UDC 523.6

Physical properties of comet 81P Wild 2

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81P/Wild 2 is the STARDUST space mission target. This comet was selected because of its newness as a Jupiter family comet and because of the discovery of a trajectory offering a low encounter velocity of only 6.1 km·s^{-1}. Observations over a wide range of heliocentric distances since 1987 have enable us the greatly enhance our knowledge of 81P/Wild 2, as required to mount a successful space mission. We want to present four sets of observations of comet 81P/Wild 2 which were made in order to search for rotational period of the nucleus during November 11–12, 1996, June 26–28, 1998, September 26–28, 1998 and August 12–17, 1999 using the University of Hawaii 2.2 m telescope. At the time of the observations, the comet was at heliocentric distances, r = 2.28, 3.61, 4.01 and 4.98 AU. The comet was active for all runs, and during 1996 November the coma extended >100″ (1.65×10^5 km at the distance of the comet) at PA≈262°, and during 1998 June the coma extended >51″ (1.34×10^5 km at the distance of the comet) at PA≈254°, and during 1998 September the coma extended >12″ (3.50×10^4 km at the distance of the comet) at PA≈125°, and during 1999 August the coma extended >8″ (2.90×10^4 km at the distance of the comet) at PA≈203°. Using a phase-dispersion minimization technique,we will try to find a possible rotation period.

ФИЗИЧЕСКИЕ СВОЙСТВА КОМЕТЫ 81P WILD 2, Питтихова Я., Мич К.Я. — Комета 81P/Wild 2 выбрана в качестве мишени для полета к ней космического корабля STARDUST. Эта комета принадлежит к самым новым членам семейства Юпитеровых комет и была выбрана потому, что ее орбита позволяет небольшую скорость сближения, только 6.1 км·с$^{-1}$. Наблюдения кометы с 1987 года в широком диапазоне гелиоцентрических расстояний повышают наши знания о комете 81P Wild 2, которые необходимы для успешной миссии. Мы хотим представить четыре ряда наблюдений кометы 81P/Wild 2, которые были проведены для определения периода вращения ядра в течение 11–12 ноября 1996 г., 26–28 июня 1998 г., 26–28 сентября 1998 г. и 12–17 августа 1999 г. на 2.2-м телескопе Гавайского университета. Во время наблюдений комета была на гелиоцентрических расстояниях r = 2.28, 3.61, 4.01 и 4.98 а.е. Комета была активной во все время наблюдений. В ноябре 1996 г. кома расширилась >100″ (1.65×10^5 км) в позиционном направлении ≈262°, в июне 1998 г. расширилась > 51″ (1.34×10^5 км) в позиционном направлении ≈254°, в сентябре 1998 г. кома расширилась >12″ (3.50×10^4 км) в позиционном направлении ≈125°, и в августе 1999 г. кома расширилась >8″ (2.90×10^4 км) в позиционном направлении ≈203°. Используя фазо-дисперсионную минимизационную технику, мы пытались обнаружить возможный период вращения ядра кометы.

ФІЗИЧНІ ВЛАСТИВОСТІ КОМЕТИ 81P WILD 2, Піттіхова Я., Міч К.Я. — Комета 81P/Wild 2 обрана як мішень для польоту до неї космічного корабля STARDUST. Ця комета належить до найновіших комет родини Юпітера і була обрана тому, що її орбіта дозволяє невелику швидкість зближення, тільки 6.1 км·с$^{-1}$. Спостереження комети з 1987 року в широкому діапазоні геліоцентричних відстаней збільшують наші знання про комету 81P Wild 2, що необхідні для успішної місії. Ми хочемо представити чотири ряди спостережень комети 81P/Wild 2, що були проведені для визначення періоду обертання ядра протягом 11–12 листопада 1996 р., 26–28 червня 1998 р., 26–28 вересня 1998 р. і 12–17 серпня 1999 р. на 2.2-м телескопі Гавайського університету. Під час спостережень комета була на геліоцентричних відстанях r = 2.28, 3.61, 4.01 і 4.98 а.о. Комета була активною протягом всіх спостережень. У листопаді 1996 р. кома розширилася >100″ (1.65×10^5 км) у позиційному напрямку ≈262°, у червні 1998 р. розширилася >51″ (1.34×10^5 км) у позиційному напрямку ≈254°, у вересні 1998 р. кома розширилася >12″ (3.50×10^4 км) у позиційному напрямку ≈125°, і в серпні 1999 р. кома розширилася >8″ (2.90×10^4 км) у позиційному напрямку ≈203°. Використовуючи фазо-дисперсійну мінімізаційну техніку, ми намагалися знайти можливий період обертання ядра комети.

