presence of a coma fan in the northern coma hemisphere, possibly produced by a region of enhanced activity on the nucleus.

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