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LIGHT CURVE ANALYSIS OF SIX MAIN BELT ASTEROIDS WITH EARTH MOID LESS THAN 1AU

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ABSTRACT. Six main belt asteroids 1999 HK1 (11411), 1995 AM1 (30968), 1999 XC136 (53454), 1999 JN6 (70055), 1999 UQ9 (86280), 2000 SU2 (93041) with Earth MOID less than 1AU were studied at the Baldone Astrophysical Observatory of the Institute of Astronomy of the University of Latvia in the time span range 2020-2022. The obtained light curve data together with published Minor Planet Center data in the time range 1999-2022 were analyzed with Fourier series, Lomb-Scargle periodogram, and Phase dispersion minimization methods. A plan of analysis step by step is given. The results computed from different observatories' data are compared and mean-weighted periods are obtained. The rotation periods are for asteroids: N11411 P=6.544 h, N30968 P=8.330 h, N53454 P=4.615 h, N70055 P=74.364 h, N86280 P=1.315 or 6.658 h and N93041 P=30.645 h.

Keywords: Main belt asteroids, light curve, rotation period.

АНОТАЦІЯ. Шість астероїдів головного поясу 1999 HK1 (11411), 1995 AM1 (30968), 1999 XC136 (53454), 1999 JN6 (70055), 1999 UQ9 (86280), 2000 SU2 (93041) з MOID Землі менше 1 а.о. досліджувалися в астрофізичній обсерваторії Балдоне Інституту Астрономії Латвійського університету в часовому діапазоні 2020-2022. Отримані дані кривої блиску разом з опублікованими даними Центру малих планет у часовому діапазоні 1999-2022 рр. були проаналізовані за допомогою рядів Фур'є, періодограми Ломба-Скаргла та методів мінімізації фазової дисперсії. Подано покроковий план аналізу. Результати, обчислені за даними різних обсерваторій, порівнюються та отримуються середньозважені періоди. Періоди обертання становлять для астероїдів: N11411 P=6,544 години, N30968 P=8,330 години, N53454 P=4,615 години, N70055 P=74,364 години, N86280 P=1,315 або 6,658 години і N93041 P=30,645 години. Метод рядів Фур'є дає придатні для використання результати аналізу довгих серій спостережень у декілька наступних ночей, коли період обертання не перевищує 7-10 годин. У випадках невеликих серій спостережень, розкиданих протягом великого періоду часу, з різною яскравістю в різних опозиціях, методи L-S і PDM працюють більш надійно. Метод PDM чутливий до невеликої кількості спостережень. Якщо кількість спостережень менше сотні, метод PDM здебільшого не працює. Показана методологія дозволяє аналізувати дані, точність яскравості яких становить один десятковий знак.

Ключові слова: астероїди головного поясу, крива блиску, період обертання.

1. Introduction

The investigation of asteroid properties is important for the development of the evolution theory of the Solar system and the classification of small Solar system objects. Because some of these objects can collide with the Earth, asteroids are also important for having significantly modified the Earth's biosphere. Significantly in the past, but now, every five years Chelyabinsk amount events take part as seen from the observed bolids radar compilation [NASA, 2013]. Asteroids' impact can trigger the creation of life, especially with the delivery of heavy elements to the Earth's surface. It is a crucial moment for the birth and evolution of complex life [Castillo, Vance 2008] and [Houtkooper, 2011] because the carbon-based molecules and some heavy elements serve as the building blocks of life. Asteroid studies will allow us to answer the ambiguous question about the origins of life on Earth. On the other hand, the next step in the human exploration of space will be highly dependent on extracting materials (primarily water and minerals) from the asteroids. It is highly probable that the success and viability of human expansion into space will depend on the ability to exploit space resources. Therefore, a detailed physical and compositional assessment of the population will be required during the next decade before human missions are sent to these objects.

The photometric study of light curves can obtain additional information about size, rotation period, the structure of objects, and the existence of craters and ice fields on the surface, which is very important data for space missions. Asteroids shine due to the Sun's light reflecting on their surface and depend on surface albedo (from surface characteristics: chemical composition; regoliths which cover the object). If an asteroid is not spherical its brightness might vary due to the following factors: the asteroid's distance to the observer and to the Sun is changing; the asteroid's phase. All of the above plus the shape of the asteroid and its periodic rotation, as well as the precession of the axis of rotation, determines its brightness too. All previous aspects, show the importance and complexity of light curve studies.