1. INTRODUCTION

Comet 81P/Wild 2 was discovered on January 6, 1978 by Paul Wild, using the 40/60 cm Schmidt camera of the Berne University Observatory at Zimmerwald, Switzerland [15]. At the time of discovery the total visual magnitude of Wild 2 was 13.0^m. Several other astronomers started to observe this comet all over the world. Brian Marsden calculated the first elliptical elements and orbit of comet from 29 observations taken between January 6 and February 13, 1978. 5.7 year after discovery, on September 18, 1983 the first recovery was made by James Gibson, based on the ephemeris. Gibson was using the 122/183 cm Schmidt camera on Palomar Mountain [3].

Comet 81P/Wild 2 is a Jupiter-family short-period comet of period 6.37 year. The inclination of the orbital plane is $\sim 3.2°$ to the ecliptic, and the eccentricity is ~ 0.54. Orbital studies indicate that on September 9, 1974 comet 81P/Wild 2 passed only 0.006 AU from Jupiter and this markedly changed its perihelion distance from 5.0 AU to 1.57 AU, and an aphelion distance from 24.7 AU to 5.2 AU, and the orbit from long period to short period with 6.4 years period [6].

Sanzovo et al. [11] derived water release rates of comet Wild 2 at the heliocentric distance 1.5 AU and estimated a total active area of ~ 19 km^2 on the nuclear surface, which in turn yields a lower limit of $R_N = 1.7$ km for nuclear radius. The same result — nuclear radius of 1.7 km, obtained from the analyses of the continuum fluxes of comet Wild 2 by A'Hearn and Millis [1] at wavelengths of 3930, 4120, 5240Å for the 1978 return prior to perihelion; by Osip et al. [9] and Torres [13], respectively, in the band passes 5240 and 4770Å for pre-perihelion distance for the 1978, 1984, 1997 returns and also by Fink et al. (1999) at 6250Å at pre- and post-perihelion distances. Analyses show visual and infrared albedos of 0.04 and 0.03 and dust grain densities of 1.0 and 0.3 g·cm^{-1}.

Comet 81P/Wild 2 belongs to the family with intermediate ratios of dust-to-gas mass release rates [10]. More than 20 years since its 1978 return, we verify that the activity of the comet does not appear to change very much. From the power laws for the 1978 and 1997 returns Sanzovo et al., [11] find that near perihelion, at $r = 1.49$ AU, comet Wild 2 loses total mass at a rate of $\sim 800 - 820$ kg·s^{-1}. On the base of the orbital period $P \sim 6.4$ year, the lower limit of nuclear radius $R_N = 1.7$ km and a mean nuclear density of ~ 0.5 g·cm^{-3}, they estimated that Wild 2 loses $\sim (1.6 - 1.7) \cdot 10^{11}$ tons of gas and dust at each apparition.

This comet is often called a "fresh" comet. The low cometary encounter velocity, only 6.1 km·s^{-1} and a moderate V_∞ of 6.5 km·s^{-1} upon return to Earth, was discovered by Chen–Wan Yen [14] and also its newness as a Jupiter family comet, made the comet Wild 2 a natural target for the discovery class sample return space mission STARDUST.

