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4979 Otawara: flyby target of the Rosetta mission*

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Abstract. An international observing campaign was organized to determine the physical and chemical characteristics of asteroid 4979 Otawara, which is the first target of the Rosetta mission (flyby on July 10, 2006). Knowledge of the physical parameters of the flyby targets is required for both refinement of the design of the spacecraft and the instrument payload, and optimization of the mission trajectory and scenarios. We present the results of observations obtained from December, 1998 through March, 1999. The spectral classification of 4979 Otawara could be either a pyroxene and/or olivine-rich S-type asteroid or a V-type asteroid, a member of the Vesta dynamical family. Further observations are needed in order to discriminate between the two spectral types. The synodic rotation period of Otawara is $P_{syn} = 2.707 \pm 0.005$ hr. The lower limit for the axial ratio of the enveloping ellipsoid is $a/b \geq 1.3$. The circular effective radius is 2.0 or 1.3 km in the case of an S-type or a V-type asteroid, respectively. A lower limit on its density is obtained: $\rho_{min} \geq 1.9\,\mathrm{g\,cm^{-3}}$ if we assume that Otawara is an aggregate or rubble pile object. However, if Otawara is a single solid body, no constraint can be set on its density. 4979 Otawara is a small, fast rotating asteroid (FRA) and hence, will be a particularly interesting target to be studied from a spacecraft, since no fast rotator has been visited yet.

Key words: minor planets, asteroids – planets and satellites: individual: 4979 Otawa

1. Introduction

The International Rosetta Mission is the planetary cornerstone mission of the European Space Agency. The mission is devoted to the study of the nature of primitive small bodies in the solar system. The baseline mission includes two asteroid flybys: 4979 Otawara on July 10, 2006 and 140 Siwa on July 23, 2008, and the exploration of comet 46P/Wirtanen. The Rosetta spacecraft will rendezvous with the comet in March 2012 at 4.2 AU from the Sun. The spacecraft will be put into an orbit around the comet nucleus and an instrumented probe will land on the nucleus surface.

Several other spacecraft missions to comets and asteroids are now either on their way, under development, or in the planning stages. These include NEAR, Deep Space 1, Stardust, Contour and Muses C. Knowledge of the physical parameters of the target bodies is required for both refinement of the designs of the spacecraft and their instrument payloads and optimization of the mission trajectories and scenarios.

An international observing campaign was organized to determine the physical and chemical characteristics of the Rosetta asteroid targets. Results for 140 Siwa have been published by Schober & Stanzel (1979), Harris & Young (1980), Lagerkvist et al. (1992) and Barucci et al. (1998). This paper deals with the first results obtained for 4979 Otawara.

2. Observations and data reduction

We observed 4979 Otawara during seven runs from December, 1998 to March, 1999. The purpose of these observations was to obtain lightcurve photometry, color photometry and spectroscopy. The specifics of the observations, including observing conditions and orbital geometry for the asteroid are shown in Table 1.

2.1. Observations

Steward Observatory (SO): Two nights of data were obtained on December, 13–14, 1998 with the 2.3 m telescope of Steward Observatory on Kitt Peak (Arizona). The telescope was equiped with the facility 2k×2k CCD imaging system at the cassegrain

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* partly based on observations carried out at the European Southern Observatory (ESO) of La Silla, Chile, and at Steward Observatory, University of Arizona, Tucson, AZ USA.

Table 1. Observational circumstances

UT date	r (AU)	δ (AU)	α (deg.)	Telescope	Filter or $\delta\lambda$
1998 Dec 13	2.463	1.714	17.9	Steward Obs. 2.3m	R
1998 Dec 14	2.462	1.704	17.6	Steward Obs. 2.3m	R
1998 Dec 16	2.462	1.686	17.1	Pic du Midi Obs. 1.0 m	R
1998 Dec 17	2.461	1.676	16.8	Pic du Midi Obs. 1.0 m	R
1998 Dec 18	2.460	1.666	16.5	Pic du Midi Obs. 1.0 m	R
1999 Jan 08	2.248	1.503	8.1	Haute-Provence Obs. 1.2 m	V
1999 Jan 12	2.245	1.483	6.2	Haute-Provence Obs. 1.2 m	V
1999 Jan 20	2.439	1.457	2.1	Pic du Midi Obs. 1.0 m	R
1999 Jan 23	2.437	1.453	0.6	Pic du Midi Obs. 1.0 m	R
1999 Jan 24	2.436	1.452	0.5	Pic du Midi Obs. 1.0 m	R
1999 Jan 23	2.437	1.453	0.6	Table Mountain Obs. 0.6m	R
1999 Feb 14	2.418	1.497	10.7	European Southern Obs. NTT 3.6m	BVRI
1999 Feb 15	2.417	1.502	11.2	European Southern Obs. NTT 3.6m	BVRI
1999 Feb 16	2.416	1.507	11.6	European Southern Obs. NTT 3.6m	BVRI
1999 Mar 15	2.389	1.722	20.9	European Southern Obs. 1.5m	4500–9000 Å
1999 Mar 16	2.388	1.732	21.2	European Southern Obs. 1.5m	4500–9000 Å

