A&A 397, 325–328 (2003)
DOI: 10.1051/0004-6361:20021437

Astronomy
&
Astrophysics

Thermal observations of MUSES-C mission target (25143) 1998 SF$_{36}$ ⋆

T. Sekiguchi[1,2], M. Abe[3], H. Boehnhardt[2], B. Dermawan[4], O. R. Hainaut[2], and S. Hasegawa[3]

[1] National Astronomical Observatory, 2-21-1 Osawa, Mitaka, Japan
e-mail: `t.sekiguchi@nao.ac.jp`
[2] European Southern Observatory (ESO), Alonso de Cordova 3107, Vitacura, Santiago, Chile
e-mail: `hboehnha@eso.org, ohainaut@eso.org`
[3] Institute of Space and Astronautical Science (ISAS), 3-1-1 Yoshinodai, Sagamihara, Kanagawa, Japan
e-mail: `abe@planeta.sci.isas.ac.jp; hasegawa@planeta.sci.isas.ac.jp`
[4] School of Science, The University of Tokyo, Department of Astronomy, Bunkyo, Tokyo
e-mail: `budydr@cc.nao.ac.jp`

Received 2 April 2001 / Accepted 25 September 2002

Abstract. We present thermal observations of MUSES-C mission target, (25143) 1998 SF$_{36}$. The mid-IR radiation in the *N*-band (11.9 μm) was measured using the ESO 3.6 m telescope with TIMMI2. Assuming the Standard Thermal Model and combining the thermal flux in the *N*-band with the time-resolved absolute magnitude in optical, the derived diameter and the geometric albedo are 0.35 (±0.03) km and 0.23 (+0.07, −0.05), respectively. While these values are model-dependent, we conclude that this Apollo class asteroid is of small size and its albedo is consistent with spectroscopic classification as an S-type asteroid.

Key words. infrared: solar system – minor planets, asteroids – space vehicles

1. Introduction

Near Earth Asteroid (NEA) (25143) 1998 SF$_{36}$, which was discovered by the LINEAR project of MIT Lincoln Laboratory, is the target object of the MUSES-C space mission. MUSES-C is a joint project of the Institute of Space and Astronautical Sciences (ISAS) of Japan and the National Aeronautics and Space Administration (NASA) of the USA to explore the asteroid, to acquire a sample of the surface material and to return it to the Earth (Fujiwara et al. 1999). Its launch is scheduled for May 2003, arrival at the asteroid in June 2005 and return to the Earth in June of 2007. According to its orbital elements (see Table 1), NEA 1998 SF$_{36}$ whose orbital period is about 1.5 years, is classified as Apollo-type asteroid, with semimajor axis ≥1.0 AU and perihelion distance ≤1.017 AU.

On 2001 March 29 the object approached the Earth to within 6.4 million kilometers. Extensive ground-based observations were carried out during this approach period in order to determine the asteroid's size, shape, rotation and surface characteristics (Binzel 2001; Binzel & Rivkin 2001; Hicks et al. 2001; Sekiguchi et al. 2001). The results presented here were obtained in the framework of this ground-based support to the MUSES-C mission preparation.

Table 1. Orbital parameters of 1998 SF$_{36}$.

semimajor axis	1.323 (AU)
perihelion distance	0.953 (AU)
aphelion distance	1.693 (AU)
eccentricity	0.280
inclination	1.728 (degree)
orbital period	1.52 (year)
Orbit type	Apollo

Orbital elements are published in MPEC 2001-F08.

2. Observations and basic data reduction

Thermal observations of 1998 SF$_{36}$ were performed on 2001 March 14.24 UT. *N*-band (11.9 μm) images were taken with the ESO 3.6 m telescope and the TIMMI2 instrument at the La Silla Observatory in Chile. TIMMI2, the Thermal Infrared Multi-Mode Instrument 2 (Reimann et al. 2000), has a 240 × 320 pixel AsSiBIB detector. The image scale used for our observations is $0\farcs2$ pixel^{-1} which gives a field of view of $51'' \times 51''$.

Observations: 1998 SF$_{36}$ was visible on the 3.6 m guiding camera, therefore the telescope could be guided directly on the object. Individual TIMMI2 detector integration time (DIT) was

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Send offprint requests to: T. Sekiguchi,
e-mail: `t.sekiguchi@nao.ac.jp`

⋆ Based on observations performed with the 3.6 m telescope at the European Southern Observatory, La Silla, Chile.

Table 2. Observing geometry and conditions for 1998 SF_{36}.

Date (UT)	start–end (UT)	RA[a] h m s	Dec[a] ° ′ ″	r^b (AU)	Δ^c (AU)	Phase Angle (deg)	Air mass	Sky
14 Mar. 2001	05:39–06:01	13 17 49	+18 36 52	1.0592	0.073920	27.532°	1.54–1.62	photometric

[a] J2000.0 astrometric right ascension and declination of target.

