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ORBITAL ENERGY DURING THE EVOLUTION OF THE ORBITAL DYNAMICS OF ASTEROID 4179 TOUTATIS

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ABSTRACT

In our previous work, we investigated the orbital dynamics of Asteroid 1934 CT (or 1989 AC or 4179 Toutatis) from epoch 2012-Jul-24 (JDE2456132.5) using the Mercury program package. Asteroid 4179 Toutatis has an Earth and Mars crossing orbit with semimajor axis a = 2.5292 AU and eccentricity e = 0.6294, and therefore the perihelion distance is q = 0.9373 AU and the aphelion distance is Q = 4.1211 AU. After more than 300,000 years, asteroid 4179 Toutatis will escape from the Solar System, but during this time, it will have close-encounters with other planets from Venus to Uranus. As a continuation of this project, we investigated its energy changes in each close encounter. We also determine the energy of this asteroid when it escapes from the Solar System. The result is that during its orbital evolution, the energy of this asteroid changes and gives us negative, zero and positive values.

Key words: Orbital Dynamics: Asteroid 4179 Toutatis

1. INTRODUCTION

Asteroid 1934 CT (or 1989 AC or 4179 Toutatis) is an Apollo-Alinda group asteroid, with semimajor-axis a = 2.5292 AU and eccentricity e = 0.6294, so that the perihelion distance is q = 0.9373 AU and the aphelion distance is Q = 4.1211 AU (Siregar & Soegiartini, 2012). The orbital period of this asteroids is around 4 years, so the orbital resonance is 1:4 with the Earth and 3:1 with Jupiter. With q = 0.9373 AU and an aphelion distance of Q = 4.1211 AU, 4179 Toutatis is a planet crosser object, from Venus to Uranus. Periodic close encounters with the major planets are needed for the understanding of cosmogonical problems and have a connection with the stability of the orbital motion of asteroids, so it is very important to study the stability of the asteroids.

2. THE ORBIT OF 4179 TOUTATIS

The orbital elements of 4179 Toutatis were downloaded from the JPL Small-Body Database Browser, which D.K Yeomans reported as shown in Table 1. The epoch of this data is 2456800.5 or 2014-May-23, 00:00:00 UT.

2.1. The Numerical Integration

The orbital evolution of 4179 Toutatis is investigated by numerical integration of the Classical Newtonian equation:

$$\ddot{\vec{r}}_i = \sum_{j \neq i} \mu_{ij} \frac{(\vec{r}_j - \vec{r}_i)}{\vec{r}_{ij}{}^3} \qquad (1)$$

Table 1
Orbital Elements of 4179 Toutatis at epoch 2456800.5 (2014-May-23, 00:00:00 UT)

	Nominal value (V_0)	Std. Dev (1σ)
Semimajor axis, a [AU]	2.53364	1.1709×10^-2
Eccentricity, e	0.62977	3.4839×10^-5
Inclination, i [deg]	0.44711	3.6936×10^-4
Longitude of ascending node, Ω [deg]	124.35770	$1.1102\times$10-3
Argument Perihelion, ω [deg]	278.75800	0.9764×10^-3
Mean anomaly, M [deg]	135.25027	6.5946×10^-2

with μ_ij = $k^2 m_i$,k^2=G, with i iterated for the Sun, 4179 Toutatis and all the major planets.

All the major planets, from Mercury through Neptune, were included as perturbing bodies (The Earth is taken at the Earth–Moon barycenter as being one body, with the Moon's mass added to the Earth's). The time span of more than 300,000 years is being taken from time = 0 from the epoch 2456800.5 (2014-May-23, 00:00:00 UT). The Mercury 6 program package (Chambers, 1999) was used as the integrator with the Bulirsch-Stoer N-body algorithm in double precision, which is slow but accurate in situations during encounter passages. The results of the numerical integration show that close encounters between 4179 Toutatis asteroid and some of the major planets happen often.

