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Letter to the Editor

Spectroscopy of 46 P/Wirtanen during its 1997 apparition

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Abstract. Comet 46P/Wirtanen was observed during five observing runs around its perihelion passage from 1997 January 28 to June 02. The spectra acquired extend from 5200 to 10000 Å at spectral resolutions of 12 Å and 18Å. A total of 16 spectral averages, each comprising about 40 minutes of integration time, were obtained. The production rate of H_2O near perihelion averaged 2.7×10^{28} molecules/sec. The continuum strength Afρ was 129 cm while the production rates respectively of the parents of C_2, CN and NH_2 were 5.7, 3.2 and 5.6 $\times$ 10^{25} molecules/sec. Our estimated error for all these quantities is 20%. The production rate ratios relative to water can be compared to our larger sample of comets (Fink & Hicks 1996) with the following results: the C_2 and CN abundance ratios are slightly below average but the NH_2 ratio is definitely enhanced putting P/Wirtanen among the top few comets in that category. Its Afρ/H_2O ratio is very close but slightly below the median of our comet sample. Reduced to 1 AU P/Wirtanen ranks near the 40% level of our ordered list of the H_2O production rates of 20 comets. If the production rate of water is combined with P/Wirtanen's estimated radius of 0.6 km, it implies that virtually the whole surface area of the comet is active. Our measured Afρ values combined with those obtained by photometry yield a fairly tight heliocentric activity dependence of $r^{-3.8}$ with no pre-post perihelion asymmetry. This agrees well with the general heliocentric brightness dependence of Jupiter family comets. Taking all this data together, P/Wirtanen appears to be a rather typical member of the Jupiter family of comets.

Key words: comet spectrophotometry – Wirtanen – production rates – dust

1. Introduction

During the spring of 1997 we made a special effort to obtain observations of 46 P/Wirtanen (henceforth abbreviated to Wirtanen) since this comet is the target of the European Space Agency mission Rosetta. Given the comet's orbital period of 5.46 years, the present perihelion passage of 1997 March 14, was the only one that allowed a reasonably detailed study of the comet's activity, appearance and production rates, before the planned spacecraft launch in Jan. 2002. The comet slowly moved from a southerly declination of -8° at the end of January to 30° by mid May so that it was well placed for observations in the northern hemisphere.

In our observations we concentrated on spectroscopy since no spectra from any previous apparition existed for Wirtanen and we therefore felt that the acquisition of such data was of overriding importance. Spectroscopy gives an important visual impression of the comet's spectral appearance and allows the most accurate determination of production rates. The present comet apparition was not a very favorable one since the comet never exceeded a solar elongation of $40^{\circ}-50^{\circ}$. Its small solar elongation meant that at most an hour or so in the evening, after it got dark and before the air mass rose too high was available for observations. In addition the comet never became very bright. Thus we felt ourselves fortunate to obtain a good series of spectra during dark time (i.e. near new moon) at the beginning of February, March, April, May and June. A log of our spectroscopic observations is given in Table 1. The first two runs at the beginning of February and March were before perihelion, the other three followed perihelion.

We discuss in this paper the spectra obtained for Wirtanen during the observing dates in Table 1, the continuum and emission fluxes deduced from our data, production rates of H_2O and the parents of C_2, CN, and NH_2, and the continuum strength as measured by Afρ. We also compare the production rate ratios and Afρ/H_2O values with our spectroscopic data base of many comets to see how Wirtanen fits into the ensemble of a large group of comets and we determine the heliocentric distance dependence of Wirtanen's activity using its Afρ values.

2. Observations and data reductions

All of our observations were carried out at the Catalina site 154 cm (61″) telescope of the University of Arizona Observatories. The spectrometer used was designed and built by Uwe Fink for planetary CCD spectroscopy investigations (Fink et al., 1980). It has been used extensively for comet observations (Fink & DiSanti 1990, Fink 1992, Fink 1994, Fink & Hicks 1996, Hicks & Fink 1997).