focus. The CCD was binned 2×2 for data taking, giving an image scale of 0.32 arcsec per pixel. The data were taken with the Harris R filter (λ=0.63 microns). Both nights were photometric with seeing of 1.5–3 arcsec. Integration times were 400 to 600 sec. The telescope was guided at the asteroid rate.

Pic du Midi Observatory (PDM): 4979 Otawara was observed with the Pic du Midi Observatory (France), 1 m telescope during two runs: in December, 1998 (16, 17 and 18) and January 1999 (20, 23 and 24). The telescope was equiped with a Thomson CCD imaging system (388×284). A F/D=6 focal reducer was used giving an image scale of 0.75 arcsec per pixel. The data were taken with the Cousins R filter (λ=0.60 microns). The nights were photometric with an average seeing of 1.8–2.2 arcsec. Integration times were 180 to 300 sec. guided at sidereal rate.

Haute Provence Observatory (OHP): 4979 Otawara was observed during the nights of January 8 and 12, 1999 with the 1.2 m telescope of Haute-Provence Observatory, France. The CCD was a TK 1024×1024, and the pixel-scale was 0.69 arcsec. The data were obtained with the Cousins V filter (λ=0.53 microns), and the exposure times ranged from 60 to 420 sec. The nights were not photometric, with a seeing of 2.4–3 arcsec. Thus, only relative photometry between the asteroid and the comparison stars was possible for this run.

Table Mountain Observatory (TMO): 4979 Otawara was observed on January 23, 1999 at Table Mountain Observatory (California). A Photometrics CCD (1024×1024) was used at the cassegrain focus of the 0.6 m telescope. The image scale was 0.52 arcsec per pixel. Digital images were recorded through a Bessel R filter with central wavelength of 0.64 microns. The night was photometric and the seeing ranged between 1 and 3 arcsec. The exposure time was 720 sec. The telescope was guided at the asteroid rate.

European Southern Observatory, NTT: Broadband color observations were obtained on February 14–16, 1999 using the SuSI2 CCD camera of the 3.6 m ESO New Technology Telescope (NTT) on La Silla, Chile. The image scale was 0.16 arcsec per pixel. Digital images were recorded through Bessel B, V, R, and I filters with central wavelengths at 0.421, 0.544, 0.642 and 0.795 microns, respectively. The nights were photometric with an average seeing of 1.2–1.8 arsec. The integration times were 60 to 90 sec.

European Southern Observatory, 1.5 m: Spectroscopic observations of 4979 Otawara were obtained in March, 1999 at the European Southern Observatory on La Silla (Chile). The 1.5 m telescope was equipped with a Boller & Chivens spectrograph and a Loral Lesser CCD detector (2048×2048 pixels). The grating used had 225 gr/mm, with a dispersion of 331 Å/mm in the first order. The CCD has 15 μm square pixels, giving a dispersion of about 5 Å/pixel in the wavelength direction. The spectral range is about $0.48 < \lambda < 0.88$ μm with a FWHM of about 10 Å. The spectra were recorded through a slit oriented in the east–west direction. The slit was opened to about 8 arcsec in order to reduce effects due to differential refraction and the possibility of losing signal due to guiding errors of the telescope.

The spectroscopic observations of 4979 Otawara were performed on two different nights: the first on 15 March 1999, at 01 31 27 UT, with a 1 hour exposure, the second on 16 March 1999, at 01 11 58 UT, with 1 hour and 10 minutes of exposure time. During the observations, Otawara had a visual magnitude of about 18.4 and was at an airmass of about 1.6.

