Astron. Astrophys. 326, 1268–1276 (1997)

ASTRONOMY AND ASTROPHYSICS

Rotation of comet 46P/Wirtanen

K.J. Meech[1], **J.M. Bauer**[1], **and O.R. Hainaut**[1,2]

[1] Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
[2] European Southern Observatory, Casilla 19001, Santiago, Chile

Received 14 March 1997 / Accepted 23 May 1997

Abstract. We have observed comet 46P/Wirtanen during 1996 June, August and November using the University of Hawai‘i 2.2m telescope. At the time of the observations, the comet was at heliocentric distances, r = 2.99, 2.53 and 1.83 AU. During the August run observations were made in order to search for light curve variations due to rotational modulation of the nucleus. The comet was active for all runs, and during 1996 August the coma extended $>16''$ (1.8×10^4 km at the distance of the comet) at PA $\approx 325°$, and during 1996 November the coma extended $>20''$ (2.5×10^4 km at the distance of the comet) at PA $\approx 75°$. The surface brightness profile exhibited a gradient slope of -1.6 and -1.4 in August and November, respectively, only slightly steeper than that expected by radiation pressure and phase angle effects alone. Using a phase-dispersion minimization technique, we find a possible rotation period near 7.6 hours. The color of the nucleus plus dust is $B-V$ = 0.756 ± 0.009, $V-R$ = 0.456 ± 0.009 and $R-I$ = 0.366 ± 0.009 averaged over the three runs.

Key words: comets: 46P/Wirtanen – space vehicles

1. Introduction

46P/Wirtanen is the primary target for the European Space Agency's *Rosetta* mission which will study the onset of cometary activity from beyond a heliocentric distance r = 3 AU through perihelion (Schultz, 1996). In order to ensure the success of the encounter and optimize the mission parameters, it is important to determine the basic physical properties of the comet, including nucleus size and shape, rotation period, as well as characterize the cometary activity versus r. Jorda and Rickman (1995) have compiled an excellent summary of the observations of the 7 previously observed perihelion passages. Due to its chaotic orbit, large perihelion distance prior to the 1974 apparition, and its projected position against the galactic plane, there were few early observations of 46P/Wirtanen. Based on observations when the comet was at $r < 2.6$ AU, Jorda and Rickman (1995) inferred a nucleus size of $r_N < 2$ km, with a fairly large active surface area ($\approx$ 20%). Boehnhardt et al. (1996a) recovered the comet at r = 4.62 AU during 1995 June, while it was probably still inactive. Using the new orbit, Hainaut and West (1996) re-observed the comet during 1996 March at r = 3.51 AU, and there was still no evidence of coma. Boehnhardt et al. (1996b) re-observed the comet during 1996 April at r = 3.30 AU at which point the comet exhibited a $4''$ coma. During 1996 July, Parker et al. (1996) used the Faint Object Spectrograph in the UV to obtain an upper limit to the albedo of Wirtanen of $p_v < 0.07 \pm 0.03$. More recently, on 1996 August 28, Lamy (1996) used the WFPC2 on HST to image the inner coma in an attempt to detect the nucleus. At Δ = 1.5 AU, the resolution would have been $\approx$ 47 km at the comet, insufficient to resolve the nucleus directly, however, it was possible to extrapolate the coma contribution in to the central region, and from this infer a nucleus size. Assuming a geometric albedo of p_v = 0.04, they determined a mean effective radius, r_N = 0.58 km. In addition, they noted that the inferred nucleus brightness varied from R = 21.6-21.9 during 1.5 hours.

Send offprint requests to: K.J. Meech, IfA, Hawai‘i

2. Observations

We observed the comet from the University of Hawai‘i 2.2m telescope on Mauna Kea during three runs in 1996 June, August and November. The specifics of the observations, including observing conditions and orbital geometry for the comet are shown in Table 1. The images were obtained using the Tektronix 2048 × 2048 CCD camera using the Kron-Cousins photometric system (B: λ_0 = 4380Å, $\Delta\lambda$ = 1077Å; V: λ_0 = 5450Å, $\Delta\lambda$ = 836Å; R: λ_0 = 6460Å, $\Delta\lambda$ = 1245Å; I: λ_0 = 8260Å, $\Delta\lambda$ = 1845Å). All of the images were guided at cometary rates.

June 1996: The weather was photometric during the June run, with excellent seeing on the first night ($0\overset{''}{.}6$). Because of the faintness of the comet, we obtained only a few images for the purpose of compiling a light curve of the development of its brightness as a function of distance. A composite 1200 sec image from 1996 June 13 is shown in Fig. 1a.

August 1996: A series of twenty eight 10 minute exposures were taken over a span of 5.4 hours on the first night and a total of 18 exposures were taken the second night covering a total time span of 3.8 hours. During the exposures, the non-sidereal guiding caused field star trails of slightly less than $10''$ in length on each frame. A composite image of the first night's observations is shown in Fig. 1b. The coma is seen to extend to at least 1.8×10^4 km (16″) projected at the distance of the comet at PA $\approx 305°$. The composite was created from 10 images when the comet was clear of field stars, by calculating the shifts between images based on a 2 step process. Guiding errors were calibrated by computing an average frame offset from the measured centroids of ≈ 20 field stars. The shifts due to the motion of the comet were computed from the comet's ephemeris positions and the plate scale of the CCD (0.″219 pix^{-1}). The seeing varied between 1.″4 and 1.″6 throughout the first night, and between 1.″7 and 2.″8 the second night. The beading in the star trails is due to the finite update time of the TV guider. The first night was photometrically stable, and on the second night we had to terminate the observations early because of fog and high humidity, however this did not affect the calibration of the data we observed prior to closing.

November 1996: Finally, 2 images of the comet were obtained on 1996 November 12, under conditions of good seeing (0.″7). Because there was some thin cirrus on this night no standard stars were obtained, and the fields will have to be recalibrated. Therefore, no absolute calibration is available. The composite image is shown in Fig 1c, and the projected coma is seen extending to 2.5×10^4 km (20″) at PA $\approx 74°$which is approximately in the anti-solar direction.

All the images were reduced in the standard manner, using flat fields obtained on the evening and morning twilight sky. The resultant frames were flat to better than 0.1% across the CCD. Additionally, the images were cleaned of cosmic rays, using the *cosmicray* routine in IRAF (the Image Reduction and Analysis Facility, Tody (1996)). The thresholds for cosmic ray removal were determined by computing robust sky statistics, using 5-σ of the sky noise for the cutoff for cosmicray detection. The frames were calibrated using the standard stars of Landolt (1992). Observations of typically 20-40 stars were obtained over a range of air-masses, and with a wide dispersion of colors to fit for both extinction and color terms. The calibrated photometry from the first two runs is presented in Table 2.