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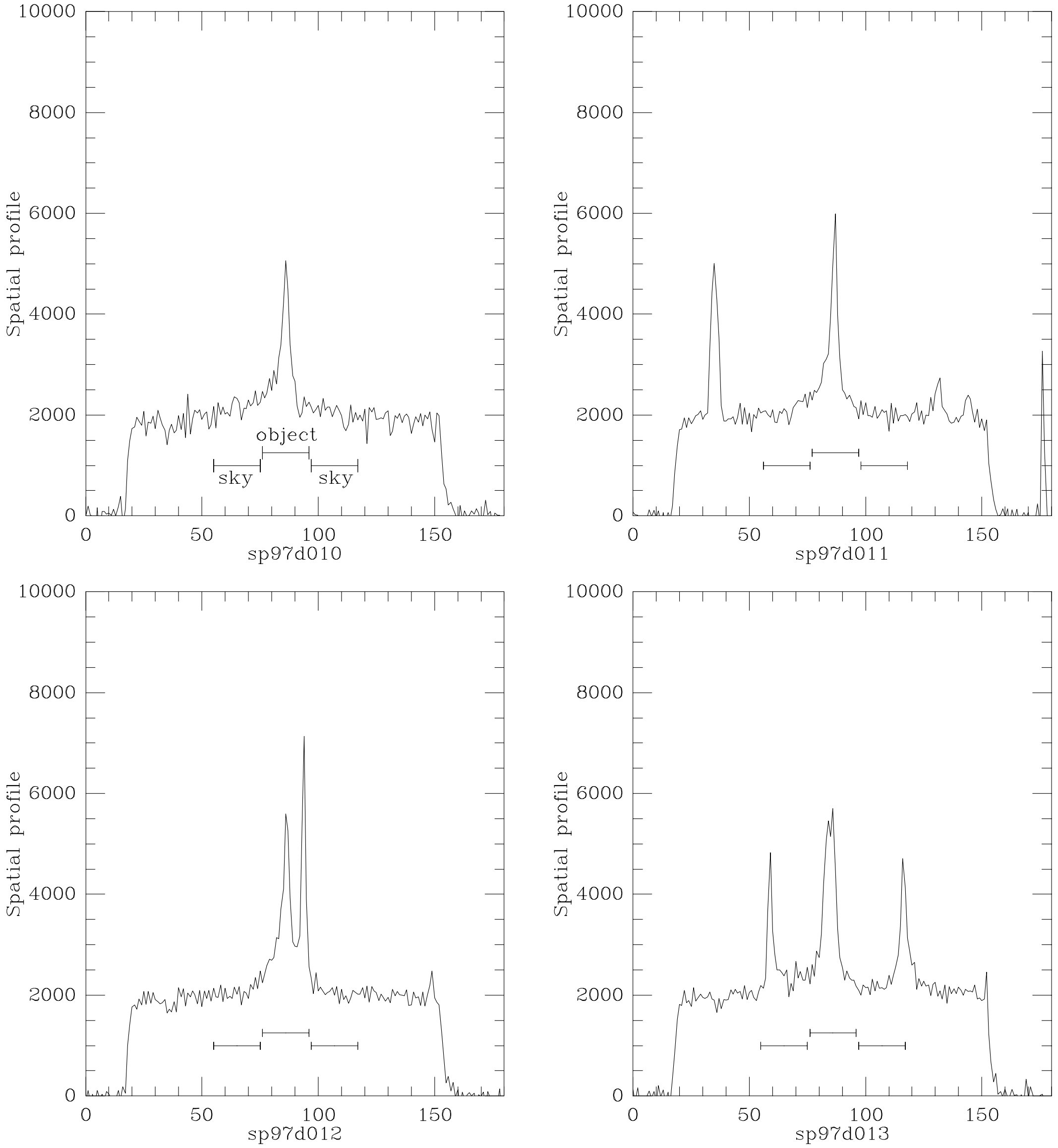

Fig. 1. Intensity profiles along the slit for the four 10 minute exposures of 1997 April 29 at a wavelength of 6700Å. The sky level is near 2000 counts. The comet signal is centered near row 85 with a net peak signal of about 3000 counts. The asymmetric continuum profile with the tail towards lower row numbers can clearly be seen. Our object window of 21 pixels and the two adjacent sky windows are marked on the exposure sp97d010. Except for this exposure all others are compromised by stars passing through the slit

The main aspects of our instrument have therefore been described in the above publications. The detector consists of a thinned 800 × 800 Texas instrument CCD with 15 μm square pixels of which we use a section of 800 columns by 180 rows for imaging our spectrum. The spectral range extends from 5200 to 10000Å at a dispersion of 7.21 Å/pixel. The spatial field of view along the slit is 300$''$ at a scale of 1.5$''$/pixel. For most of our observations the tailpiece of the telescope was rotated so that the spectrograph slit was aligned with the parallactic angle. This ensured that no signal was lost by differential refraction which presented a problem for the relatively high airmasses of Wirtanen. Our slit rotation angles are given in Table 1.

To carry out the guiding we use a dichroic beam splitter which sends the blue portion of the comet's light to our CCD guiding camera and lets the red portion go through to our spectrograph. Our guiding cycle is typically 1 min (30 sec integration and 30 sec readout plus guide). Guiding commands are sent automatically to the telescope, and are of the order of 0.2$''$-0.3$''$. These guiding corrections combined with our typical seeing of 1$''$-1.5$''$ keeps the comet nucleus well centered even in our narrowest 0.25 mm (2.5$''$) slit width.

In our reduction procedure we first interpolate over column defects and the many cosmic ray strikes in the image. The spectrum is then summed over an object window. The nucleus of the comet is centered in the object window. The sky is subtracted using two adjacent and symmetrically placed sky windows each 21 pixels (31.5$''$) in width. Sky subtraction on a wavelength by wavelength basis is necessary because of the many OH night