2. Data set for analysis

At the Baldone Astrophysical Observatory (IAU Code 069) astronomers operate with a Schmidt-type 1.2-meter telescope installed with two STX-16803 CCDs.The brightness limit in the visual range of the telescope without a filter is 22 magnitude at night with good transparency and calm images. CCD parameters are quantum effectivity of about 80 percent, the size of one pixel is 9*9 microns, and linear size 4096*4096 pixels, which corresponds to 53*53 arcmin of the field of view. In the three last years, the observation has been devoted to the studying dynamics of main belt asteroids in the G(RP) passband, especially those of which the Earth MOID is less than 1 AU. Observations also managed to use nights with a small phase of the Moon. The list of observable asteroids was compiled using the Minor Planet Center NEO checker [MPC, 2023] and MPC light curve database [ALCDEF, 2023]. A sample of studied main belt asteroids with Earth MOID less than 1 AU, with a brightness greater than 18 magnitudes without period data are given in Table 1.

Table 1: list of studied asteroids

Asteroid	Design.	Earth MOID	Sun, P (y)	Absol. mag.
11411	1999 HK1	0.78600	2.50	15.41
30968	1995 AM1	0.76539	3.47	14.39
53454	1999 XC136	0.91428	2.71	15.14
70055	1999 JN6	0.67361	3.59	15.07
86280	1999 UQ9	0.72111	2.58	
93041	2000 SU2	0.83457	3.68	

3. Light curves analysis

The G(RP) magnitudes for reference stars were taken from the GAIA DR2 release [Brown et al. 2018]. For processing one series of observations were used 30-40 reference stars with colors close to the Sun; some brighter and some dimmer, than moving objects. The images were analyzed by calibrated and measured using Lemur software [Savanevych, 2022]. Measurement of magnitudes of objects was made after the application of standard procedures of master flat and master dark images. For further processing selected only that series where the reference star's brightness errors at an average are smaller than 0.05 magnitudes. It helps to discard observations with poor sky instant transparency. Each measurement of an asteroid consists of a time and apparent magnitude couple.

Both values must be corrected for each measurement series because the distance of an asteroid relative to Earth and to the Sun changes. Time changes by reducing to the first moment of observations were made by equation:

$$t_i = t_0 + \frac{D_0 + D_i}{c},$$

where D is the asteroid's distance from the observer.

The magnitudes of all series are corrected depending on the distance from the observer and from the Sun [Zeigler, Hanshaw, 2016]:

$$\Delta m_i = m_i - 5\log(\frac{D_0 R_0}{D_i R_i}),$$

where D is the asteroid distance from the observer and R is the distance to the Sun and R_0, D_0 is the same for the first observation in the first series.

The last is magnitude correction by phase effect:

$$\Delta m_i = (Ph_0 - Ph_i)k,$$

where k is the slope coefficient of the phase diagram for phases in intervals 10 to 30 degrees, Ph_i and Ph_0 are i and the first phase in series, respectively. We thus use linear regression to fit the lightcurve amplitude-corrected data.

After time and brightness corrections, deriving asteroid periods from their lightcurves by the Fourier series analysis method [Pravec, Harris, 2000]. A detailed description of the algorithm is given by [Kwiatkowski et al., 2009].

The Fourier method is very sensitive to gaps in observations, especially when summarizing data from a small series of observations, as well as data from different oppositions, where there are large shifts in the brightness range. In this situation, the Lomb-Scargle (L-S) periodogram [VanderPlas, 2018] and Phase Dispersion Minimization (PDM) [Stellingwerf, 1978] methods.

All brightness data from the whole in Table 2 mentions observatories' measurements of asteroid brightness are analyzed with three methods in the range 0.1 to 100 hours if the number of observations exceeds 70 in the specified passband.

Table 2: observatories from which data are analized

Observatory (IAU Code)/Space mission	Observa-tion period	Passband
Baldone (069)	2022.03-2023.03	G(RP)
Mauna Loa (T08)	2019.01-2022.08	o, c
Haleakala (T05)	2018.05-2022.08	o, c
Catalina Sky Survey (703)	2005.12-2023.05	V, G
Zwicky Transient Facility (I41)	2014.02-2022.08	r, g
Lincoln Laboratory ETS (704)	1999.04-2010.09	c
Catalina Sky Survey (G96)	2019.01-2022.06	G
Ponte Uso (G45)	2014.03-2017.03	r
Transiting Exoplanet Survey Satellite (C57)	2018.09-2018.10	G

