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Letter to the Editor

Spectral evolution of ROSETTA target comet 46P/Wirtanen*

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Abstract. The compositional evolution of the coma of ROSETTA target comet 46P/Wirtanen was studied along its pre-perihelion orbit. At 2.34 AU the first gaseous species, CN and C_3, were detected. C_2 and NH_2 arose at 2.0 AU. The production rate curves of gas and dust show a steep increase between 1.8 AU and 1.6 AU indicating a distinct change of the outgassing conditions. The C_2 production increases more rapidly with decreasing solar distance than CN. As one consequence the C_2/CN ratio strongly varies with heliocentric distance. Due to this variation a classification of 46P/Wirtanen by the taxonomy introduced by A'Hearn et al. (1995) distinguishing comets with *typical* abundance ratios from *carbon-chain depleted* comets, is impossible. It would be classified as *depleted* beyond about 1.6 AU whereas it would be designated *typical* at smaller distances. The knowledge of the unexpected changes in the activity curves of 46P/Wirtanen will help to optimize the ROSETTA mission scenario in particular with regard to science operations.

Key words: comets – coma composition – space missions

1. Introduction

Jupiter family comets represent a large group of the short-period comets in the Solar System. As their aphelia lie between 5 AU and 6 AU, they are in principle observable along their entire orbit. Thus, they are excellently suited to serve as targets for a complete description of the physico-chemical evolution of a comet along its orbit. It has been realized over the years that the evolution of the activity of a comet as it moves along its orbit is of the utmost importance to understand the structure and compositon of its nucleus. Now, the European Space Agency is preparing the International Rosetta Mission (ROSETTA), a rendez-vous mission to Jupiter family comet 46P/Wirtanen ($P \approx 5.5$ yrs) dedicated to study its nucleus and coma evolution from onset of activity beyond 3 AU through perihelion. This mission will provide an unprecedented, unique data set of in-situ measurements regarding a single comet which will enable us to derive many yet unknown parameters. However, just one single comet will be studied by ROSETTA. It is therefore crucial to be able to establish the proper correlation between the results that will be furnished by the space rendez-vous and the data that can be obtained by remote observations from Earth. We have monitored the evolution of activity of comet 46P/Wirtanen along the same part of the orbit that will be covered by the space mission. These observations provide valuable information on the ROSETTA target comet for the preparation of the mission and are at the same time an important complement to the space mission itself. They will be needed to put the results expected from the ROSETTA Mission into a larger context by establishing a link between the spacecraft data and the information which can be retrieved from remote sensing observations and can then be transferred also to other comets.

2. Observations and data reduction

In 1996 comet 46P/Wirtanen moved towards perihelion (perihelion passage: March 14, 1997) along the part of its orbit that will eventually be covered by the ROSETTA mission. The comet was monitored from ESO, La Silla, while moving inbound from 3.5 AU to 1.1 AU heliocentric distance, r, by means of broadband filter imaging and spectrophotometry. The analysis of the imaging was done by Boehnhardt et al. (1997). Here we present the results of the spectrophotometric observations obtained from July to December, 1996 (2.8 AU to 1.6 AU). The spectra were taken with the *ESO Faint Object Spectrograph and Camera 2* (EFOSC2) mounted on the 2.2m ESO/MPI Telescope except for Nov. when a similar instrument (EFOSC1) was used at the ESO 3.6m Telescope. In July EFOSC2 was still equipped with its old, less sensitive CCD, whereas for all other EFOSC2 ob-

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* based on observations obtained at ESO La Silla within ESO programmes No. 57.F-0290 and 58.F-0413

