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Gravitational and non-gravitational effects in the orbital motion of asteroid 2022 AE1

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Abstract. Asteroid 2022 AE1 with a diameter of about 70 m, discovered at the very beginning of 2022, approached the Earth on December 31, 2021 at a minimum distance of 0.0664 au. The potential hazard of a collision with the Earth during the next close approach in 2023 was estimated by astronomers at 1 in 1700, which raised widespread public concern. Subsequent observations made it possible to refine the asteroid's orbit and showed that the collision will be avoided. However, the upcoming close encounters of this asteroid with the Earth and, especially, with Venus, as well as possible approaches with the main belt asteroids, require not to weaken the attention to this object. Gravitational and non-gravitational effects can have a significant impact on its orbit and, as a consequence, lead to a collision with one of the inner planets. In this work, the displacements of asteroid 2022 AE1 under the influence of solar radiation pressure were calculated over several time intervals for various values of the average density of the object. Furthermore, the diurnal and seasonal components of the Yarkovsky effect were calculated for various rotation periods and axial tilt angles of the asteroid. As a result of the simulation, possible orbits of the asteroid were obtained and a probability estimation of the asteroid collision with the Earth was made.

Keywords: potentially hazardous asteroids, solar radiation pressure, the Yarkovsky effect

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Гравитационные и негравитационные эффекты в орбитальном движении астероида 2022 AE1

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Аннотация. В данной работе были вычислены отклонения астероида 2022 AE1 под действием светового давления, а также сезонные и суточные составляющие эффекта Ярковского. В результате моделирования получены возможные орбиты астероида и сделана оценка вероятности столкновения астероида с Землей.

Ключевые слова: потенциально опасные астероиды, световое давление, эффект Ярковского.

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Introduction

Asteroid 2022 AE1 was discovered by astronomers from the Mount Lemmon Observatory (USA) at the very beginning of 2022. It approached the Earth on December 31, 2021 at a minimum distance of 0.0664 au, with an apparent magnitude of 20.6. This fairly large object of about 70 m in size [1] came close (at a distance of 0.0173 au) to the Earth for the last time on July 4, 1966. Despite the apparent magnitude of 18.0, it was not discovered then due to unfavorable observing conditions.

Initial observations of this asteroid, undertaken by observatories around the world after its discovery, have revealed a high chance of a collision with the Earth in July 2023, which raised major concern. Collision hazard has been confirmed by the AstOD (Asteroid Orbit Determination) automated system, which is used to calculate the orbits of discovered asteroids and assess their potential hazard on the Palermo Scale. Thus, the asteroid 2022 AE1 was assigned one of the highest ratings. Then the asteroid had disappeared from the field of view due to the full moon for some time, and thereafter the resumed observations made it possible to improve the initial calculations. In fact, it turned out that the asteroid will avoid colliding with the Earth by flying past at a safe distance of about 9 Mkm.

Considering all of the above, the study of both gravitational and non-gravitational effects in orbital motion of asteroid 2022 AE1 is of great interest.

Features of Orbital Motion

The EPOS software package [2] developed at the Pulkovo Observatory has been used to study the orbit of asteroid 2022 AE1. New elements of the orbit, based on all the latest world observations, make it possible to correct the forecast of close encounters of this asteroid with the planets. Table 1 contains data for two centuries.

Table 1

Upcoming close encounters of asteroid 2022 AE1 for two centuries

Date	Distance (au)	Planet
01.07.2023	0.0595	Earth
15.08.2039	0.0245	Venus
02.09.2055	0.0645	Venus
03.10.2071	0.0432	Venus
10.06.2089	0.0527	Venus
12.06.2105	0.0326	Venus
04.10.2119	0.0664	Venus
17.09.2135	0.0598	Venus
07.07.2151	0.0076	Earth
21.08.2151	0.0606	Venus
21.07.2169	0.0525	Venus
05.07.2176	0.0049	Earth
06.04.2187	0.0561	Venus

Two closer approaches to the Earth will occur in the next century. Not so close, but more numerous and, most importantly, almost periodic encounters with Venus are expected. It can be assumed that in the end this object will either collide with one of the inner planets (probably Venus), or its movement will become more chaotic.

The aphelion distance of asteroid 2022 AE1 is Q = 2.273 au. Consequently, its orbit is partially located in the main asteroid belt, where encounters with tens of thousands of other objects (more than 630000 with a perihelion distance of less than 2.28) are possible. Therefore, one can speak confidently about the stability of its orbit only after studying its motion in this region of the solar system.