2.2. Data reduction

Photometry: The CCD images obtained were reduced and calibrated in a standard manner using aperture photometry (PHOT task in IRAF Digiphot package, MAGNITUDE/CIRCLE in MIDAS, and ASTROL software developped by Francois Colas from IMCCE). First, an average bias frame was subtracted from each science image. Pixel-to-pixel variations in the CCD sensitivity were removed by dividing the frames by a median of several images (flats) of the twilight sky. The instrumental magnitudes were measured using aperture photometry. The radius of the aperture used was typically about twice the average seeing. This was deemed optimum since it is large enough to include most of the point spread function, yet small enough to minimize background sky noise. Sky subtraction was performed using a 7–12 pixels wide annulus around the asteroid or reference star. Finally, for magnitude calibration purposes, observations of standard stars (Landolt, 1992) were obtained over a wide range of airmasses and stellar types. The zero point, extinction and colour terms obtained from the Landolt fields were then used to convert instrumental magnitudes to apparent magnitudes. The errors quoted take into account both the instrumental error given by photon statistics alone and the calibration error. The latter error came from the scatter in the field star photometry. When the sky conditions were not photometric, as on the nights of 8 and 12 January 1999, the data have been reduced taking into account the differential extinction between the asteroid and the comparison stars.

Spectroscopy: During each night, we also recorded bias, flat–field, calibration lamp, spectrophotometric standard and solar analog stars (Hardorp, 1978) spectra at different intervals throughout the night. The solar analog stars (we observed Hyades64, HD44594, HD89010, HR6060, HD144585, HD76151) are necessary to remove the solar contribution from the spectra of the asteroid and to obtain the asteroidal reflectivity versus wavelengh. The spectral behaviour of the stars was very similar during each night. Moreover, to obtain Otawara's reflectivity, we used the solar analog with the closest airmass to that of the asteroid, that is HD 44594 for the first observation, and Hyades 64 for the second.

The spectra were reduced using standard data reduction procedures with the software packages Midas and IDL. The spectra are normalized to unity at 5500 Å and have been smoothed with a median filter technique.

3. Reflectance Properties

3.1. Colors

BVRI band images were obtained at the NTT (ESO) on February 14 to 16, 1999. The B - V, V - R and V - I colors are presented in Table 2. These colors fall within the S spectral type region (Schevchenko & Lupishko, 1998). However information at longer wavelength is necessary to distinguish between other close spectral types such as the types M or V. The BVRI data will be compared and discussed along with the spectroscopic results presented below.

3.2. Spectrum

The spectra obtained on the two nights in March (Fig. 1) appear very similar. The reflectance slope measured in the spectral range 5000–8000 Å, is $8.2 \pm 0.1\%/10^3$ Å, for the night of 15 March 1999 and $7.1 \pm 0.2\%/10^3$ Å, for the night of 16 March 1999. Small differences are associated with noise and also with the presence of spurious characteristics due to a non-perfect subtraction of sky absorption bands. Both spectra show a strong

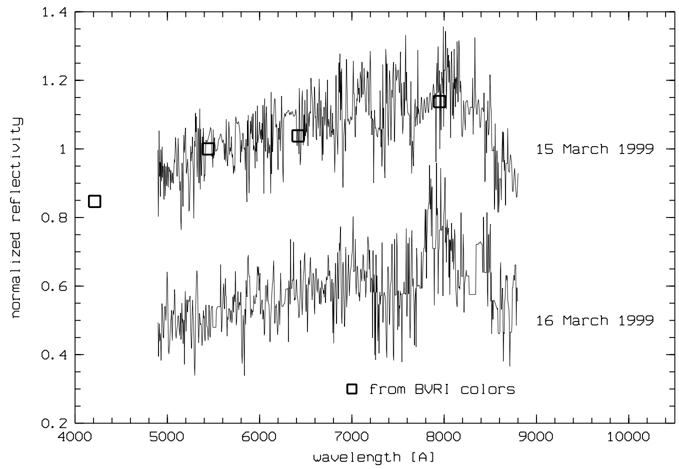

Fig. 1. Reflectance spectra of 4979 Otawara obtained on March 15 (top) and 16 (bottom), 1999. The spectra are normalized to unity at 5500 Å and have been vertically offset for clarity. Broadband color data from the ESO NTT on February 14–16, 1999 are also plotted (squares) on the top spectrum.