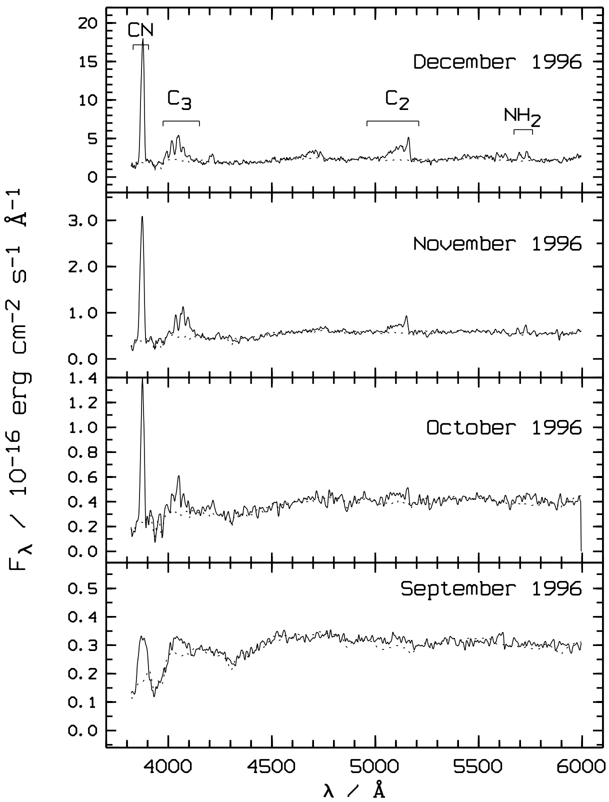

Fig. 1. Evolution of the spectrum of 46P/Wirtanen. The continuuum is fitted as a dotted line.

servations a new UV flooded chip was used which led to an increase in sensitivity by a factor of 7 in the blue and 2 in the red. The spectral resolutions are specified in Table 2. The slit width was 2″ in July, Sept. and Dec. and 1.″5 in Oct. and Nov. (slit length = 5.′7). The centering of the slit on the comet was evaluated before and after each exposure. Only well-centered spectra were kept for the analysis.

The spectra were reduced using the ESO/MIDAS and NOAO/IRAF standard reduction contexts for long-slit spectra. After bias subtraction, flatfielding and wavelength calibration the spectra were flux calibrated using the spectrophotometric standard stars Feige110, LT1020 and LT 377. As the comet did not fill the field of view of our CCD the sky could be determined on both sides of the comet and was subtracted accordingly. All spectra obtained during each observing run were co-added. 46P/Wirtanen was rather faint and did not show considerable short-term variability as is evident from broad-band imaging photometry (Meech et al., 1997; Boehnhardt et al., 1997). The co-addition of spectra taken on consecutive nights therefore led to an improved signal-to-noise ratio without introducing a measurable error due to possible short-term variations. The production rates were initially determined from fluxes integrated over slit lengths corresponding to the entire detectable comet. As the coma increased in size over the months, we used a common slit length of 4″ for our analysis, after confirming that this has insignificant influence on the the resulting production rates. The emission band fluxes in a rectangular aperture (4″ × slitwidth) are given in Table 1. For the continuum subtraction we measured the continuum bordering each emission band and approximated the continuum contribution to the band by interpolating between left-hand and right-hand continuum. We also fitted a solar analog to the spectra to demonstrate the overall shape of the continuum (Fig. 1). For CN, C_2, and C_3 the fluxes were converted into column densities using the fluorescence efficiencies applied by A'Hearn et al. (1995) (taking into account the dependences on heliocentric distance and velocity in the case of CN (Schleicher, 1983)). For NH_2 we used unpublished recalculated g-factors which do not differ by more than ∼ 10% from those of Tegler & Wyckoff (1989) for the bands observed here. The production rates in Table 2 were determined with the Vectorial model (Festou, 1981) and the lifetimes given by Schulz et al. (1994) for CN, C_2 and C_3. For NH_2 we used τ_p = 5300s and τ_d = 62000s (at 1 AU), average values derived from scale-lengths given by Cochran et al. (1992) and Fink & Hicks (1996). The parent velocity was varied as 0.85 km/s × $r^{-0.5}$ (Cochran & Barker 1986) while the daughter velocity was arbitrarily set to 1 km/s. If the emission of a particular species was not detectable in a spectrum, the 3σ upper limit to its production rate was determined. To check our results we additionally calculated the production rates with the Haser model using the parameters of A'Hearn et al. (1995) for CN, C_2 and C_3. Although the absolute values of the Haser production rates are systematically higher than those of the Vectorial model, all effects described in this paper were confirmed to be present in both cases. The dust production was derived from a region in the spectrum (5200 Å – 5250 Å) which is known to represent clean continuum. It is given in $Af\rho$, a quantity introduced by A'Hearn et al. (1984) and now widely used to measure the production of dust in comets. The empirical correlation determined by one of us (CA) from published values of $Af\rho$ and of the dust production rate $Q_{\rm d}$, for various comets near 1 AU indicates that with $Af\rho$ in 10^3 cm and $Q_{\rm d}$ in 10^6 g/s, these two quantities are expressed, approximately, by the same simple number (cf. Arpigny et al., 1998). The production rates are given with the 3σ error of the average value computed from the individual spectra.

