Astron. Astrophys. 335, L50–L55 (1998)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

Narrowband photometric results for comet 46P/Wirtanen

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Received 13 November 1997 / Accepted 13 March 1998

Abstract. Narrowband filter photometry was performed on the ROSETTA spacecraft target, comet 46P/Wirtanen, at Lowell Observatory in 1991 and 1997. Production rates were determined for OH, NH, CN, C_3, and C_2, along with a measure of the dust production, $A(\theta)f\rho$. Relative abundances were computed, and a comparison to other comets indicates that this comet has a "typical" composition and a very low dust-to-gas ratio. The peak value of $A(\theta)f\rho$ was 138 cm, while the OH production rates, used in conjunction with a standard water production model, yield a peak water production of $\sim 1.0\times10^{28}$ mol s^{-1} at perihelion and suggest a minimum active surface area of ~ 1.8 km^2. Finally, a comparison to comet Halley puts Wirtanen into context with previous in situ comet measurements.

Key words: comets: general – comets: individual: 46P/Wirtanen – techniques: photometric

1. Introduction

Dozens of comets are observable every year, yet, for various reasons, most are never studied in much detail. Until recently, comet Wirtanen had been one of these objects: an inherently faint comet with unfavorable recent apparitions. In 1994, however, the European Space Agency announced that comet Wirtanen was the target for the ROSETTA spacecraft mission, which prompted numerous observing campaigns during the 1997 apparition. Characteristics of the nucleus and cometary environment that will impact the mission design and objectives include the size and composition of the nucleus and its activity level with respect to heliocentric distance. Furthermore, the safety of the spacecraft is a concern, so evaluation of the comet's dust production rates and dust-to-gas ratio is a priority for ground-based studies. Ultimately, comparing Wirtanen to other comets will help establish how results from the ROSETTA mission can be extended to comets in general.

Narrowband photometric measurements of Wirtanen were obtained at Lowell Observatory to determine the comet's basic composition and activity levels. As part of a larger comet database study (A'Hearn et al. 1995) a single measurement was obtained in 1991, well before Wirtanen was chosen as the ROSETTA target. During the 1997 apparition, an effort was made to obtain data in support of the spacecraft mission. Throughout both of these apparitions, however, the observing geometry was poor, and, during the months around perihelion, Wirtanen was always within 50° of the sun. This put the comet at high airmass near twilight, with only a short amount of time for observations. (Competition with comet Hale-Bopp for observing time further limited the number of measurements.) Overall, the observing geometry was similar, but reversed, in the two apparitions, with the Earth on opposite sides of the sun.

This paper presents our combined data set. The production rates of dust and different molecular species are given, and, where sufficient data exist, heliocentric distance relations are discussed. Abundance ratios, water production, and the dust-to-gas ratio are also calculated, and these results are compared to those of the overall database compiled by A'Hearn et al. (1995). A taxonomic classification of the comet is determined, along with an estimate of the active surface area. Finally, Wirtanen is compared to comet Halley to put it into context with previous spacecraft measurements.

2. Observations and data reduction

Observations of comet Wirtanen were obtained on a total of six nights using either the 42-inch (1.1-m) Hall telescope or the 31-inch (0.8-m) telescope at Lowell Observatory. The single observational set from the 1991 apparition was measured 21 days prior to perihelion, when the comet was at a heliocentric distance r_H=1.12 AU. Our earliest observations during the 1997 apparition were obtained in mid-February, one month before perihelion, and our final observation was made in early July when Wirtanen was at a heliocentric distance of 1.72 AU. A conventional photoelectric photometer equipped with pulse-counting electronics was employed for all observations. Generally, a total of seven narrowband filters were used to isolate the emission from five gaseous species – OH, CN, C_2, C_3, and NH – and the continuum in the blue-green (4845 Å) and the near-UV (3650 Å). In June and July 1997, however, the comet was too faint to be observed with all of the filters. Most of the observations were obtained with the International Halley Watch (IHW) filter set (A'Hearn 1991); however, on 5 March 1997, one