The 4179 Toutatis asteroid suffers many close encounters with some of the major planets, which makes this

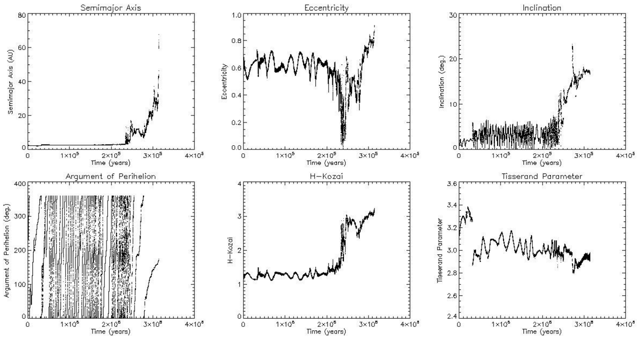

Figure 1. The evolution of the orbital elements of 4179 Toutatis asteroid over more than 300,000 years from t=0. The leaps in value of the semimajor axis are caused by close-encounter events with the major planets, from Venus to Uranus. In fact, a close-encounter will lead to a leap in value for all the orbital elements, not only for the semimajor axis but for the eccentricity and inclination as well (Siregar & Soegiartini, 2012).

asteroid's motion chaotic (Yoshikawa, 2002). Figure 1 shows the variation of orbital elements for more than 300,000 years from time = 0. The variations of the orbital elements are not seen to be periodic, and change in many ways. These changes are caused by close encounters with major planets, from Venus to Uranus. In this paper, we define a close encounter with a planet as when the distance of 4179 Toutatis is less than 3 times the Hill-radius from the planet, $3R_H$ (Cuntz & Yeager, 2009):

$$R_h = a_p(1 - e_p)(\frac{m_p}{3M_*})^{1/3} \quad (2)$$

where p stands for the planet and * for the Sun. The body in this area is under the gravitational influence of the planet. Close-encounters will change the orbital elements during its evolution.

2.2. *Integration Parameter*

In this integration, the Sun is taken as the centre, and the 8 major planets (Mercury to Neptune) as gravitational perturbers in the motion of 4179 Toutatis. A time span integration of 500,000 years from the epoch t=0 is used for seeing pronounced variations in the orbital evolution occur. Numerical integration of the Classical Newtonian equations has been performed. The integration time step was set to be 0.5 days, sufficient for this study since the relative errors in total energy and total angular momentum in the system are smaller than 10^{-10}. This integration will stop if e = 1. The Mercury_6 package (Chambers, 1999) was used to execute the integration, and IDL data processing was applied to process the data.

2.3. *Tisserand Parameter for Asteroid 1566 Icarus*

The Kozai mechanism (Kozai, 1962) is considered as a secular interference by Jupiter on the asteroid, as for long period-evolution the exchange of angular momentum with the asteroid can not be ignored. Kozai resonance is a resonance in which the value of the average precession of the nodal points of an object is the same, both are large and it is a measure of the value of precession of the perihelion. Objects in Kozai resonance experience oscillations in eccentricity and inclination, whereby when eccentricity increases, the inclination decreases, and vice versa.

For objects that orbit with eccentricity e and inclination i, relative to the larger object, it will follow the Kozai parameter is

$$H_{Kozai} = \sqrt{a(1 - e^2)}cosi \quad (3)$$

Equation 3 is known as the Kozai mechanism, which tends to a constant value. The Kozai mechanism causes a periodic exchange between the angle of inclination i and eccentricity e of the orbit which follows the relation of orbital eccentricity increasing with decreasing angle of orbital inclination of 4179 Toutatis. Over its evolution, the longitude of the ascending nodes also changes periodically, as shown in Figure 1, over the range 0° to 360°.

A close encounter will change the orbital elements of this asteroid, thus causing the orbit of 4179 Toutatis to change into a new orbit. As a result of close encounters, all the value of the orbital element are changed and the values jump to a new orbital element values. 4179 Toutatis has new orbital elements, and forgets the events preceding the new orbital element value. The Kozai parameter controls the value of orbital elements, where by increasing the value of orbital eccentricity e, the value of orbital inclination i decreases, and vice versa. In addition, changes in the value of the orbital eccentricity e and orbital inclination i will influence the changes in the value of semimajor axis a as well.