[b] r is the heliocentric distance.

[c] Δ is the geocentric distance.

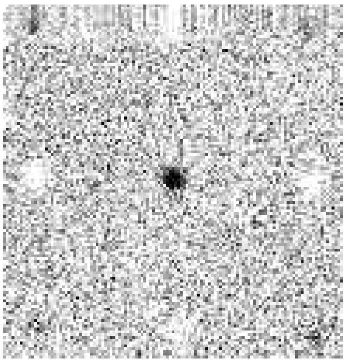

Fig. 1. N-band (11.9 μm) image of 1998 SF_{36} on March 14, 2001. Chopping and nodding amplitude are 10.″0. North is to the top, and West is toward the right.

16.13 millisec. The observations were performed as a series of 4 exposures using secondary mirror chopping and telescope nodding as follows: 100 DIT read-outs were taken at two chopping positions that were 10″ apart from each other in the North-South direction. This chopping-integration cycle was repeated 30 times, then the telescope was moved by 10″ in East-West direction and the same 30 chopping-integration was repeated as before. Two exposure series of 1998 SF_{36} were obtained with a total integration time of 193.56 s. The infrared standard star HD 47105, whose N-band (12 μm) flux is 5.04 Jy, was observed at higher air mass (1.70) and lower air mass (1.48) than 1998 SF_{36} (air mass, 1.5–1.6). The observing conditions are listed on Table 2.

Basic data reduction: the TIMMI2 reduction pipeline automatically subtracts the pairs of "chopped" images and co-adds all the frames of the whole chopping/nodding sequence (equivalent to one exposure series). Hence, the resulting image data has 2 positive and 2 negative images of the object. The four subimages of 1998 SF_{36} were shifted to the same pixel coordinates and co-added (the negative ones after multiplication by −1).

Flatfield correction is not applied to our data since the proper flatfielding method of the TIMMI2 image as not yet been established and flatfield images were not obtained during our observing run. As a consequence, according to information provided by the TIMMI2 instrument scientist (H. U. Käufl, ESO Garching), we have to assume an error of up to 10% for the photometry in addition to the errors in photometric measurements, due to lack of flatfield correction of our data.

Figure 1 shows the N-band image of 1998 SF_{36} surrounded by the 4 fainter positive ghosts at each corner and 4 fainter negative ghosts in the middle of each side. These ghosts result from the image processing described above.

3. Results and interpretations

The count rate of 1998 SF_{36} and of the standard star were measured from the respective N-band images with aperture photometry. The aperture size was chosen to be three × the full-width-at-half-maximum of the object and standard star image, i.e. 3 × 0.″84. The flux of 1998 SF_{36} was determined to be 0.256 ± 0.043 Jy. The given errors refer to the errors of the photometry measurement including the uncertainty from non-flatfielding.

Next, the phase angle correction was applied. Matson (1971) studied the thermal phase coefficients of asteroids in N-band (8.5 μm, 10.5 μm, 11.6 μm). We used their average IR phase coefficient $\beta_E = 0.01$ mag deg^{-1} as given by Lebofsky & Spencer (1989). Despite the fact that phase functions of asteroids at any wavelength may actually follow a non-linear relation, the correction factor applied here is generally considered to be a good approximation for phase angles ≤30° (Morrison 1977), hence applicable to our 1998 SF_{36} observations (at phase angle of 27.5°).

3.1. Thermal infrared radiation

The thermal flux density of mid-IR radiation from asteroids is given by

$$S_\nu = \pi\,\varepsilon \left(\frac{r}{\Delta'}\right)^2 B_\nu(T), \tag{1}$$

where r is the radius of 1998 SF_{36} [m], $\varepsilon = 0.9$ (Lebofsky et al. 1986) is the infrared emissivity, Δ' is the geocentric distance [m] and the Planck function $B_\nu(T)$ for the effective surface temperature T [K], which is described with the observed frequency ν, Planck constant h and light speed c

$$B_\nu(T) = \frac{2\,h\nu^3}{c^2}\left[\exp\left(\frac{h\nu}{k\,T}\right) - 1\right]^{-1}. \tag{2}$$

The effective surface temperature of 1998 SF_{36} is determined by the energy balance at the surface of the asteroid. It depends on several unknown parameters including the albedo distribution, emissivity, density, heat conductivity and heat capacity of the surface material, spin period and the orientation of its spin pole with respect to the Sun. Due to several unknown quantities, we are not able to derive exactly the temperature distribution on its surface. However, to a first level approximation, the effective temperature ($T_{\rm eff}$) of non-sublimating a sphere (Lebofsky & Spencer 1989) is given by

$$T_{\rm eff} = \left[\frac{S_\odot\,(1-A)}{r^2\,\sigma\,\varepsilon\,\eta\,\chi}\right]^{\frac{1}{4}}, \tag{3}$$

