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VLT observations of comet 46P/Wirtanen*

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Abstract. Comet 46P/Wirtanen, prime target of ESA's ROSETTA mission, was successfully observed at the Very Large Telescope Observatory in Chile: on 17 May 1999 with the Test Camera at the Cassegrain focus of the 8.2-m VLT Kueyen telescope and on 8 December 2001 with FORS1 at Unit Telescope 4 Yepun. May 1999: no coma was detected at heliocentric distance $r = 4.98$ AU. From the measured brightness in the Bessell R-filter, a mean nucleus radius of 555 ± 40 m is derived (for a geometric albedo of 0.04 and a phase darkening of 0.04 mag/deg). The nucleus signal varies during the 2.7 h observing interval and a peak-to-peak amplitude of $\sim$0.38 mag is determined. The measured lightcurve is in agreement with a rotation period of 6–7.5 hours and a ratio of the main nucleus axes of at least 1.4. The non-detection of a coma allows one to put an approximate upper limit for Afρ of <0.45 cm (suggesting a dust production rate of 0.05 kg/s). December 2001: a weak and condensed coma seems to be present in the seeing disk of the comet at 2.9 AU inbound, causing a higher brightness than expected from the previous size estimates of the nucleus. The colour of the comet appears very red ($V-R$ spectral gradient $\sim$47%/100 nm). The Afρ value of the comet was 6.5 ± 2 cm (equivalent to a dust production rate of about 1 kg/s).

Key words. comets: individual: 46P/Wirtanen – comets: general

1. Introduction

ROSETTA, the Planetary Cornerstone Mission of the HORIZON 2000 programme of the European Space Agency ESA, aims for a rendez-vous and close-up study of the physico-chemical properties of a cometary nucleus and of its coma environment. 46P/Wirtanen, a Jupiter family comet with an orbital period of 5.5 years (Belyaev et al. 1986), was chosen as the prime target for this mission that is scheduled to be launched in early 2003 with arrival at the comet in 2011. Following the rendez-vous at about 4.6 AU from the Sun, the ROSETTA orbiter with its scientific instruments will explore the comet for about one year starting around 3.5 AU to perihelion at 1.06 AU solar distance. During the early near-nucleus study phase, a lander with the Surface Science Package and 9 on-board experiments will be deployed onto the nuclear surface.

ESA's mission analysis has demonstrated that some physical properties of the nucleus will play a crucial role for the success of the rendez-vous and also for the descent of the ROSETTA lander to the nucleus: its size and shape, its rotation and its activity at 3 AU from the Sun and beyond.

A very first assessment of the nucleus size, based upon photographic images of the comet obtained during earlier apparitions (Rickman & Jorda 1995) resulted in an estimate for the radius $R = 2.5$ km (assumed albedo = 0.04). More recent CCD detections of the nucleus point towards a radius below 1 km. Boehnhardt et al. (1997) estimated $R \sim 690$ m. Images obtained in March 1996 (Hainaut, private communication) put an upper limit of $R \sim 900$ m.

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* Based on observations obtained at the VLT Observatory Cerro Paranal of European Southern Observatory ESO in Chile.

