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Asteroid 2867 Steins

II. Multi-telescope visible observations, shape reconstruction, and rotational state

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ABSTRACT

Context. Asteroid 2867 Steins is the first target of the Rosetta space mission with a flyby scheduled in September 2008.
Aims. An early physical characterization is needed to optimize the flyby parameters and the science operations, and to maximize the scientific return. The aim of this article is to characterize the shape and rotational state of this asteroid.
Methods. We compile a set of 26 visible light curves whose phase angle coverage extends from 7.5° to 41.7°, and perform their simultaneous inversion relying on convex modeling.
Results. The full three-dimensional solution for asteroid 2867 Steins is rather spherical with axial ratios $a/b = 1.17$ and $a/c = 1.25$. The rotational state is characterized by a sidereal period of 6.04681 ± 0.00002 h, and the pole direction defined by its ecliptic coordinates $\lambda \approx 250°$ and $\beta \approx -89°$ has an uncertainty of about 5°. It is therefore almost exactly perpendicular to the ecliptic plane, and the viewing geometries are thus restricted to only ±20° about Steins' equator. Consequently, the shape model is not strongly constrained, and the polar flattening has an uncertainty of about 10%. Inversion is basically scale-free, and absolute scaling comes from a measurement of its thermal emission with the Spitzer Space Telescope (Lamy et al. 2008, A&A, 487, 1187), yielding overall dimensions of 5.73 ± 0.52, 4.95 ± 0.45, and 4.58 ± 0.41 km.

Key words. minor planets, asteroids – techniques: image processing

1. Introduction

This article on asteroid 2867 Steins, the first target of the Rosetta space mission, is the second in a series of four companion articles.

- Article I (Jorda et al. 2008) describes the lightcurve data obtained with the OSIRIS narrow angle camera (NAC) aboard the Rosetta spacecraft itself, and discusses the photometric properties (color, phase function).
- This present article (II) presents multi-telescope visible observations, shape reconstruction and rotational state.
- Article III (Lamy et al. 2008) presents thermal radiometry obtained with the Spitzer Space telescope, and focuses on the size, albedo, and thermal properties.
- Article IV (Barucci et al. 2008) reports on the thermal emissivity, and discusses the mineralogical composition and taxonomic classification.

The reader is referred to article I for the general context of the investigation and for a summary of our present knowledge of asteroid Steins.

This present article reports on several observational campaigns that have produced a set of 26 light curves. They are then simultaneously inverted to yield a solution for the shape of the asteroid as well as its rotational state. Our measurements of its thermal flux with the SST (Lamy et al. 2008) allow us to derive its overall dimensions.

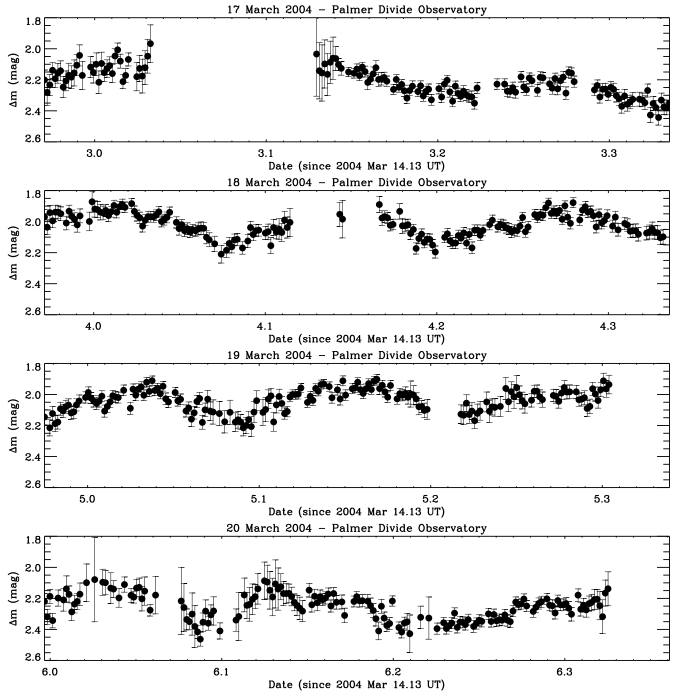

Fig. 1. The four light curves of asteroid 2867 Steins obtained at Palmer Divide Observatory on 17, 18, 19, and 20 March 2004.

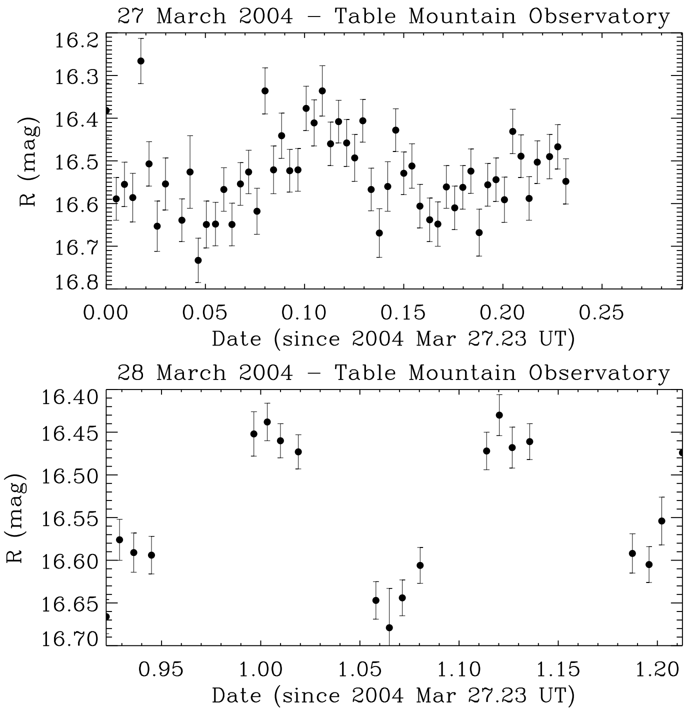

Fig. 2. The two light curves of asteroid 2867 Steins obtained at Table Mountain Observatory on 27 and 28 March 2004.