3. Results and discussion

The first gaseous species was firmly detected at *r* = 2.35 AU on Sept. 10, 1996. Fig. 1 shows the co-added spectra of the observing runs where gaseous emissions were detected. The spectrum was still featureless in July and attempts to detect any gaseous emission with the 1.5 Danish telescope in August 1996 also led to negative results (N. Thomas, priv. com.). All spectra obtained during the observing run in September clearly exhibit the CN (0-0) band at 387.5 nm. The C_3 band at 405.0 nm is also visible in the co-added spectra. Due to the low spectral resolution in September (Table 1) the solar Ca doublet around 395 nm is not resolved. It shows as a broad dip in the spectrum. As a consequence about 50% of the CN and most of the C_3 band depicted in the September spectrum of Fig. 1 are actually due to the underlying continuum. Thus, C_3 emission is only marginally present above the detection limit. C_2 and NH_2 were

Table 1. Photometric fluxes of comet 46P/Wirtanen

Date 1996	r AU	lg F (erg cm^{-2} s^{-1}) CN	C_2	C_3	NH_2
July 10-11	2.81	-15.35[a]	-15.30[a]	-15.71[a]	-16.03[a]
Sep. 10-15	2.34	-15.11	-15.67[a]	-14.93	-15.97[a]
Oct. 15-18	2.04	-14.74	-15.14	-14.81	-15.35[b]
Nov. 14-15	1.81	-14.00	-14.40	-14.12	-15.26
Dec. 08-12	1.60	-13.51	-13.65	-13.63	-14.40

[a] 3σ upper limits from noise in neighbouring continuum
[b] From high-resolution spectra, aperture (4.″5 × 1.″5)

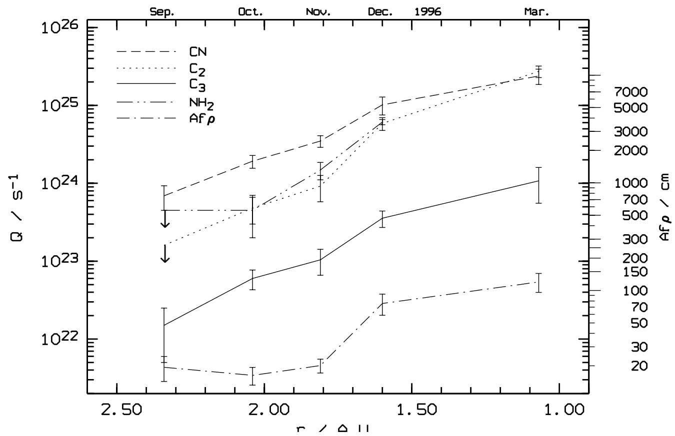

Fig. 2. Gas production rates and *Afρ* versus heliocentric distance. For the March data provided by Farnham & Schleicher (1997 and priv. com.) an error of 20% was assumed.

first detected in mid-October. Four NH_2 bands (7-0, 8-0, 9-0, 10-0) were clearly detected in high-resolution spectra in the red out to 7300 Å (not shown here). The presence of the 6-0 band is probable. As in comet Hale-Bopp at large *r* (Rauer et al., 1997), we observe, though to a lesser degree, an "odd-even anomaly", the even bands of NH_2 being appreciably stronger than the odd bands. Because of the limited space we cannot discuss these observations here and confine ourselves to quoting the NH_2 production rate determined from them. Fig. 2 demonstrates the evolution of the production rates as a function of heliocentric distance for all gaseous species and the dust (in *Afρ*).

