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Ground-based observations of Phoebe (S9) and its rotational dynamics

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Abstract. Analysis of CCD observations of Phoebe, the 9th satellite of Saturn (visual magnitude of about 16.5), with a mirror astrograph ZA-320M at Pulkovo Observatory in Saint-Petersburg are presented. Photometric observations are performed both in the integral band of the telescope and in bands BVR of the Johnson system. Reference catalogues USNO-A2.0 (for R - filter and integral observations) and Ticho-2 (for V and B - filters) were used. Rotational light-curve data for Phoebe taken over a short time span (2 - 8 hours) for several nights are presented. Numerical investigation of the evolution of Phoebe's rotational dynamics is carried out. The probability of Phoebe's capture in resonant states that are distinct from 1:1 is estimated.

Keywords. planets and satellites: Phoebe, techniques: photometric, solar system: formation.

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1. Introduction

In the Solar System, potential candidates that could still be in a chaotic or nonsynchronous state are satellites having distant or eccentric orbits – the so called irregular satellites. There is a probability of their capture in resonant states that are distinct from 1:1. Phoebe, Saturn's 9th satellite, is the only irregular satellite with known inertial parameters and fast nonsynchronous rotation. Its retrograde, eccentric and inclined orbit indicates that it could be an object captured from a heliocentric orbit. Numerical investigation of the evolution of Phoebe's rotational dynamics and theoretical estimation of its tidal despinning time are carried out in this study.

Since Phoebe has a fast and nonsynchronous rotation, which is sufficiently reliable (Melnikov (2002), Devyatkin *et al.* (2004)), its observations are important for revealing probable changes of its rotation characteristics. More then 250 photometric and about 150 astrometric observations of Phoebe were obtained during 2007 - 2008 (Aleshkina *et al.* (2009)).

Our observational program is performed with an automatically-operated 0.32-m mirror astrograph ZA-320M at Pulkovo observatory in Saint-Petersburg (Latitude: 059 46 15.000 N, Longitude: 030 19 45.000 E, Altitude: 75.00 m), having the following characteristics: $D = 320$ mm, $F = 3200$ mm, $M = 65"$/mm, limit magnitude 19^m, and a CCD detector FLI (1024×1024 pixels, 28' $\times$ 28 ').

2. Phoebe - 9th satellite of Saturn

Phoebe is an irregular satellite of Saturn with known inertial parameters, fast rotation and an eccentric, inclined orbit. It is supposed to be an ice-rich body coated with a thin layer of dark material (Cruikshank *et al.* (2008)). Phoebe's orbital, inertial and physical characteristics are presented in Tables 1 and 2. Values are given in these tables for:

Table 1. Orbital parameters of Phoebe (according to Jacobson (2006)).

r (10^6 km)	12.947780
e	0.1635
n (deg/day)	0.6541824
T_orb (day)	550.31
i (day)	175.986

Table 2. Inertial and physical parameters of Phoebe.

Parameter	Value	Ref.	Parameter	Value	Ref.
$P_{rot}(h)$	9.2735 ± 0.0006	Bauer *et al.*(2004)	albedo	0.081 ± 0.002	Simonelli *et al.* (1999)
$R(10^5 cm)$	106.6 ± 1.1	Jacobson *et al.* (2005)	A/C	0.93623	1
$Gm(km^3/s^2)$	0.5531 ± 0.0006	Jacobson *et al.* (2005)	B/C	0.94455	1
$\rho(g/cm^3)$	1.633 ± 0.049	Jacobson *et al.* (2005)	$g(cm/s^2)$	4.87	2
$a_e/b_e/c_e, (km)$	108.6/107.7/101.5	Johnson *et al.* (2000)	$\mu(dyn/cm^2)$	10^{11}	3

Notes:
[1] The inertial parameters $A/C, B/C$ are calculated by means of formulas for a triaxial ellipsoidal satellite of homogeneous density $A/C = (b_e^2 + c_e^2)/(a_e^2 + b_e^2), B/C = (a_e^2 + c_e^2)/(a_e^2 + b_e^2)$.
[2] The value of gravitational acceleration g is calculated as $g = Gm/R^2$.
[3] Values of rigidity μ for planetary satellites are practically unknown; the theory gives $\mu = 5 \times 10^{11} dyn/cm^2$ for rock with $\rho = 2$ g/cm^3 and $\mu = 3.5 \times 10^{10} dyn/cm^2$ for ice with $\rho = 1$ g/cm^3 (Dobrovolskis (1995))

r, e, i, n, T_{orb} – semi-major axis, eccentricity, inclination of orbit, mean motion and orbital period, respectively, and a_e, b_e, c_e – semi-axes of ellipsoid of inertia, P_{rot}, R, Gm, ρ - rotation period, mean radius, gravitation constant of Phoebe and its mean density, respectively.

3. Photometric observations of Phoebe

Photometric observations were performed both in the integral band of the telescope (300–900 nanometers) and in bands V and R of the Johnson system. Reference catalogues USNO-A 2.0 (for R filter and integral observations) and Ticho-2 (for V filter) were used. In 2007 – 2008 we obtained about 250 frames of Phoebe. All our observations of 2007 – 2008 are available on www.ad-astra.len.su/Phoebe07-08.html.