Table 2. Colors of 4979 Otawara

UT date	B-V	V-R	V-I
1999 Feb 14	0.87 ± 0.02	0.37 ± 0.01	0.84 ± 0.02
1999 Feb 15	0.86 ± 0.02	0.46 ± 0.02	0.83 ± 0.02
1999 Feb 16	0.82 ± 0.03	0.38 ± 0.02	0.82 ± 0.03
weighted mean	0.86 ± 0.01	0.40 ± 0.01	0.83 ± 0.01

absorption feature longwards of 8000 Å. This feature is the well known 0.9 μm band associated with silicate minerals (pyroxene and olivine). Its position and depth is related to the presence and abundance of both silicates (Gaffey et al. 1993).

The relative reflectances obtained from the BVRI color photometry are also plotted in Fig. 1. The reflectivity has been computed using solar colors. It can be seen that the broadband colors agree quite well with the spectroscopic measurements.

In order to characterize the spectral type of Otawara, we used the G-mode analysis applied to asteroids by Barucci et al. (1987) and Birlan et al. (1996). We found that the spectral types V and SV are most likely to match the spectrum of Otawara in Fig. 2. Extended spectral coverage (especially beyond 1 μm) and knowledge of the albedo would allow us to discriminate between the two spectral types. The V-type is associated with the asteroid 4 Vesta and HED meteorites (Binzel & Xu 1993).

The SV type is somewhat intermediate between the V and S-types. The appearance of the strong 0.9 μm band is suggestive that Otawara is a pyroxene and/or olivine-rich S-type asteroid

The possible association with the V-type is surprising and exciting. Indeed, all the known V-type asteroids are either members of the Vesta dynamical family (Zappala et al. 1995, Binzel & Xu 1993) or are near-Earth asteroids (Cruikshank et al. 1991). Asteroid 4979 Otawara is a main belt asteroid and does not belong to either of these populations. However, according to Migliorini et al. (1997) the Vesta family is much more extended than previously determined and extends close to the ν_6 and 3:1

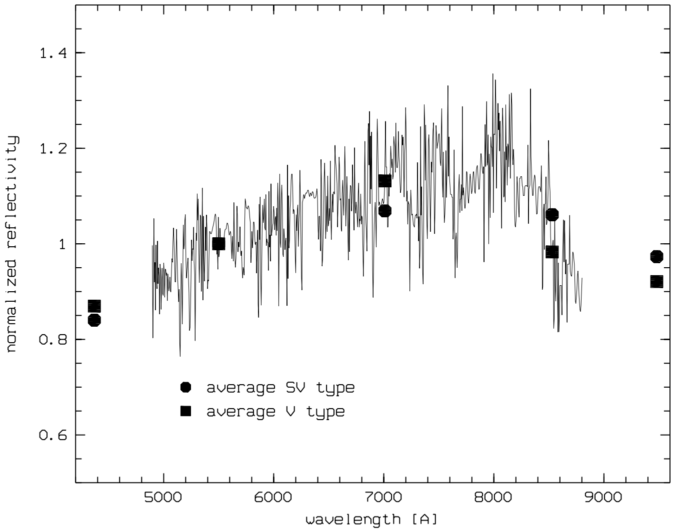

Fig. 2. Spectrum of 4979 Otawara compared with the mean spectrum of SV and V spectral type asteroids (Birlan et al., 1996).

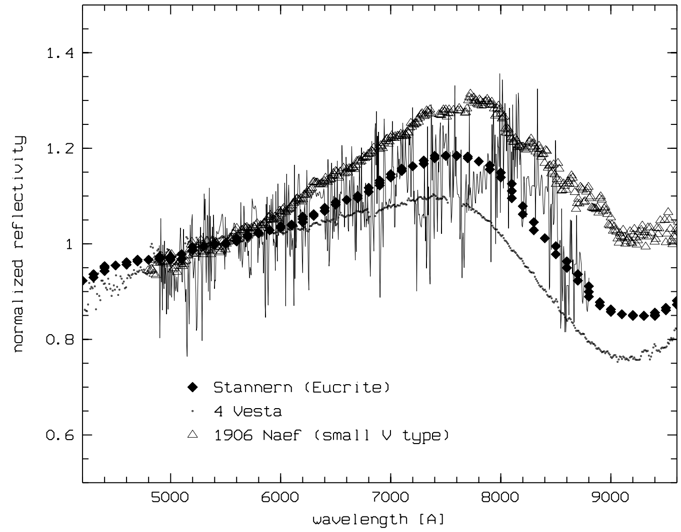

Fig. 3. A good match is obtained between the spectrum of 4979 Otawara and the spectrum of a eucrite (filled diamonds). The spectra of 4 Vesta (dotted line) and 1906 Naef (open triangles) are plotted for comparison. Eucrite spectrum is from Gaffey (1976) and spectra of Vesta and Naef are from SMASS (Xu et al. 1995).