Between 2.3 AU and 1.8 AU the gas production rates are slowly increasing with decreasing solar distance. A steeper increase in the production rate curves of all gaseous species and the dust is obvious between 1.8 AU and 1.6 AU. The inclusion of photometric data obtained around 1.1 AU (Farnham and Schleicher, 1997 and priv. com.) shows that the production rate of C_2 continues to increase at a higher level than the CN production. Consequently, the C_2/CN ratio rises from 0.25 around 2 AU to 1.1 around 1.1 AU.

The steep increase in production rates between 1.8 AU and 1.6 AU and the increase in the C_2/CN ratio was also confirmed with the Haser model. Note that the simple connection of the available data points in Fig. 1 results in a smooth increase in production rates between 1.6 AU and 1.1. AU. This does not necessarily reflect the real behaviour of the comet. However, due to the lack of observations it is impossible to say how the production rates in this region increase with decreasing r. A strong increase of the C_2 production rate as compared to CN between 2.0 AU and 1.5 AU was already reported for comet West (A'Hearn et al., 1977). (Our re-calculation with the model parameters used in this paper confirm this result.) A subsequent study of 14 comets indicated an apparent depletion of C_2 relative to CN for both, periodic and dynamically new comets (A'Hearn & Millis, 1980) at distances larger than 2 AU. Unfortunately, the data were not sensitive to the location of a possible division within the interval from 1.5 AU to 2.0 AU since only one comet, 81P/Wild 2, was observed in that region (around 1.80 AU and 1.50 AU). Newburn and Spinrad (1989) conclude from a later study that the C_2/CN production rate ratio changes continuously with r in the 5 comets for which they have measurements at different distances.

Unfortunately, they have no data beyond 2 AU, rather large gaps in the coverage of the relevant region or they mixed pre- and postperihelion data in order to increase the number of data points. A relatively sharp change of gas and/or dust production and of the C_2/CN ratio is therefore very unlikely to be detected in these data. It is equally unlikely to find it in the photometric study of 85 comets by A'Hearn et al. (1995), because here the step size of *r* was binned such that the region relevant to this effect lies within one binning interval (1.58 AU – 2.00 AU) with the result that a possibly present abrupt change is averaged out. Nevertheless, A'Hearn et al. (1995) still see the change in the C_2/CN ratio described by Newburn and Spinrad (1989), but the size of the effect is much smaller.

A comparison of the activity curves depicted in Fig. 2 with the lightcurve of comet 46P/Wirtanen obtained in broad-band R reveals that also the R brightness of the comet much steepens between 1.8 AU and 1.6 AU (Boehnhardt et al., 1997; Meech et al., 1997). Furthermore, comet 46P/Wirtanen was previously reported to have displayed a similar rapid rise of brightness during its past two apparitions (Morris, 1994). These events were, however, manifested by only one data point before the increase and the subsequent measurements continued only at around 1.2 AU. The concomitant increase in the production rates of gaseous trace species, the dust production, the R brightness and in the C_2/CN ratio between 1.8 AU and 1.6 AU indicates a distinct change of the outgassing conditions during this part of the orbit. As the dust is dragged out of the nucleus by sublimating volatiles, the observed increase of dust production by a significant factor probably requires a parallel increase in production of a more abundant gaseous species and may be related to water becoming the main driver of activity in 46P/Wirtanen. Unfortunately, no data exists on the water production rate for this part of the orbit. The only measurement close to it was obtained at 2.47 AU (Aug. 25.9, 1996) revealing a 5.5σ detection of OH corresponding to a water production rate of (2.6 $\pm$ 0.5) $\times 10^{26}$ s^{-1} (Stern et al., 1997). This value is consistent with the extrapolated

