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Dust production and coma morphology of 67P/Churyumov-Gerasimenko during the 2002/2003 apparition

II. A comparative study of dust production in 46P/Wirtanen and 67P/Churyumov-Gerasimenko during their 2002/2003 apparition

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Abstract. A comparison is made of the light curves and and dust production of the initial target for the ROSETTA mission, 46P/Wirtanen and the new target 67P/Churyumov-Gerasimenko during their recent 2002/2003 apparition. The study is based on amateur CCD monitoring using a standardised method to produce consistent photometry in Johnson-Kron-Cousins system. Although the dust production of the two comets is similar at perihelion ($Af\rho \approx$ 200-cm), dust production in 46P/Wirtanen peaked before perihelion, while in 67P/Churyumov-Gerasimenko it peaks after perihelion. Dust activity shows the same post-perihelion dependence with heliocentric distance in both comets. Overall 67P/Churyumov-Gerasimenko has a dust production rate an order of magnitude greater at the same heliocentric distance post-perihelion as 46P/Wirtanen, but 46P/Wirtanen has greater maximum dust production immediately prior to perihelion.

Key words. comets: individual: 46P/Wirtanen, 67P/Churyumov-Gerasimenko – techniques: photometric – instrumentation: miscellaneous

1. Introduction

Comet 67P/Churyumov-Gerasimenko is the new target of the ROSETTA mission after its failure to meet the strict launch window for an Ariane-boosted encounter with the original target 46P/Wirtanen. The observational and dynamical history of 67P/Churyumov-Gerasimenko has been discussed in Paper I (Kidger 2003).

46P/Wirtanen was discovered on January 15th 1948 by Carl Wirtanen from Lick Observatory as a 17th magnitude object that was already receeding from perihelion. At the discovery apparition the comet was only sparsely observed over a short arc – 9 astrometric positions were measured, covering an arc of 54 days – and was not initially recognised as being of short period. Wirtanen himself recovered the comet at Lick in 1954 very close to the predicted position, allowing a definitive orbit to be calculated (Herget 1960) that substantially confirmed the provisional orbit of Merton (1954). Since then 46P/Wirtanen has been observed at 9 apparitions, with only the 1980 return to perihelion unobserved as an unfavourable viewing geometry and a Jupiter encounter in 1977 that reduced the orbital period and perihelion distance conspiring to make recovery impossible. The orbit of 46P/Wirtanen has been investigated by Vaghi & Rickman (1982). A major perturbation by Jupiter occurred in 1971, reducing the orbital period from 6.7 to 5.9 years and the perihelion distance from 1.61 to 1.26 AU, and again in 1977, which reduced both the period and perihelion distance still further to 5.5 years and 1.08 AU respectively (Belyaev 1986)[1]. A slight further reduction in the perihelion distance has occurred since, with q = 1.064 AU at the 1997 return and q = 1.059 AU in 2002, meaning that the comet now has considerably greater activity than when first discovered. The current period at the 2002 return is 5.44 years.

46P/Wirtanen was first identified as a potential spacecraft encounter object by Kazakova et al. (1981) and selected as the target for the ROSETTA mission. Due to the loss of the launch window for an encounter with the comet using an Ariane V booster an alternative mission target, 67P/Churyumov-Gerasimenko, was selected. The important

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[1] A preliminary version of the revised and updated catalogue, which includes 46P/Wirtanen, is available at the url: http://astro.savba.sk/cat

Table 1. Details of observers and observations.

Observer	Telescope	MPC site code	Location	No. measures (10″)	No. multiaperture
José Manteca	0.30-m S/C	170	Catalonia (Spain)	6	0
Ramón Naves & Montse Campàs	0.30-m S/C	213	Catalonia (Spain)	8	2
Esteban Reina	0.25-m S/C	232	Catalonia (Spain)	2	1
Rolando Ligustri	0.35-m S/C	235	Talmassons (Italy)	3	1
Albert Sánchez	0.30-m S/C	442	Catalonia (Spain)	2	0
Giovanni Sostero	0.31-m Baker-Schmidt	473	Remanzacco (Italy)	0	3
Juan Rodríguez	0.30-m S/C	620	Majorca (Spain)	2	0
Julio Castellano	0.20-m S/C	939	Valencia (Spain)	3	0
Juan Lacruz	0.30-m S/C	J87	Madrid (Spain)	3	0

differences, particularly in radius and activity between 46P/Wirtanen and 67P/Churyumov-Gerasimenko make careful characterisation of 67P/Churyumov-Gerasimenko and comparison of its properties with 46P/Wirtanen important to the success of the ROSETTA mission.