resonances (a $\approx$ 2.15 and a $\approx$ 2.5 respectively). The position of Otawara in proper elements space is a = 2.168AU, e = 0.117 and sin i = 0.0071. Therefore, 4979 Otawara, which lies close to the ν_6 resonance, may in fact be a Vesta family member.

We also found a good match for the spectrum of Otawara with the spectrum of a eucrite meteorite, (Gaffey et al., 1976) suggesting once again a V-type classification (Fig. 3). The spectra of two Vesta family members: 4 Vesta and 1906 Naef are also plotted in Fig. 3. The latter one is a small asteroid (d = 6 km) like 4979 Otawara (see next section). It can be seen that Otawara' spectrum is comparable and certainly lies in the spectral range of the Vesta family.

4. Photometry

4.1. Rotation period

Because different filters were used in the observations and the observations were made over a wide range of phase angles, we analysed the three sets of photometric data independently in order to search for the asteroid's rotation period: 1) the data obtained in December, 1998 with the R filter ($16.5 < \alpha < 17.9$ degrees where α is the phase angle), 2) the data obtained in January 1999 with the R filter when the asteroid was very close to opposition ($0.5 < \alpha < 2.1$ degrees) and 3) the data obtained with the V filter in January 1999 ($6.2 < \alpha < 8.1$ degrees). We determined the synodic rotation period and the corresponding uncertainty by assuming a double-peaked lightcurve and by applying a Fourier analysis as described in Harris et al. (1989). We found rotation period of 2.707 $\pm$ 0.005, 2.707 $\pm$ 0.005 and 2.63 $\pm$ 0.01 hours for the three data sets, respectively. The disagreement in the third data set is likely the results of the fact that these data were taken under non-photometric conditions. Combining all three data sets, we found the best rotation period for Otawara

$$\mathrm{P_{syn}} = 2.707 \pm 0.005\,\mathrm{hr}.$$

The composite lightcurves, shown in Figs. 4, 5 and 6, are consistent and have symmetric double-peaks, typical of a ellipsoidal shape-dominated lightcurve. The peak-to-peak amplitude is 0.25 $\pm$ 0.04 mag for the December R data, 0.29 $\pm$ 0.05 mag for the January R data and 0.27 $\pm$ 0.03 mag for the January observations in the V filter.

4.2. Shape

The highest peak-to-peak amplitude is Δm = 0.29. If we assume that the brightness variation of Otawara is purely shape-induced, with no albedo features, we can model the asteroid as a tri-axial ellipsoid with semi-axes a, b and c where $a > b > c$. We, then can estimate a lower limit for the axial ratio:

$$\frac{a}{b} \;\geq\; 10^{0.4\Delta m} \tag{1}$$

The lightcurve amplitude of 4979 Otawara thus implies an axis ratio of $a/b \geq 1.3$. This corresponds to an elongation of at least 30%.

4.3. Size

We attempted to fit the data using the standard H, G magnitude system. Due to insufficient data, poor coverage down to subdegree phase angles and possibly the use of different R filters, we could not obtain reliable absolute magnitude and slope parameters. Thus we choose to compute the absolute magnitude assuming G = 0.24 (S-type) and 0.49 (V-type). These latter values are the mean values of the parameter G for the respective compositional types, calculated from a sample containing 98 objects (Schevchenko & Lupishko, 1998).