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Send offprint requests to: T.L. Farnham observational set was also obtained with the new Hale-Bopp (HB) filter set (Farnham et al. 1998), in which the continuum is measured in the near-UV (3448 Å), blue (4450 Å), and green (5260 Å). A typical observational set (see Table 1) consisted of several integrations totaling 60 seconds or more with each filter, while automatically tracking at the comet's rate of motion, with associated sky measurements of between 10 and 60 seconds taken at least 15 arcminutes away from the comet. Sufficient sky measurements were obtained to compensate for the effects of changing twilight. Wirtanen appeared very diffuse due to its relatively high gas-to-dust ratio, so large photometer entrance apertures were generally utilized to ensure that the comet was centered. Because we could not detect Wirtanen visually in June or July 1997, we pointed by means of a relative offset from the nearest PPM star, tracked at the comet's rate of motion, and used the largest available aperture. Tests of this offset pointing technique indicate that the resulting pointing accuracy should have been better than 10 arcseconds. This pointing uncertainty, combined with previous tests of the effects of pointing accuracy on resulting fluxes in several other comets, indicate that, except for the June data, uncertainties in our measurements due to centering inaccuracy are much lower than other uncertainties discussed in the next paragraph. Possible errors in centering in the July data are overwhelmed by the low contrast of the comet signal to the sky signal.

Because of the unfavorable observing circumstances (high airmass, changing twilight sky, and/or bright moon on some nights), we performed an extensive analysis to determine the sources and the size of the uncertainty for each data point. Possible sources included the photon statistics of both the comet measurement and its corresponding sky measurement, the effects of changing sky brightness during twilight, and uncertainties associated with the determination of the underlying continuum for each emission band. The results of this analysis provided a qualitative understanding of the dominant uncertainties for each measurement, and allowed us to quantitatively incorporate each of the components in quadrature to produce a formal value of sigma. As it turns out, changes in sky due to twilight were determined sufficiently accurately in all cases that it was a minor component compared to other factors. More importantly, the sky often comprised a large fraction of the signal in the comet measurement, so we performed tests in which we changed the sky value by one sigma to investigate how uncertainties in the underlying sky value propagated through to affect the final result. Results of the overall analysis show that the errors are dominated by photon statistics in the measurement of the continuum in the comet and its associated sky value; an additional, sometimes dominant, uncertainty was introduced in the emission measurements by the effects of continuum subtraction.

Photometric reductions and subsequent standard modeling were performed following our normal procedures and using our current model parameters (cf. A'Hearn et al. 1995), and so will be only briefly summarized here. Numerous standard star measurements were obtained to determine nightly extinction and absolute flux calibration coefficients. After continuum subtraction, emission band fluxes were converted to molecular abundances and, with application of the Haser model, to production rates (*Q*). Continuum fluxes were converted to a proxi for dust production, $A(\theta)f\rho$, the product of the albedo, *A*, at the observed phase angle, θ; the filling factor, *f*, of the grains within the field-of-view; and the projected radius of the aperture, ρ. No correction for phase angle was applied because the phase angles ranged from only 24 to 45 degrees, a region over which the phase function is expected to vary by less than about 30% (cf. Schleicher et al. 1998).

3. Results and discussion

The observational parameters for each data point, along with the reduced molecular and continuum fluxes, are listed in Table 1. The data for the 3650 Å filter have very low signal and, in addition, are contaminated by C_3 emissions (due to the high gas-to-dust ratio), so these measurements are not tabulated and will not be discussed further. Table 2 lists the corresponding fluorescence efficiencies (L/N) for species that exhibit a Swings effect (and thus vary with observational circumstances), the production rates (Q) for the gas species and $A(\theta)f\rho$ for the continuum. The production rates and $A(\theta)f\rho$ are plotted as a function of heliocentric distance in Fig. 1.

Looking first at a comparison of the results from the two apparitions, it is evident that the single observational set from 1991 (triangles) is in good overall agreement with the 1997 observations obtained at similar heliocentric distances. However, note that the 1991 set was obtained three weeks after perihelion, while the corresponding 1997 data were obtained between one and five weeks prior to perihelion. In addition, the orbit also changed slightly, with the perihelion distance decreasing from 1.083 AU in 1991 to 1.064 AU in the current apparition (arrows in Fig. 1). This combination of circumstances makes it difficult to determine whether the small apparent differences between apparitions for CN and C_2 and the larger differences seen in NH and $A(\theta)f\rho$ are due to asymmetries about perihelion or due to the effects caused by the change in orbit. [Note: due to a continuing shift in the IHW NH filter bandpass, the 1997 measurements capture 16% less of the available NH flux than that obtained in 1991. Accounting for this difference would result in an increase of only 0.07 in log Q(NH) for the 1997 measurements.]