Potentially hazardous objects for asteroid 2022 AE1, i.e. all those whose interorbital distance does not exceed 0.05 au, have been found using the EPOS software package. At the same time, no restrictions have been imposed on the absolute magnitude H, and, consequently, on the size. The number of such objects have turned out to be 30393. The search for close encounters is a very time-consuming task, especially if one looks for encounters for years and decades to come. Therefore, we have limited ourselves to larger objects, although the picture will be incomplete under this condition. Fig. 1 shows a histogram of the sizes of objects from this list. It can be seen that the vast majority of the sizes do not exceed 6 km. However, there are also 243 larger asteroids: Lamberta (147 km), Desiderata (109 km), Chaldaea (71 km), Dike (67 km) and others.

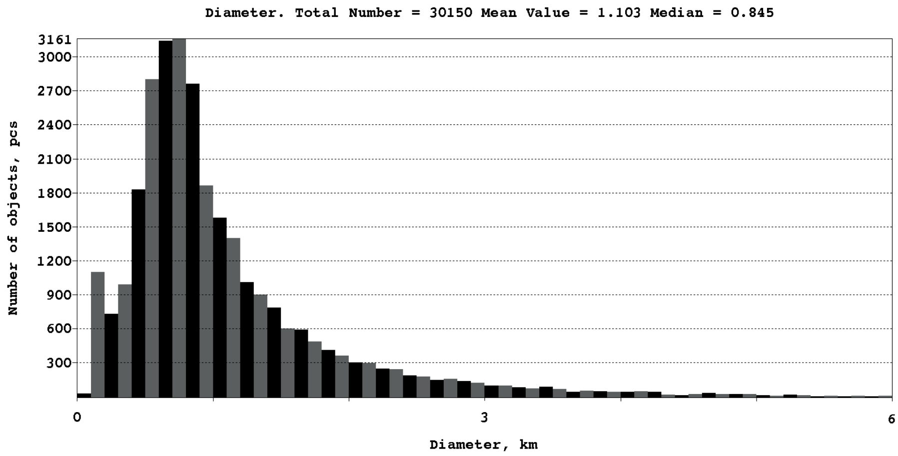

Fig . 1. Size distribution of potentially hazardous objects for asteroid 2022 AE1

Fig. 2 shows the distribution by perihelion distance and orbital inclination. Clusters corresponding to families of asteroids (from top to bottom: Phocaea, Eunomia, Flora) are seen.

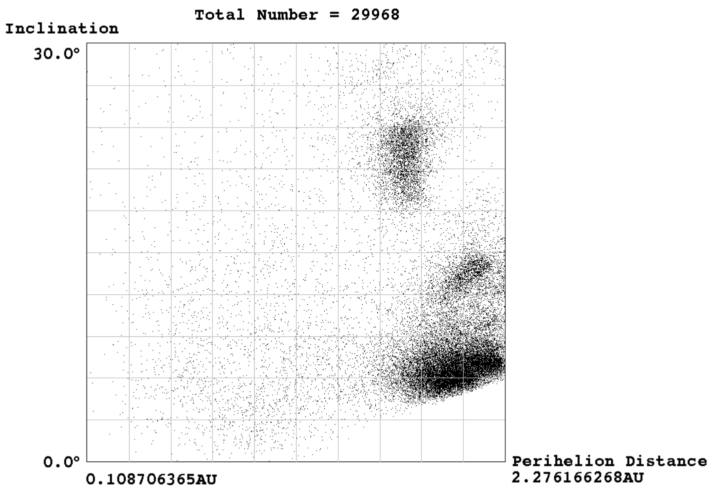

Fig. 2. Distribution of potentially hazardous objects for asteroid 2022 AE1 by perihelion distance and orbit inclination