Results of differential photometry over a short time span (2-8 hours) for 11 observational nights are presented in Table 3. The brightness of stars in the integral band of the instrument was calculated using the values of B and R for these stars from a USNO-A 2.0 catalog. It is the only catalog containing both astrometric and photometric information for stars falling within the instrument's field of view, although it has low accuracy (0.15^m) of photometric data. A considerable number (in general about 30-50) of star images suitable for measurement made it possible to slightly compensate for the low accuracy of the catalogue. The brightness of stars in the V band was taken from Ticho-2. The intrinsic accuracy indicated for each value is a standard deviation obtained by averaging the Phoebe brightness values relative to each of the measured stars on a frame. Mean values of accuracy are equal to $0.07^m, 0.05^m$ and 0.3^m for the integral, R and V bands, respectively. The average value of color index for Phoebe (Fig.1b) for the performed dense observational series 2008.03.24 (in the instrumental system) is $< R - V >= 1.6$.

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Table 3. Statistics of photometric observations of Phoebe 2007 - 2008 (number of frames).

Date	Time span (h)	Integral band	R - filter	V - filter	B - filter
2007-03-26	5.25	20	–	–	–
2007-03-30	3	–	16	5	–
2007-03-31	1.5	–	5	–	–
2007-04-01	3.5	22	–	–	–
2007-04-16	3.5	18	–	–	–
2008-01-28	1.5	1	5	1	1
2008-02-25	2	5	6	6	6
2008-03-21	5	1	2	5	–
2008-03-24	8	18	21	18	–
2008-03-28	2	8	7	–	–
2008-03-31	6.5	29	13	–	–

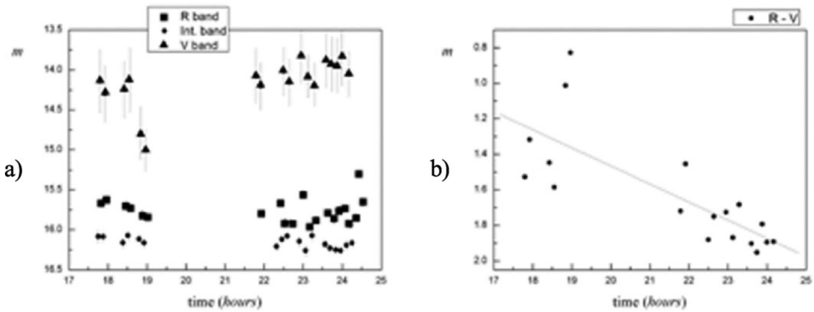

Figure 1. Photometric observations of Phoebe. (a) Light-curves over a short time span obtained on 24.03.2008. (b) The average value of the color index $< R - V >$ (in the instrumental system).

4. Rotational dynamics of Phoebe

A numerical investigation of the evolution of Phoebe's rotational dynamics was carried out, using the same dynamical model as in the previous paper Aleshkina (2009). Because irregular satellites are potential candidates for still being in chaotic or nonsynchronous states, the probability for Phoebe being captured in resonant states that are distinct from 1:1 and its stability were estimated.

Theoretical estimates for the probability of Phoebe being captured in the 3:2 resonant state for two models of tidal interaction Murray & Dermott (2006) yield 0.7 and 0.5, respectively. Results of our numerical experiments show that for different initial conditions (spin angle $0.5 < \psi_0 < 1.77$ and angular velocity $6 < \omega_0/n < 14$) the probability of Phoebe's capture in spin-orbit resonant states 5:2, 2:1, 3:2 is high. At the same time, before capture, there are long periods of time (about a hundred thousand years) when Phoebe is in nonsynchronous resonant states (for instance, Fig. 2 shows the capture in resonance 3:2 and a chaotic zone in resonant state 2:1). Estimation of resonance stability was obtained according to criteria derived in Murray & Dermott (2006). For modern orbital parameters of Phoebe all of its possible resonant states are stable.

We also estimated the tidal despinning time of Phoebe τ_D (Table 4) both theoretically (according to Dobrovolskis (1995)) and by numerical experiments.

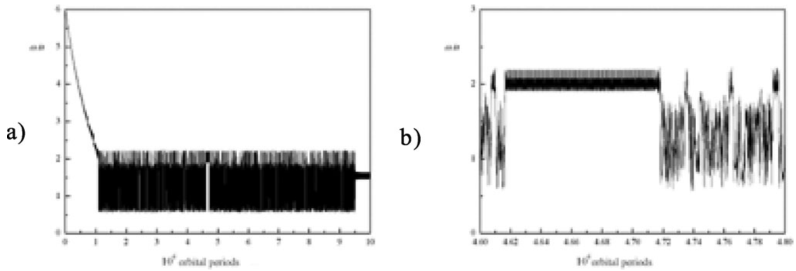

Figure 2. Capture in resonance 3:2. (a) Initial conditions $\psi_0 = 1.27$, $\omega_0/n = 6$, (b) Chaotic zone between 4.5 and 5 millions orbital periods in (a).

Table 4. Tidal despinning time of Phoebe.

	τ_D (year)
Numerical experiment	1.5×10^{13}
Theoretical estimation	10^{15}
Peale (1977)	1.7×10^{14}

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