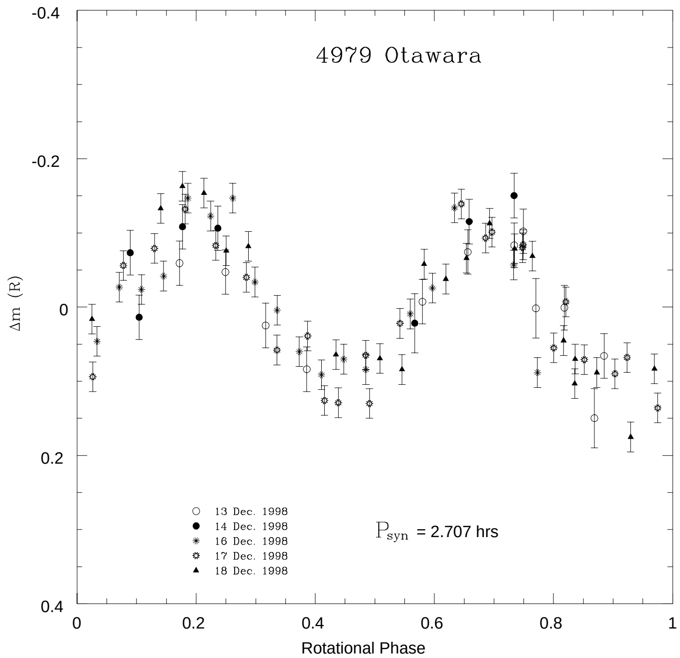

Fig. 4. Composite lightcurve of 4979 Otawara in rotational phase obtained in December 1998 in the R filter.

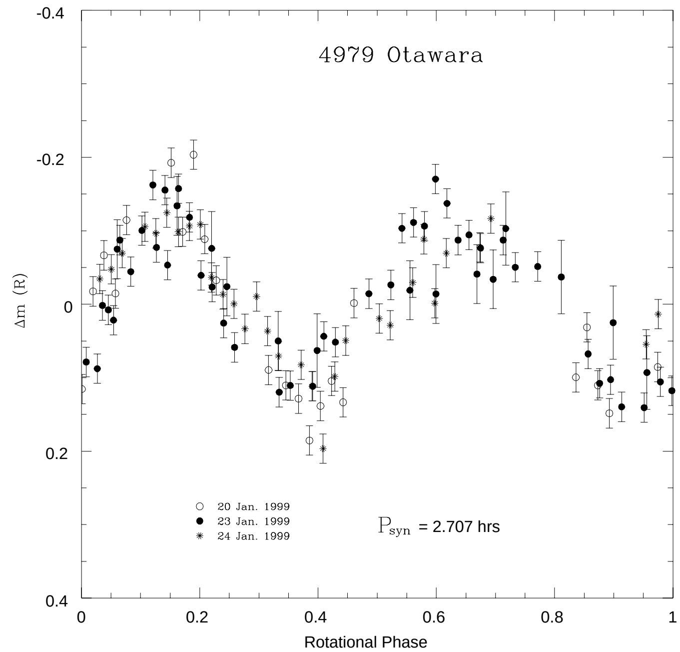

Fig. 5. Composite lightcurve of 4979 Otawara in rotational phase obtained in January 1999 in the R filter.

The absolute magnitude H_R is computed following Bowell et al. (1989). The mean absolute magnitude for all the nights in the R filter is:

$$\mathrm{H_R} = 14.08 \pm 0.04 \quad \text{assuming an S-type,}$$
$$\mathrm{H_R} = 14.23 \pm 0.04 \quad \text{assuming an V-type.}$$

If we assume an albedo of 0.19 or 0.38 as typical respectively for S and V-type asteroids (Tedesco et al. 1989), these correspond to a circular effective radius of 2.0 or 1.3 km, for S and V-types respectively. Knowing its axial ratio, (assuming $b = c$) we can then infer that 4979 Otawara is an elongated body having semi-axes $a = 2.4$ km and $b = 1.9$ km for a typical S-type albedo, and $a = 1.6$ km and $b = 1.2$ km for a V-type albedo.

5. Internal properties

Given its small size and its rotation period, 4979 Otawara belongs to a group of special interest, the small and fast rotating asteroids (FRAs). Typically observed lightcurve amplitudes of FRAs like Otawara are much smaller than those of slower rotators, indicating that the FRAs are less elongated, rather spheroidal bodies. For instance, for NEAs with $P > 4$ hr, the mean amplitude is 0.69 ± 0.05 mag, whereas for $P < 4$ hr, the mean amplitude is 0.21 ± 0.03 mag (Pravec, 1999). Observational and theoretical studies of small, fast rotating asteroids show that they have distinct properties that bring important information to our understanding of the collisional evolution of the asteroid population (see Pravec, 1999 for the latest review of this subject). In particular, FRAs, unlike asteroids with longer periods, are near the rotational break-up limit for aggregates with no tensile strength, assuming plausible bulk densities for asteroids.