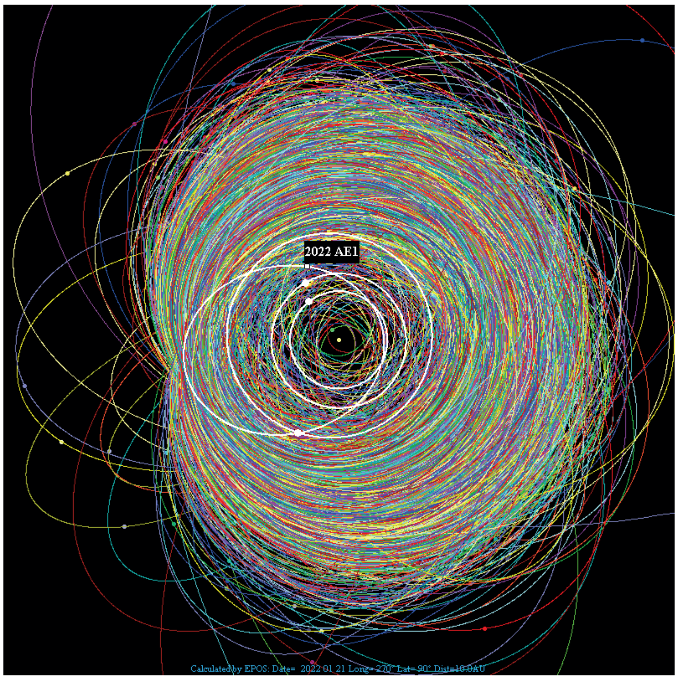

Fig. 3. Orbits and positions of Venus, the Earth, Mars, asteroid 2022 AE1 and potentially hazardous objects to it on January 21, 2022

Fig. 3 shows the orbits of three planets (Venus, the Earth, Mars), asteroid 2022 AE1 and identified potentially hazardous asteroids larger than 1 km, as well as their positions on January 21, 2022.

Estimation of Non-Gravitational Effects

Model calculations of the influence of such non-gravitational effects as solar radiation pressure and the Yarkovsky effect, which is a non-gravitational acceleration in motion caused by anisotropic re-emission of solar radiation by the surface of an asteroid, were performed for asteroid 2022 AE1.

The calculations have been carried out for the following initial data for the epoch 2459600.5 (2022-01-21):

e = 0.54592866 is the eccentricity [3],

a = 1.470237 au is the semi-major axis [3],

H_v = 23.50 is the absolute magnitude in V band [3],

D = 70 m is the diameter [1],

n = 0.55287027°/d is the mean motion [3],

M = 39.444720° is the mean anomaly [3],

P_{rev} = 651.1473 d is the sidereal orbital period [3],

δ = 0.14 is the geometric albedo derived from the formula [4]

$$\lg D = 3.122 - 0.5\lg\delta - 0.2H_v, \quad (1)$$

k = 1.06 is the optical coefficient derived from the formula [5]

$$k = 1 + 4\delta/9. \quad (2)$$

Some unknown characteristics of the asteroid have been taken as average, namely, ε = 0.9 is the emission coefficient, $K = 10^{-2}$ W/m·K is the thermal conductivity, C = 500 J/kg·K is the heat capacity [6]. The following rounded values of 5, 10, 15 h acceptable for an asteroid of this size and the standard angle values of 0°, 45°, 90°, 135°, 180° have been taken as the rotation period P_{rot} and the axial tilt angle γ in the absence of real ones, respectively.

Table 2

Displacements of asteroid 2022 AE1 for 1, 129 and 154 years at various density values

ρ (kg/m^3)	|Δ*r*| (km)			|Δ*l*| (km)			|Δ*d*| (km)		
	1 (yr)	129 (yr)	154 (yr)	1 (yr)	129 (yr)	154 (yr)	1 (yr)	129 (yr)	154 (yr)
1380	0.63	445.98	504.81	0.54	1192.02	1384.38	0.83	1215.60	1402.27
2710	0.32	227.10	257.06	0.27	607.00	704.96	0.42	619.02	714.07
3137	0.28	196.19	222.07	0.24	524.38	609.00	0.36	534.76	616.88
5320	0.16	115.69	130.95	0.14	309.21	359.11	0.22	315.33	363.75

Since the asteroid density is also unknown, the solar radiation pressure calculations have been performed for three different mean densities ρ of the main spectral types of asteroids: C-type carbonaceous asteroids (1380 kg/m^3), S-type silicaceous asteroids (2710 kg/m^3), and M-type metallic asteroids (5320 kg/m^3) [7]; as well as for their arithmetic mean (3137 kg/m^3). The Yarkovsky effect has been calculated only for the arithmetic mean of the density of the main spectral types (3137 kg/m^3).