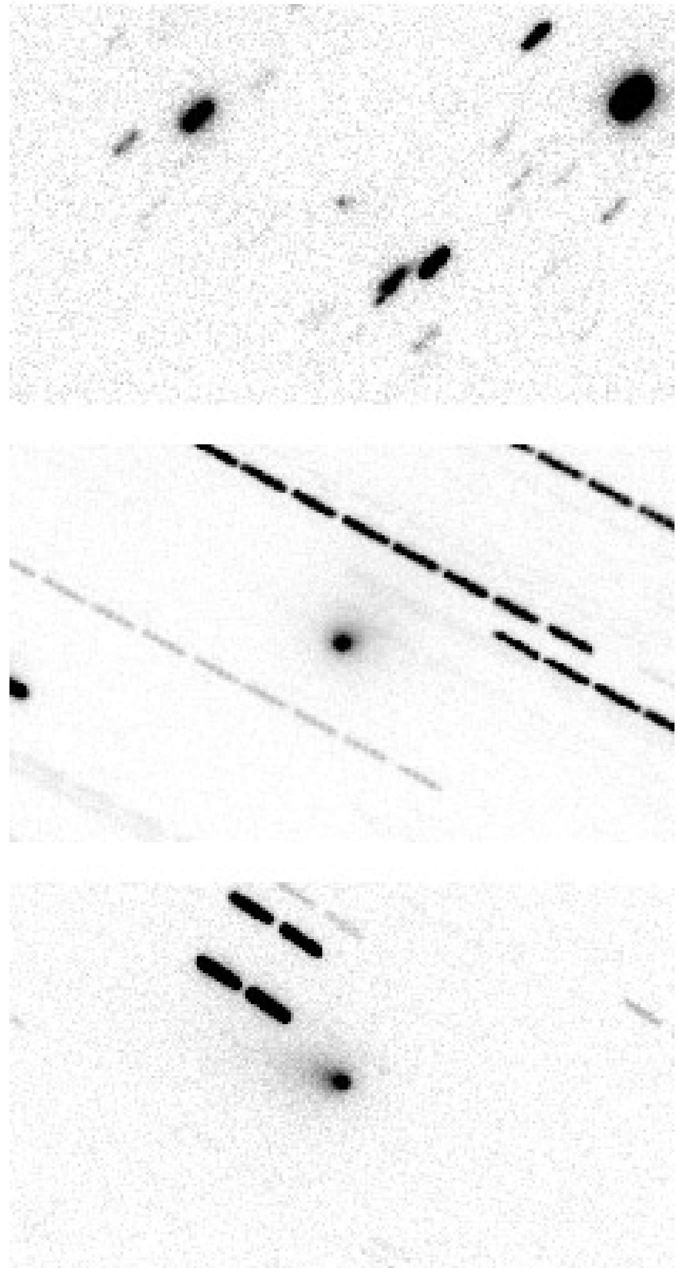

Fig. 1. a (top) Image of Comet 46P/Wirtanen obtained on 1996 June 14. The total integration time was 1200 sec through an R filter. The comet is the untrailed object located at the image center. The 109″-wide image is 1.9×10^5 km across at the distance of the comet (Δ = 2.398 AU). The PA of the extended heliocentric radius vector is 254.2°. **b** (middle) Image of comet 46P/Wirtanen obtained on 1996 August 17. The image is a composite of ten 600 sec images through an R filter. The image is 1.2×10^5 km across at the distance of the comet (Δ = 1.551 AU). The PA of the extended heliocentric radius vector is 4.6°. **c** (bottom) Image of Comet 46P/Wirtanen obtained on 1996 November 12. The total integration time was 1200 sec through an R filter. The image is 1.3×10^5 km across at the distance of the comet (Δ = 1.683 AU), and the PA of the extended heliocentric radius vector is 82.1°. North is at the top, East at the left in all images.

3. Analysis

3.1. Photometry

The extraction of the comet flux from the CCD frame was done using the program *basphotc* (see Buie and Bus, 1992 for a description of the software). The flux was accumulated within a circular aperture centered on the center of light and the sky background flux was determined from an annulus centered on the comet. The statistical moments of the sky sample were used to reject any bad pixels or field stars found in the sky annulus. The smallest aperture possible was selected to minimize the contamination from the coma while including the most light from the core. We found that the optimum aperture size was 2.″5 radius for the comet. For the June data, where there was little coma, we used a sky annulus between 6–15″, and for the August data a sky annulus between 9–11″. We measured the

Table 1. Observing circumstances

UT Date	Telescope	Obs[1]	r [AU][2]	Δ [AU][2]	α [AU][2]	Tail[3]	Seeing[4]	SkyB[5]	#[6]	Filter[7]	Sky[8]
06/13/96	UH2.2m	MHK	2.993	2.417	−17.89	253.9	0.6	20.8	7	VRI	Phot
06/14/96	UH2.2m	MHK	2.986	2.398	−17.80	254.1	1.0	20.7	3	R	Phot
08/17/96	UH2.2m	MHB	2.533	1.551	7.11	4.3-5.1	1.5	20.8	28	BVRI	Phot
08/18/96	UH2.2m	MHB	2.526	1.546	7.35	8.0-8.5	1.7-2.8	20.8	17	BVRI	Phot
11/12/96	UH2.2m	MHBP	1.830	1.683	32.38	82.1	0.7	N/A	2	R	Cirrus

Notes: [1]M = K. J. Meech, H = O. R. Hainaut, K = D. Kakazu, B = J. M. Bauer and P = C. Petersen (Univ. CO); [2]r, Δ, and α are the heliocentric and geocentric distances [AU], and phase angle [deg] respectively; [3]Position Angle [deg] of the extended heliocentric radius vector (i.e. expected tail direction); [4]Average seeing FWHM [$''$]; [5]Night sky brightness in the R filter [mag arcsec^{-2}]; [6]Number of images obtained on each night; [7]Filters on the Kron-Cousins system; and [8]Sky conditions.