Table 2. Production rates, Q, and abundance ratios

Date 1996	July 10-11	Sep. 10-15	Oct. 15-18	Nov. 14-15	Dec. 08-12	Feb. 12[a] 1997	Feb. 15[a] 1997	Mar. 5[a] 1997
r (AU)	2.81	2.34	2.04	1.81	1.60	1.14	1.12	1.07
phase (°)	13	137	103	80	65	38	38	40
Q_{CN} (10^{24}) s^{-1}	<1.20	0.69±0.24	1.92±0.36	3.49±0.60	10.17±2.63	13.5(15.8)	14.2(19.5)	23.9(26.9)
Q_{C_2} (10^{24}) s^{-1}	<0.26	<0.16	0.48±0.18	0.92±0.34	5.87±1.10	14.4(16.2)	16.0(19.1)	27.4(26.9)
Q_{C_3} (10^{23}) s^{-1}	<0.41	0.15 ± 0.12	0.60±0.17	1.04±0.38	3.56±0.85	8.0(14.5)	12.3(28.8)	10.8(24.0)
Q_{NH_2} (10^{24}) s^{-1}	<0.72	<0.45	0.45±0.25	1.48±0.37	6.12±0.46	-	-	-
$Af\rho$ (cm)	<14	19±6	16±3	20±3	76±17	51	50	120
C_2/CN	-	-	0.25	0.26	0.58	1.06(1.03)	1.13(0.98)	1.15(1.00)
C_3/CN	-	0.05	0.03	0.03	0.04	0.06(0.13)	0.09(0.15)	0.05(0.09)
λ (nm)	340-920	320-1020	320-603	330-630	320-603	-	-	-
$\Delta\lambda$ (nm)	≈5	4.7	1.8	2.0	1.8			

[a] Values from Vectorial model. Haser model values in parenthesis (Farnham & Schleicher, 1997 and priv. com.)

CN production rate assuming the typical CN/OH abundance ratio of ~ 0.003.

The fact that the C_2/CN production rate ratio in comet 46P/Wirtanen strongly depends on its heliocentric distance has implications to the practical application of the new taxonomy of comets introduced by A'Hearn et al. (1995). Here two taxonomic groups were introduced that distinguish comets with *typical* abundance ratios from comets that are *carbon-chain depleted*. The criterion for this taxonomy is the C_2/CN production rate ratio with a comet being *depleted* if $C_2/CN < 0.66$. When applying this taxonomy to comet 46P/Wirtanen it would fall into the category *depleted* beyond 1.6 AU and be designated *typical* at smaller r. Thus, one has to be careful when designating a comet *depleted* if it was observed exclusively at larger distances from the sun. It is well known that the production rates of CN and C_2 vary with r according to different laws in many comets. A'Hearn et al. (1995) assume power laws to represent the approximate r-dependences, i.e. Q(CN) and Q(C_2) vary as r^k and $r^{k+\Delta k}$ with $\Delta k \neq 0$ (Δk often negative) as obtainable from their Table V. In such cases the production rate curves (straight lines in double logarithmic representation) would cross at a certain r and the comet will necessarily become *depleted* beyond this distance. For positive Δk reverse changes may occur. Reviewing the data by A'Hearn et al. (1995) with respect to the distribution of observations along the orbit it turns out that of the 29 comets designated *depleted*, 22 were observed exclusively beyond 1.7 AU. For one of these comets, 81P/Wild 2, the C_2/CN ratio is derived near 2.33 AU and the approximate r-dependence of the production rates is given in their Table V resulting in $\Delta k \approx -3$. Consequently, comet 81P/Wild 2 should be expected to show *typical* abundance ratios below ~ 1.7 AU if the above argumentation is valid. This was indeed the case for its 1978 passage, when it was measured near 1.8 AU and 1.5 AU (A'Hearn & Millis, 1980). Comet 67P/Churyumov-Gerasimenko on the other hand is *depleted* at 1.4 AU with a positive Δk and should therefore change to *typical* beyond 2.3 AU.

We conclude that the C_2/CN ratio is strongly dependent on the heliocentric distance for some comets and that the criterion for carbon-chain depletion must take this into account. As long as this is not accurately done the existence of an entire population of carbon-chain depleted comets that might come from the Kuiper belt as proposed by A'Hearn et al. (1995) is in question. New observations are therefore needed to re-examine the outgassing behaviour of comets along their orbits. Our new knowledge of 46P/Wirtanen not only helps to optimize the ROSETTA Mission in particular in view to science operations, but emphasizes the need for this kind of long-term rendez-vous missions with a comet.

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