Tancredi et al. (2000) estimate an absolute magnitude of the nucleus of $H_0 = 15.6$ and hence a radius of 2.5 km for 67P/Churyumov-Gerasimenko, making it one of the larger comets in the Jupiter family. A short review of other measures of the nucleus size is given in Paper I. This makes it a significantly larger object than 46P/Wirtanen, which has $H_0 = 18.4$ and an estimated radius of 0.7 km from photometry at large heliocentric distance (Tancredi et al. 2000). Other estimates include 0.555 ± 0.40 km from VLT observations near aphelion (Boehnhardt 2002) and 0.60 ± 0.02 km from profile separation using the HST (Lamy et al. 1998). Many of the properties of 46P/Wirtanen are well studied, although there is still some doubt about the rotation period with alternative values of 7.6 h (Meech et al. 1997) and 6 h (Lamy et al. 1998), with both being compatible with observations with the VLT (Boehnhardt 2002). The measured gas production rates are consistent with the measured radius of the nucleus only if the active fraction is close to 1 (Schulz et al. 1999) for the canonical albedo of 4% assumed for cometary nuceli.

In this paper we compare the light curve and dust activity of the two comets using the parameter $Af\rho$ developed by A'Hearn et al. (1984).

2. Observations

A detailed description of the observing technique and data analysis method is given in Paper I. We transform the R magnitude given by astrometry against USNO A2.0 to the standard Landolt R using the formula

$$R_{\rm Landolt} = 0.949 * (R_{\rm USNO} - 0.74). \quad (1)$$

Note that the correction is small (typically ~0.2 mag over the magnitude range of photometry for most comets and particularly the range of magnitudes reported in this paper.

A total of 49 measures of 46P/Wirtanen are reported here. These data were obtained by 9 observers on 13 nights. This corresponds to 34 individual integrations of which 19 correspond to multi-aperture photometry of a single photometric observation and the rest to photometry in the 10 arcsec aperture only. The photometry reported here covers a period from $T - 15.6$ d to $T + 247$ d. The observers and number of points reported by each are shown in Table 1.

Additionally, we extend the light curve of 67P/Churyumov-Gerasimenko presented in Paper I by 25 days to $T + 283$ days by the inclusion of additional data on 2 further nights by Albert Sánchez at MPC site 442, increasing the light curve coverage to a total of 53 individual nights.

3. The light curve

The raw light curve of 46P/Wirtanen is shown in Fig. 1 after transformation to the Landolt-Kron-Cousins R and correction for the changing geocentric distance. Data are shown for apertures of 10, 20 and 40 arcsec. The x-axis is shown as days from perihelion. The light curve sampling is relatively poor in this case, especially when compared with the light curve of 67P/Churyumov-Gerasimenko. The comet's geocentric distance was almost constant until $T + 20$ days. We see though that the light curve is clearly asymmetric about perihelion, with maximum at $T \leq 16$ days. In contrast to 67P/Churyumov-Gerasimenko, no evidence of seen of a perihelic outburst. The light curve is broadly similar to the one published in the Internet by Seichii Yoshida (`http://www.aerith.net/comet/catalog/0046P/2002.html`), although as our data is standardised the dispersion in our light curve is considerably less. Yoshida suggests that an outburst of amplitude 3 magnitudes took place between $T + 29$ and $T + 55$ days, with the light curve returning rapidly to quiescence. Our light curve is seriously undersampled at that time with data in V and in large apertures only, from Giovanni Sostero at MPC site 473 at $T+36$ and $T+53$ days. The observation at $T+36$ days is significantly brighter than equivalent data at $T - 9$ and $T - 15$ days at an epoch when the light curve was expected to show a significant fade, but we cannot completely confirm this outburst due to lack of data at the key epoch, although the data shown in Fig. 1 is strongly suggestive of an outburst of amplitude ~1.5 mags in an aperture of 20 and 40 arcsec. Note that, as these points were taken in V and are subject to considerable gas contamination of the continuum, the equivalent values of $Af\rho$ that are calculated