Table 2. Journal of 46P/Wirtanen observations

Date[1]	JD[2]	Mid UT	χ[3]	F[4]	Mag $\pm\ \sigma$	Date[1]	JD[2]	Mid UT	χ[3]	F[4]	Mag $\pm\ \sigma$
6/13/96	247.9867	11:40:50	2.524	R	21.633 ± 0.118	8/17/96	312.9475	10:44:26	1.599	R	19.233 ± 0.006
6/13/96	247.9867	11:40:50	2.524	R*	21.683 ± 0.080	8/17/96	312.9558	10:56:24	1.611	R	19.287 ± 0.020
6/13/96	247.9954	11:53:25	2.308	R	21.601 ± 0.100	8/17/96	312.9640	11:08:06	1.628	R	19.240 ± 0.006
6/13/96	247.9954	11:53:25	2.308	R*	21.683 ± 0.069	8/17/96	312.9721	11:19:46	1.652	R	19.253 ± 0.022
6/13/96	248.0040	12:05:47	2.136	I	21.512 ± 0.294	8/17/96	312.9802	11:31:27	1.681	R	19.279 ± 0.007
6/13/96	248.0040	12:05:47	2.136	I*	21.502 ± 0.187	8/17/96	312.9883	11:43:08	1.719	R	19.264 ± 0.007
6/13/96	248.0123	12:17:39	1.999	I	21.225 ± 0.202	8/17/96	312.9964	11:54:48	1.763	R	19.229 ± 0.008
6/13/96	248.0123	12:17:39	1.999	I*	21.320 ± 0.142	8/17/96	313.0045	12:06:29	1.817	R	19.253 ± 0.007
6/13/96	248.0211	12:30:26	1.875	V	21.942 ± 0.101	8/17/96	313.0126	12:18:12	1.881	R	19.213 ± 0.021
6/13/96	248.0211	12:30:26	1.875	V*	22.113 ± 0.076	8/17/96	313.0207	12:29:52	1.957	R	19.228 ± 0.007
6/13/96	248.0899	14:09:24	1.413	R	21.372 ± 0.088	8/17/96	313.0288	12:41:31	2.046	R	19.233 ± 0.007
6/13/96	248.0899	14:09:24	1.413	R*	21.532 ± 0.066	8/17/96	313.0370	12:53:13	2.152	R	19.205 ± 0.007
6/14/96	249.0026	12:03:45	2.119	R	21.286 ± 0.069	8/17/96	313.0451	13:04:57	2.277	R	19.208 ± 0.008
6/14/96	249.0026	12:03:45	2.119	R*	21.434 ± 0.051	8/17/96	313.0533	13:16:47	2.431	I	18.947 ± 0.044
6/14/96	249.0109	12:15:42	1.984	R	21.379 ± 0.073	8/17/96	313.0616	13:28:40	2.617	B	20.307 ± 0.009
6/14/96	249.0109	12:15:42	1.984	R*	21.540 ± 0.055	8/18/96	313.8247	07:47:30	2.200	R	19.225 ± 0.009
6/14/96	249.0973	14:20:10	1.389	R	21.268 ± 0.057	8/18/96	313.8334	08:00:06	2.080	R	19.265 ± 0.009
6/14/96	249.0973	14:20:10	1.389	R*	21.389 ± 0.042	8/18/96	313.8423	08:12:54	1.977	V	19.735 ± 0.012
8/17/96	312.8370	08:05:16	2.072	R	19.299 ± 0.024	8/18/96	313.8507	08:25:02	1.896	R	19.247 ± 0.008
8/17/96	312.8465	08:19:00	1.965	I	18.936 ± 0.012	8/18/96	313.8589	08:36:52	1.830	I	18.883 ± 0.016
8/17/96	312.8548	08:30:57	1.886	B	20.473 ± 0.008	8/18/96	313.8671	08:48:39	1.775	V	19.634 ± 0.011
8/17/96	312.8631	08:42:54	1.820	V	19.703 ± 0.008	8/18/96	313.8753	09:00:27	1.729	B	20.361 ± 0.010
8/17/96	312.8732	08:57:27	1.754	R	19.226 ± 0.007	8/18/96	313.8835	09:12:18	1.690	I	18.845 ± 0.015
8/17/96	312.8820	09:10:07	1.707	R	19.215 ± 0.006	8/18/96	313.9240	10:10:32	1.598	R	19.278 ± 0.009
8/17/96	312.8903	09:22:03	1.672	R	19.196 ± 0.006	8/18/96	313.9325	10:22:46	1.596	R	19.300 ± 0.008
8/17/96	312.8984	09:33:45	1.644	R	19.210 ± 0.006	8/18/96	313.9406	10:34:31	1.601	R	19.290 ± 0.008
8/17/96	312.9065	09:45:24	1.622	R	19.233 ± 0.006	8/18/96	313.9488	10:46:20	1.610	R	18.298 ± 0.053
8/17/96	312.9151	09:57:45	1.606	R	19.219 ± 0.006	8/18/96	313.9570	10:58:07	1.625	R	19.281 ± 0.053
8/17/96	312.9232	10:09:25	1.596	R	19.219 ± 0.006	8/18/96	313.9652	11:09:51	1.647	R	19.337 ± 0.009
8/17/96	312.9313	10:21:06	1.591	R	19.211 ± 0.006	8/18/96	313.9734	11:21:42	1.675	R	19.295 ± 0.008
8/17/96	312.9394	10:32:46	1.592	R	19.220 ± 0.006	8/18/96	313.9815	11:33:23	1.709	R	19.506 ± 0.009

Notes: [1]1996, [2]Mid-exposure Julian Date – 2450000; [3]Airmass; [4]Kron-Cousins filter. All measurements were made from 600 sec integrations. Unless marked with "*", which represents a measurement through a 2.″0 aperture, all measurements were made through a 2.″5 radius circular aperture.

magnitudes of several field stars of equal or greater brightness to the comet on each frame in order to do relative photometry. We measured flux values using the aperture photometry techniques described above. A 12$''$ aperture sufficiently encompassed the entire signal from any field standard, and owing to the trailing, no centroid fitting was employed for the aperture centering. For the first night's data, eighteen field standards were chosen from thirty nine measured stars, and for the second night fifteen field standards were chosen. In addition, several faint stars along the path of the comet were measured in each frame so that their average total flux could be calculated for subtraction from the frames where they were in the photometry aperture with the comet.