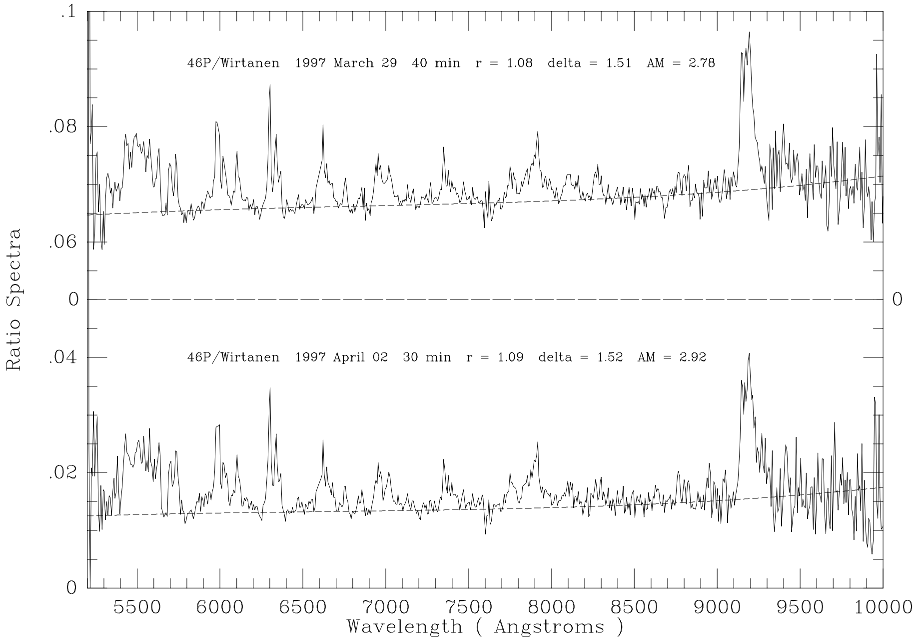

Fig. 2. Ratio spectra of comet 46P/Wirtanen with the solar type comparison star BS2141 at a slit width of 0.25 mm or a spectral resolution of 12Å. The y axis units are fractional flux units relative to the solar comparison star. The scale is the same for both spectra but is labelled for the bottom spectrum only, while the displaced zero level for the top spectrum is indicated. The dashed line represents our continuum fit which we subtract to obtain the cometary emission intensities. The continuum slope is moderately red in agreement with our other comet data (e.g. Fink & Hicks 1996). These two spectra represent the highest signal-noise data that we obtained for 46P/Wirtanen

Table 1. 46P/Wirtanen: 1997 Spring summary of spectral observations:

Run	Date	Expos. (mins.)	Slitwidth (mm)	AM	r (AU)	Δ (AU)	Phase angle(°)	Pos.[a] angle(°)
97A	Jan 28	40	0.50	2.97	1.22	1.65	36.3	0
	Feb 02	40	0.25	3.54	1.19	1.64	36.7	0
	Feb 04	40	0.25	2.26	1.18	1.63	36.9	+50
		20	0.50	3.83	1.18	1.63	36.9	+50
97B	Mar 02	30	0.50	2.45	1.08	1.54	39.6	+58
	Mar 03	40	0.25	2.32	1.07	1.54	39.7	+60
	Mar 06	40	0.25	2.69	1.07	1.53	40.0	+58
97C	Mar 29	40	0.25	2.78	1.08	1.51	41.2	+60
	Apr 02	30	0.25	2.92	1.09	1.52	41.2	+60
97D	Apr 29	40	0.25	2.67	1.23	1.62	38.3	+60
	Apr 30	40	0.25	2.60	1.23	1.63	38.2	+60
	May 01	40	0.25	3.60	1.24	1.64	38.0	+60
	May 02	50	0.50	3.44	1.24	1.64	37.8	+60
	May 03	40	0.50	2.85	1.25	1.65	37.6	0
97E	Jun 01	30	0.50	2.43	1.47	1.92	31.3	+60
	Jun 02	40	0.50	3.01	1.48	1.94	31.0	+60

[a] Position angle of slit in the sky plane. A position angle of 0° means that the slit is oriented N-S.

sky emission lines which become more severe towards 10000Å and exceed the comet signal manyfold. We usually reduce our data using several object windows which allows us to check its consistency and minimizes possible systematic effects. For Wirtanen we used object windows of 21 pixels (31.5″) and 41 pixels (61.5″).

This procedure is not quite as straightforward as it seems since there are often a sizeable number of field stars that pass through the slit. This necessitates shifting the object or sky windows slightly, or in the worst case throwing out several exposures. To avoid compromising a small number of long exposures we usually take a series of medium duration 10 min exposures. The problem of interfering stars was particularly severe during the observing run at the beginning of May. It is illustrated in Fig. 1 by spatial profiles of the four 10 min exposures used for 1997 April 29. The figure also illustrates our typical placement of the object and sky windows and the typical cometary spatial profiles. Most other exposures in the April 29 observing run were similarly compromised.

The “raw spectrum” generated in the above manner is divided by the spectrum of a solar type comparison star taken at an airmass matched to that of the comet. The resulting ratio spectrum is quite flat having the telluric absorptions, the solar intensity distribution and the instrumental response function removed. The spectrum exhibits the cometary continuum slope and emission intensities.

An example of such a spectrum is given in Fig. 2 for the observation dates of March 29 and April 02. Both data sets were taken with a slit width of 0.25 mm (2.5″) yielding a spectral resolution of about 12Å. The March 29 data consists of the sum of four 10 minute exposures while the April 02 data comprises three 10 minute exposures. Each is divided by an appropriate sum of the solar type comparison star BS 2141. The solar type comparison stars that we use are selected from a survey list of such objects by Schuster (1976) using 13 color photometry.

To obtain the emission intensities we subtract a fit to the continuum which is indicated by a dashed line in Fig. 2. Next, fractional emissions are calculated for the $\Delta v = -1$ Swan system C_2 band, the 0,10,0 and 0,8,0 NH_2 bands, the 6300Å OI emission and the red 2-0 and 1-0 CN bands. The wavelength boundaries for these emission windows are the same for all of our comet analyses and are listed in a Table in Fink & Hicks (1996). These fractional intensities are then converted back to counts/second by multiplying by the mean count value of the comparison star spectra in each of the windows equivalent to the comet emissions. The resulting counts/sec in the emission windows are converted to photons/sec m^2 by observing absolutely calibrated standard stars each night whose flux is listed in Johnson (1980). For these standard stars the slit is opened to 1.0 mm (10″); along the slit we use an integration window of 21 pixels (31.5″). Thus essentially all of the light from the standard star is captured.