Knowledge of the rotation period, activity of comet like jets, dust and gas production, nucleus size and shape is needed to plan photographic aspects of the mission as well as to estimate the gravity field against which the dust must escape. These information are also important for the safety reasons — how well shielded the spacecraft has to be, how close can fly by to comet and when is the best time to approach the comet.

2. OBSERVATIONS

We observed the comet from the University of Hawai'i 2.2 m telescope on Mauna Kea during four runs in 1996 November, 1998 June, September and 1999 August. 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 with the Kron–Cousins filters (B: $\lambda_0 = 4380$Å, $\Delta\lambda = 1077$Å; V: $\lambda_0 = 5450$Å, $\Delta\lambda = 836$Å; R: $\lambda_0 = 6460$Å, $\Delta\lambda = 1245$Å; I: $\lambda_0 = 8260$Å, $\Delta\lambda = 1888$Å. Note: B and V are essentially the same in the Johnson and Kron–Cousins/Mould systems). All of the images were guided non-sidereal with the cometary rates.

The composite image was created 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 field stars. The shift due to the motion of the comet were computed from the comet's ephemeris positions and the plate scale of CCD (0.219″/pix).

3. DATA REDUCTION

All the images were reduced using standard methods. Flat fields obtained on the evening and morning twilight sky and cleaned of bad pixels and cosmic rays, using the standard routines in IRAF (the Image Reduction and Analysis Facility). The frames were calibrated with the standard stars of Landolt [4, 5], which were observed on each photometric night.

Observations of typically 20 standard stars were obtained over a range of air-masses, and with a wide dispersion of color to fit for both extinction and color terms. We measured the magnitudes of several 20–30 field stars on each frame in order to do relative photometry. 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 extinction in the comet's measured signal.

4. ANALYSIS AND DISCUSSION

4.1. Photometry

The extraction of the comet flux from the CCD frame was performed using the circular aperture photometry "PHOT" IRAF software. The photometry routine automatically finds the centroid of the image within the user-specified photometry aperture, with the sky background determined in an annulus lying immediately outside the photometry aperture (for stellar images), or selected from an average of many sky positions outside the extent of any coma. The inner radius of sky annulus 10.0″ with the width of 5.0″ was used to measure the average of the sky background and also used to reject any bad pixels or field stars found in the sky annulus. The errors quoted for the final reduced photometry include both the statistical photon noise of the measurements and the external errors associated with the transformation to the standard system.

We used different aperture size from $1-5''$ for comet photometry and $4-5''$ aperture size for a sky annulus and field stars. We plotted the brightness for a different aperture versus time and found that the optimum aperture size, where the brightness was the most constant, was 3.0″ except for August 1999 data where aperture size 2.0″ fitted better. The aperture correction for August 1999 data is −0.323 mag

Table 1. Observing Circumstances

UT Date	T days	r AU	Δ AU	α deg	Φ deg	PA ″	Seeing mag	Avgb	#	Fil	Sky
11/11/96	-176	2.281	1.744	24.06	0.460	264	0.7	15.67	14	R	Cirrus
11/12/96	-175	2.275	1.724	23.99	0.461	260	0.6	15.62	20	RI	Cirrus
06/26/98	177	3.604	2.772	10.60	0.711	251	1.0	17.82	7	R	Photom
06/27/98	178	3.609	2.767	10.34	0.717	254	1.0	17.81	13	R	Photom
06/28/98	179	3.614	2.762	10.08	0.723	256	0.9	17.85	13	R	Photom
09/26/98	268	4.010	3.430	12.65	0.665	120	1.0	19.54	17	VRI	Photom
09/27/98	269	4.015	3.450	12.75	0.663	125	1.1	19.45	19	R	Photom
09/28/98	270	4.020	3.460	12.85	0.661	129	0.9	19.51	19	R	Photom
08/12/99	586	4.970	4.029	4.78	0.857	198	1.1	21.44	48	VRI	Photom
08/13/99	587	4.973	4.025	4.56	0.863	200	1.0	21.30	6	R	Photom
08/14/99	588	4.975	4.020	4.35	0.869	201	0.9	21.30	8	RI	Photom
08/15/99	589	4.977	4.017	4.14	0.875	203	0.8	21.37	45	VRI	Cirrus
08/16/99	590	4.979	4.013	3.93	0.881	205	0.7	21.54	8	R	Cirrus
08/17/99	591	4.981	4.011	3.71	0.887	206	1.0	21.41	35	VRI	Photom