The dynamics of objects near the major-planet region (NEO) is strongly influenced by close-encounters with the planets. In every encounter, the speed of the object trajectory will be boosted, which causes the semimajor axis to jump or change into a new value, depending on the geometry and mass of each planet encountered. The changes of the semimajor axis a are correlated with the changes of orbital eccentricity e and orbital inclination i, indicated by the Tisserand parameter. Relative to Jupiter with semimajor axis a_J (Opick, 1976), the Tisserand parameter is given by:

$$T_J = \frac{a_J}{a} + 2\sqrt{\frac{a(1 - e^2)}{a_J}}cosi \quad (4)$$

where J denotes Jupiter.

The three-body problem refers to the system of the Sun, planet, and comets or asteroids, assuming no other objects affect the dynamics of the orbital system. Calculating T_J during interactions between the small body and planetary objects is useful in understanding the results of such interactions, and the presence of T_J allows the determination of the qualitative relationship between orbital parameters before and after close encounters.

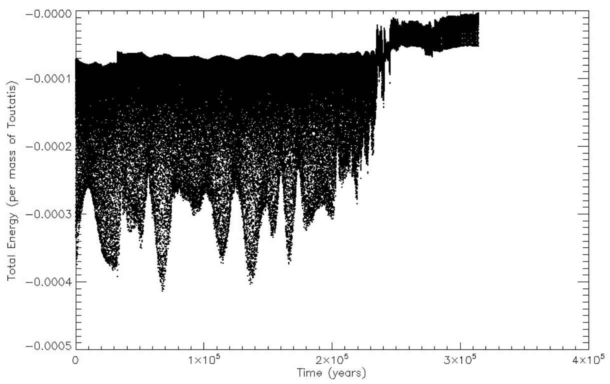

Figure 2. The total energy during the evolution of the orbital dynamics of 4179.

From Equation 4, $T_J = 3$ is for objects with semimajor axis equal to the semimajor axis of Jupiter, with orbital eccentricity e = 0 and orbital inclination i = 0 (Chamberlain, 2007). Most of the time the asteroid has T_J>3. For 4179 Toutatis, the value T_J changes from T_J>3 to T_J<3, so we predict that 4179 Toutatis will change from asteroid to Jupiter Family Comet.

2.4. Close Encounters

There are some close encounters between 4179 Toutatis and major-planets before it escapes from the Solar system. Sitarski (1998) determined that 4179 Toutatis will have a close-encounter with the Earth on 2069-Nov-05.66, with a distance of 0.020 AU, but in our integration, this asteroid will close-encounter with the Earth 57.29 years after 2014-May-23 (or 2071-Sept-05.92) with a distance of 0.0198 AU or less than Earth's MOID (0.05 AU), so 4179 Toutatis is a PHA (Potentially Hazardous Asteroid).

After many close-encounters with the Earth, Venus and Mars, Toutatis will have many close-encounters with the Jovian planets, Jupiter to Uranus. Slowly but surely, the orbital elements of 4179 Toutatis will incraese and the eccentricity, e, towards a value of 1, which means 4179 Toutatis will escape from the Solar system.

2.5. The Energy Changes

The total energy E_T can be found from the equation:

$$E_T \quad = \quad E_K + E_P = \frac{1}{2} m_T v_T^2 - m_T \sum_{j \neq i} \frac{\mu_{ij}}{r_i} \qquad (5)$$

where m_T denotes 4179 Toutatis's mass and v_T its velocity.

A close-encounter between 4179 Toutatis and any major planet changes in the total energy of this asteroid, as we can see in Figures 2, with the total energy finally increasing to a positive value. This means that the 4179 Toutatis asteroid will be ejected from the Solar System by gravitational perturbation.

3. CONCLUSIONS

As an asteroid, the Tisserand parameter of 4179 Toutatis is T_J>3. After many close-encounters with major planets the Tisserand parameter shows relatively stability at T_J<3, which shows that dynamically, 4179 Toutatis changes from an asteroid to a Jupiter-family comet. We predict 4179 Toutatis will be ejected from our Solar System by looking at the increase of its eccentricity, e, to 1.

With the change of total energy from negative-value to zero (positive-value), there exists a migration from an elliptical orbit to a parabolic or hyperbolic orbit.

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