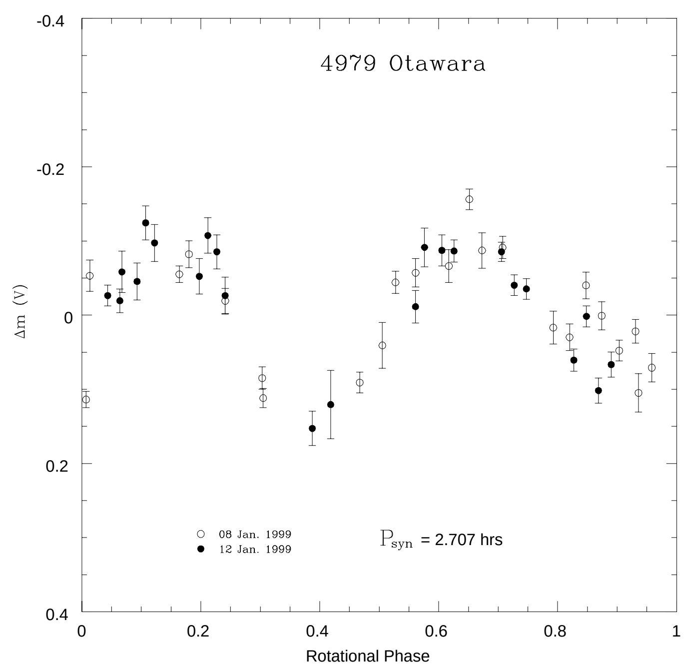

Fig. 6. Composite lightcurve of 4979 Otawara in rotational phase obtained in January 1999 in the V filter.

If Otawara is an aggregate or "rubble pile" object we can constrain its density knowing its rotation period and shape. If a body has no tensile strengh, a minimum density is required in order to resist centrifugal disruption. This is obtained by simply equating the centrifugal acceleration with the gravitation acceleration for the elongated body. Thus the minimum density ρ_{min}

for a body with axis ratio a/b and rotation period P is (Harris, 1996)

$$\rho_{min} \approx \left(\frac{3.3^h}{P}\right)^2 \frac{a}{b} \qquad (2)$$

Applying this formula to 4979 Otawara, we find:

$\rho_{min} \geq 1.9.$

This density rules out densities as low as that of the C type asteroid 253 Mathilde ($\approx 1.3 \pm 0.4$ g cm^{-3}) found by the NEAR spacecraft team (Veverka et al. 1997) but allows densities comparable to that of 243 Ida (2.6 ± 0.5 g cm^{-3}) found by the Galileo imaging team (Belton et al. 1995). Hovewer, if 4979 Otawara is a single, consolidated body, then the fast rotation period gives us little information about its density.

6. Conclusion and discussion

Asteroid 4979 Otawara was observed on seven occasions from December 1998 through March, 1999. The main results of these observations are the following:

- Otawara exhibits a solar reflected spectrum indicating either a pyroxene and/or olivine-rich S-type asteroid, or a V-type asteroid, a member of the Vesta dynamical family. Further observations, in particular at near-infrared wavelenghs are needed in order to discriminate between the two spectral types.
- The synodic rotation period of Otawara is $P_{\rm syn} = 2.707 \pm 0.005$ hr.
- The lower limit for the axial ratio of the enveloping ellipsoid is $a/b \geq 1.3$.
- The circular effective radius is 2.0 or 1.3 km in the case of an S-type or a V-type asteroid, respectively.
- 4979 Otawara is a small, fast rotating asteroid (FRA). A lower limit on its density is obtained, $\rho_{min} \geq 1.9$, if we assume that Otawara is an aggregate or "rubble pile" object.

Asteroid 4979 Otawara will be a particularly interesting target to be studied from a spacecraft, since no fast rotator asteroid has been visited yet. The fast rotation of Otawara will allow the onboard Rosetta remote sensing instruments to image and measure the asteroid surface characteristics during one complete rotation of the asteroid at the highest possible resolution.

Further CCD photometric observations near opposition, occuring at different celestial latitudes, are necessary in order to determine the rotation pole direction of this asteroid. Also, additional spectroscopic observations are needed, in particular observations in the near infrared. Spectra taken at different rotational phases (Doressoundiram et al., 1997) will give a better estimate of the surface composition and its homogeneity/heterogeneity.

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