The raw fluxes in photons/sec m^2 for each of our observation dates and the two apertures of 31.5″ and 61.5″ are listed in Table 2. We feel our raw fluxes must be available to other researchers with more sophisticated models or more up-to-date molecular parameters. We point out that the fluxes listed have sky windows of 31.5″ immediately adjacent to the object windows subtracted. Thus some cometary emission or continuum intensity is also subtracted out. This must be taken into account in any model interpretation.

Table 2. 46P/Wirtanen: Measured flux in slit (photon sec^{-1} m^{-2}) or for continuum (photon sec^{-1} m^{-2}Å^{-1})

Date	Apert.	Species				Cont.^{a}
	arc-sec	OI ^{1}D^b	C_2	CN	NH_2	
Jan 28	5.0×31.5	(100)	1030	900	460	7.24
	5.0×61.5	(114)	1560	1340	600	8.69
Feb 02	2.5×31.5	(68)	680	620	320	6.58
	2.5×61.5	(84)	1350	1010	430	7.18
Feb 04	2.5×31.5	(80)	760	690	330	6.03
	2.5×61.5	(100)	1150	1130	420	7.04
	5.0×31.5	(130)	1530	1170	570	10.39
	5.0×61.5	(170)	2570	2430	730	12.36
Mar 02	5.0×31.5	260	2700	2120	740	15.54
	5.0×61.5	260	4300	3470	950	18.30
Mar 03	2.5×31.5	124	1430	1200	410	8.86
	2.5×61.5	143	2600	1940	530	9.91
Mar 06	2.5×31.5	158	1420	1190	390	9.86
	2.5×61.5	170	2230	1960	490	11.52
Mar 29	2.5×31.5	84	1250	910	340	7.88
	2.5×61.5	101	2010	1670	450	9.15
Apr 02	2.5×31.5	130	1630	1320	500	9.15
	2.5×61.5	160	2310	2220	540	10.27
Apr 29	2.5×31.5	(40)	440	350	150	4.11
	2.5×61.5	(38)	660	540	180	4.86
Apr 30	2.5×31.5	(29)	310	400	130	3.53
	2.5×61.5	(26)	670	680	170	4.07
May 01	2.5×31.5	(30)	260	350	88	3.25
	2.5×61.5	(30)	530	660	66	5.03
May 02	5.0×31.5	(55)	640	520	200	6.11
	5.0×61.5	(56)	1090	1080	230	7.89
May 03	5.0×31.5	(55)	560	570	230	5.58
	5.0×61.5	(62)	1070	1020	290	6.07
Jun 1/2	5.0×31.5	(11)	180	270	70	1.69

[a] photons $sec^{-1}m^{-2}$Å^{-1} at 6250Å

[b] OI^{1}D fluxes in parentheses are 40% of the measured flux in the 6300 Å OI+NH_2 complex.

3. Discussion

We present a summary of our data in Fig. 3 for a slit width of 0.50 mm and in Fig. 4 for a slit width of 0.25 mm. For Wirtanen we did not know before we started our reduction procedure which slit width would be preferable. The wider width of 0.50 mm (5″) is more suitable for faint comets since it captures more light and is more forgiving of small tracking and guiding errors. It will thus yield better absolute photometry. The spectral resolution with this slit is of the order of 18Å. The narrower slit of 0.25 mm (2.5″) yields a better resolution of about 12Å (full width at half maximum intensity), as measured from emission lines of comparison lamps, but it is more sensitive to the above-mentioned effects. The higher resolution of 12Å is especially important for separating the 6300Å OI ^{1}D line from the 6335Å NH_2 complex and the 6364Å OI ^{1}D line. In order not to introduce any systematic effects we took observations at both slit widths for most of our 1997 spring observing runs, except for 1997 June when the comet clearly was too faint for the 0.25 mm slit, and shortly after perihelion March 29/ April 02 when we could safely stick to the 0.25 mm slit width. The data for these two dates has already been displayed in Fig. 2.

Our summary data in Figs. 3 and 4 shows that Wirtanen, quite fortunately, displays readily visible molecular emissions and a moderate continuum level for all of our spectral observing