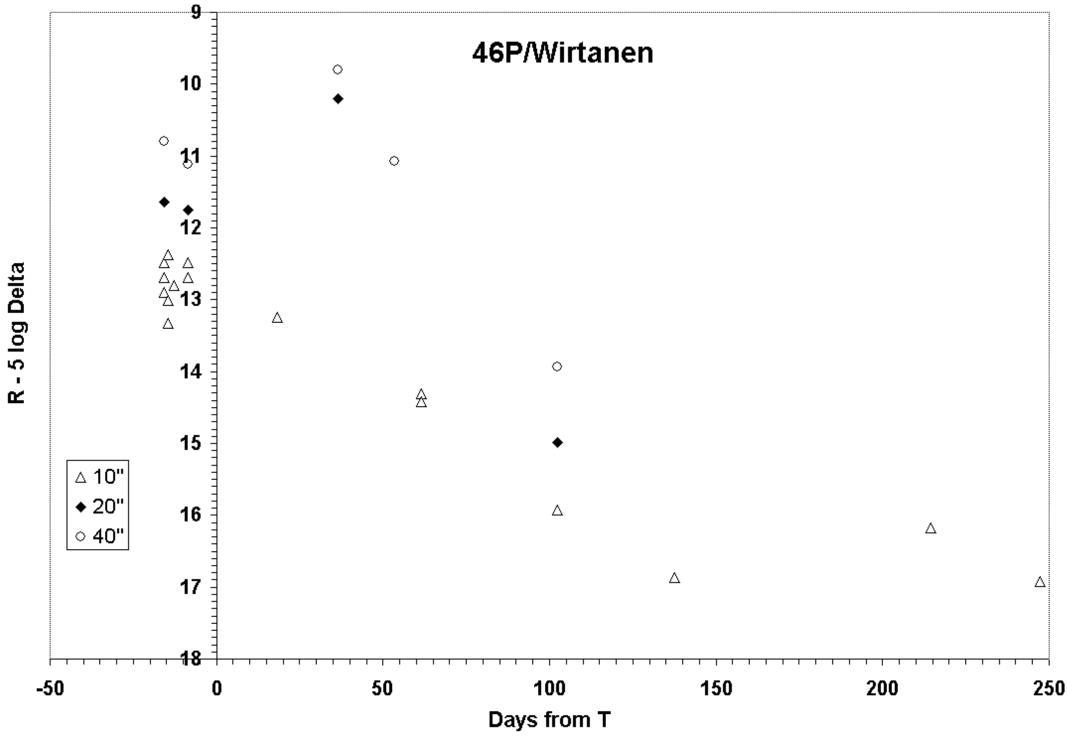

Fig. 1. The light curve of 46P/Wirtanen in R, after normalisation, in fixed apertures of 10, 20, and 40 arcsec, plotted from the data described in the text. The light curve is plotted as a function of days from perihelion (T), there is an apparent, short-lived outburst at $T + 30$ d, which is also registered in Seichii Yoshida's light curve published in the Internet at the url `http://www.aerith.net/comet/catalog/0046P/2002.html`. The data in V in large aperture are approximated to R assuming solar colours.

from them are consistently too high by a factor of 2−3 and are not used in this paper.

Similarly, we see two points at late times that are significantly discrepant. These may indicate an outburst of the comet at $T > 200$ days, but this is well after the end of the light curve given by Yoshida and thus cannot be confirmed.

The 1997 return of 46P/Wirtanen is well covered by Yoshida (`http://www.aerith.net/comet/catalog/0046P/1997.html`) but no equivalent outburst event is seen in the light curve post-perihelion, which shows a fast rate of rise and fall centred on perihelion, typical of a highly evolved object. No possible outbursts are seen.

The archive of multiaperture photometry allows us to obtain basic information about the coma morphology during the 2002/3 apparition. We may approximate the coma profile by fitting the photometry in each aperture for each individual date of the type

$$R = \log a + b \log r. \quad (2)$$

Where: "R" is the magnitude in R; "r" is the diameter of the aperture in arcseconds; and "a" and "b" are constants. The constant "b" we refer to as the *coma index*, while "a" is related in a non-trivial fashion to the absolute magnitude, but will not be further considered here.