An approximate heliocentric distance dependence, log Q or log $A(\theta)f\rho$ vs. log r_H, can be determined for those species observed during June and July 1997 at r_H = 1.49 and 1.72 AU, respectively. The resulting post-perihelion dependencies for CN, C_2, and dust all have power-law exponents of approximately -4, which is in the mid-range of values found by A'Hearn et al. (1995) for periodic comets. We can investigate the distance dependence before perihelion by combining our results near perihelion with data obtained by other observers at larger heliocentric distances. Applying our standard modeling to the fluxes reported by Schulz et al. (1998) for distances between 2.34 and 1.60 AU, we again derive a slope of about -4 for CN and a slightly steeper slope for C_2. The OH band in the near-UV was measured at heliocentric distances of 2.72, 2.47 and 1.31 AU

Table 1. Observing circumstances and photometric fluxes for Comet 46P/Wirtanen

					Aperture		log Emission Band Flux ($\text{erg cm}^{-2}\text{s}^{-1}$)					log Cont. Flux ($\text{erg cm}^{-2}\text{s}^{-1}\,\text{Å}^{-1}$)
UT Date	r_H (AU)	Δ (AU)	Δ Time[a] (days)	Tele.[b]	Diameter (arcsec)	log ρ[c] (km)	OH	NH	CN	C_3	C_2	λ4845[d]
1991 Oct 11.47	1.118	1.409	+20.8	L42	37.8	4.29	−10.49	−11.48	−10.56	−11.27	−10.79	−13.74
1997 Feb 12.14	1.137	1.600	−30.0	L42	75.3	4.64	−10.34	−11.74	−10.54	−11.38	−10.66	−13.84
1997 Feb 15.11	1.124	1.590	−27.0	L42	75.3	4.64	−10.33	−11.43	−10.48	−11.07	−10.58	−13.84
1997 Mar 5.12	1.071	1.536	−9.0	L31	55.1	4.49	−10.47	−11.37	−10.52	−11.16	−10.55	−13.48
1997 Mar 5.12	1.071	1.536	−9.0	L31	55.1	4.49	−10.51	—	−10.51	−11.09	−10.49	−13.58
1997 Mar 5.13	1.071	1.536	−9.0	L31	109.7	4.79	−10.06	−10.92	−10.17	−11.06	−10.20	−13.28
1997 Jun 4.18	1.494	1.961	+82.0	L42	149.9	5.03	—	—	−10.88	—	−11.00	−14.11
1997 Jul 1.18	1.721	2.311	+109.0	L31	109.7	4.96	—	—	−11.47	—	−11.48	−14.30

[a] Time from perihelion.
[b] Telescope ID: L42 = 42-inch (1.1-m), L31 = 31-inch (0.8-m).
[c] Projected aperture radius.
[d] λ5260 for the HB filters (second observational set on March 5).