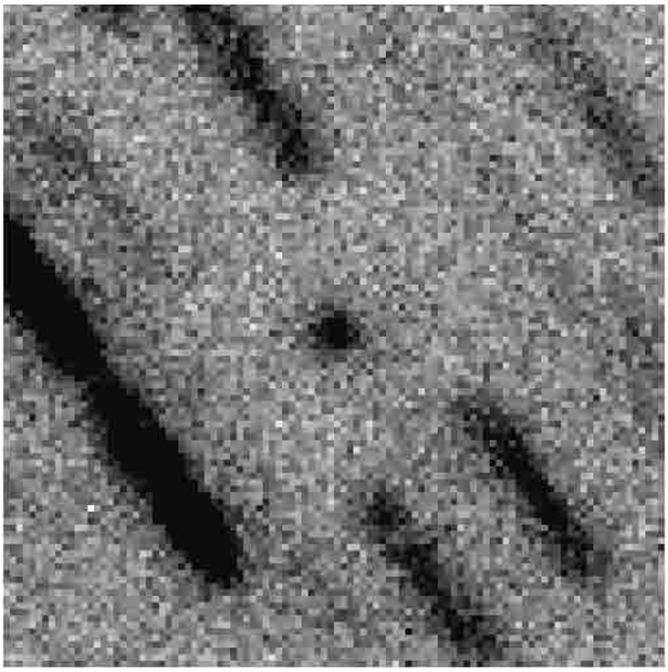

Fig. 1. Comet 46P/Wirtanen in May 1999. Twelve individual exposures in a broadband *R* filter, obtained on 16–17 May 1999 and each lasting 8 min, have been co-added. North is in the upper right corner, East is left of North. The field of view is 16 × 16″. Stellar images are trailed, due to the differential telescope tracking to follow the comet's motion.

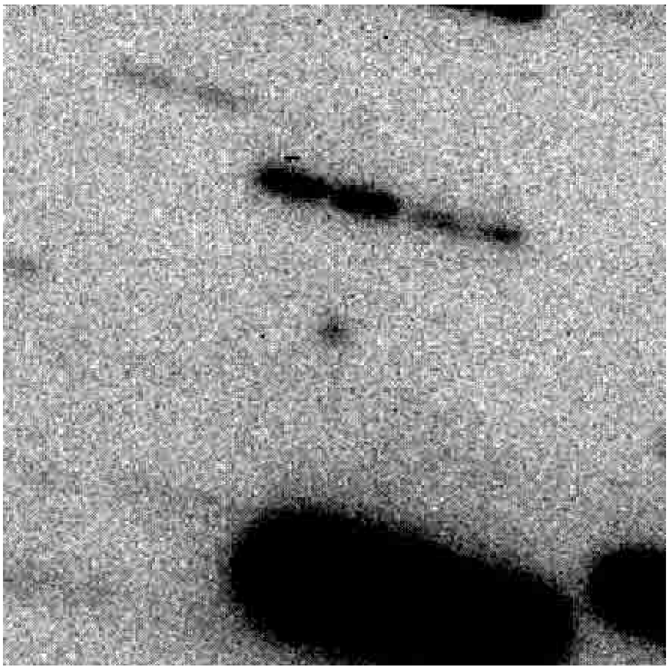

Fig. 2. Comet 46P/Wirtanen in December 2001. Co-added image of 2 *R* and 2 *V* filter exposures, obtained on 8–9 December 2001 with a total integration time of 10 and 7.5 min, respectively. North is up and East to the left. The field of view is 40 × 40″. Stellar images are trailed, due to the differential telescope tracking to follow the comet's motion.

HST observations in August 1996 when the comet was at $r = 2.6$ AU and already surrounded by a large coma, gave $R = 600$ m (Lamy et al. 1998). Results based on the gas and dust production of the comet (Schulz & Schwehm 1999) argue for a radius of 1 km or more.

Two values for the rotation period of the comet are given in the literature: 7.6 h by Meech et al. (1997) and 6 h by Lamy et al. (1998). The estimated body axes ratios are >1.3 and >1.2, respectively. As demonstrated by Drechsel et al. (2000), brightness variations of the very inner coma as measured by Meech et al. are subject to seeing changes and may thus not represent the "real" lightcurve of the cometary nucleus. Although made close in time, both published measurements of the rotation period are not fully in agreement to each other.