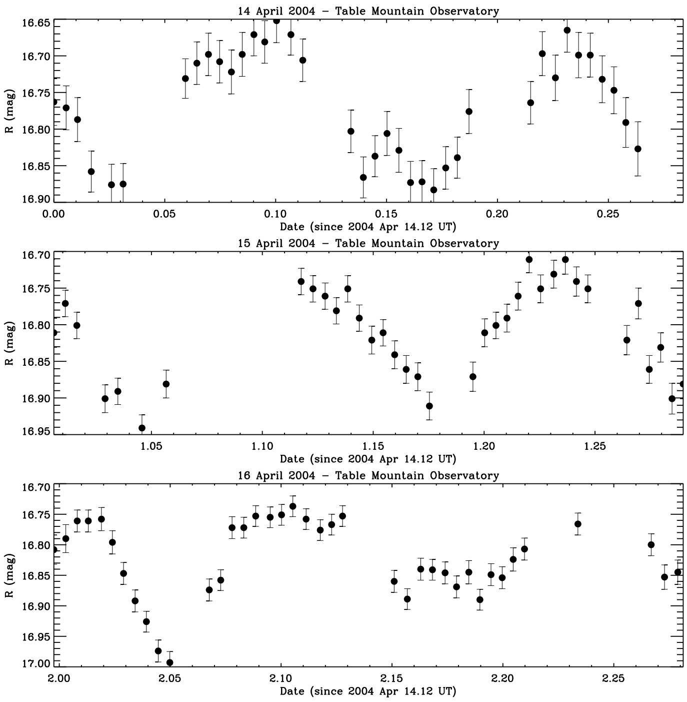

Fig. 3. The three light curves of asteroid 2867 Steins obtained at Table Mountain Observatory on 14, 15, and 16 April 2004.

2. Observations

Observations reported below were obtained at six different ground-based observatories and with one spacecraft; the complete list is given in Table 1.

2.1. Palmer Divide Observatory

Asteroid 2867 Steins was observed with the 0.5 m, Ritchey-Chretien telescope at the Palmer Divide Observatory (PDO), Colorado, on 14 and from 17 to 20 March 2004 (Investigator: Warner). A 1024 × 1024 pixel CCD was used with a clear filter to maximize throughput. The asteroid was observable below two air masses for about 9 h per night. A total of 24, 140, 171, 169, and 155 clear-filter images of the asteroid were taken on nights 1, 2, 3, 4, and 5, respectively. In each case, the images were tracked at the asteroid's rate of motion and the exposure time was set at 90 s. The resulting light curves are relative only, and are displayed in Fig. 1

2.2. Table Mountain Observatory

Asteroid 2867 Steins was observed with the 0.6 m, Ritchey-Chretien telescope at the Table Mountain Observatory (TMO), California, on 27–28 March 2004 (Investigators: Hicks, see Hicks et al. 2004), on 14–16 April 2004 (Investigators: Weissman, Lowry & Choi, see Weissman et al. 2007), and finally on 16–17 January 2007 (Investigators: Weissman & Choi). Images were obtained with the facility camera, using a Photometrics 1024 × 1024 pixel thinned and back-illuminated CCD, mounted at the Cassegrain focus of the $f/16$ telescope, and with the Johnson-Kron-Cousins R-filter. The pixel scale was 0.52″/pixel. For all images the telescope was tracked at the asteroid's rate of motion. The asteroid was observed for about 7.5 h per night for the March 2004 run, about 6 h per night for the April 2004 run, and about 7 h per night for the January 2007 run. A total of 55 images of the asteroid field were obtained on 27 March, 20 on 28 March, 38 on 14 April, 36 on 15 April, 39 on 16 April, 26 on 16 January, and 28 on 17 January. Typical exposure times ranged from 360 to 600 s. Concerning the April run, only the nights of 14 and 16 April were photometric thus calibration frames of the Steins star fields for the 15 April observation were obtained on a later run at TMO under photometric conditions. Concerning the January run, the seeing was rather poor during the two nights. The light curves in the JKC R band are displayed in Figs. 2, 3, and 4.