After correcting the measured magnitudes for extinction, we used the deviations of the field star magnitudes in each frame from their nightly average values to correct for frame-to-frame

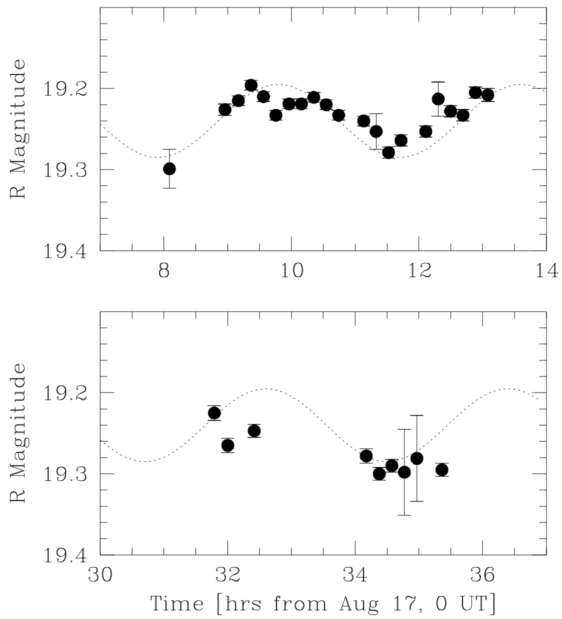

Fig. 2. R-band photometry of Comet 46P/Wirtanen from 1996 August through a 2.″5 radius aperture. The best-fit period of 7.6 hours is plotted (as a 3.8 hr period sine curve, assuming that the actual light curve is double-peaked) with an amplitude of 0.045 mag (dotted line) for comparison We don't attempt to represent any higher orders of the light curve because of the limited dataset. Data with large error bars are those which have been corrected for field star contamination.

Table 3. 46P/Wirtanen coma colors

UT Date	B-V	V-R	R-I
6/13/96	—	0.480 ± 0.086	0.235 ± 0.120
8/17/96	0.770 ± 0.011	0.450 ± 0.011	0.381 ± 0.013
8/18/96	0.727 ± 0.015	0.439 ± 0.013	0.354 ± 0.012
Average	0.756 ± 0.009	0.456 ± 0.008	0.366 ± 0.009
Solar‡	0.62	0.36	0.28

Notes: ‡Solar colors in the Kron–Cousins system as transformed from the Johnson solar colors (Allen, 1973) using the relationships of Fernie (1983).

extinction variations in the comet's measured signal. The average frame to frame variations for August 17 were extremely small, typically < 0.007 mag, indicating that the night was very stable. Likewise, we found that the fog which caused the early termination of observations on August 18 affected only the last two observations, and these have not been included in Table 2.

3.2. Period search

Standard period search techniques were used to find the period of the light curve, including both a minimization of the χ^2 statistic for goodness-of-fit and a phase dispersion minimization technique, PDM, (Stellingwerf, 1978) modified to weight the data according to their errors. The χ^2 technique computes the sum of the residuals of the data minus an assumed light curve variation (here, a sine curve) as a function of frequency or period. The best fit period (regardless of the actual light curve shape) should fall at the minimum of χ^2. The PDM technique minimizes the variance of the data which has been converted to a phase for each trial period and grouped into bins. The Θ–statistic as defined by Stellingwerf, is the ratio of the total data variance to the combined bin variance. Significant periods are those for which the minimum in the PDM Θ statistic plot falls below 1.0. We tested a range of periods between 2.5 and 5.9 hours. As shown in Fig. 3, the minimum is rather broad for the August data. This is because the night 2 data is too sparse to help constrain the period, and our observing interval on night 1 was nearly the same as the length as the period. Therefore our present data set cannot completely constrain the rotation period, however the deepest minimum is near $P \approx 3.8$ hrs. Both techniques yielded similar values. Assuming a double-peaked light curve, this leads to a rotation period near 7.6 hours. The phased light curve is shown in Fig. 4. This is different from our preliminary estimate near 6.7 hrs (Bauer et al., 1996) due to the addition of the night 2 data, and the correction of field star contaminated data points which extended the time baseline of the observations. The data show a very low amplitude of variation, probably ≤ 0.045 mag (of the order of 5× the error bars).

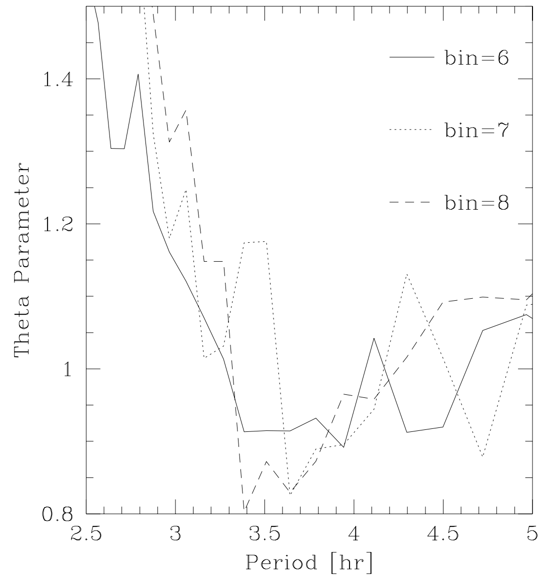

Fig. 3. Phase dispersion minimization Θ – parameter for periods between 2.5 and 5.0 hours for the data from 1996 August. Three different binning intervals are shown.

The rotation period is typical of other small comet nuclei (Meech, 1997) which range between 3-15 hours. The rotation is relatively rapid which implies that for thermal modelling, fast rotating models may be more appropriate.

3.3. Heliocentric light curve

The data from this paper, Boehnhardt et al. (1997), Fink et al. (1997) and the *Minor Planet Circulars* are shown in Fig. 5 which plots the reduced magnitude, R(1,1,0) as a function of r. A

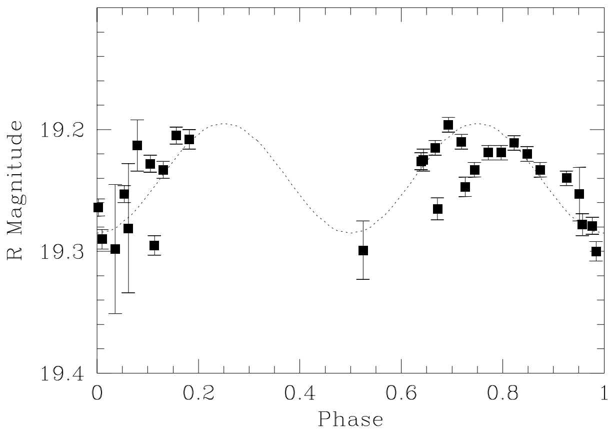

Fig. 4. Comet 46P/Wirtanen data from 1996 August phased to the rotation period of 7.6 hours. Phase of $\phi = 0$ occurred at JD = 2450312.9875. A sine curve with P = 7.6 hrs and amplitude of 0.045 mag is plotted as a dotted line for reference.