Information about the activity level of this comet at large solar distances hardly exists. Before the last perihelion passage in 1996–1997, the most distant observations of the comet were made at $r = 2.5$ AU (Rickman & Jorda 1995) when it was most likely active. CCD images taken in April 1996 show the comet with coma at $r = 3.2$ AU from the Sun inbound (Boehnhardt et al. 1996). At $r = 4.6$ AU from the Sun inbound no coma was detected (Boehnhardt et al. 1997). In VLT Test Camera images of 1998, a dust coma was clearly surrounding the nucleus at $r = 4.05$ AU outbound (ESO Press Release Photos 28/98). In summary, the activity status of Comet 46P/Wirtanen beyond $r \sim 4$ AU from the Sun is widely unexplored.

In the following we describe new imaging observations of Comet 46P/Wirtanen, obtained at the ESO VLT Observatory during 1999 and 2001. The goal of these observations was to accurately estimate the size of nucleus and to assess its activity status near aphelion and close to 3 AU, the distance at which the ROSETTA lander will be dropped onto the nucleus. Beyond that, some constraints could also be set for the rotation period and body axes ratio of the nucleus.

2. Preparation work for the 1999 observations

Close to aphelion, the nucleus may be "dormant" (without activity) or at least at a very low activity level such that the sunlight directly reflected from its surface could be detected in ground-based images. For an assumed radius of about 500–700 m (Boehnhardt et al. 1997; Lamy et al. 1998), the nucleus of 46P/Wirtanen would be as faint as 25–26 mag. Moreover, during the 1999 opposition (the time for which we planned the observations) the comet was in front of the outskirts of the Milky Way. In principle any 23 mag background object (star, galaxy) within a few arcsec of the comet at the time of the observation could make accurate photometric measurements of the target impossible.

In order to avoid sky regions of too crowded star background and thus to reduce the risk for unsuccessful measurements of the comet, a careful inspection of the star environment along its trajectory in the sky during 1999 was carried out. The aim of this preparation work was to identify sky regions with dark clouds or with significant light attenuation of the background objects. Also bright stars (<18 mag) along the trajectory must be avoided since they produce huge haloes of scattered light with detrimental effects on the detection of the comet. Considering visibility aspects (dark sky conditions, minimum observing window of 2 hours above 30 deg altitude) for the observing site (ESO Paranal Observatory in Chile), a number of potentially favourable observing dates for the comet were found. Unfortunately, no passage of the comet in front of a very dark Galactic cloud happened in 1999.

3. Observations

The new observations of Comet 46P/Wirtanen were performed at the 8.2 m Kueyen UT2 and Yepun UT4 telescopes (the 2nd and 4th Unit Telescopes of the ESO Very Large Telescope VLT) at Cerro Paranal in Chile during 16–17 May 1999 and 6–9 December 2001. Very good seeing conditions ($0.4-0.6''$ in May 1999 at low airmass; $1.0-1.3''$ in December 2001 at airmass above 2) prevailed during the observations of the comet. The latter observations were taken during twilight with relatively high sky background. Another attempt (11–12 September 1999) to observe the comet far from the Sun was unsuccessful (comet not detected) because of fainter (0.5 mag) object brightness and worse seeing conditions ($>0.7''$) than in May 1999. The latter observations are not described here.

The images on 16–17 May 1999 were obtained with the VLT Test Camera at the Cassegrain focus of UT2. This camera is a direct imager (scale = 525 μm/$''$), equipped with Bessell broadband filters ($UBVRI$) and a 2048×2048 pixel EEV CCD chip (24 μm pixel size, field of view $93 \times 93''$). During the observations of 46P/Wirtanen, only R filter exposures were taken with 2×2 pixels binning (effective pixel scale = $0.09''$/pixel). The telescope tracking and autoguiding were adjusted to the cometary motion in the sky. The chosen integration time of 8 min was short enough to reduce the risk of star trails passing across or nearby the comet during the exposure to an acceptable limit and it was long enough to guarantee a signal-to-noise ratio (S/N) of about 10 for the comet. However, such a short exposure time together with the anticipated S/N imposed rather tight constraints on the image quality of the moving target: better than $0.6''$.