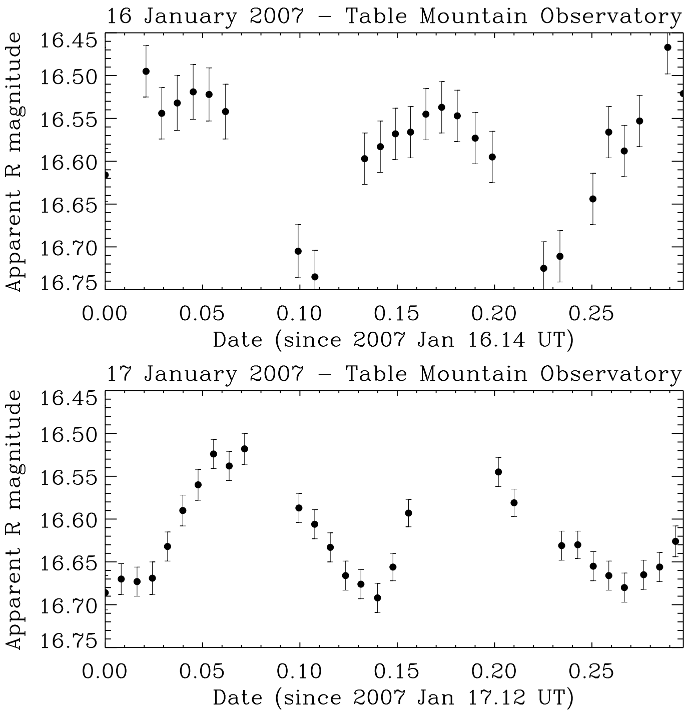

Fig. 4. The two light curves of asteroid 2867 Steins obtained at Table Mountain Observatory on 16 and 17 January 2007.

2.3. Cerro Tololo Inter-American Observatory

Asteroid 2867 Steins was observed with the 0.9 m, Ritchey-Chretien SMARTS telescope at the Cerro Tololo Inter-American Observatory (CTIO), near La Serena, Chile on four half-nights, 2, 7, 9, and 11 August 2005 (Investigators: Weissman & Choi). Images were obtained with the facility camera, using a Tektronix 2048 × 2046 pixel thinned, anti-reflection coated, and back-illuminated CCD, mounted at the Cassegrain focus of the $f/13.5$ telescope, and with the standard broadband Harris R-filter. The pixel scale was 0.396″/pixel. For all images the telescope was tracked at the asteroid's rate of motion. The asteroid was located close to opposition and at a southernly declination of –29°. Because only half-nights were available, observations below two air masses were possible for ~5.5 h per night, though on some nights extra time was available. This still allowed the observers to capture almost one complete rotation each night. A total of 71 images were obtained on 2 August, 74 on 7 August, 93 on 9 August, and 101 on 11 August, providing excellent temporal coverage. Typical exposures were 120 s. Sky conditions were generally clear but with light cirrus, and thus were not photometric; so the extracted lightcurves are relative only (Fig. 5).

2.4. Itajuba Observatory

Asteroid 2867 Steins was observed with the 0.6 m Zeiss telescope at the Itajuba observatory, Pico dos Dias (PdD), Brazil on 2 nights, 4 and 5 August 2005 (Investigators: Colas & Kryszczynska). Images were obtained with the facility camera, using an EEV 400 × 290 pixel, thick, ultraviolet coated CCD, mounted at the Cassegrain focus of the $f/12.5$ telescope, and a R filter. Additional frames were obtained with a V filter for calibration purposes. They were tracked at the sidereal rate of motion, and the exposure time was limited to 60 s to avoid smearing. During the first night 220 images were obtained covering ~5 h, i.e., almost a full rotational period. The coverage was

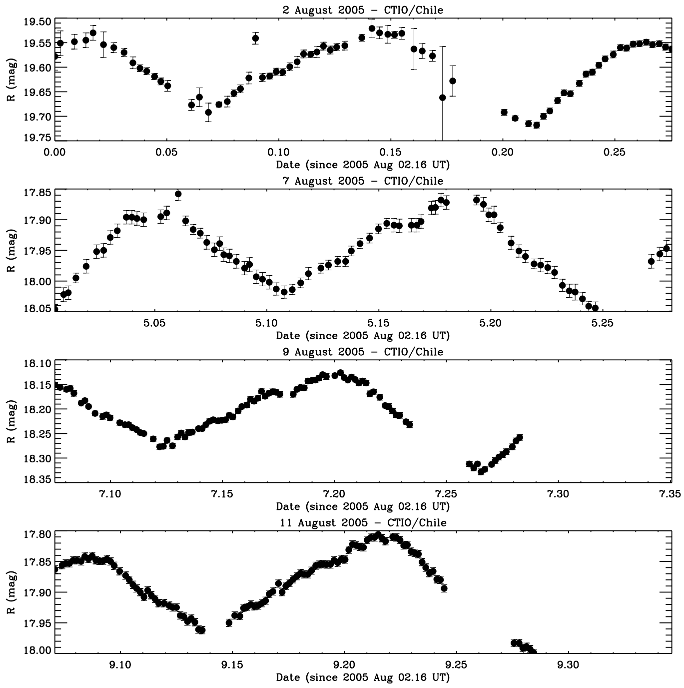

Fig. 5. The four light curves of asteroid 2867 Steins obtained at Cerro Tololo Inter-American Observatory on 2, 7, 9, and 11 August 2005.