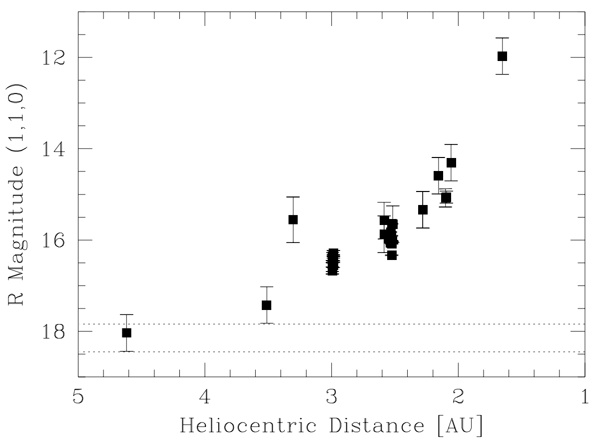

Fig. 5. Comet 46P/Wirtanen broadband R data reduced to unit r, Δ, and zero phase plotted versus r. Data are from this paper, Boehnhardt et al. (1995), Fink et al. (1997), and the Minor Planet Circulars No. 26953, 27351, 27688–9, 27955, 28120, and 28338. The dotted lines represent the likely brightness range for the bare nucleus (see text).

linear phase coefficient of 0.04 mag deg^{-1} was used to compute R(1,1,0). The horizontal lines correspond to the best estimate of the flux contribution from a bare nucleus, using the nucleus size from Lamy (1996) and assuming a geometric albedo between p_v = 0.04–0.07, where the low end is typical of measured dark nuclei (Meech, 1997) and 0.07 is the upper limit from Parker et al. (1996). The rotational brightness variation, with an amplitude of $\approx$ 0.045 mag, is not evident on the composite light curve. From the figure, it is clear that activity probably began near r = 4 AU, although the image obtained at 3.51 AU does not show any coma.

3.4. Surface brightness profiles

The radial surface brightness profile of the coma can provide basic information about the variation of the grain column density along the line of sight through the coma as a function of projected distance from the nucleus. In addition, solar radiation pressure limits the extent of the coma in the sunward direction, and the extent of this region will depend on the grain velocity, scattering properties and composition. Fig. 6 presents the surface brightness gradient profile for 46P/Wirtanen computed from a composite image of nine 600 sec exposures from 1996 August 17, and the corresponding gradient plot for the two 1996 November images is shown in Fig. 7. The term SB as shown in the figure is a surface brightness computed from

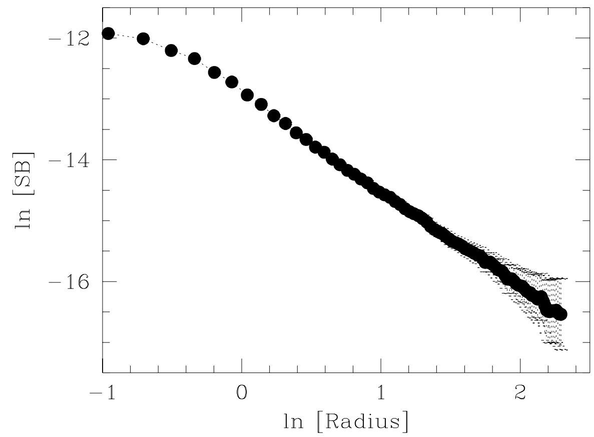

Fig. 6. Surface brightness gradient profile for comet 46P/Wirtanen from 1996 August 17. The slope of the profile beyond 1$''$ is -1.62 ± 0.07. See discussion for a description on conversion of SB to absolute flux units (W m^{-2} Sr^{-1}).

$$\ln(SB) = -0.921034\ m_{SB} \quad (1)$$

where m_{SB} is the surface brightness expressed in mag arcsec^{-2}. This can be converted to an absolute flux using the absolute flux densities found in Bessell (1979) for the Kron-Cousins system using

$$SB = \Delta\lambda\ 10^{0.4(q_\lambda - m_{SB})} \quad (2)$$

where $q_R = -29.117$ (to give SB in W m^{-2} Sr^{-1}), and $\Delta\lambda$ = 1245Å is the bandpass.

A linear least-squares fit to the curve beyond 1$''$ (i.e. outside the area affected by seeing) gives a slope of -1.62 ± 0.07 in August and a slope of -1.43 ± 0.08 in November. A canonical isotropic steady-state coma should produce a profile with a slope of -1, and radiation pressure effects and phase angle effects can produce profiles as steep as -1.5 (Jewitt & Meech, 1987). Profiles which have slopes steeper than -1.5 may be caused by non-steady state emission, or by fading grains, whereas shallower profiles require a source function in the coma (e.g. fragmenting grains or production of gas from grains).

3.5. Discussion

We can use the observed rotational amplitude to determine a minimum axis ratio for the comet. Assuming that the bare nu-

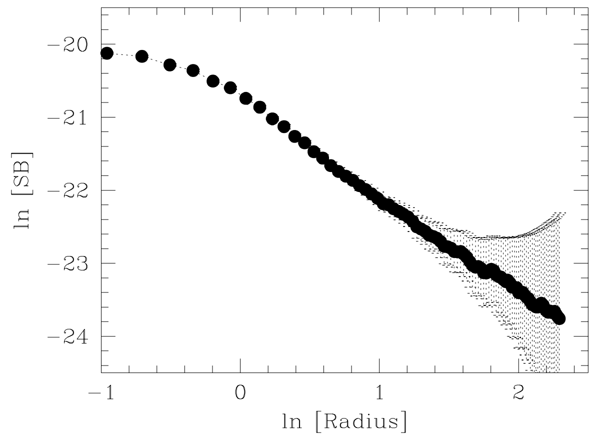

Fig. 7. Surface brightness gradient profile for comet 46P/Wirtanen from 1996 November 12. The slope of the profile beyond 1″ is -1.43 ± 0.08. The scale for SB is only relative because of cirrus on this night (no absolute calibration is currently available).

cleus can be modeled as a tri-axial ellipsoid with axis dimensions $a > b > c$, most likely rotating along the shortest axis, the area of the nucleus projected on the plane of the sky would vary from πac to πbc in case of an aspect angle (between the line of sight and the rotation axis) of 90°, and be constantly equal to πab if the aspect angle is 0°. Since the scattered light is proportional to the projected area of the nucleus, the range of the light curve will vary from 0 (for a 0°aspect angle) to $a : b$ (90°aspect angle). The measured amplitude of the light curve can therefore be interpreted as a lower limit for the $a : b$ ratio, using the following relation for the inverse ration:

$$\epsilon = b : a \leq 10^{-0.4\Delta m} \tag{3}$$

where Δm is the full range of the light curve in magnitudes. However, because the comet is active, with a coma, the light curve range gets diluted by scattered light from the coma, so that the actual light curve range we observe is a lower limit. From the range of the light curve shown in Fig. 5 ($\Delta m \approx 0.09$), we obtain $a : b \geq 1.09$. We attempted to employ the method of Meech et al. (1993) to use the change in the amplitude of the rotational light curve as a function of aperture size to constrain both the coma-free projected axis ratio and the nucleus size, however, the data were not high enough signal-to-noise and did not have a long enough time baseline for this method to produce reliable results.