The observations on 8–9 December 2001 were performed with the FORS2 instrument at the Cassegrain focus of UT4. FORS2 is a focal reducer type instrument equipped with a SITE CCD chip (24 μm pixel size = $0.2''$, field of view $6.8 \times 6.8'$). For the comet imaging we used broadband filters (V Bessell and a special R band filter of similar central wavelength and equivalent width as the Bessell R filter, however using a transmission range that avoids extremely bright sky lines). Since all images were taken in evening twilight with high sky background, shorter integration times (60–300 s) were used. The telescope tracking was set to follow the motion of the comet in the sky.

Apart from the comet exposures, calibration images of Landolt (1992) standard star fields distributed over an airmass range of 1.04–1.42 were obtained together with sky flat-fields and bias exposures.

Table 1 summarizes the viewing geometry and atmospheric conditions during the observations of Comet 46P/Wirtanen for both observing runs, together with some results discussed in Sect. 5.

4. Data reduction

The data reduction of the comet and standard star exposures was done in a standard way: bias subtraction, flat-field division, cosmic ray cleaning. The photometric zero point for the R and V filter images was obtained from the images of the Landolt standard star fields. However, since the airmass sampling and coverage of these calibration images were not sufficient and the star background of the comet images changed with time during the observing window, the filter extinction coefficient could not be obtained from the images of the observing nights. Instead, the respective extinction coefficient (0.09 mag/airmass unit in R and 0.12 mag/airmass unit in V) obtained with FORS during commissioning were applied. Colour corrections are only applied for the Dec. 2001 data (in May 1999 only R band images are available). The brightness values of the comet and of the standard stars were measured by aperture photometry using MIDAS (MIDAS = Munich Image and Data Analysis Software distributed by ESO). For the comet photometry, only exposures of the object without any star blends (including the area of the sky level aperture) were analysed. The 2σ error of the comet photometry is around ± 0.1 mag. This error includes the estimated uncertainties from the adopted extinction and the missing colour corrections.

5. Results

5.1. 1999 observations

Size of the nucleus: Fig. 1 depicts Comet 46P/Wirtanen in May 1999 at 5 AU from the Sun. From a rigorous numerical analysis (see below), we conclude that at least 90 percent of the measured brightness of the comet is due to sunlight reflected at the surface of the nucleus. The size of the nucleus can therefore be inferred directly from the integrated flux of the cometary images, as measured in the frames.

The (equivalent or mean) radius of the comet is calculated from the mean (averaged over the useful images; see Table 1) R filter brightness of the comet, according to the standard equation, as given for instance in Huebner (1992; Chap. 2.2.1, Eq. (2.1)). The albedo is assumed to be 0.04. Linear phase darkening correction is applied (coefficient 0.04 mag/deg). The radius uncertainty is calculated from the 2σ error (0.15 mag) of the mean value of the

Table 1. Observing geometry of the comet, atmospheric conditions and main results.

Date	17 May 1999	09 Dec. 2001
Observing Interval	06:50–10:05 UT	00:15–00:52 UT
Telescope+Instrument	UT2+TC	UT4+FORS2
Sun Distance of Comet	4.98 AU	2.91 AU
Earth Distance of Comet	4.00 AU	3.57 AU
Phase Angle of Comet	3.5 deg	41.5 deg
Integration Time	420 s	60, 100, 200, 300 s
Filters Used	Bessell R	Bessel V, special R
Total Number of Exp.	21	8
Useful Exposures	15	4
Airmass Range	1.05–1.90	2.15–2.85
Seeing	$0.4-0.6''$	$1.0-1.3''$
Sky conditions	photometric	clear
Sky Background Limit	28 mag/$('')^2$	25.5 mag/$(''^2)$
Mean R Brightness of Comet	25.15 ± 0.15 mag	22.6 ± 0.1 mag
Mean V Brightness of Comet	—	23.4 ± 0.1 mag
Intrinsic $V-R$ Colour of Comet	—	0.45 ± 0.15 mag
Nucleus Radius of Comet	555 ± 40 m[a]	$1000/1700 \pm 170$ m[b]
Axis Ratio of Nucleus	$>1.4 \pm 0.1$[c]	—
Rotation Period	~6 h[d]	—
Afρ	<0.45 cm	6.5 ± 2 cm[e]