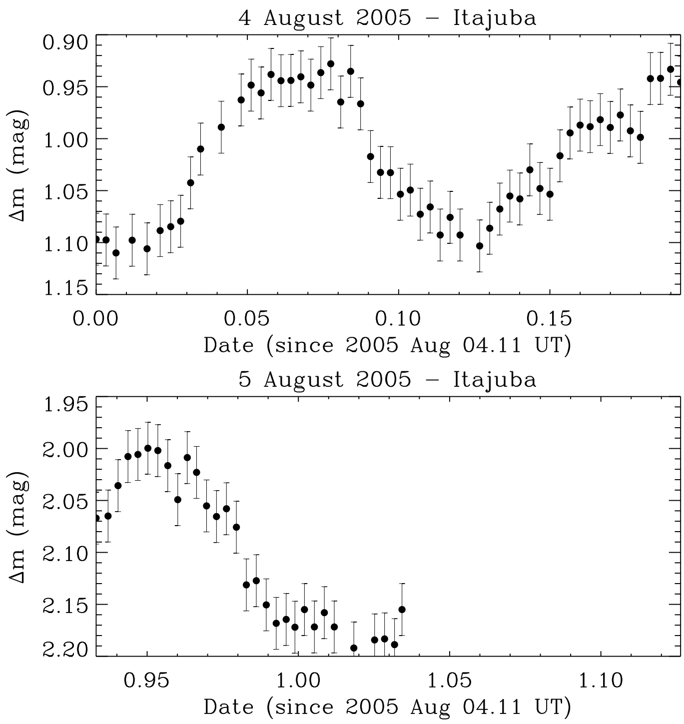

Fig. 6. The two light curves of asteroid 2867 Steins obtained at Itajuba Observatory on 4 and 5 August 2005.

extended during the second night with 120 images over ~2.6 h. Photometric conditions were excellent both nights. Calibration images taken with the R and V filters were combined to calculate the $V-R$ color index of the field stars, and stars with indexes close to that of the asteroid were subsequently used for differential photometry. Therefore, the light curves in the R filter are relative only, and the individual data points correspond to averages of four consecutive images (Fig. 6).

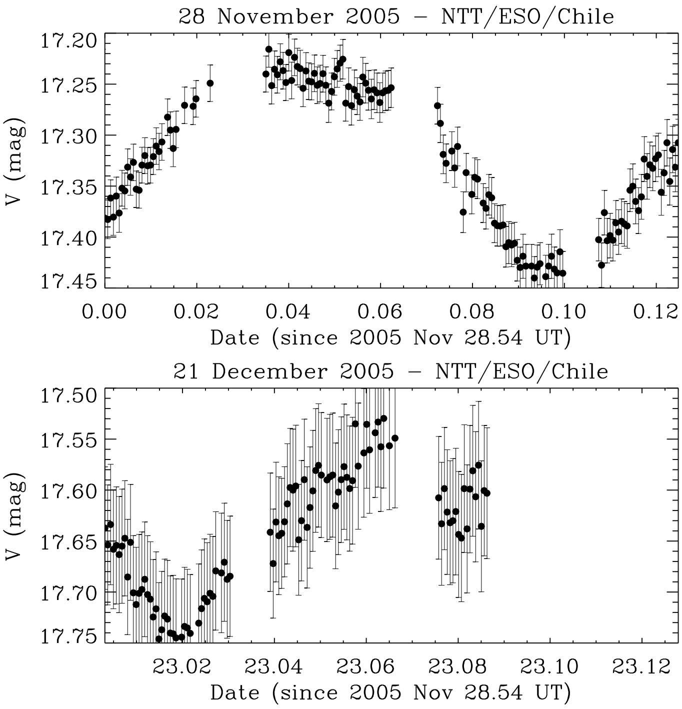

Fig. 7. The two light curves of asteroid 2867 Steins obtained at ESO on 29 November and 22 December 2005.

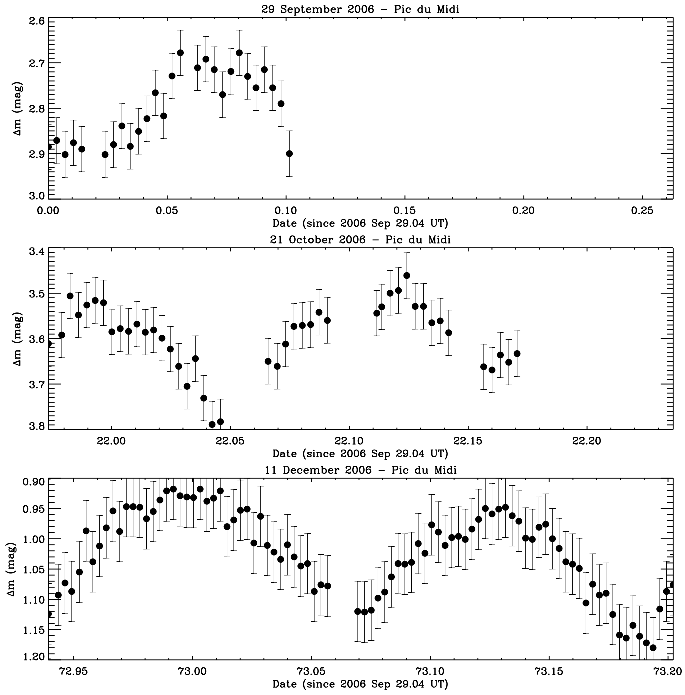

Fig. 8. The three light curves of asteroid 2867 Steins obtained at Pic-du-Midi Observatory on 29 September, 21 October, and 11 December 2006.