However, because we have additional information about the size of the nucleus from Lamy (1996), we can correct for the dilution of the range by the coma. Fink et al. (1997), in observations obtained during 1996 October at r = 2.1 AU, found no systematic brightness variations which could be ascribed to a rotating nucleus. As seen from Fig. 5, the comet at this time was on a rapidly brightening portion of the light curve and it is possible that increased scattered light from the coma dominated the comet's brightness so that the brightness modulations by the nucleus were no longer detectable. The total light scattered (brightness, $B_{\rm Tot}$) is composed of the flux from the nucleus ($B_{\rm Nuc}$) and coma ($B_{\rm Coma}$):

$$B_{\rm Tot} = B_{\rm Nuc} + B_{\rm Coma} \tag{4}$$

where

$$B_{\rm Nuc} = p_v\, r_N^2\, 10^{-0.4(m_\odot + \alpha\beta)}/(2.235 \times 10^{16}\, r^2\, \Delta^2) \tag{5}$$

where $m_\odot = -27.10$ is the R magnitude of the sun, β = 0.04 mag deg^{-1} is the assumed phase coefficient, p_v = 0.04 – 0.07 is the expected range for the geometric albedo, r_N is the nucleus radius [km], and r and Δ are expressed in AU. For a coma with a simple surface brightness profile varying as:

$$SB = k\, p^G \tag{6}$$

where SB is the surface brightness [W m^{-2} Sr^{-1}], p is the aperture radius [″], G is the surface brightness gradient determined above, and k is a normalization constant, it was shown by Meech et al. (1993) that the total light curve range is given by:

$$\Delta m(p) = -2.5\ \log \frac{\epsilon \frac{zB_N}{1+\epsilon} + p^{G+2}}{\frac{zB_N}{1+\epsilon} + p^{G+2}} \tag{7}$$

where B_N is the rotationally averaged nucleus brightness, $z = (G + 2)/\pi k$ and $k = SB_0 p_0^{-G}$ for any point in the surface brightness profile (beyond the region affected by seeing).

Table 4 summarizes the observed total average R magnitude at four heliocentric distances as a function of the photometry aperture used. For each observation the expected brightness of the nucleus is computed, along with an estimate of the fraction that the nucleus contributes to the total comet brightness within the aperture, using r_N = 0.58 km and p_v = 0.04. From the first entry in the table, it seems unlikely that the albedo could be as high as the upper limit given by Parker et al. (1997), p_v = 0.07. The Boehnhardt observation at r = 4.62 AU is an average magnitude determined from 55 frames taken over a large fraction of the rotational period, and therefore represents the rotationally averaged brightness. For an albedo of p_v = 0.07, the nucleus brightness alone should be r = 24.03 which is just marginally consistent with the observed brightness of $r = 24.2 \pm 0.3$. Using the HST estimate of r_N = 0.58 km for the nucleus, we can calculate the expected light curve range, Δm (columns 9 and 11) and the corresponding nucleus axis ratios for different values of p_v (columns 10 and 12). For the case of p_v = 0.04, the calculation yields Δm = 0.09 mag for 1996 August and Δm = 0.04 mag for 1996 October, with an axis ratio $a : b$ = 2.3. The very small light curve range for October, coupled with the larger aperture (4″.65) used by Fink et al. (1997) and the larger errors ($\sigma \approx 0.05$, with scatter up to 0.5 mag) probably explains why rotational variations were not detected. In columns 11 and 12, the same calculation is done using p_v = 0.07, and this yields a smaller axis ratio $a : b$ = 1.3, and reduced ranges (Δm = 0.06, and 0.02, respectively). The range Δm = 0.06 for 1996 August is consistent with our data, however, the albedo is probably lower than 0.07.

Table 4. Relative nucleus / Coma contributions

UT Date	r^1	Δ^1	α^1	p^2	$m^3_{Tot}(p)$	m^4_{Nuc}	f^5_{Nuc}	p_V = 0.04		p_V = 0.07		**Refs**[10]
								Δm^6	**a:b**[7]	Δm^8	**a:b**[9]	
6/26/95	4.621	3.610	2	N/A	24.2 ± 0.3	24.64	0.67 ± 0.2	–	–	–	–	1
6/13-14/96	2.990	2.408	-17.8	2.5	21.39 ± 0.03	23.45	0.15 ± 0.004	–	–	–	–	2
8/17-18/96	2.530	1.549	7.2	2.5	19.25 ± 0.001	21.70	0.10 ± 0.0001	0.09	2.3	0.06	1.3	2
10/11-12/96	2.096	1.569	27.1	4.65	18.73 ± 0.11	22.12	0.044± 0.005	0.04	2.3	0.02	1.3	3

Notes: [1]Heliocentric, geocentric distance [AU] and phase angle [deg]; [2]Radius of observing aperture [″]; [3]Average total (nucleus plus coma) R magnitude within the aperture; [4]expected magnitude of the nucleus at the specified distances assuming p_v = 0.04; [5]fraction of light within the aperture contributed by the nucleus; [6]expected rotational light curve range assuming p_v = 0.04; [7]axis ratio for $\Delta m(8/96)$ = 0.09 and p_v = 0.04; [8]expected rotational light curve range for p_v = 0.07; [9]axis ratio for p_v=0.07, $\Delta m(8/96)$ = 0.06; [10]References: 1 = Boehnhardt et al. (1997), 2 = this paper, 3 = Fink et al. (1997).

There is the additional constraint observed by Lamy (1996) that the brightness of the comet varied between $R = 21.6 - 21.9$ over a 1.5 hour time-span, which corresponds to roughly half the time needed to exhibit the maximum range under optimum conditions. It should be noted that these brightnesses are consistent with the bare nucleus only for albedos as low as p_v = 0.04. Assuming that the true bare nucleus light curve range is Δm = 0.6 from the HST observations, the implied $a : b$ = 1.74, which predicts Δm = 0.06 and 0.02 for August and October, respectively, is consistent with the present observations.