[a] For an albedo of 0.04 and a linear phase correction of 0.04 mag/deg.
[b] For an albedo of 0.04 without/with linear phase correction of 0.04 mag/deg.
[c] Assuming a prolate ellipsoid and no variations of the surface albedo.
[d] Based on partial lightcurve.
[e] Corrected for contributions from nucleus reflected sunlight.

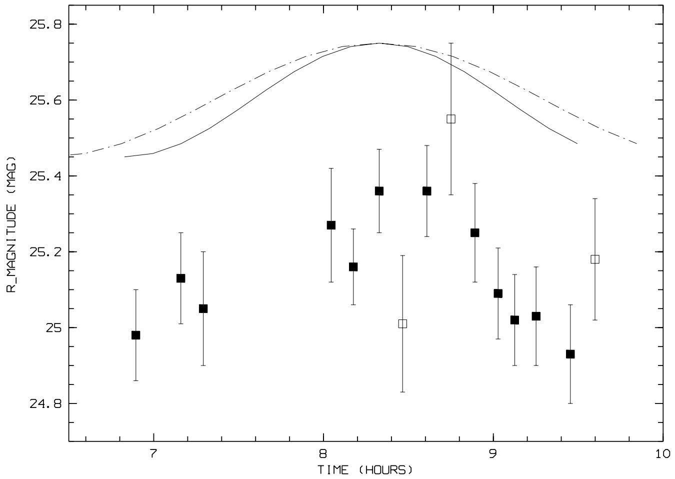

Fig. 3. Lightcurve of Comet 46P/Wirtanen on 17 May 1999. Filled square = measurements with ±0.12 mag error, open square = measurements with larger errors. The plotted lines in the upper part of the figure mimic the rotation lightcurve of the nucleus assuming a rotation period of 7.6 h (broken line; Meech et al. 1997) and of 6h (full line; Lamy et al. 1998); amplitude = 0.15 mag & minimum = 15 May 1999, 8.328 UT.

comet photometry. The summary of the results is given in Table 1.

The value of 555 ± 40 m for the size of the nucleus of Comet 46P/Wirtanen, obtained from the 1999 observations, is in agreement – within the respective uncertainties – with the earlier estimates that were based upon ground-based (Boehnhardt et al. 1997) and HST (Lamy et al. 1998) imaging of this comet (both corrected to adjust the parameters for the albedo, the phase darkening and the R filter brightness of the Sun). This quantitative agreement with the earlier results may also be considered as an a posteriori “validation” of the rather different analytical and numerical methods applied to the two older data sets. On the other side, the radius values obtained from gas production rates of the comet (Schulz & Schwehm 1999) seem to be unrealisticly high since – in order to be consistent with our data – they imply extremely low surface albedo (0.75 percent or less) hitherto not yet measured in comets (smallest value is 2 percent; Meech 2002).

Brightness variability, nucleus shape and rotation: the useful comet photometry covers a time interval of about 2.7 h and, because of the faintness of the object and the 8-min integration time used, it is of mediocre accuracy (2σ error = ±0.12 mag). The lightcurve (see Fig. 3) exhibits a systematic variability that exceeds the measurement error. We therefore attribute this variation to intrinsic brightness changes of the comet. The observed variations could be part of an approximately sinusoidal lightcurve with a total amplitude of about or a little more than 0.15 mag. Although the time coverage is short and the variability of