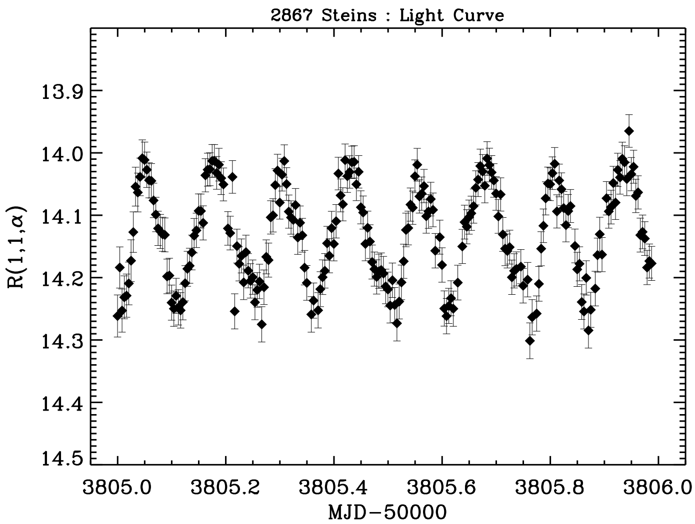

Fig. 9. The light curve of asteroid 2867 Steins obtained with the OSIRIS-NAC camera on 11 March 2006.

2.5. European Southern Observatory

Asteroid 2867 Steins was observed with the 3.5 m New Technology Telescope (NTT) at the European Southern Observatory (ESO), La Silla, Chile on two nights, 29 November and 22 December 2005 (Investigators: Barucci, Carvano, Fornassier). Images were obtained with the SUSI2 instrument equipped with a mosaic of two EEV 2048 × 4096 thinned, anti-reflection coated CCDs, and with the Bessel *V* filter. The pixel scale was 0.085″/pixel. The asteroid was observed for about 4 h both nights: 148 images were obtained on 29 November and 104 images on 22 December 2005, all with an exposure time of 30 s. Absolute calibration was performed with Landolt fields (Landolt 1992) each night. The resulting light curves in the *V* band are displayed in Fig. 7.

2.6. Pic-du-Midi Observatory

Asteroid 2867 Steins was observed with the 1 m telescope at the Pic-du-Midi Observatory, France on three nights, 29 September, 21 October, and 11 December 2006 (Investigators: Colas & Vachier). Images were obtained with a Thomson THX 7863 388 × 284 pixel CCD, mounted at the focus of a $F/D = 6$ focal reducer giving a scale of 0.75″/pixel, and a broadband MTO DH710B filter with a pass band extending from 530 to 900 nm to maximize throughput and to avoid bright sky emissions. All images were tracked at the asteroid projected rate of motion, and the exposure time was set to 300 s for the first two nights, and to 240 s for the last one. A total of 27 images were obtained on 29 September, 44 on 21 October, and 90 on 11 December. The last observation extended over ∼6.2 h, thus covering a full rotational period. Photometric conditions were excellent during the three nights. Additional calibration images taken with the *R* and *V* filters were combined to calculate the $V - R$ color index of the field stars, and stars with index close to that of the asteroid were subsequently used for differential photometry. Therefore, the lightcurves are relative only (Fig. 8).

2.7. OSIRIS-NAC observations

Asteroid 2867 Steins was continuously observed for 24 h with the OSIRIS narrow angle camera (NAC) aboard the Rosetta spacecraft on 11 March 2006 (Jorda et al. 2008, Küppers et al. 2007). This camera is equipped with a 2048 × 2048 pixel thinned, back-illuminated CCD, mounted at the focus of the $f/8$ telescope, but only subframes of 512 × 256 pixel centered at the expected position of Steins were transmitted. The pixel scale was 3.9″/pixel. A very broadband filter centered at 618 nm and with a *FWHM* of 460 nm was used to maximize the

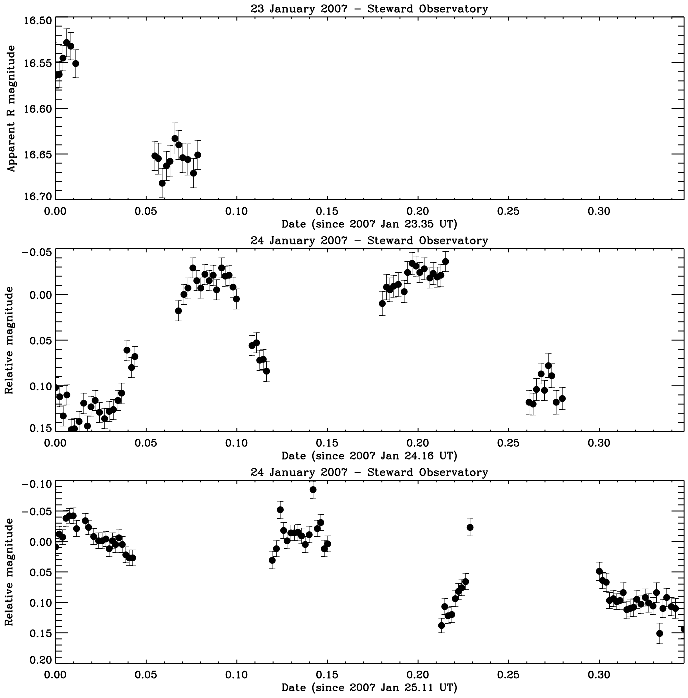

Fig. 10. The three light curves of asteroid 2867 Steins obtained at Steward Observatory on 23–25 January 2007.

throughput. The Rosetta spacecraft tracked the expected motion of Steins, and a total of 238 images with 300 s exposure time each were obtained, one image every 6 minutes. Absolute photometry was performed using the solar analog 16 Cyg B to obtain *R*-band magnitudes (JKC system). The resulting light curve is displayed in Fig. 9.