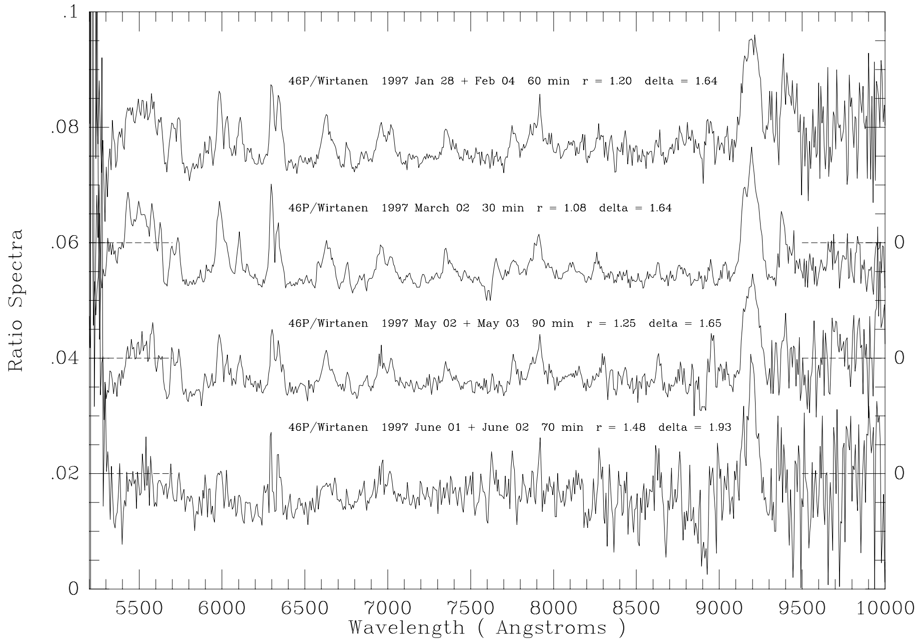

Fig. 3. Summary of P/Wirtanen ratio spectra from 1997 Jan 10 to 1997 June 02 for a slit width of 0.50 mm (resolution ∼18Å). Zero levels are displaced as indicated on the side. For all these dates the comet shows relatively well developed emissions and a moderate continuum level. The comet's brightness faded quite fast as evidenced by the increasing noise level for the June 01/02 data

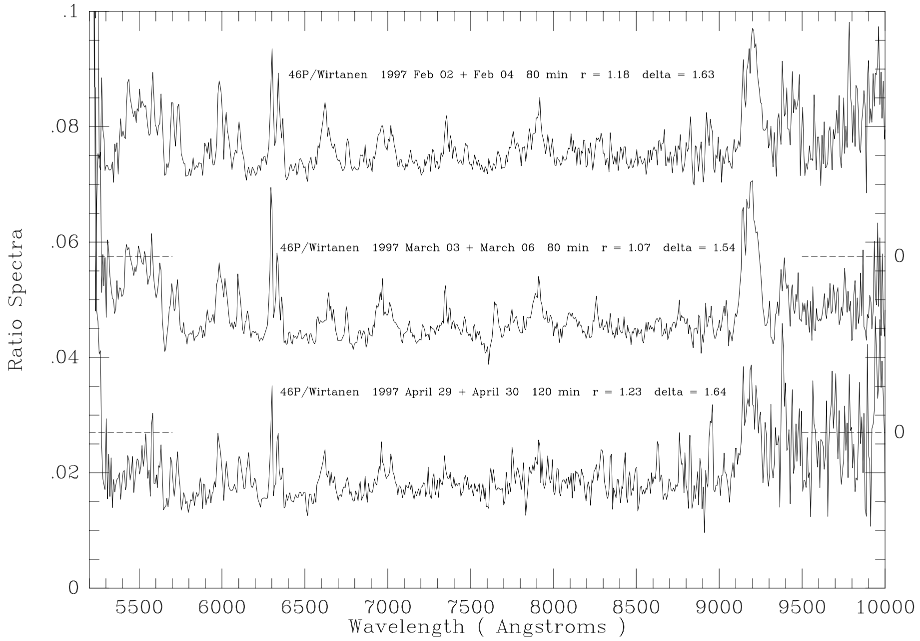

Fig. 4. Summary of our P/Wirtanen ratio spectra for a slit width of 0.25 mm (resolution ∼12Å). The increased spectral resolution over Fig. 3 particularly for the OI 6300-6364Å complex is quite evident. Zero levels are displaced as indicated on the side

runs. This is in contrast to the data of 81P/Wild 2 and C/1995 O1 Hale-Bopp. Both of these comets exhibited extremely high continuum levels with quite feeble emission bands superposed. By 1997 June 01/02 the noise level starts to come up and the emissions are harder to see. All the spectra show an increase in noise from about 8000 to 10000Å due to the decreasing cometary intensity and the increasing levels of the night sky. A visual inspection of the spectra shows no major change in the relative emission intensities or continuum values during our observation period. This is corroborated by our production rate analysis below.

Our calculated production rates and Afρ values for 46 P/Wirtanen are shown in Table 3. Production rates are calculated both for a 21 pixel (31.5″) object integration window and a 41 pixel (61.5″) window. We use a simple Haser model to obtain cometary emission luminosities for each species. We input both the object window and the sky windows of our data reduction into our Haser model program so that the subtracted cometary emission is accounted for properly. The Haser scale lengths and molecular g factors that we use are given in Table 3 of our 39 comet paper (Fink & Hicks 1996). The one exception is the g factor for NH_2 which should be halved (so that NH_2 production rates are doubled) because Arpigny (1994) pointed out that the even bands and the odd bands of NH_2 each account for only half the population in the ground state of the NH_2 molecule.

Table 3. 46P/Wirtanen: Summary of production rates (10^{25} molecules/sec)