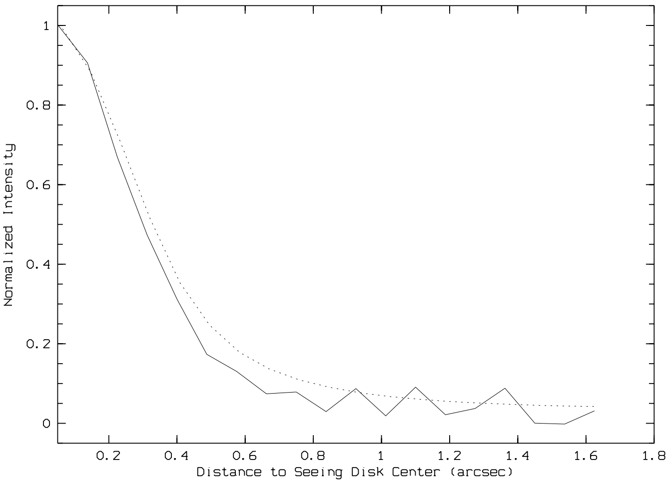

Fig. 4. Seeing profiles of the comet image and of a reference star: 16–17 May 1999. The plots show the profile of the seeing disk of the comet (solid line) in the co-added images of Fig. 1 and of a bright reference star (dashed line).

the comet signal is not very well sampled during the first observing hour because of star blends, we anticipate that we covered one minimum and that maximum brightness occured close in time to the beginning and to the end of the observing interval.

Since coma contamination is less than 10 percent (see below), the variation may be produced by the rotating nucleus itself and the observed lightcurve may cover about half of a rotation cycle. For comparison, we have drawn two artificial lightcurves in Fig. 3 that mimic the expected variations for rotation periods of 7.6 h and 6 h as suggested for Comet 46P/Wirtanen by Meech et al. (1997) and Lamy et al. (1998), respectively. Even though, the observed data resemble a little better the 6 h lightcurve, they are clearly not good enough to firmly exclude the 7.6 h period for the nucleus rotation. Moreover, the comparison of the measured variability with the artificial lightcurves suggests that the actual lightcurve of the nucleus rotation may deviate from exact sinusoidal shape.

From the peak-to-peak amplitude of the measured photometry (0.38 mag), a lower limit of the large-to-small axis ratio of 1.4 ± 0.1 can be estimated for the nucleus of the comet (neglecting albedo variations across the surface). A similar albedo variability must be assumed if the lightcurve would be produced by reflectivity variations of the surface alone.

The conclusions on the nucleus rotation and axes ratio are tentative only in view of the photometric errors and the short time coverage of Comet 46P/Wirtanen in our VLT observations.

Coma detection and nucleus activity level: in order to estimate possible coma contamination in the cometary image, the following analysis was performed: 12 exposures with the comet image well isolated and without obvious star or galaxy blends were aligned to the same pixel coordinates for the comet and they were then co-added. The resulting image of the comet (96 min total integration time) has a limiting magnitude $\sim$28 mag/$('')^2$. Visual inspection of the immediate neighbourhood of the comet image does not reveal the presence of a coma around the nucleus. The full-width-at-half-maximum ($FWHM$) of the co-added comet image is $\sim 0.5''$ and thus in good agreement with seeing data measured with the on-site seeing monitor during the observing period. The same alignment and co-addition procedure was applied to stellar images in order to average, at least approximately, the seeing variations in the star trails during the 12 exposures.

In a next step, we have analyzed the seeing disc profile of the comet and that of reference stars in the co-added frames. Since the stellar images are trailed, the profile of a reference star is produced from a perpendicular cut through the trail, averaged along the trail axis (excluding the first and last 8 pixels of the trail). We have chosen a star of high signal-to-noise ratio as a reference. The radial profile of the comet image is obtained by averaging the flux in concentric rings (width 1 image pixel) with the center of the seeing disk as zero point in radial direction. Both profiles are then normalized: maximum value = 1 and background = 0. Figure 4 shows the comparison between the comet and stellar profiles. Apart from a minor difference in the width (which is artificial because the maximum normalization corresponds to an estimated mean value of the comet flux within the noise bandwidth), there is no obvious indication for the presence of a weak coma in the comet profile (the star profile is even slightly wider than the one of the comet). In particular, the wings of the comet profile run parallel to those of the reference star. From the comparison of the star and comet profiles we estimate the detection limit for a faint coma in the seeing disk of the comet to be around 20 percent, i.e. we believe that the S/N of our data allows to detect deviations of the comet seeing disk from a stellar one if they are larger than ±10 percent.