2.8. Steward Observatory

Asteroid 2867 Steins was observed with the 1.55 m Kuiper telescope at the Mt. Bigelow site of the Steward Observatory on 23–25 January 2007 (Investigators: Weissman, Choi, Lowry & Larson). Images were obtained with the Mont4K camera, with a Fairchild 4096 × 4097 backside processed CCD, and with the Johnson-Kron-Cousins *R*-filter. The pixel scale was 0.28″/pixel. For all images, the telescope was tracked at the asteroid's rate of motion. Exposure times were 120 s. The asteroid was observed for about 1.9 h on 23 January (17 images); 6.7 h on 24 January (65 images); and 8 h on 25 January (69 images). Only the first night was photometric yielding apparent *R* magnitudes in the JKC system, while the magnitudes for the other two nights are relative (Fig. 10).

3. Light curves inversion, shape reconstruction and rotational state

In order to reconstruct the shape of asteroid 2867 Steins, we apply the standard inversion procedure developed by Kaasalainen et al. (2001) to the whole set of 26 light curves presented in the above section. This method makes use of all data points (both relative and calibrated photometry) but operates in relative photometry to find a physical shape and rotation model, albeit with a large number of free parameters, that accurately reproduces the photometric data down to the noise level. The simultaneously-determined parameters describe the sidereal rotational period, the pole direction, and the shape of the body. The inversion relies on convex modeling performed in the parameter space describing the Gaussian image of a shape; this image is then transformed into shape information in radius space. Due to the so-called Minkowski stability, convex inversion is quite stable against the incorrectness of the scattering model (including slight albedo variegation) or other systematic or random errors. The choice of a scattering law has no significant impact on the result: as shown by Kaasalainen et al. (2001), the chosen model does not make much difference for light curve inversion. Further details can be found in Kaasalainen and Lamberg (2006) & Kaasalainen & Ďurech (2007).

There were a sufficient number of observing geometries of 2867 Steins for a unique solution; the October and December 2006 data were particularly important in favoring only one pole choice. All 26 light curves could be reconstructed with a smooth shape model, and no large-scale irregularities are apparent. Figure 11 displays a representative subset of six light curves with the corresponding fits calculated from the model, while Fig. 12 displays three views of the model, two equatorial, and one pole-on.

The best pole direction has ecliptic coordinates $\lambda \approx 250°$ and $\beta \approx -89°$ with an uncertainty of about 5°. Obviously, the latitude uncertainty encompasses all longitudes, so the formal error bar of longitude amounts to ±180°. The error envelope however differs from circular, and the uncertainty region is more oriented along the $\lambda = 70/250°$ meridian. The nominal solution given above corresponds to RA = 91° and Dec = −67° (J2000). The pole direction is apparently almost exactly perpendicular to the ecliptic plane, and the viewing geometries are therefore restricted to only ±20° about Steins' equator, so the shape model is not strongly constrained. In particular, the polar flattening is poorly determined, and has an uncertainty of about 10%. Finally the best estimate of the sidereal rotational period is 6.04681 ± 0.00002 h.

Photometric inversion is basically size-scale free. We used our thermal infrared measurements of 2867 Steins obtained with the SST to sure the absolute size of the asteroid. A thermal model was applied to the above shape model, its thermal light curve was calculated taking into account the geometry of the SST observations, and it was fitted to the observed light curve. More detail can be found in Article III of these series. The nominal overall dimensions of the body are then 5.73, 4.95, and 4.58 km along the *x*-, *y*-, and *z*-axes, respectively. The systematic uncertainty on the size is discussed in Article III, and amounts to 9%. As explained above, there is a ∼10% additional uncertainty on the polar flattening. The total surface area and volume of the asteroid are respectively 79.2 km^2 and 64.3 km^3. For an E-type asteroid, we can reasonably assume a bulk density of 2000 ± 500 kg m^{-3}, yielding a mass in the range 1.7×10^{15}–2.8×10^{15} kg.

4. Conclusions

Our muti-telescope observations of asteroid 2867 Steins, the first target of the Rosetta mission, have enabled us to determine its main physical properties. From the simultaneous inversion of our set of 26 visible light curves obtained between 2004 to 2007 and at solar phase angles from 7.5° to 41.7°, it emerges the picture of a rather spherical body having axial ratios $a/b = 1.17$ and $a/c = 1.25$. The three-dimensional model has been scaled using the thermal emission measured with the SST (Lamy et al. 2008), and the overall nominal dimensions are 5.73, 4.95, and 4.58 km. Assuming a bulk density of 2000 ± 500 kg m^{-3}, its mass lies in the range 1.7×10^{15}–2.8×10^{15} kg. The rotational state is characterized by a sidereal period of 6.04681±0.00002 h,