Notes: UT Date is date of observation; T is time from perihelion in days (measured from the 5/6/97 perihelion); r, Δ, α are the heliocentric and geocentric distance [AU], and α is the phase angle [deg]; Φ is phase function; PA is a position angle [deg] of the extended heliocentric radius vector, measured from north to east; average seeing FWHM [″]; AvgB is a average comet brightness [mag] on each night; number of images obtained on each night; Fil is a filter on the Kron–Cousins system; sky condition.

Table 2. 81P/Wild 2 Coma Colors

UT Date	$V-R$	$R-I$
11/12/96		0.448 ± 0.002
09/26/98	0.517 ± 0.008	0.799 ± 0.010
08/12/99	0.533 ± 0.045	0.318 ± 0.048
08/14/99		0.415 ± 0.037
08/15/99	0.491 ± 0.033	0.374 ± 0.033
08/17/99	0.500 ± 0.035	0.300 ± 0.035
Average	0.510 ± 0.030	0.442 ± 0.028
Solar color	0.36	0.28

to get a brightness of the comet with aperture radius $3.0''$. The R-band photometry from all four runs are shown in Figures 1 and 2.

We measured the magnitudes of 20–30 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 $5''$ aperture sufficiently 95% encompassed the entire signal from any field standard.

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 extinction variations in the comet's measured signal.

For the non-photometric data from nights in November 1996, the comet fields were re-imaged on March 29, 2001 and as many field stars as possible were measured on both the calibration image and the non-photometric image. Differential photometry was used to calculate the calibrated brightness of the comet. This technique works well for up to ~0.5 mag of extinction. Unfortunately, we don't have any calibration for non-photometric nights in August 1999, but we were able to calibrate the brightness of the field stars which overlap with the previous or next night when the weather was photometric.

To make the composite images of the comets, measurements of the centroids of a large number of field stars were used to compute the offsets between the individual images (from telescope guiding errors, or dithering shifts). After these offsets were applied, the ephemerides rates for 81P/Wild 2 were used in combination with the image plate scale to calculate shifts to simulate guiding on the comet, and then the images were added.

Table 1 summarizes photometry from all of the runs. The phase function, Φ, is given by:

$$\Phi(\alpha) = 10^{-0.4\Delta m}, \tag{1}$$

where $\Delta m = 0.035\alpha$ [8].

4.2. Period Search

We use a standard method to search for periodicity in the light curve; which consists of a minimization of the χ^2 statistic for goodness-of-fit and phase dispersion minimization [12] modified to weight the data according to their errors. This technique is simply an automated version of the classical method of distinguishing between possible periods, in which the period producing the least observational scatter about the mean light curve is chosen. This approach is convenient because: 1) It is well suited to cases in which only a few observations are available over a limited period of time, especially if the light curve is highly non-sinusoidal. 2) An optimum light-curve shape is obtained, which can be subtracted from the data to allow a search for other periods to be made. 3) Also, the computation is very straightforward, allowing complete automation of the period search.