Table 2. Production rates for Comet 46P/Wirtanen

			log L/N[a] ($\text{erg s}^{-1}\text{ molecule}^{-1}$)			log Q (molecule s^{-1})					log $Af\rho$ (cm)
UT Date	log r_H (AU)	$\dot{r}_H$ (km s^{-1})	OH	NH	CN	OH	NH	CN	C_3	C_2	λ4845[b]
1991 Oct 11.47	0.048	+5.7	−14.576	−13.259	−12.322	$27.89^{+.03}_{-.03}$	$25.80^{+.05}_{-.06}$	$25.41^{+.02}_{-.02}$	$24.36^{+.05}_{-.06}$	$25.40^{+.02}_{-.02}$	$2.05^{+.03}_{-.03}$
1997 Feb 12.14	0.056	−8.1	−14.765	−13.126	−12.409	$27.87^{+.13}_{-.19}$	$25.00^{+.16}_{-.40}$	$25.20^{+.02}_{-.02}$	$24.16^{+.20}_{-.28}$	$25.21^{+.02}_{-.02}$	$1.71^{+.10}_{-.13}$
1997 Feb 15.11	0.051	−7.4	−14.785	−13.120	−12.412	$27.89^{+.07}_{-.09}$	$25.29^{+.24}_{-.75}$	$25.25^{+.02}_{-.02}$	$24.46^{+.08}_{-.10}$	$25.28^{+.02}_{-.02}$	$1.70^{+.04}_{-.04}$
1997 Mar 5.12	0.030	−2.7	−14.773	−13.177	−12.516	$27.84^{+.11}_{-.15}$	$25.53^{+.17}_{-.32}$	$25.42^{+.01}_{-.02}$	$24.39^{+.15}_{-.22}$	$25.41^{+.03}_{-.05}$	$2.14^{+.09}_{-.12}$
1997 Mar 5.12	0.030	−2.7	−14.773	−13.177	−12.516	$27.81^{+.10}_{-.13}$	—	$25.43^{+.03}_{-.03}$	$24.46^{+.06}_{-.07}$	$25.46^{+.03}_{-.03}$	$2.03^{+.11}_{-.15}$
1997 Mar 5.13	0.030	−2.7	−14.773	−13.177	−12.516	$27.90^{+.17}_{-.26}$	$25.58^{+.16}_{-.42}$	$25.44^{+.02}_{-.02}$	$24.37^{+.25}_{-.96}$	$25.45^{+.03}_{-.04}$	$2.04^{+.14}_{-.22}$
1997 Jun 4.18	0.174	+14.2	−14.236	−13.220	−12.373	—	—	$24.85^{+.09}_{-.06}$	—	$24.90^{+.12}_{-.12}$	$1.47^{+.17}_{-.16}$
1997 Jul 1.18	0.236	+14.7	−14.228	−13.223	−12.372	—	—	$24.60^{+.18}_{-.32}$	—	$24.75^{+.15}_{-.26}$	$1.61^{+.51}_{\text{und}}$

[a] Fluorescence efficiencies are for r_H = 1 AU, and are scaled by r_H^{-2} in the reductions.
[b] λ5260 for the HB filters (second observational set on March 5).

by Stern et al. (1998) using HST. Applying the Haser model to their column densities and linearly extrapolating to perihelion (with an associated slope of about -4.5) gives excellent agreement with our perihelion results. This slope is 0.4 less steep than that derived by Stern et al., consistent with their having used a vectorial model with an $r_H^{-0.5}$ velocity-dependence for the parent.

Unfortunately, a similar investigation of the r_H-dependence for dust yields an ambiguous result. Measurements of $A(\theta)f\rho$ were reported by Lamy et al. (1998) and Fink et al. (1998), in addition to measurements by Schulz et al. (1998) and Stern et al. (1998). Our data and that of Fink et al. provide the only coverage near and after perihelion, and these results are in good agreement. However, a comparison of pre-perihelion measurements from various observers shows considerable apparent scatter between different observing runs. For instance, the HST data sets (Stern et al. 1998 and Lamy et al. 1998) imply that $A(\theta)f\rho$ remained nearly constant with a value of about 20 cm from 2.7 to 1.3 AU. While the Schulz et al. measurements from 2.3 to 1.8 AU are consistent with this value, their measurement at 1.6 AU gives a result of 76±17 cm. Furthermore, Fink et al. obtained a value of 85 cm at 1.22 AU, only two weeks after the final HST measurement. Finally, Fink et al. present $A(\theta)f\rho$ values of between 2 and 8 cm at distances from 3.0 to 2.1 AU, based on CCD imaging by Fink et al. (1997) and Meech et al. (1997). These results are considerably lower than the HST results at similar r_H. The variations described here are much too large to be explained by phase angle effects, and, while none of the apparently discrepant observations were obtained concurrently, no pattern is evident associated either with instrumentation or with wavelength. Therefore, these variations in $A(\theta)f\rho$, while quite large, presumably reflect intrinsic variations in the comet's