Date	Apert. arc-sec	Species H_2O^a	C_2	CN	NH_2	Afρ^b (cm)
Jan 28	5.0×31.5	(1710)	3.44	2.00	5.00	84
	5.0×61.5	(1710)	3.21	1.90	5.02	86
Feb 02	2.5×31.5	(1770)	3.92	2.42	5.98	119
	2.5×61.5	(1970)	4.08	2.52	6.42	114
Feb 04	2.5×31.5	(2060)	4.26	2.65	6.10	107
	2.5×61.5	(2280)	4.04	2.74	6.12	109
	5.0×31.5	(2090)	4.48	2.32	5.56	113
	5.0×61.5	(2290)	4.66	3.02	5.56	114
Mar 02	5.0×31.5	3280	5.45	2.92	5.34	137
	5.0×61.5	2850	5.43	3.02	5.48	137
Mar 03	2.5×31.5	2510	5.50	3.17	5.56	126
	2.5×61.5	2670	6.36	3.28	5.76	124
Mar 06	2.5×31.5	3160	5.43	3.11	5.18	139
	2.5×61.5	3020	5.41	3.28	5.14	142
Mar 29	2.5×31.5	1690	5.02	2.51	4.70	113
	2.5×61.5	1820	5.11	2.92	4.94	115
Apr 02	2.5×31.5	2660	6.84	3.78	7.10	126
	2.5×61.5	3010	6.11	4.05	6.14	132
Apr 29	2.5×31.5	(1110)	2.90	1.55	3.04	79
	2.5×61.5	(950)	2.68	1.52	2.86	82
Apr 30	2.5×31.5	(800)	2.07	1.81	2.64	69
	2.5×61.5	(650)	2.76	1.92	2.72	69
May 01	2.5×31.5	(840)	1.79	1.61	1.88	64
	2.5×61.5	(760)	2.26	1.92	–	87
May 02	5.0×31.5	(970)	2.25	1.24	2.24	75
	5.0×61.5	(860)	2.36	1.61	2.04	83
May 03	5.0×31.5	(970)	1.99	1.37	2.62	70
	5.0×61.5	(950)	2.33	1.53	2.56	65
Jun 01/02	5.0×31.5	(310)	1.27	1.29	1.42	32

[a] H_2O production rates in parentheses were obtained by taking 40% of the measured flux in the 6300Å $OI+NH_2$ complex as applied in Table 2.

[b] Afρ values have been corrected to a common phase angle of 40° using the scattering curves of Divine (1981, 1986).

Our calculation of Afρ values from our continuum intensities at 6250Å follows the original definition given by A'Hearn et al.,1984. In this definition A is the single scattering albedo of the particles, f is the fraction of our observing aperture filled by particles and ρ is our observing aperture radius. Since the column intensity of the dust falls off as $1/\rho$, the quantity Afρ is independent of aperture size within the coma and is thus a good quantitative measure closely comparable to the comet's total magnitude. All of our Afρ values are corrected for a phase angle of 40° using the dust scattering phase function by Divine (1981, 1986). The phase angle of 40° is close to the average for our Wirtanen observations.

Table 4. OI^a and $C_2{}^b$ pure fractions

Run	Date	OI 21 pix	OI 41 pix	C_2 21 pix	C_2 41 pix
97A	Jan 28	14.5%	3.00%	81.0%	83.4%
	Feb 02	13.7%	8.90%	77.2%	80.6%
	Feb 04	24.0%	31.0%	81.5%	78.8%
		20.3%	18.8%	81.6%	83.4%
97B	Mar 02	43.4%	36.7%	86.6%	87.0%
	Mar 03	39.3%	36.4%	88.9%	85.9%
	Mar 06	46.8%	44.8%	85.2%	89.0%
97C	Mar 29	34.8%	32.9%	87.7%	88.5%
	Apr 02	38.3%	39.4%	81.9%	84.1%
	$< 5 >$	40.5% ±4.6%	38.0% ±4.3%	86.0% ±2.7%	86.9% ±2.0%
97D	Apr 29	31.4%	13.6%	83.0%	90.1%
	Apr 30	17.5%	–	78.2%	83.9%
	May 01	44.4%	59.2%	86.2%	92.8%
	May 02	34.2%	22.5%	83.3%	89.3%
	May 03	21.5%	11.0%	80.1%	84.4%
97E	Jun 01/02	–	–	72.0%	–

[a] For OI we list: (measured 6300 Å counts - 0.90 measured 6330Å NH_2 counts)/measured 6300Å counts.

[b] For C_2 we list: (measured 5500Å C_2 complex counts - 0.60 NH_2 0,10,0 band counts)/measured 5500Å C_2 complex counts.

Since the OI ^{1}D line at 6300Å is contaminated by emission from the NH_2 0,8,0 band our standard procedure is to subtract 0.90 of the intensity of the 6334Å NH_2 peak to obtain the pure OI flux in the 6300Å complex. The factor of 0.90 comes from high resolution spectra by Arpigny et al. (1987) and appears to be quite robust over a wide range of geocentric and heliocentric distances.

Using this procedure we show in Table 4 our determination of the percentage of pure OI flux in the 6300Å OI + NH_2 complex (see Table 4 footnote). It is seen that these fractions are quite consistent for our good signal-to-noise-ratio spectra straddling perihelion, (beginning of March and beginning of April). They yield an average of ∼40% for both 21 pixel and 41 pixel object windows. For the other observation dates our data shows considerable scatter. This leads to rather large variations in the comet's water production rate. To avoid this we decided to apply the fraction of 40% pure OI in the 6300Å complex to all the rest of our data. We note that this percentage will be different from comet to comet but should be constant for a particular comet as long as the NH_2/H_2O ratio is not a function of heliocentric distance. While there is no guarantee that this is the case, we note that for 1P/Halley this ratio was quite constant over a heliocentric distance range from 0.73 to 2.5 AU (Fink 1994).