The PDM technique computes the sum of the residual of the data minus an assumed light curve variation as a function of frequency or period. The best fit period (regardless of the actual light curve shape) should fall at the minimum of the 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. Mathematically, this is a lest-squares fitting technique, but rather than a fit to given curve (such as a Fourier component), the fit is

relative to the mean curve as defined by the means of each bin. The θ statistic 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 4 hours and 5 days on the data of all four runs together as well as for each single run, without strong proof of periodicity. From the first three runs we don't have enough data to cover enough long interval to see some period. Three nights of the last run on August 12, 15 and 17, 1999 had enough points to cover short period — couple hours, but still not enough observations if
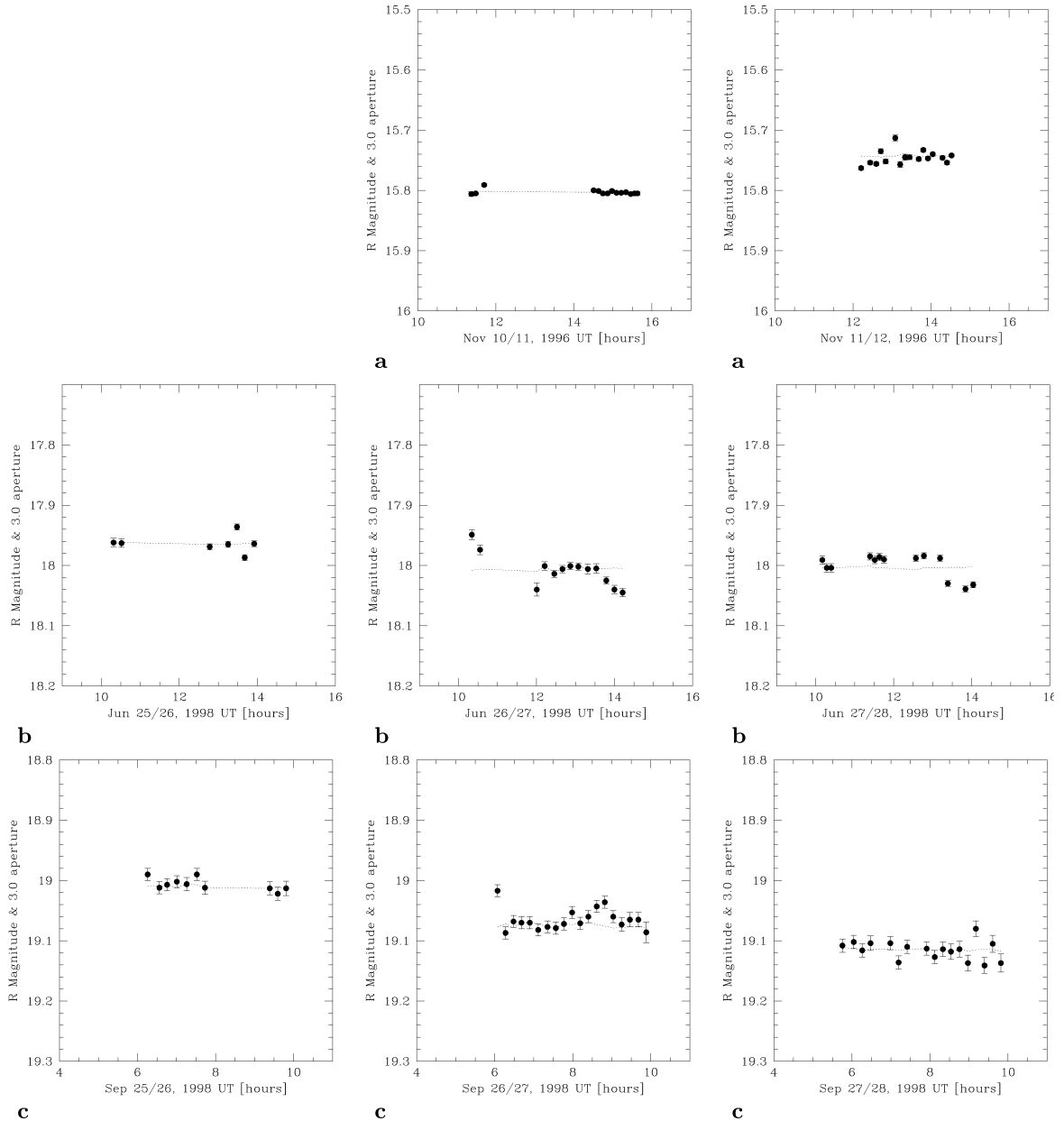
Fig. 1. R-band photometry of Comet 81P/Wild 2 through a 3.0″ aperture. The dashed line is average of normalized field stars. **a**. November 11–12, 1996; **b**. June 26–28, 1998; **c**. September 26–28, 1998