The solar radiation pressure calculations have been carried out using the numerical integration of the motion equations by the Everhart method on three time intervals: 1, 129 and 154 years, which corresponds to close encounters of the asteroid with the Earth in 2023, 2151 and 2176. The calculation process has been described in detail in [8]. As a result, the following values have been obtained: the asteroid displacement along the heliocentric radius vector Δr, the asteroid displacement along the longitude Δl, and the total asteroid displacement Δd. The calculation results are presented in Table 2. It should be noted that the displacements Δr, Δl, Δd are non-linear in time and decrease with increasing density.

Calculations of the rate of change in the semi-major axis of the orbit *a* of asteroid 2022 AE1 under the influence of the diurnal $(da/dt)_d$ and seasonal $(da/dt)_s$ components of the Yarkovsky effect $(da/dt)_{d+s}$ depending on the rotation period P_{rot} , and the axial tilt angle γ of the asteroid have been conducted using the Gauss-Everhart integrator [9] and the model taken from [6]. The calculation results are presented in Table 3.

Table 3

Rate of change in the semi-major axis of the orbit *a* of asteroid 2022 AE1 under the influence of the diurnal $(da/dt)_d$ and seasonal $(da/dt)_s$ components of the Yarkovsky effect $(da/dt)_{d+s}$ depending on the rotation period P_{rot} and the axial tilt angle γ of the asteroid

P_{rot} (h)	γ (°)	$(da/dt)_d \cdot 10^{-6}$ (au/Myr)	$(da/dt)_s \cdot 10^{-8}$ (au/Myr)	$(da/dt)_{d+s} \cdot 10^{-6}$ (au/Myr)
5	0	4.1180	0	4.1180
	45	2.9119	–3.5710	2.8762
	90	0	–7.1421	–0.0714
	135	–2.9119	–3.5710	–2.9476
	180	–4.1180	0	–4.1180
10	0	3.5104	0	3.5104
	45	2.4822	–3.5710	2.4465
	90	0	–7.1421	–0.0714
	135	–2.4822	–3.5710	–2.5179
	180	–3.5104	0	–3.5104
15	0	3.1241	0	3.1241
	45	2.2090	–3.5710	2.1733
	90	0	–7.1421	–0.0714
	135	–2.2090	–3.5710	–2.2447
	180	–3.1241	0	–3.1241

The influence of the diurnal component $(da/dt)_d$ on the semi-major axis a is maximum when the rotation axis is perpendicular to the orbit plane at 0° and 180°, and is equal to 0 at 90°, which fits the case when the rotation axis lies in the orbit plane. The effect of the seasonal component $(da/dt)_s$, on the contrary, is maximum at 90°, and becomes zero at 0° and 180°. The maximum heating of a hemisphere is reached sometime after the summer solstice due to the thermal inertia of matter. Therefore, the resulting reactive impulse has a component directed opposite to the motion direction of an asteroid and leading to a decrease in the semi-major axis a. At the same time, the change in the rotation period of the asteroid P_{rot} has not been affected the seasonal component $(da/dt)_s$. The Yarkovsky effect is the result of the action of both components $(da/dt)_{d+s}$. It can induce both an acceleration of the orbital motion, that is an increase in the semi-major axis a at $\gamma <$ °90, and a deceleration, that is a decrease in the major semi-axis a at $\gamma \geq 90°$, depending on the direction of rotation of an asteroid with respect to the direction of orbital motion.

Conclusion

Future close encounters of asteroid 2022 AE1 with the Earth and, especially, with Venus, as well as possible approaches with the main belt asteroids, require further high-precision astrometric observations and improvement of its orbit. Gravitational and non-gravitational effects can significantly change the asteroid orbit and, consequently, lead to a collision with one of the inner planets.

Calculations have shown that the maximum displacements of asteroid 2022 AE1, caused by solar radiation pressure, can be 0.22-0.83 km per 1 year (which corresponds to a close approach in 2023), 315.33-1215.60 km per 129 years (close approach in 2151) and 363.75-1402.27 km per 154 years (close approach in 2176), depending on its density.

The rate of change in the semi-major axis of the orbit of asteroid 2022 AE1 under the influence of the Yarkovsky effect can be from -4.1180$^{\cdot 6-}$10 to 4.1180$^{\cdot 6-}$10 au/Myr, depending on the assumed rotation period and the axial tilt angle of the asteroid.

From the data obtained, it can be seen that solar radiation pressure has a more noticeable effect on the motion of a given asteroid with the given physical characteristics in a fairly short period of time than the Yarkovsky effect.

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