Table 5. P/Wirtanen: Production rates and production rate ratios near Perihelion

	Q(10^{25} mol/sec)				A$f\rho$	Ratio to H_2O $^o/_{oo}$			
	H_2O	C_2	CN	NH_2	(cm)	C_2	CN	NH_2	A$f\rho$
Mar 02	3070	5.44	2.97	5.48	137	1.77	0.97	1.79	44.6
Mar 03	2590	5.93	3.23	5.66	125	2.29	1.25	2.19	48.3
Mar 06	3090	5.42	3.20	5.16	140	1.75	1.04	1.67	45.3
Mar 29	1760	5.06	2.71	4.82	114	2.88	1.54	2.74	64.8
Apr 02	2830	6.47	3.91	6.62	129	2.29	1.38	2.34	45.6
Average	2670	5.66	3.20	5.55	129	2.20	1.24	2.15	49.7
18 comets:[a]					Max	3.9	3.2	2.6[b]	211[c]
					Average	2.7	1.6	1.6	60
					Min	1.6	0.9	0.8	7.7

[a] These values are from Fink & Hicks (1996); the values have been corrected slightly to account for more precise Haser sky correction used in present analysis. Ratios for P/Giacobini-Zinner, Yanaka (1988r), and P/Schwassman-Wachmann 3 have been excluded.

[b] NH_2 ratios are twice those listed in Fink & Hicks (1996) to take into account the corrected g factors pointed out by Arpigny (1994).

[c] Analysis of the dust production of 39 comets has not been completed and so these values are our best preliminary estimates.

Similarly, but not as seriously, the Swan C_2 complex of Δv = -1 centered at 5500Å is contaminated by the 0,11,0 NH_2 band. We have estimated the intensity ratio of this band to that of our measurable 0,10,0 NH_2 band for comet Yanaka (Fink 1992) which has no discernible C_2 emission. We have applied this correction to our measured C_2 fluxes. The correction is relatively minor and is only necessary for comets with low C_2 abundance (i.e. Giacobini-Zinner type comets) or for comets with relatively high NH_2 abundance. Our corrected pure C_2 flux as a percentage of the raw measured 5200Å flux is also listed in Table 4. It can be seen that this percentage is quite consistent for the whole of our Wirtanen observation series.

To determine production rates and see where Wirtanen fits into the ensemble of comets we restrict ourselves to the data around perihelion at the beginning of March and beginning of April. The production rates for these dates in units of 10^{25} molecules/sec and the continuum level A$f\rho$ in units of cm are summarized in Table 5. The production rates listed are averages of our 21 and 41 pixel object windows. The last four columns of this table give the ratios of the parents of C_2, CN, and NH_2 and the continuum A$f\rho$ (cm) to the production rate of H_2O. According to the calculations of Festou & Feldman (1981) quenching of OI by collisions should not be a problem for the relatively low water production rates of Wirtanen, unlike the situation for bright comets such as Hyakutake and Hale-Bopp.

The production rate ratios for each species in Table 5 are quite consistent. The standard deviation is $\sim$ 20% which we estimate to be our approximate accuracy for these ratios. Within these errors of measurement, the constancy of these ratios extends to all of our spring 1997 observations. The exception is a possible indication that the A$f\rho$/H_2O values are higher for our post-perihelion runs at the beginning of April and June. This is somewhat uncertain however, because of our estimate of the pure OI ^{1}D intensity and the noise in the spectra. Within the limited heliocentric range of observation, comet Wirtanen thus follows 1P/Halley for which the ratios of the production rates were constant over the heliocentric distance range 0.73–2.5 AU (Fink 1994; though this paper suggested that the A$f\rho$/H_2O ratio has a heliocentric distance dependence we have since found that this is due to an incorrect phase correction used).

At the bottom of the table we compare the Wirtanen results with the values of the 18 comets that showed good emissions in our 39 comet paper (Fink & Hicks 1994). It is seen that Wirtanen's C_2 and CN abundance ratios are slightly below the average but its NH_2 abundance is definitely enhanced putting Wirtanen in the top three comets of our sample in regard to its relative NH_2 abundance. The quantity A$f\rho$/H_2O is a quantitative indicator of the dust/gas ratio in comets but because A$f\rho$ does not measure the dust production rate directly the ratio does not have meaningful units. The ratio is best used to compare the relative dustiness of comets. In this respect comet Wirtanen falls slightly below, but very close to the median of our comet sample studied so far.

Our average water production rate at a distance of 1.08 AU straddling perihelion is 2.67×10^{28} molecules/sec. Quite interestingly the estimated water production rate of 4×10^{28} by Jorda & Rickman (1995) is rather close to our measured number. To obtain this value Jorda & Rickman used the reported visual magnitudes of Wirtanen from its 1984 and 1991 apparition and an empirical relationship between a comet's water production rate and its visual magnitude (Jorda, Crovisier & Green 1992). This empirical relationship works well for Wirtanen since we have now shown above that the Afρ/H_2O or dust to gas ratio (which can vary by a factor of 10–20 for different comets) was very close to the median value of our larger comet sample as discussed above.

We can combine our measured water production rate and an estimate of the comet's nuclear radius of $\sim$0.6 km (Lamy 1996, Fink et al.,1997, Meech et al.,1997) to estimate the fraction of the active area of the comet. For the evaporation rate of ice we have recourse to a recent preprint by Huebner and Boice (1997) which employs fairly sophisticated models to calculate the insolation induced vapor flux of ice. At 1.08 AU these authors obtain an average vapor flux of 6.8×10^{17} for a slow rotator and 2.8×10^{17} molecules/cm^2 sec for a fast rotator. By comparison, Jorda & Rickman (1995) use a value of 5×10^{17}. We thus obtain a required surface area of 3.9 km^2 for a slow rotator and 9.5 km^2 for a fast rotator. A comet with a radius of 0.6 km has a surface area of 4.5 km^2. We are thus lead to the conclusion that essentially the whole surface of the comet must be actively outgasing. Quite possibly, the whole comet surface is covered by a fairly substantial dark mantle of accumulated dust and debris which is outgasing fairly uniformly over its entire surface with little or no bare ice exposed.