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the period is long — several hours or days. Also during all the observing runs the comet was still active and this can badly effect the period determination. Unfortunately, there are no other published evidence about comet Wild 2 period which will can give us a guideline. This comet is not ready yet to give up its secret easily.

4.3. Heliocentric Light Curve

The data from this paper and Meech and Newburn [6] are shown in Figure 3, which plots the reduced magnitude $R(1,1,0)$ to unit heliocentric distance r, geocentric distance Δ and zero phase α as a function of heliocentric distance r. To compute $R(1,1,0)$ we used a linear phase coefficient of 0.03 mag·deg^{-1}. The horizontal lines correspond to the likely best estimate of the flux contribution from a bare nucleus. From the figure, it is clear that activity probably began near heliocentric distance $r = 5$ AU and all our data were taken during the active stage of the comet.

5. CONCLUSIONS AND FUTURE OBSERVATIONS PLAN

81P/Wild 2 data obtained on 14 nights have shown that the comet is very dusty, with residual activity out to near $r = 5.0$ AU. However, the emission is fairly uniform, without the presence of a large number of jets or other coma features. 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. As you can see for Wild 2 this isn't quite right because the comet was active at almost $r = 5.0$ AU.
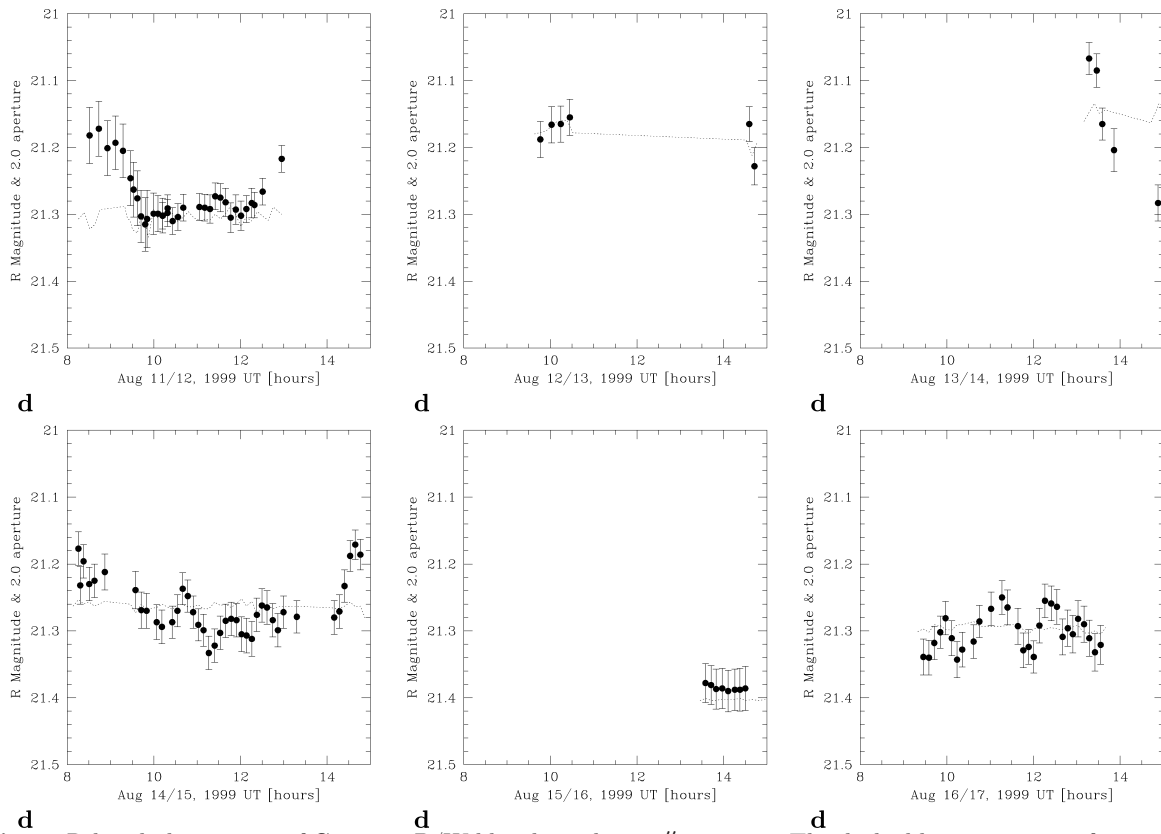