Coma profiles are shown in Fig. 2. The profile which is shown is the mean of all observations reported for that date where multiple data exist. For a "typical" comet which has a $1/r$ brightness distribution we find a slope of the coma of $b \approx -2.5$.

The mean coma index for the data presented in the text is −2.5, showing that the coma of 46P/Wirtanen follows a standard $1/r$ brightness distribution. The corresponding CCD images these are available in chronological order at `http://www.iac.es/galeria/mrk/comets/46p/46p.htm`. There are no obvious changes in the coma morphology with time. This is in contrast to 67P/Churyumov-Gerasimenko, which shows an increasingly difuse coma with a point-like central condensation at late time and an increasingly steep coma profile.

Although using an aperture of a fixed angular diameter gives information on light curve structure and behaviour, it has the disadvantage of measuring a variable quantity of light from the coma as a function of heliocentric and geocentric distance. To measure the gas and dust production from the nucleus as a function of the heliocentric distance it is necessary to measure in an aperture of a fixed physical diameter. This can be done by using the multiaperture photometry to calculate the photometry for any given aperture when combined with the previously calculated coma index. In this case we define a physical aperture of 10 000 km, close to the equivalent size of the 10 arcsec aperture at the typical geocentric distance during the 2002/2003 apparition of both 46P/Wirtanen and 67P/Churyumov-Gerasimenko. Further details of this choice and its rationale were given in Paper I.

The ROSETTA mission rendezvous and encounter will take place more than a year before perihelion and an important part of the mission science is planned to be carried out during the pre-perihelion period, thus it is the comparison of this

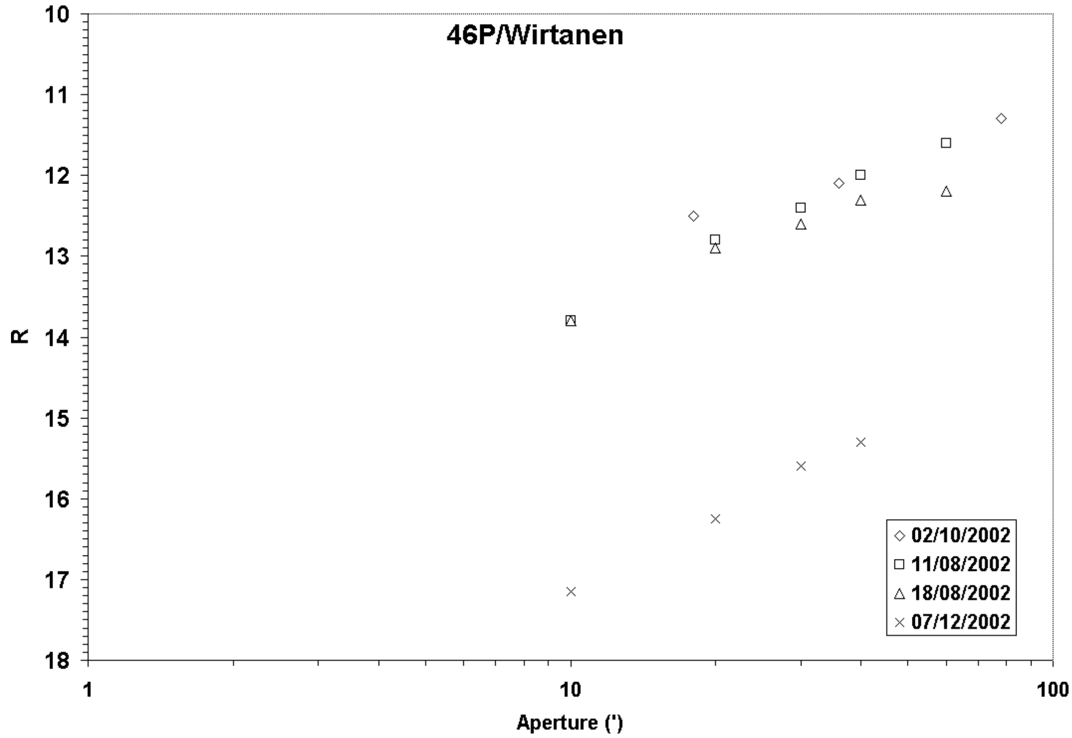

Fig. 2. Coma profiles of 46P/Wirtanen as determined by data taken in multiple apertures. Note that over 4 months and a wide range of magnitude the coma profile stays almost constant.