In this somewhat simplistic model we have assumed that the comet surface terrain consists of two types only: active areas with exposed fresh water ice and a high albedo close to 1.0, and inactive areas of accummulated debris with a low albedo.If the active areas are severely darkened by dust contamination, their water evaporation rate per unit area could be considerably higher than that assumed in the model by Huebner and Boice. Conversely however, a thicker low albedo crust would inhibit the free evaporation of water ice perhaps bringing its rate back down to that of the high albedo case. We hope that the spacecraft experiments aboard Rosetta will be able to resolve some of these questions.

To determine the development of the comet's activity versus heliocentric distance (r_H) we employ our measured Afρ values. Clearly Afρ is a good measure of the comet's dust production. It can also serve as a good indicator of the comet's gas production rate even though this cannot be measured over as large a range of distances. We have demonstrated for the present comet as well as for 1P/Halley (Fink 1994), and for C/1996 B2 Hyakutake (Hicks & Fink 1997) that the ratio Afρ/H_2O is constant over the range of heliocentric distances for which the gas production rate could be measured.

We plot in Fig. 5, $\log_{10}$ Afρ versus $\log_{10} r_H$. In addition to our present spectroscopically determined numbers we also plot the Afρ values determined in our Wirtanen photometry paper Fink et al.(1997) and the photometry of Meech et al.(1997). We converted the R magnitudes listed in Meech et al.(1997) to Afρ values by subtracting a nuclear contribution assuming a Wirtanen radius of 0.60 km and a geometric albedo of 0.04. The Afρ values were then corrected to a common scattering phase angle of 40°.

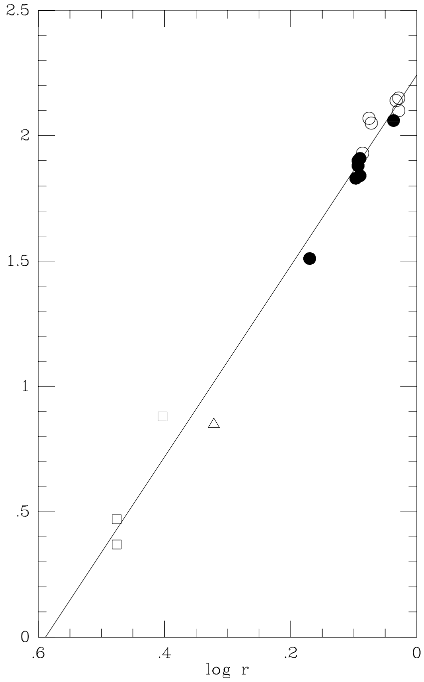

Fig. 5. Log-log plot of Afρ versus the heliocentric distance r. All Afρ values have been corrected to a scattering angle of 40°. Open circles represent our pre-perihelion points. Closed circles are post-perihelion spectroscopic points. Open squares are from Meech et al. (1997). Open triangles are from Fink et al. (1997). Solid line is a least squares fit to all the data yielding a slope of 3.8

Quite interestingly the spectroscopic Afρ values near perihelion and the photometric Afρ's at large r_H can all be represented by a single straight line. No pre-post perihelion asymmetry is evident in our spectroscopic data. A least squares fit yields a line with a slope of 3.8. Even separately the two data sets each fit essentially the same straight line. The comet's activity level as represented by Afρ thus has a heliocentric dependence $r^{-3.8}$. For comet 1P/Halley we found a dependence of $r^{-2.5}$ and for Hyakutake we found $r^{-1.5}$. Converting the Afρ heliocentric dependence to a stellar magnitude scale, and without concerning ourselves with the constant term we obtain:

$$\begin{aligned} \text{observed mag.} &= \text{const.} + 5\log\Delta + 5\log r_H + 9.5\log r_H \\ &= \text{const.} + 5\log\Delta + 14.5\log r_H \end{aligned}$$

We can compare this expression with the visual lightcurve data for Wirtanen that we assembled a few years ago for the apparition in 1984 and 1991 (Hergenrother & Fink,1994). A rough fit to this data yielded a coefficient of 17.5. An almost identical coefficient of 17.9 was obtained by Jorda & Rickman (1995). We feel that the visual lightcurve coefficient may be slightly higher than a fit to our Afρ values since the visual magnitudes include the substantial C_2 emissions. At larger heliocentric distances their contribution to the visual brightness will fade considerably because of the increase in scale length for the C_2 emissions. Our coefficient of 14.5 is in excellent agreement for typical periodic comets. In a statistical study of

62 comets, Kamel (1996) finds an average coefficient of 18.5 (2.5 × 7.4) and a median coefficient of 15.3.

4. Conclusions

Combining our results we find that Wirtanen has a water production rate which is right in the middle of that for periodic comets. Its dust/gas ratio is also very typical as are the production rate ratios of C_2/H_2O and CN/H_2O. The ratio of NH_2/H_2O is somewhat high but not excessively so. Its brightness variation with heliocentric distance follows that of an average periodic comet well. We conclude that Wirtanen appears to fit well into the Jupiter family which is the most common type of periodic comet. Wirtanen should represent an excellent sample to be investigated in an in depth study with a variety of instruments on board of the Rosetta spacecraft.

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