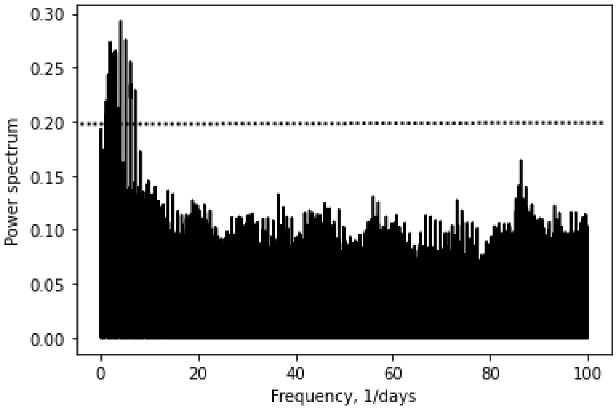

Figure 1: The power spectrum of asteroid N53454, method L-S

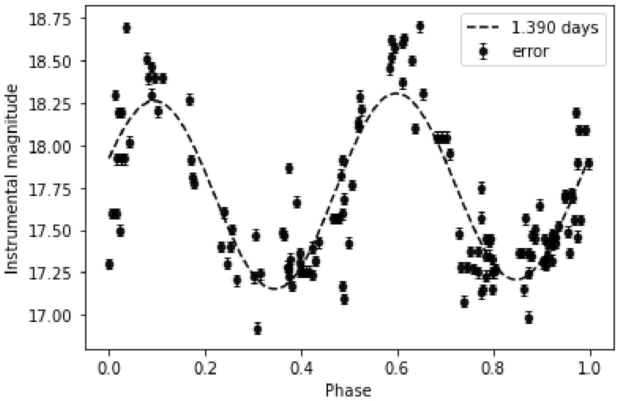

Figure 2: The light curve of asteroid N93041, method L-S

According to the obtained power diagrams, peaks with a probability greater than 20% were selected (see example in Fig. 1).

The surroundings of these separated periods were studied in more detail within a range of plus or minus 2 hours, in order to clarify the possible rotation period. Data from all observatories were similarly analyzed.

Possible periods must satisfy two criteria. A)The light curve should show two maxima and two minimum troughs during one cycle. An example is presented in Fig. 2). B)The shape of the peak in the power spectrum must be similar somewhat resembling a Gaussian distribution (an example is presented in Fig. 3).

All thus allocated periods were cross-correlated. Matching periods from whole observatories with a 3% tolerance were extracted as true rotation period sets. Small discrepancies in values are removed by weighted mean methods. Period values are weighted by the number of observations and by the value of peak probabilities in the power spectrum. The average value is accepted as the true rotation period of the studied asteroids and displaced in Table 3 together with the amplitude of variation in G(RP) passband and their types from [ALCDF, 2023].

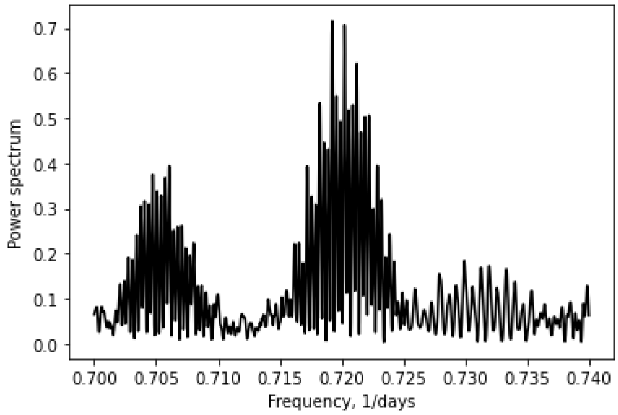

Figure 3: The power spectrum of asteroid N93041, method L-S

Table 3: Results of analyze

Asteroid	Period(h)	error	Ampl.	Type
11411	6.544	0.006	0.8	SE
30968	8.330	0.027	0.4	S
53454	4.615	0.022	0.4	SE
70055	74.364	0.067	0.6	S
86280	1.315 6.658	0.005 0.032	0.4	C
93041	30.645	0.007	1.2	S

4. Conclusion

- Asteroids N70055 and N93041 have great rotation periods: 74.322 h and 30.645 h respectively.
- Asteroid N82680 has two possible rotation periods. The first 1.315 h and 6.658 h. Small amounts of observation don’t allow unambiguously choosing the amount of rotation period.
- The Fourier series method gives usable results analyzing long series observation in multiple following nights when the rotation period isn't longer than 7-10 hours.
- In cases of small series of observations scattered over a large period of time, with differences in brightness in different oppositions, the L-S and PDM methods work more reliably.
- The PDM method is sensitive to a small number of observations. If the number of observations is less than a hundred, the PDM method mostly does not work.
- The shown methodology allows analyzing data whose brightness accuracy is one decimal.

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