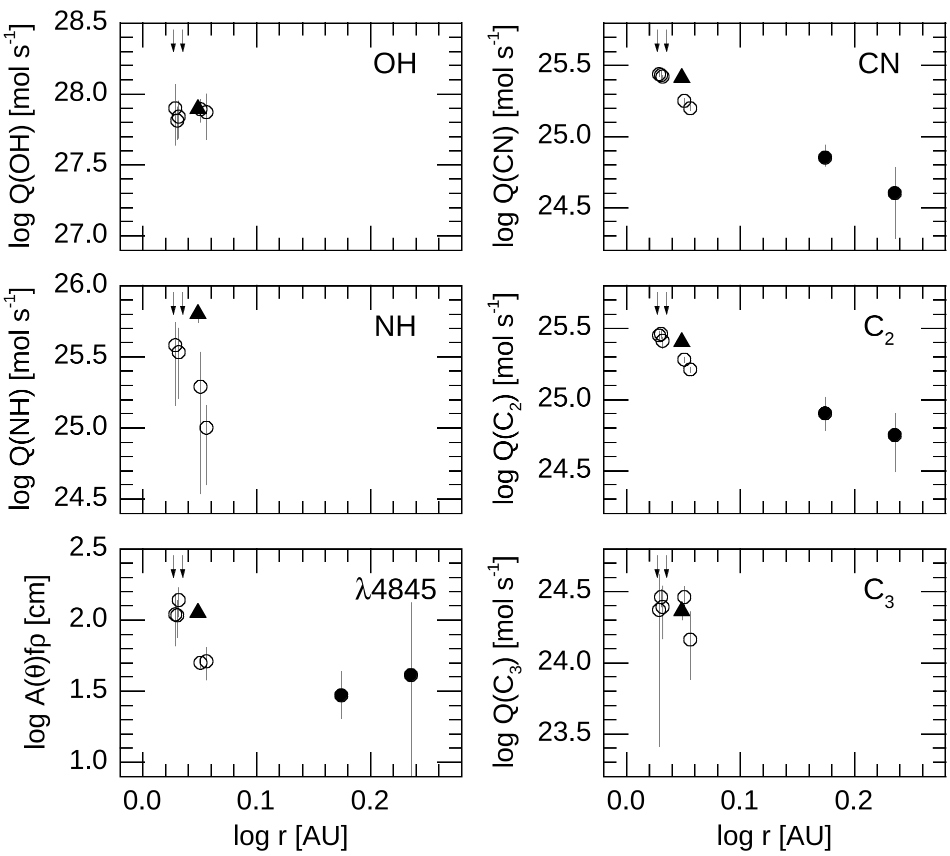

Fig. 1. Production rates for the molecular species and $A(\theta)f\rho$ for the continuum at 4845 Å (or 5260 Å), plotted with respect to heliocentric distance. The 1991 data are shown as triangles and the 1997 data as circles, with pre- and post-perihelion observations denoted by open and filled symbols, respectively. For clarity, the first and last data points on 5 March have been offset slightly in log r by -0.004 and +0.004, respectively. Arrows at the top of each panel mark the perihelion distances for each apparition (1.083 AU on 20 September 1991, 1.064 AU on 14 March 1997).

dust production with a time scale of weeks, although, due to the sparseness of data, rotation-induced variation cannot be ruled out. Unfortunately, improved temporal coverage of Wirtanen's behavior prior to perihelion is unlikely to be obtained until the 2008 apparition, due to unfavorable observing circumstances in 2002.

Abundance ratios of the trace gas species to OH can be compared to those of well-observed comets in the A'Hearn et al. (1995) database. For Wirtanen, the log of the unweighted production rate ratios are as follows: CN/OH = -2.50 ± 0.12, C_2/OH = -2.49 ± 0.12, C_3/OH = -3.49 ± 0.12, and NH/OH = -2.36 ± 0.30. (Only the six observational sets obtained near perihelion are included in these ratios, as OH was not measured in June or July 1997.) These values clearly classify Wirtanen as "typical" in composition; A'Hearn et al. found that approximately one-half of Jupiter-family comets are typical, while the remainder are depleted by varying degrees in the carbon-chain species (i.e., C_2 and C_3). This compares to non-Jupiter-family comets, nearly all of which are typical in their composition. Spectroscopic observations obtained during the second half of 1996 were used by Schulz et al. (1998) to derive the C_2-to-CN ratio. They claim to have detected a strong trend with heliocentric distance, with Wirtanen showing greater depletions of C_2 at larger distances, and even being classified as depleted at 1.6 AU. However, this trend is certainly due in part to an artifact of differences in modeling. Recalculating Qs using the fluxes from Schulz et al. with our own model and scalelengths (the same parameters used by A'Hearn et al. to define the classification system) increases their C_2-to-CN ratios by factors of 2.6 to 2.3. The resulting ratios are: 0.48±0.20 in October 1996 (r_{H} = 2.04 AU), 0.48±0.19 in November (1.81 AU), and 0.89±0.28 in December 1996 (1.60 AU), where we have propagated the original percent sigmas to obtain uncertainties on these ratios. This recalculation gives a C_2-to-CN ratio showing almost no depletion at the closest distance, and even the earlier measurements are, within the observational errors, marginally consistent with a classification of typical ($C_2/CN > 0.66$). For comparison, our own measurements in February 1997 yield production rate ratios of 1.02±0.07 and 1.07±0.07 (1.14 AU, 1.12 AU); furthermore, within the uncertainties, results from March through July (perihelion through 1.72 AU post-perihelion) are consistent with the February abundance ratios.