Fig. 2. R-band photometry of Comet 81P/Wild 2 through a 2.0″ aperture. The dashed line is average of normalized field stars. **d**. August 12–17, 1999

- The comet was observed at 5 heliocentric distances over a period from 1996 November through 1999 August. When combined with other previous observations, the brightening of the comet as a function of heliocentric distance r suggests that the activity began near $r = 5.0$ AU.
- The color determination in Table 2 shows that the comet is slightly redder than the Sun.
- We have observed a slight variation in the light curve of comet 81P/Wild 2 but not enough to obtain a rotation period.
- We don't have enough data to cover possible rotation period if this is longer than a couple hours. From the August 1999 data, which have enough points to well cover few hours and can proof a couple hours period, we conclude that a possible period has to be longer than 9 hours, probably few days.
- The reason why we couldn't obtained any rotation period can be that the comet Wild 2 has a spherical shape of the nucleus, or unfortunately, during all our observations was the orientation between Wild 2, Earth and Sun the same. Also the fact that the comet was active during all observation didn't help us.
- We are planning to prepare a few long term observations, minimum 6–10 days to cover a possible long rotation period during next comet aphelion at December 2006. At this time the heliocentric distance of the comet will be $r = 5.31$ AU and the relative brightness $m_R = 22.5$ mag. We will try to use 4-m and bigger telescope and hopefully this will reveal the rotation period.
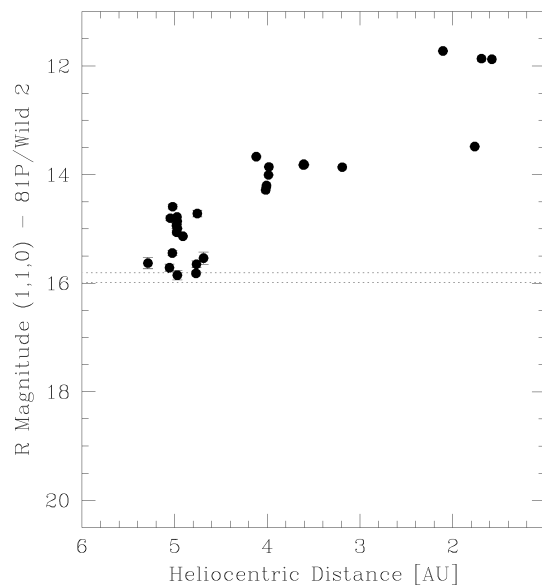
Fig. 3. Comet 81P/Wild 2 broadband date reduced to unit r, Δ, and zero phase plotted versus r. Data are from this paper and Meech and Newburn (2002). The dotted lines represent the likely brightness range for the bare nucleus.

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