epoch of activity for the two comets that is most critical to the ROSETTA mission. We see that although 67P/Churyumov-Gerasimenko is more active post-perihelion, this is mainly due to the perihelic outburst that the comet suffered and that appears to be a habitual part of its perihelic behaviour (see Paper I). However, although our light curve coverage only extends to $T - 16$ days due to the poor visibility of both comets during the months prior to perihelion, we see that the activity of both objects is comparable at the epoch immediately prior to perihelion. 46P/Wirtanen shows a significant perihelion asymmetry in the sense of greater activity pre-perihelion than post-perihelion, while 67P/Churyumov-Gerasimenko shows it in the opposite sense. Our data suggests that, for the 2002 returns, at $T \sim -20$ days 46P/Wirtanen probably had a slightly higher level of activity than 67P/Churyumov-Gerasimenko.

The light curve for 46P/Wirtanen in a fixed 10 000 km aperture can be approximated by the relation:

$$R(10\,000\ \mathrm{km}) = 12.65 + 5\log\Delta + 18.05\log r. \quad (3)$$

For a range of heliocentric distance $1.07 < r < 1.96$ AU

Where "R(10 000 km)" is the R magnitude integrated over a 10 arcsec aperture using the transformation defined in Eq. (1) to convert the raw data to the standard Johnson-Kron-Cousins scale.

Note that the power law of the brightness against heliocentric distance is the same as that for 67P/Churyumov-Gerasimenko at $r < 1.91$ AU *post-perihelion*, although the absolute magnitude at this epoch is 2.5 mag (a factor of 10 in flux) fainter.

To compare dust production in the two comets we calculate $Af\rho$ (A'Hearn et al. 1984). As $Af\rho$ is aperture insensitive we calculate the values for the same physical aperture of 10 arcsec for both comets. Fink et al. (1998) have shown that at the 1997 apparition data in different apertures give essentially identical values of $Af\rho$ for 46P/Wirtanen. This eliminates the uncertainties involved in converting the the flux received for each comet to an aperture of the same physical size. The result is shown in Fig. 3.

Both comets have $Af\rho \approx 200$-cm at perihelion, which should be compared to the values of 19 000-cm measured for 1P/Halley at the time of the space probe encounters in 1986 (Osip et al. 1992), and the value of $Af\rho \approx 500$-cm for 19P/Borrelly, the target of the Deep Space 1 mission. However, the values exceed the equivalent maximum ones for 2P/Encke calculated in the same way during the 2003 apparition by a factor of $\approx$2, thus both comets may be considered relatively active objects of the Jupiter family.

4. Discussion

The data presented here suggest that at least close to perihelion during the pre-perihelion phase the activity of the new mission target for ROSETTA (67P/Churyumov-Gerasimenko) is comparable to or slightly less than that of the original mission target (46P/Wirtanen) at its 2002 return. Various groups obtained measures of $Af\rho$ for 46P/Wirtanen during the 1997 return. Data has been published by Jockers et al. (1998), Farnham & Schleicher (1998), Fink et al. (1998), Lamy et al. (1998), and by Schulz et al. (1998). A comparison of data between the 1997 return from the cited works and for the 2002 return (the data presented here) is shown in Fig. 4.