We also note that systematic effects can result due to sampling significantly different-sized fractions of the coma and then extrapolating to a total abundance using model parameters that do not exactly match the spatial distribution of the species. Even the relatively large photometer entrance apertures we employed sampled only a few percent of the C_2 in the coma, while the spectrograph measurements sampled less than 0.1%. Determinations of the C_2 abundance are particularly susceptible to this problem, since its radial profile has often been reported to be less steep in the innermost coma than can be fit with a standard Haser model (or any simple two-generation model) because C_2 originates from multiple parents and grandparents (cf. Schulz et al. 1994). When small apertures are used for sampling, such as was the case for the spectroscopic measurements, this can give an underestimate of the C_2 production. The resulting effect can yield an r_H-dependence of C_2/CN qualitatively consistent with that reported by Schulz et al., given the somewhat unusual observing circumstances during 1996 – the geocentric distance increased while the heliocentric distance decreased, so progressively smaller fractions of the coma were observed at larger heliocentric distances. While this effect was apparently not evident in the 1996 data (Schulz, private communication), the poor observing circumstances throughout this apparition prevented the acquisition of good signal-to-noise measurements of the spatial distribution of C_2 in Wirtanen.

In spite of these difficulties in analyzing abundance ratios, it is true that the determination of a specific value used to delineate between two classes of objects is somewhat arbitrary, as noted by A'Hearn et al. (1995), and changing this value slightly would correspondingly change the designation of comets near the dividing line. This is especially the case for the C_2-to-CN ratio, where there is a progression in the degree of depletion of carbon-chain molecules rather than a simple dichotomy (see A'Hearn et al. Fig. 15a). As Schulz et al. (1998) correctly note, if a comet's C_2-to-CN ratio varies with r_H, then its classification could also change depending on the distance at which it is observed. However, even if their results for Wirtanen are accepted without qualification, Schulz et al. overstate the significance of these variations on the A'Hearn et al. taxonomy. While A'Hearn et al. discussed a heliocentric distance dependence for C_2/CN from 1 to 3 AU for well-observed comets, it was too small to have an effect on the basic taxonomic classification – numerous comets display little or no trend with distance, and most of the carbon-chain depleted comets in their database were depleted by significantly more than a factor of 2. Therefore, the overall division into two classes is secure, even though a small percentage of comets may vary sufficiently to change their individual classification.

In the particular case of Comet Wirtanen, if the C_2-to-CN ratio actually varied by almost a factor of 2 between 1.81 and 1.60 AU – 0.48±0.19 to 0.89±0.28 – then this would imply that Wirtanen changed exceptionally quickly. A rapid change in ratios would most likely be the result of a seasonal effect, with different active regions on the surface having somewhat different compositions, changing their relative levels of activity as a function of orbital position rather than as a function of heliocentric distance. This phenomenon has been observed in several comets, but usually with the abundances of all of the minor gas species varying together with respect to OH (e.g. A'Hearn et al. 1985, A'Hearn et al. 1995). Again, improved temporal coverage will be required to determine the extent to which a seasonal effect might be present in comet Wirtanen.