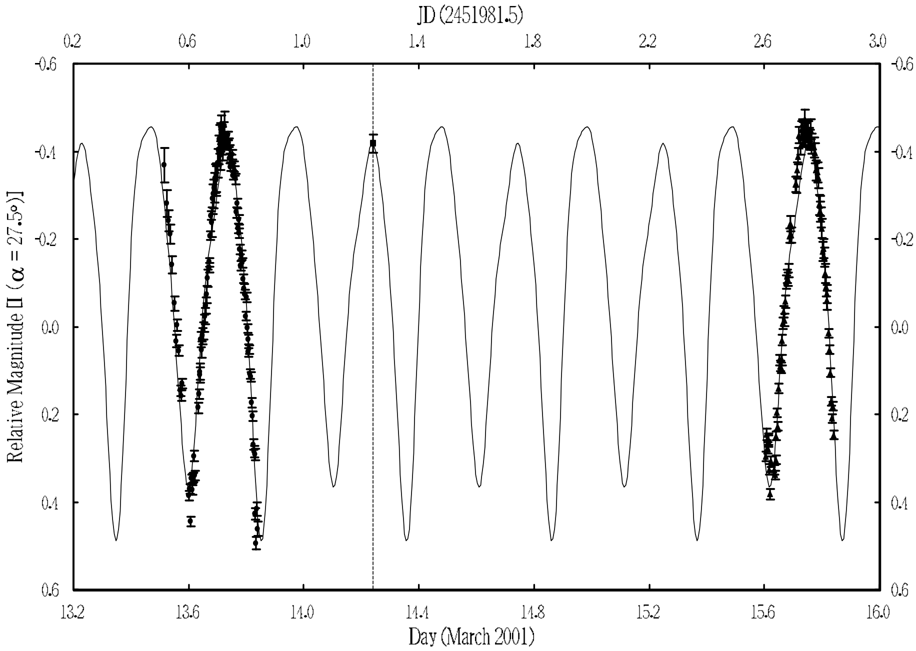

Fig. 2. Fitted lightcurve of 1998 SF_{36} (solid line) using the photometric data of the object measured on March 13 UT (circle) and 15 UT (triangle) for phase angle 27.5°. The dashed line and square denote day of March 14.24 UT and the estimated asteroid's magnitude, respectively.

where $S_{\odot} = 1365$ W m^{-2} is the solar constant and $\sigma = 5.671$ W m^{-2} K^{-4} is the Stefan–Boltzmann constant. r is the heliocentric distance [AU]. The correction factor η is called "beaming factor". It adjusts the surface temperature to compensate for the angular distribution of the thermal emission. Here, we adopt $\eta = 1.2$ which was derived for near-Earth asteroids (NEAs) by Harris (1998). This model is known as the Near Earth Asteroid Thermal Model (NEATM). The rotation correction factor χ which expresses effects of rotation around its axis is taken as 2 on the Standard Thermal Model (Jewitt & Kalas 1998) for a slow rotator, since the rotation period of 1998 SF_{36} is more than a half day (12.15 ± 0.02 hr; Abe et al. (2002a, 2002b), 12.13 ± 0.02 hr; Dermawan et al. (2002)).

The bond albedo A and geometric albedo are related by

$$A = p\,q \tag{4}$$

$$\simeq p_V\,q, \tag{5}$$

where p and p_V are the bolometric geometric albedo and the geometric albedo in the V-band, respectively. q is the bolometric phase integral. In the H-G system described by Bowell et al. (1989), q is derived from the slope parameter G, via

$$q = 0.290 + 0.684\,G, \tag{6}$$

Abe et al. (2002a, 2002b) made a compilation of optical observations by various observers and determined its slope parameter $G = 0.21 \pm 0.10$. Therefore, Eq. (5) gives $A = (0.43 \pm 0.07) \times p_V$. The relation between size and albedo derived from infrared observations and the model equations above is depicted in Fig. 3 as "increasing" graphs (radius increasing with albedo).

3.2. Optical constraints

Using the absolute magnitude H which corresponds to the V magnitude at 0° phase angle and heliocentric and geocentric distance of 1 AU, the geometric albedo p_V and the diameter D [km] of asteroid are related by (e.g., Fowler & Chillemi 1986)

$$\log_{10} D = 3.1236 - 0.2H - 0.5\log_{10}(p_V). \tag{7}$$

Since the H value was determined by Abe et al. (2002a, 2002b) from the compilation data of optical photometric observations, we here adopt $H = 19.9 \pm 0.10$ as the center value of lightcurve amplitude in V-band.