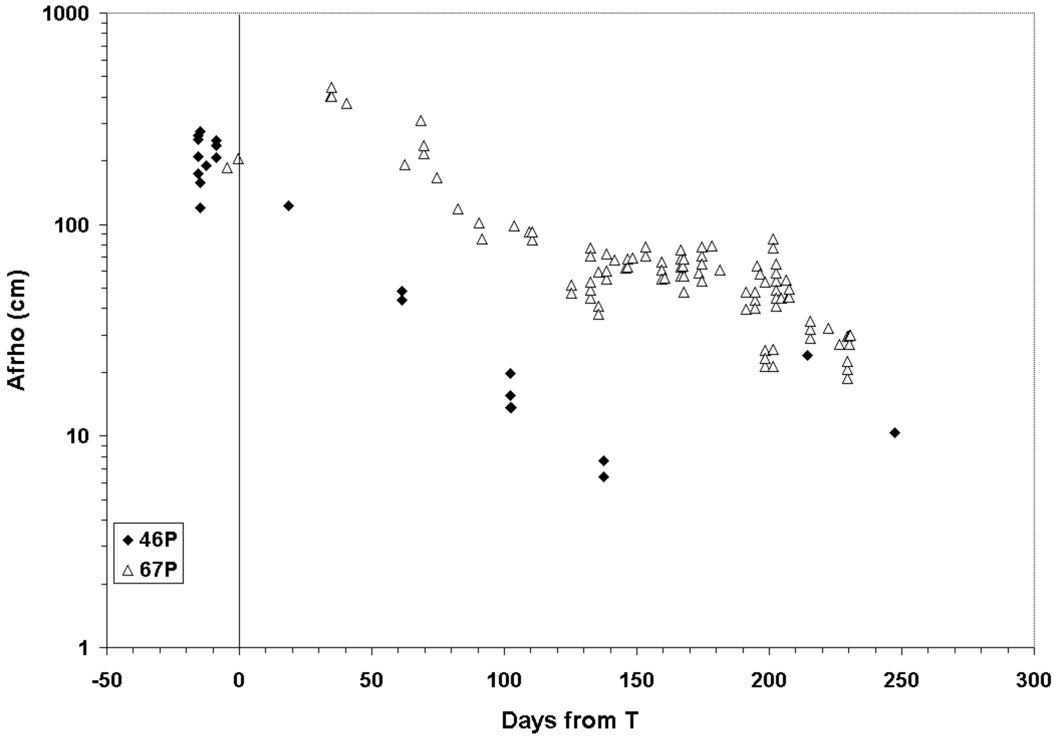

Fig. 3. Variation of $Af\rho$ for 46P/Wirtanen and 67P/Churyumov-Gerasimenko with time. Values are calculated only from photometry in R.