Table 1. Journal of observations of 2867 Steins

UT date	R_h (AU)	Δ (AU)	α (°)	λ (°)	β (°)	Filter	Telescope	Observers
2004 Mar. 17.30	2.59	1.63	7.5	163.1	14.6	Clear	PDO	Warner
2004 Mar. 18.28	2.59	1.64	7.8	162.9	14.5	Clear	PDO	Warner
2004 Mar. 19.26	2.59	1.64	8.1	162.6	14.5	Clear	PDO	Warner
2004 Mar. 20.30	2.59	1.64	8.5	162.4	14.4	Clear	PDO	Warner
2004 Mar. 27.35	2.58	1.66	10.9	160.9	14.0	*R*	0.6-m TMO	Hicks et al.
2004 Mar. 28.30	2.58	1.67	11.2	160.7	13.9	*R*	0.6-m TMO	Hicks et al.
2004 Apr. 14.26	2.56	1.77	16.8	158.2	12.5	*R*	0.6-m TMO	Weissman, Lowry & Choi
2004 Apr. 15.29	2.56	1.78	17.1	158.2	12.4	*R*	0.6-m TMO	Weissman, Lowry & Choi
2004 Apr. 16.24	2.56	1.79	17.4	158.1	12.3	*R*	0.6-m TMO	Weissman, Lowry & Choi
2005 Aug. 02.30	2.03	1.08	13.7	331.1	–19.0	*R*	0.9-m CTIO/Chile	Weissman, Choi & Lowry
2005 Aug. 07.29	2.03	1.06	12.0	330.1	–19.3	*R*	0.9-m CTIO/Chile	Weissman, Choi & Lowry
2005 Aug. 09.33	2.03	1.06	11.3	329.7	–19.3	*R*	0.9-m CTIO/Chile	Weissman, Choi & Lowry
2005 Aug. 11.32	2.03	1.06	10.8	329.2	–19.4	*R*	0.9-m CTIO/Chile	Weissman, Choi & Lowry
2005 Aug. 04.21	2.03	1.07	13.0	330.7	–19.1	Johnson *R*	0.6-m Itajuba	Colas & Kryszczynska
2005 Aug. 05.10	2.03	1.07	12.7	330.5	–19.2	Johnson *R*	0.6-m Itajuba	Colas & Kryszczynska
2006 Sep. 29.09	2.59	2.57	22.4	106.1	4.8		1.05-m PdM	Colas & Vachier
2006 Oct. 21.11	2.62	2.30	22.2	110.7	6.2		1.05-m PdM	Colas & Vachier
2006 Dec. 11.11	2.66	1.78	11.7	110.3	10.4		1.05-m PdM	Colas & Vachier
2005 Nov. 28.60	2.14	1.93	27.4	334.8	–8.8	*V*	NTT/ESO/Chile	Barucci et al.
2005 Dec. 21.58	2.17	2.22	25.8	344.0	–7.0	*V*	NTT/ESO/Chile	Barucci et al.
2006 Mar. 11.50	2.30	1.06	41.7	75.4	–9.0	Clear	NAC	Jorda et al.
2007 Jan. 16.29	2.68	1.73	6.7	101.5	12.1	*R*	TMO	Weissman & Choi
2007 Jan. 17.26	2.68	1.74	7.0	101.2	12.1	*R*	TMO	Weissman & Choi
2007 Jan. 23.40	2.69	1.77	9.2	99.8	12.1	*R*	TMO	Weissman & Choi
2007 Jan. 24.29	2.69	1.77	9.5	99.6	12.1	*R*	TMO	Weissman & Choi
2007 Jan. 25.29	2.69	1.78	9.8	99.4	12.1	*R*	TMO	Weissman & Choi

Note: Date: mid-point of the exposure; r_h, Δ: heliocentric, geocentric distances; α: solar phase angle; λ, β: observer-centric ecliptic longitude and latitude of the asteroid; Itajuba: Pico dos Dias, Itajuba, Brazil; PDO: Palmer Divide Observatory, Colorado; PdM: Pic du Midi Observatory, France; TMO: Table Mountain Observatory, California.