We conclude that the comet image is not – noticably – contaminated by a coma. This implies that (1) the coma activity of the comet has ceased or has decreased to a very low level at $r \sim 4.9$ AU outbound and (2) that the measured brightness of the comet is due to sunlight reflected directly at the nucleus (thus allowing an estimate of the size of the bare nucleus).

The limiting magnitude of 28 mag/$('')^2$ for the combined exposure of 96 min total integration time allows to estimate an upper limit for Afρ, the parameter for the dust activity of the comet that can be obtained directly from observations (see A'Hearn & Schleicher 1984 for the definition of Afρ). With an aperture size of 3 times the $FWHM$ of the combined comet image (aperture $\rho = 1.35''$) we get Af$\rho < 0.45$ cm for our May 1999 observations of 46P/Wirtanen. Using a different approach: about the same amount of Afρ could be hidden in the seeing disk without being detected; this follows from the 20 percent limit for the detectability of profile deviations mentioned above.

Assuming a linear scaling law between the dust production rate and Afρ and using the values for Afρ and $Q_{\rm dust}$ published in Colangeli et al. (1998; when the comet

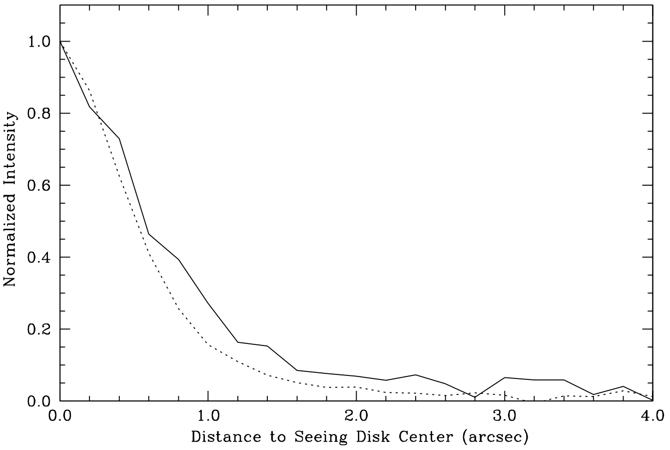

Fig. 5. Comparison of the seeing profile of the comet image and of a reference star: 8–9 December 2001. The profiles were obtained from the comet (solid line) and a reference star (dashed line) in Fig. 2.

was at 2 and 2.5 AU from the Sun pre-perihelion) we estimate the upper limit of the dust production Q_{dust} to be about 0.05 kg/s. This result, however, should be considered with great care since it is based on model assumptions and scaling laws for which we do not know from observational evidence whether they can be applied to Comet 46P/Wirtanen or not. For instance, the outflow momentum and gas-to-dust coupling in a possibly CO dominated coma at 5 AU may be significantly different from the conditions in a water dominated coma at 2 and 2.5 AU from the Sun with the likely consequence that the limit for the dust production rate may be underestimated.

5.2. 2001 observations

The observations in 2001 were conducted at very low elevation (30–20 deg) in western evening twilight sky. The sky background was much higher than during dark-time observations which reduced the detectibility of the object. Nevertheless, Comet 46P/Wirtanen was recovered in these images and broadband filter photometry and radial brightness profiles could be obtained.