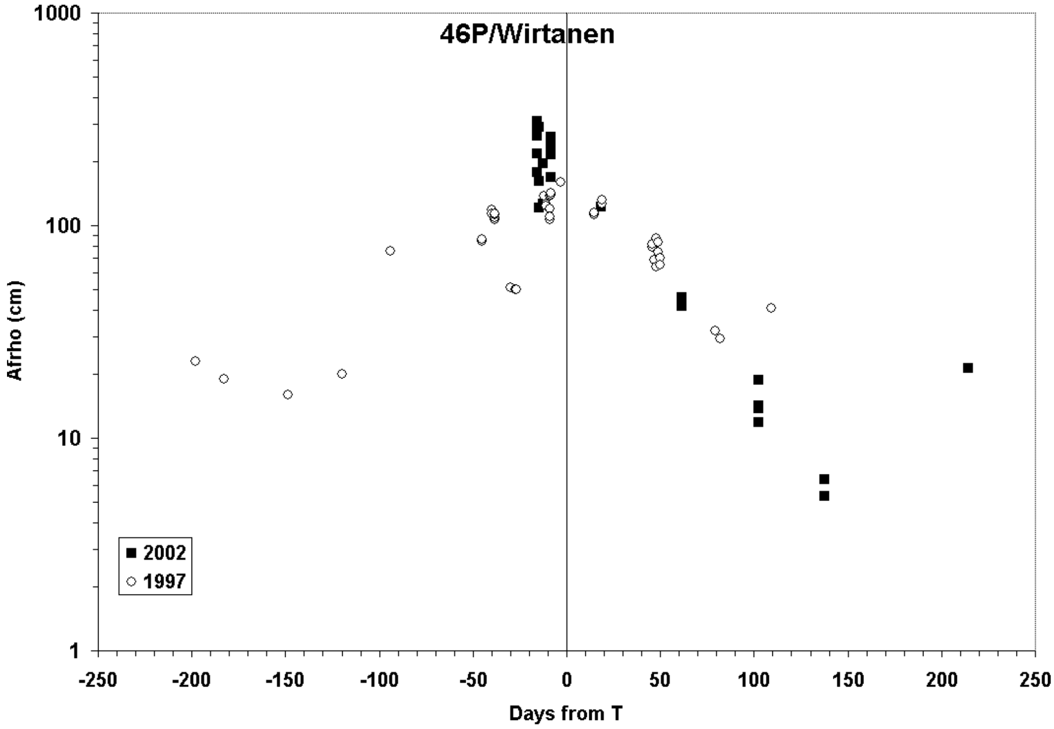

Fig. 4. A comparison of the variation of $Af\rho$ for 46P/Wirtanen with time during the 1997 and 2002 returns. Data for 2002 taken from this paper. Data for 1997 taken from: Jockers et al. (1998), Farnham & Schleicher (1998), Fink et al. (1998), Lamy et al. (1998), and from Schulz et al. (1998).

The data from 1997 shows considerable scatter during the pre-perihelion epoch but is in good agreement with the data presented here, suggesting that the light curve of 46P/Wirtanen is highly reproducible at different returns, as is that of 67P/Churyumov-Gerasimenko, although in the case of the latter the historical light curve data is seriously incomplete. The agreement also demonstrates that the amateur photometric data used here gives dust production rate data of a comparable quality to narrow band filter photometry taken on professional telescopes.

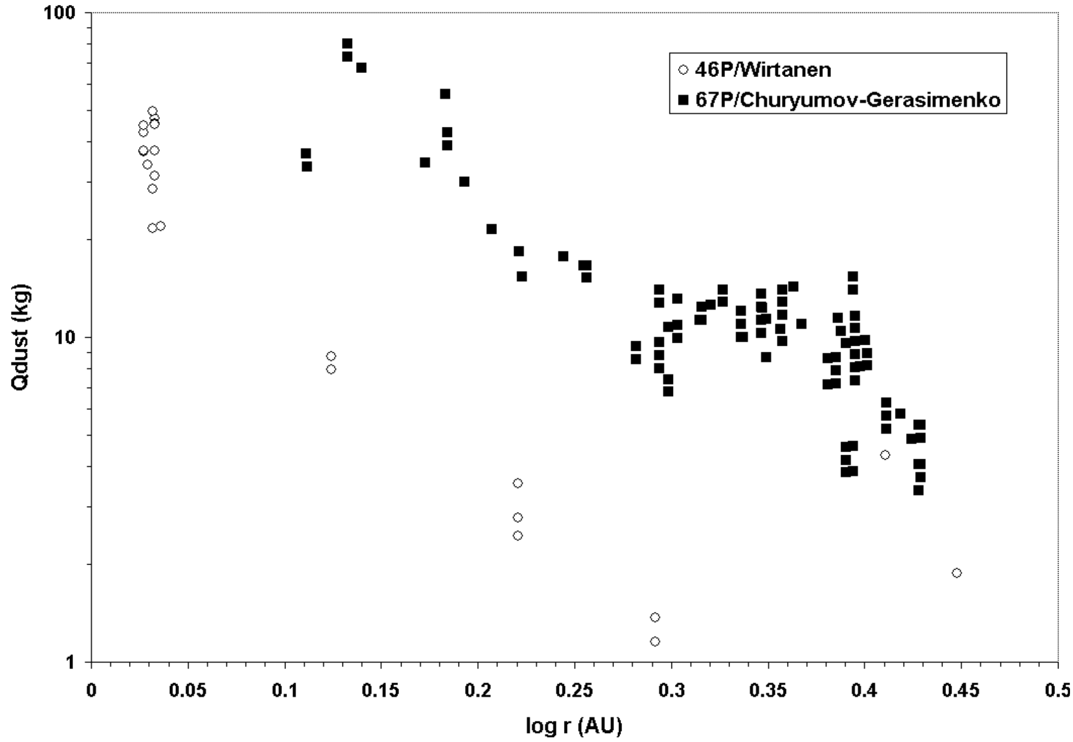

Fig. 5. The derived dust production rate (Q_d) for 46P/Wirtanen and for 67P/Churyumov-Gerasimenko during the 2002/03 apparition, plotted against the logarithm of the heliocentric distance, estimated from the data presented in the text assuming the conversion factor from $Af\rho$ to Q_d calculated by Osip (1992).