The water production of Wirtanen can be determined directly from the OH production rates. We use the same empirical procedure used by A'Hearn et al. (1995) (see also Schleicher et al. 1998), which incorporates differences between the Haser and vectorial models, an r_H-dependence of the parent velocity, and a nominal water-to-OH photo-dissociation branching ratio of 90%. Over our limited range of r_H for which OH was measured, the resulting conversion factor varied from 1.27 to 1.32. The resulting mean water production rate near perihelion is $1.0 \pm 0.1 \times 10^{28}$ mol s^{-1}. As discussed earlier, our OH results are completely consistent with a linear extrapolation of the HST measurements from OH spectroscopy obtained between 1.3 and 2.7 AU (Stern et al. 1998). Our water value is also consistent with the water production rate estimate of 7×10^{27} mol s^{-1} on 10 February 1997 based on Lyman-α emission (Bertaux 1997), and with a 3-sigma upper limit for Q(OH) of 1.5×10^{28} mol s^{-1} during February based on a non-detection of the 18-cm radio emission by Crovisier (private communication). The only apparently discrepant water determinations are those based on OI [^{1}D] measurements by Fink et al. (1998). Their results are consistently two to three times greater than other determinations, possibly due to the difficulty in removing contamination from NH_2 emission and telluric forbidden oxygen, coupled with the uncertainty in the value of the water-to-forbidden-oxygen branching ratio (cf. Budzien et al. 1994).

We can combine our water production rate with a standard water vaporization model (based on Cowan and A'Hearn 1979) to determine the minimum mean active area required to produce the measured water (cf. A'Hearn et al. 1995). The resulting value, 1.8 km^2, is typical of other Jupiter-family comets. However, when this active area is combined with the derived radius of 0.60 km by Lamy et al. (1998), 40% of the surface must, on average, be active. While such a large active fraction appears unusual compared to the less than 3% value determined by A'Hearn et al. for the majority of Jupiter-family comets that have radius measurements, this may be the result of selection effects. Nucleus size measurements are normally obtained only for relatively inactive comets, because they more readily permit the nucleus signal to be isolated from the surrounding coma. A large active fraction also makes it unlikely that Wirtanen would have large seasonal effects, which is consistent with our having detected only a small asymmetry in gas production rates about perihelion. However, this is in apparent conflict with seasonal effects being an explanation for the possible rapid variation in the C_2-to-CN ratio.

The dust-to-gas ratio, as characterized by $A(\theta)f\rho/Q(\mathrm{OH})$, was shown by A'Hearn et al. (1995) to vary for different comets by nearly two orders of magnitude. Our value for Wirtanen near perihelion was $1.3 \pm 0.5 \times 10^{-26}$ cm s mol^{-1}, implying that the dust-to-gas ratio was quite low and only a factor of four greater than the gassiest comets in the database. Our peak value of $A(\theta)f\rho$ = 138 cm near perihelion, which is nearly identical to the peak measurements by Fink et al. (1998), can be converted to a very approximate dust production of 140 kg s^{-1}, using an empirical relation by Arpigny (private communication) – with the value of $A(\theta)f\rho$ in cm corresponding to the mass loss rate in kg s^{-1}. However, differences in grain properties and the grain size distributions among comets could significantly alter this estimated mass loss rate. For instance, detailed modeling by Lamy et al. (1998) for their HST dust measurement at 2.45 AU yielded a dust mass production of 4 kg s^{-1} when $A(\theta)f\rho$ = 23 cm – a factor of six different from what is obtained with Arpigny's simple relationship. Application of the Lamy et al. technique (1996) would yield a smaller difference from Arpigny's method as one approaches perihelion, due to the ability of increased water production to lift larger grains from the surface. However, a secure determination of the dust mass loss rate depends critically on the particle size distribution, which has not yet been measured in comet Wirtanen.

Finally, we can directly compare our results for Wirtanen with ground-based results previously determined for Comets 1P/Halley and 26P/Grigg-Skjellerup (cf. Osip et al. 1992, Schleicher et al. 1998, and A'Hearn et al. 1995), the only comets for which relevant in situ measurements have been obtained. Our derived dust-to-gas ratio for Wirtanen is identical to that of Grigg-Skjellerup and only about one-fourth to one-eighth that of Halley. Water production in Halley at a comparable heliocentric distance ($\sim$1.1 AU) was about 27× higher than what we measured for Wirtanen, while at the time of the Giotto fly-by of Halley, the water production was about 38× greater. Dust production, as measured by $A(\theta)f\rho$ in Halley during the Giotto encounter, was about 120× greater than what we measured for Wirtanen at peak production. These results indicate that comet Wirtanen is a significantly less hazardous environment for spacecraft than was comet Halley, especially given the very low velocity of ROSETTA with respect to the comet.

Acknowledgements. The 1991 data set was obtained by R. Millis. We thank R. Schulz for providing fluxes prior to publication. This work was funded by NASA grants NAG5-4146 and NAGW-5060.

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