4. Future observations

While the nucleus is surrounded by a bright coma, nucleus observations can be difficult. Based on experience with the development of activity in other short–period comets, it is probable that the coma contamination will be minimal for $r > 2.5$–3 AU. A list of the desirable observations relevant to the *Rosetta* mission is given below:

- Astrometry: good astrometric measurements will be crucial in order to refine the orbit to the level required for the rendezvous with *Rosetta*. While any image can be measured astrometrically, the coma can introduce error (the center of light of the image not being on the center of mass); therefore, images with little or no coma are more suitable for this purpose. As the solar phase has no measurable effect on the astrometry, these observations can be performed at almost any solar elongation.
- Refinement of the rotational period: an improved measurement can be obtained by combining the data obtained over several nights, possibly spread over an extended period of time. Only the general shape of the light curve has to be recognized, therefore some limited coma contamination or large solar phase angle effects are not critical. The comet can be observed near r = 2.5 AU while brighter than $R \approx 23$, so this information, crucial for the *Rosetta* mission, can be measured with a medium-sized telescope (2m-class). Using the three curves (solar elongation, magnitude and heliocentric distance) from Fig. 8, many periods suitable for such observations can be identified; the next good opportunity will occur in mid-1998. It may also be possible to measure the effects of the rotation through narrowband photometry by observing the modulation of the signal in the gaseous species as source regions rotate into and out of the sunlight as was done for 1P/Halley (Millis and Schleicher, 1986), while the comet is even more active. This technique will be more accessible to observers who do not have ready access to large telescopes.
- Coma-free light curve: a well-sampled light curve obtained without coma contamination ($r > 4$ AU) and close to opposition (to minimize the solar phase effects, solar elongation $> 160°$) can constrain the shape: the full amplitude of one light curve gives a lower limit on the axis ratio, and the (lack of) symmetry of the light curve gives some indication of albedo variations. As seen from Fig. 8, several oppositions are available for such observations, but the magnitude of the comet will always be around $R \sim 25$ or fainter, implying the need for a fairly large telescope (4m or larger) in order to get sufficient time sampling.
- Several coma-free light curves: a set of coma-free, opposition light curves obtained at different ecliptic longitudes can give a tri-axial ellipsoid model of the nucleus and its pole orientation, using, for instance, an Amplitude/Magnitude-Aspect technique (Detal et al., 1994). A good temporal sampling of the light curve is crucial to distinguish the departure from the ellipsoid model and estimate the error on the pole orientation; this departure may be caused by either a more complex shape (producing symmetric light curves) or a non-uniform albedo distribution (asymmetric light curve). As the longitude coverage during the opposition occurring before the rendezvous with *Rosetta* spans only $\sim 90°$, a full modeling of the shape and/or albedo distribution of the nucleus (using for instance the Free Albedo Map or Free Shape methods described in Detal et al., 1994) will probably not be achievable, but a coordinated use of several light curves should make the orientation of the pole available in time for planning the rendezvous with *Rosetta*.

5. Summary

- The comet was observed at 3 heliocentric distances during 1996. When combined with other published data, the brightening of the comet as a function of r suggests that the activity began near r = 3.5–4.5 AU.