One interesting difference between the 1997 and 2002 returns of 46P/Wirtanen is that the data closest to perihelion in 2002 shows higher levels of dust production than in 1997; the 1997 return shows a flat maximum to dust production from $T - 40$ d to $T + 20$ d, whereas the data from 2002 suggests that dust production was more sharply peaked, with its maximum some 20 days before perihelion. In contrast Fink et al. (1998) comment that there was no perihelion asymmetry in their data from 1997, however, an examination of all data from 1997 shows that the flat maximum of dust production at the 1997 return appears displaced some 10–20 days before perihelion, thus an asymmetry is present, although somewhat different in detail to that observed at the 2002 return. Similarly, there is no evidence of outburst activity in the light curve for the 1997 return.

It is generally assumed that there is a linear conversion from $Af\rho$ to Q_d (Boehnhardt 2002) however, while $Af\rho$ is aperture independent, the measured dust production rate (Q_d) *is* strongly model dependent, relying on assumptions about the density, and the size and velocity distribution of grains. Of these parameters, the density is the poorest known and most authors use a canonical value of 1 g/cm^3, although this is based on a model assumption rather than on direct observational evidence. This parameter will become better known after the *Stardust* sample return from 81P/Wild 2 in 2006. Model uncertainties can lead to a factor of ~2 difference between different determinations of Q_d from $Af\rho$.

In Paper I we use a scaling factor derived from Osip (1992):

$$Q_d = Af\rho/5.6. \tag{4}$$

Where Q_d is the dust production in kg/s and $Af\rho$ is measured in cm.

However, the value of the scale factor determined for 46P/Wirtanen (Colangeli et al. 1998) from ISO measurements is significantly larger, but within the stated factor of 2 model uncertainty.

$$Q_d = Af\rho/9. \tag{5}$$

Thus the dust production rates calculated here (Fig. 5) may be as much as a factor of 50% too high if the larger scale factor is correct for both comets. Better modelling is required to determine whether the value of the scaling factor is genuinely different for the two comets or not, there is though no a priori reason why the same scaling factor should apply for different objects that may have different dust characteristics. Here we assume, for no other reason than simplicity, that the value from Osip (1992) is correct for *both* comets.

The dust production of 46P/Wirtanen shows a strong dependence on the heliocentric distance, falling as $r^{-5.8}$ in our data, identical to the value for 67P/Churyumov-Gerasimenko derived in Paper I and to the dependence of OH production measured by Osip (1992) during the 1982/83 apparition of 67P/Churyumov-Gerasimenko. Fink et al. (1998) found a much flatter dependence of $r^{-3.8}$ in 1997, but this may be influenced by some points with unexpectedly large values of $Af\rho$ at late time, an effect also noted in the data presented in Osip (1992).

Although the estimated dust production *at perihelion* is similar, 67P/Churyumov-Gerasimenko has a significantly larger perihelion distance (q = 1.29 AU) than 46P/Wirtanen (q = 1.06 AU) hence, when the strong heliocentric distance dependence of dust production is taken into account, at the same heliocentric distance dust production is a factor of ~10 greater in 67P/Churyumov-Gerasimenko than in 46P/Wirtanen. However, the greater intrinsic activity of 67P/Churyumov-Gerasimenko is compensated by the fact that it will be at greater heliocentric distance during the ROSETTA encounter, thus the dust activity during the encounter with 67P/Churyumov-Gerasimenko should be comparable to the predicted activity at 46P/Wirtanen.

5. Conclusions

The agreement between the data for $Af\rho$ for 46P/Wirtanen at the 1997 and 2002 returns demostrates that the amateur photometric data used here gives dust production rate data of a comparable quality to narrow band filter photometry taken on professional telescopes, thus confirming the potential of carefully homologised amateur CCD data to provide valuable information on cometary dust production. The dust production rate (Q_d) for 67P/Churyumov-Gerasimenko at perihelion is found to be similar to the production rate observed in 46P/Wirtanen, the original target for the ROSETTA mission. The heliocentric dependence of dust production is found to be identical for the two comets thus the dust environment scenarios calculated for 46P/Wirtanen should be at least indicative of the conditions at 67P/Churyumov-Gerasimenko. Both comets are found to have highly reproducible activity at different returns (even more so in 67P/Churyumov-Gerasimenko than in 46P/Wirtanen, albeit on the basis of more limited historical light curve data), thus permitting detailed model predictions to be made on the basis of past behaviour.

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