Dermawan et al. (2002) carried out differential photometry of 1998 SF_{36} in 2001 February–March to determine its physical properties, including the rotation period. The date of our thermal observations (March 14.24 UT) was "sandwiched" by their I-band observations on March 13 and 15 UT. We used these photometric data to estimate the asteroid's magnitude on March 14.24 UT from its lightcurve. Fig. 2 displays the lightcurve fit by Dermawan et al. (2002) following a Fourier analysis method (Harris et al. 1989) with phase angle relation established by Zappalà (1990). The figure also indicates the object magnitude predicted for the time of our thermal observations. Obviously, on March 14.24 UT thermal observations were carried out very close to the secondary maximum (see Fig. 2) of the rotation lightcurve of 1998 SF_{36}: its I-band magnitude was 0.42 ± 0.02 mag brighter than the mean level. Since a color change over the rotation phase was not found in this object (Abe et al. 2002a, 2002b), the assumption that the ΔV magnitude is the same as ΔI is reasonable. Finally, we obtained the asteroid's absolute magnitude in the V-band on March 14.24 UT as $H' = 19.48 \pm 0.10$. Optical constraints expressed by Eq. (7) with H' instead of H are shown in Fig. 3 as decreasing curves.

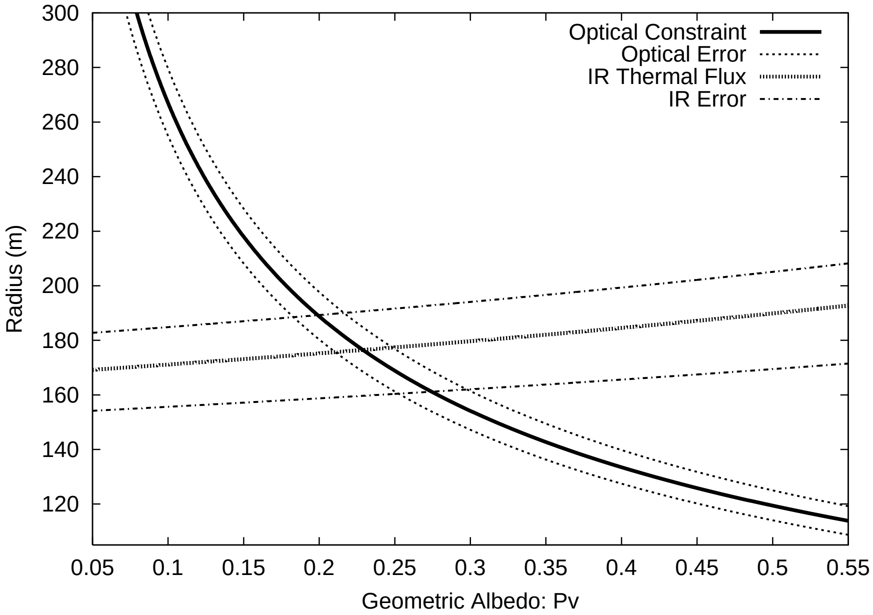

Fig. 3. Constraints on the albedo and radius of 1998 SF_{36} from thermal infrared observations and optical absolute magnitude.

Figure 3 shows the diameter versus the geometric albedo relationship – including measurement errors – defined by optical (Eq. (7)) and thermal-IR constraints (Eq. (1)). The intersection of those curves gives the best estimate for the radius r and albedo p_V of 1998 SF_{36}: $r = 176$ (+14/–16) m, $p_V = 0.23$ (+0.07/–0.05).

4. Conclusion

Binzel et al. (2001) observed this object spectroscopically in the optical to near-IR wavelength range (0.5–2.5 μm) and reported strong absorption bands at 1 μm and 2 μm. They find a similarity to the spectra of ordinary chondrite meteorites and classified 1998 SF_{36} as an S-type asteroid. The average geometric albedo value of S-type asteroids using IRAS data and according to Tholen's classification (Tholen & Barucci 1989), is 0.20 ± 0.07 (Shevchenko & Lupishko 1998). This is in good agreement with our value $p_V = 0.23$ for 1998 SF_{36}. However, some systematic errors from uncertainties in the unknown parameters may affect our results. For instance, if we adopt the "traditional" value for the beaming parameter of main belt asteroids, $\eta = 0.756$ (Lebofsky & Spencer 1989), the derived curves give $r = 145$ (+10/–14) m and $p_V = 0.45$ (+0.10/–0.06), respectively.

Despite some model-depending uncertainties, we conclude that the MUSES-C mission target 1998 SF_{36} has a small radius and that the derived albedo range close to the average value for S-type asteroids is consistent with the spectroscopic classification.

Acknowledgements. We thank Michael Sterzik & Nancy Ageorges, European Southern Observatory for observing assistance with the 3.6m telescope, and Alan Harris, Jet Propulsion Laboratory for lots of helpful comments.

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