Coma: in the images (see Fig. 2) the comet appears to be star-like. However, the signal from the comet is very weak and on a high sky background. The four useful comet images (2 R and 2 V band exposures) were processed in the same way as described in Sect. 5.1, item "Coma dection and nucleus activity level". Comparison of the profiles of the comet and a reference star in the images (see Fig. 5) suggests that a very weak coma signal may be present in the seeing disk of the comet (e.g. in the plot the radial profile of the comet is systematically higher than the stellar one). Coma activity at that distance from the Sun is already reported for the 1996 apparition of the comet (Boehnhardt et al. 1996).

Size estimate: aperture photometry gave an object brightness of $R = 22.6 \pm 0.1$ mag and $V = 23.4 \pm 0.1$ mag. The measured magnitude compares to an equivalent radius of ∼1.7 km for albedo of 0.04 and phase correction of 0.04 mag/deg. Without phase function correction the value for the equivalent radius is ∼1 km. Both values are significantly larger than the best radius values determined for the nucleus so far (Boehnhardt et al. 1997; Lamy et al. 1998, this paper Sect. 5.1). Since we suspect a coma being present around the nucleus, these estimates may not represent the actual nucleus radius, but reflect the contamination of the seeing disk by a condense dust coma.

Colour and reddening: in our 2001 observations 46P/Wirtanen appears to be a very red object. Its intrinsic $V - R$ colour (after removal of the colour of the Sun) is 0.4 ± 0.14 mag, i.e. the spectral reddening is ∼47 ± 18%/100 nm, much redder than measured for the cometary coma closer to the Sun during the previous apparition (Fink et al. 1997; Meech et al. 1997). This spectral gradient is also much redder than suggested for the nucleus (Lamy et al. 1998). A tentative explanation scenario are different dust environments (grain populations and/or properties) around the comet during the early and later phases of coma activity when approaching the Sun.

Afρ and dust production rate: Afρ was ∼6 cm in V band and ∼9 cm in R band (for a $3''$ aperture), uncorrected for contamination by reflected light from the nucleus. The latter can contribute between 10 to 30 percent of the measured light, i.e. the corrected Afρ is ∼4.2–5.4 cm in V and ∼6.7–8.1 cm in R. Applying again the simple scaling law as in Sect. 5.1, we estimate a dust production rate for the comet of the order of 1 kg/s at the time of our observations.

6. Conclusions from the new observations

With a radius of only ∼550 m, 46P/Wirtanen has one of the smallest cometary nuclei measured so far. The small brightness variations may be an indication of an elongated nucleus (minimum body axes ratio 1.4) or of albedo variations of the nuclear surface (similar factor). The nucleus rotation period is possibly in the order of 6 hours. There is no indication of coma activity at heliocentric distance $r \sim 4.9$ AU, just before the aphelion passage. Since the comet was also found widely inactive at $r \sim 4.6$ AU, when approaching the Sun (Boehnhardt et al. 1997), a dormant state of its nucleus during the aphelion arc of the orbit is likely. The small nucleus size, combined with the gas production rate measured near perihelion (Stern et al. 1998) implies a high activity level of the surface: 60 percent or more of the total surface area of the nucleus must have been active, e.g. the entire sunlit hemisphere, to explain the OH production rate of this comet as measured in January 1997, about 1 month before perihelion passage. This also implies that the areas of reduced gas production (caused maybe by a surface crust) are very small in 46P/Wirtanen as compared to other short-period comets, like 24P/Grigg-Skjellerup and 73P/Schwassmann-Wachmann 3 (see Boehnhardt et al. 1999). The nucleus seems to be active around 3 AU solar distance inbound, possibly surrounded by a very condense and red dust coma.

In conclusion, if the comet continues to behave like VLT and other observations indicate, then the ROSETTA spacecraft can expect to encounter in 2011 a small, possibly temporarily dormant cometary nucleus at its rendezvous distance of 4.6 AU from the Sun. However, the nucleus will be active at the beginning the scientific mission phase and remain so during the subsequent two years along its passage around the Sun.

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