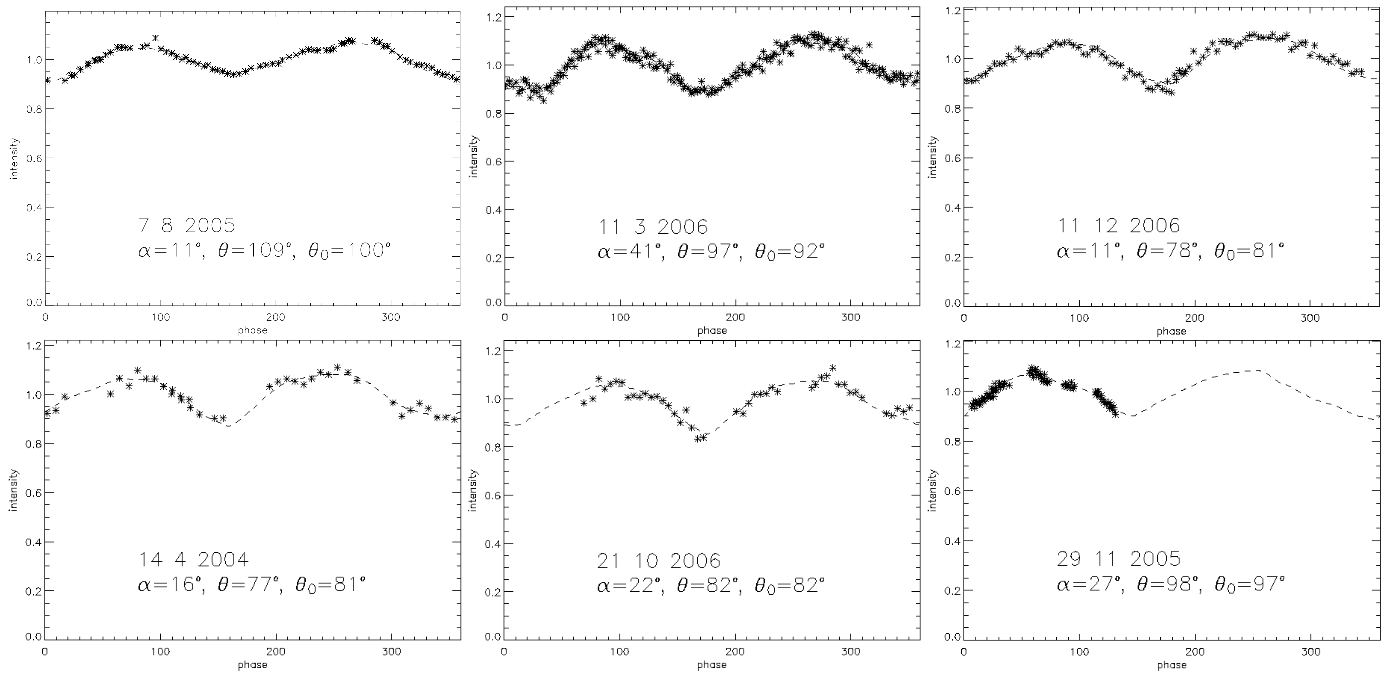

Fig. 11. Sample light curves (relative intensity) of the three-dimensional model of asteroid 2867 Steins as reconstructed by the inversion of the observations (data points). The phase folding is performed using the corresponding rotational period of 6.04681 h.

and a pole direction defined by its ecliptic coordinates $\lambda = 250°$ and $\beta = -89°$. This direction, close to perpendicular to the ecliptic plane, restricts the viewing geometries to only ±20° about Steins' equator, so the shape model, in particular the polar flattening, is not strongly constrained. Although there is an uncertainty of approximatively 5° on the orientation of the pole direction, our results indicate that it is closer to the ecliptic normal than to the orbit normal. These results suggest an evolved spin state with respect to the ecliptic rather than to the orbit, or perhaps a Cassini state. The rotational state of minor bodies

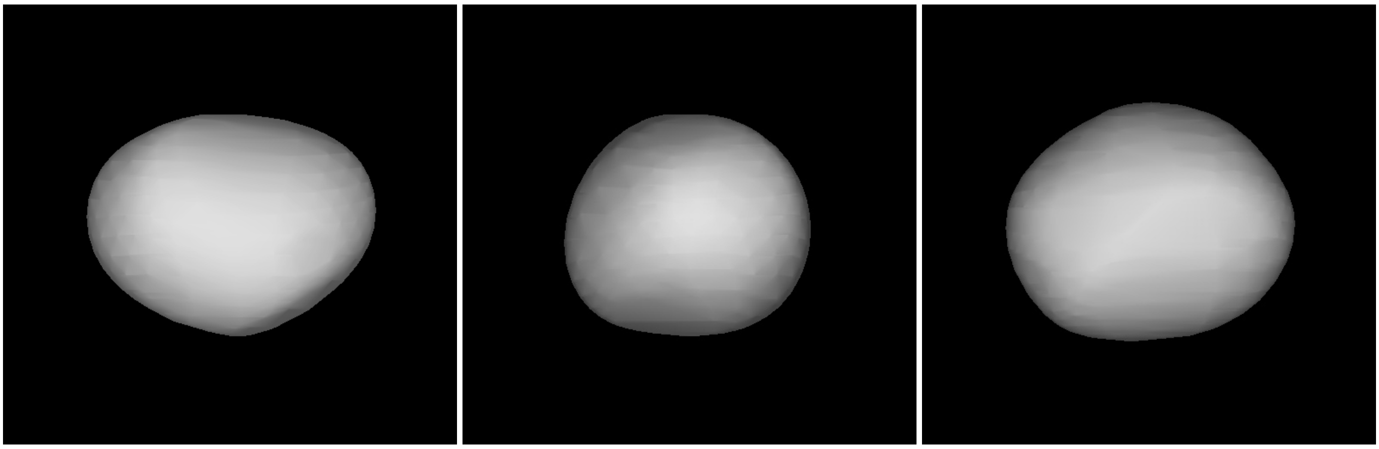

Fig. 12. Three-dimensional shape of asteroid 2867 Steins reconstructed from the inversion of 26 light curves. The two left panels are equatorial (orthogonal) views; the right panel is a pole-on view.

is the result of the initial angular momentum determined by formation processes and the angular momentum contributed by mutual collisions and by Yarkovsky thermal forces (and even tidal forces when encountering a planet). The Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) is indeed known to trigger long-term variations of both the spin rate and spin orientation of small asteroids (Rubincam 2000). As collisions are unlikely to have resulted in an orientation normal to the ecliptic plane, we conjecture that the present spin state of Steins is a probable consequence of the YORP effect. However, the verification of this hypothesis would require a detailed dynamical modeling, which is well beyond the scope of this article. The detailed characterization of 2867 Steins expected from the Rosetta mission will provide the required physical parameters with the appropriate accuracy to tackle this question in the future. In the meantime, our model has been introduced in both the ESA/ESOC and OSIRIS simulators to prepare the sequence of operations during the September 2008 flyby, and we very much hope that our work will contribute to the scientific success of the first part of the Rosetta mission.

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