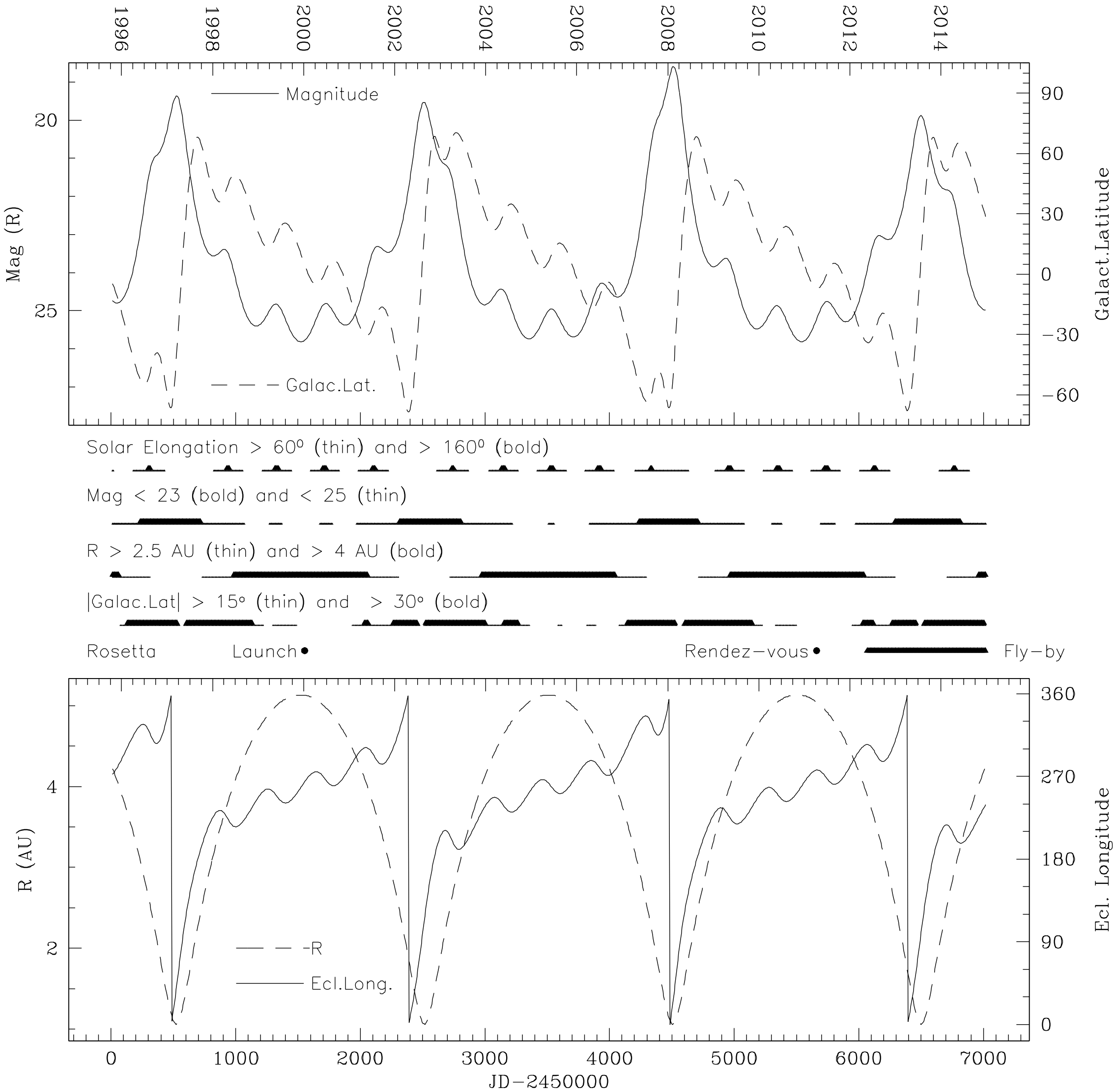

Fig. 8. Observation planner: Plotted in the top panel is the nuclear magnitude (solid line; assuming r_N = 0.58 km and p_V = 0.04) and the galactic latitude (dashed line) as a function of time (in JD, where JD 2450000 = 1995 October 9.5 [lower axis], and fractional year [upper axis], with each tick mark corresponding to 0.25 yr). In the lower panel, the heliocentric distance (dashed line) and the ecliptic longitude (solid line) are plotted. The windows of observability have been represented by the lines between the two panels: the upper one indicates when the comet emerges from out of the solar glare (solar elongation $> 60°$; thin line) and close to opposition (solar elongation $> 160°$; thick line); the second line can be used in order to select the telescope needed for the observations: a magnitude in the 23–25 range (thin line) would require a medium-sized telescope (2–4m) while mag$<$ 23 can be observed with smaller instruments. The third line indicates the probable activity level of the comet: probably no coma (thin line, $2.5 < r < 4$ AU), and certainly no coma (thick line, $r > 4$ AU). The final line shows when the observations will be more or less affected by field star contamination – least for galactic latitudes greater than 30 degrees (bold). Important dates for the *Rosetta* mission are also indicated.

- We have observed a periodic variation in the light curve of 46P/Wirtanen near 3.8 hours, which we interpret to be the signature of a brightness modulation by the nucleus rotating at a period near 7.6 hours. Because 46P/Wirtanen is so faint an object, large telescope observations are required to confirm this rotation period at a higher S/N. The next good opportunity for directly measuing the rotation of the nucleus will occur again in mid-1998. A larger aperture telescope will also enable better temporal sampling of the rotation light curve.
- The color of the coma is slightly redder than the Sun, $B-V = 0.756\pm0.009$, $V-R = 0.456\pm0.008$, $R-I = 0.366\pm0.009$.
- During August, at $r = 2.5$ AU, the coma extended to at least 1.8×10^4 km, and during November at $r = 1.83$ AU, the coma extended to at least 2.5×10^4 km in approximately the anti-solar direction.

- The surface brightness profile of the coma showed that the brightness fell off with a slope of -1.6 during August and -1.4 during November, which is slightly steeper than that expected from radiation pressure and phase angle effects alone.
- The range of variation of the light curve, 0.09 mag, suggested a minimum projected axis ratio of 1.09 for the nucleus. An analysis of the amplitude of the rotational light curve from 1996 August in comparison with the HST observations, suggests that the most probable bare nucleus axis ratio is $a : b \approx 1.7$, and that the albedo is low, near p_v = 0.04. By 1996 October, the range of the rotationally–induced modulations on the light curve would have been very small, $\Delta m \approx 0.02$, and very hard to detect.

Acknowledgements. We would like to thank Dean Kakazu (Berkeley, REU Summer student) for his assistance with the observing during June, and Carolyn Petersen for her assistance in November. We would also like to thank U. Fink for providing us with his 46P/Wirtanen data prior to publication. In addition we would like to thank R. West for his helpful comments on the manuscript. Image processing in this paper has been performed using the IRAF program. IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation. Support for this work was provided by NASA Grant No. NAGW 5015, and an NSF REU Supplement to Grant No. AST 92-21318.

References

Allen, C. W. (1973). *Astrophysical Quantities*, 3rd Ed. Athlone Press, Univ. of London, London, p. 162.

Bauer, J. M, K. J. Meech and O. R. Hainaut (1996). “Rotation of the Nucleus of Comet 46P/Wirtanen”, BAAS 28, 1083.

Bessell, M. S. (1979). “UBVRI Photometry II: The Cousins VRI System, its Temperature and Absolute Flux Calibration,and Relevance for Two–Dimensional Photometry”, PASP 91, 589-607.

Boehnhardt, H., J. Babion and R. M. West (1997). “An Optimized Detection Technique for Faint Moving Objects on a Star-Rich Background – a Search for the Nucleus of Comet 46P/Wirtanen”, A&A, in press.

Boehnhardt, H., R. M. West and J. Babion (1996a). “Comet P/Wirtanen”, IAU Circ. 6392.

Boehnhardt, H., H. Rauer, S. Motolla, and A. Nathues (1996b). “Comet P/Wirtanen”, IAU Circ. 6392.

Buie, M. W. and S. J. Bus (1992). “Physical Observations of (5145) Pholus”, Icarus 100, 288–294.

Detal, A., O. R. Hainaut, A. Pospieszalska-Surdej, P. Schils, H. J. Schober and J. Surdej (1994). “Pole, Albedo and Shape of the Minor Planets 624 Hektor and 43 Ariadne: Two Tests for Comparing Four Different Pole Determination Methods”, A&A 281, 269–280.

Fernie, J. D. (1983). “Relationships Between the Johnson and Kron-Cousins VRI Photometric Systems”, PASP 95, 782-785.

Fink, U., R. A. Fevig, S. C. Tegler, and W. Romanishin (1997). “CCD Imaging and Photometry of 46P/Wirtanen During October 1996”, Planet. Space Sci., submitted.

Hainaut, O. R. and R. M. West (1996). MPC 27351.

Jewitt, D. C. and K. J. Meech (1987). “Surface-Brightness Profiles of 10 Comets”, ApJ 317, 992–1001.

Jorda, L. and H. Rickman (1995). “Comet P/Wirtanan, Summary of Observational Data”, Planet. Space Sci. 43, 575–579.

Meech, K. J. (1997). “Physical Properties of Comets”, invited review at *Asteroids, Comets, Meteors, 1996*, Advances Space Research, submitted.

Millis, R. L. and D. G. Schleicher (1986). “Rotational Period of Comet P/Halley”, Nature 324, 646-649.

Lamy, P. (1996). “Comet 46P/Wirtanen”, IAU Circ. No. 6478.

Landolt, A. (1992). “UBVRI Photometric Standard Stars in the Magnitude Range 11.5 < V < 16.0 Around the Celestial Equator”, AJ, 104, 340–371.

Meech, K. J., M. J. S. Belton, B. E. A. Mueller, M. W. Dicksion and H. R. Li (1993), “Nucleus Properties of P/Schwassmann-Wachmann 1”, AJ 106, 1222–1236.

Parker, J. W. et al. (1996). “HST/FOS UV Observations of Chiron and Wirtanen”, BAAS 28, 8.04.

Schultz, R. (1996). “Ground-based Support for STARDUST and ROSETTA”, COSPAR Colloq. 10 Abstracts.

Stellingwerf, R. F. (1978). “Period Determination Using Phase Dispersion Minimization”, AJ, 224, 953–960.

Tody, D. (1986). “The IRAF Data Reduction and Analysis System”, *SPIE Instrumentation in Astronomy VI”*, Ed. D. L. Crawford, 627, 733-748.

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.