Orbital Evolution of Phaethon Cluster

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Introduction

- It is known that the **Geminids meteor shower** is associated with the near-Earth asteroid **(3200) Phaethon**.
- Ohtsuka et al. (2006) suggested that the asteroid **(155140) 2005 UD is a fragment** of the asteroid (3200) Phaethon.
- This point of view is discussed in (Devogèle et al. 2020).
- Hanuš et al. (2016) concluded that the orbital evolution of asteroids **(155140) 2005 UD and (225416) 1999 YC** is similar to the orbital evolution of asteroid (3200) Phaethon. Analysis of the difference in orbital angular elements (longitudes of nodes and perihelions) excludes the separation of (155140) 2005 UD and (225416) 1999 YC from (3200) Phaethon in the recent past. Probably, these events took place **more than 100 kyr ago**.
- Ryabova et al. (2019) investigated the behavior of the minimum orbital intersection distance MOID between the orbits of asteroids (3200) Phaethon, (155140) 2005 UD, and (225416) 1999 YC at an interval of 5000 years in the past. It is concluded that asteroids **(155140) 2005 UD and (225416) 1999 YC are not members of the Phaeton – Geminids meteoroid complex**. A very close approach was also noted between the asteroids **(155140) 2005 UD and (225416) 1999 YC**, which took place **in 1422**.

Method

- We have studied the **orbital evolution** of asteroids of the Phaethon cluster: (3200) Phaethon, (155140) 2005 UD and (225416) 1999 YC over **1 Myr** in the past to estimate of the age of asteroid pairs.
- We use the term "**Phaeton cluster**" to distinguish it from the "Phaeton-Geminid meteoroid complex".
- Orbital evolution was simulated using the **Orbit9** program included in the OrbFit software package. Perturbations from eight major planets, the dwarf planet Pluto, the influence of the Yarkovsky effect, the oblate of the Sun, and relativistic effects were taken into account.
- **The nominal orbital elements** for the epoch MJD 59000 (May 31, 2020) from the AstDyS were used as the initial ones.
- **The diurnal Yarkovsky effect** was taken into account in the form of **a drift of the semi-major axis** of the orbit da/dt.
- We used the value **$da/dt = -(6.9 \pm 1.9)\cdot 10^{-4}$ au/Myr** for **(3200) Phaethon** (Hanuš et al. 2018).
- For **(155140) 2005 UD**, we assumed the drift **da/dt to be zero**, since the obliquity of the asteroid's rotation axis to the plane of its orbit is $\phi \approx 87°$ (Huang et al.2021).
- For asteroid **(225416) 1999 YC**, there are no estimates of the semi-major axis drift based on the observation results; therefore, an estimate was obtained for **the absolute value of maximum of the drift rate $|da/dt|_{max} = 7.8 \cdot 10^{-5}$ au/Myr** using the normalization of the physical and dynamic parameters of the asteroid with respect to the corresponding parameters of the asteroid (101955) Bennu (Spoto et al. 2015; Del Vigna et al. 2018).
- For (225416) 1999 YC, **five variants of evolution** were considered at the values of the drift rate corresponding to different orientations of the asteroid's axis of rotation relative to the orbit plane: $da/dt = 0$ at $\phi = 90°$ or $270°$; $da/dt = \pm 1/2\ |da/dt|_{max}$ at $\cos(\phi) = \pm 1/2$, respectively; $da/dt = \pm|da/dt|_{max}$ at $\varphi = 0°$ and $180°$, respectively.
- We used standard **methods for determining the age of pairs** of asteroids in close orbits:
  - ✓ analysis of low relative-velocity close encounters of asteroids (see, e.g., Pravec et al. 2019),
  - ✓ analysis of minimum distances between orbits (see, e.g., Kuznetsov et al. 2020),
  - ✓ analysis of the simultaneous approach of the lines of nodes and lines of the apses of the orbits of asteroids (see, e.g., Rosaev and Plávalová 2017).

Results

- Based on the simulation results, over 1 Myr in the past, **no paired low relative-velocity close encounters** were revealed for the asteroids of the Phaeton cluster.
- Analysis of the evolution of the differences in the longitudes of the ascending nodes ΔΩ and the arguments of the pericenter Δ*g* (Fig. 1, 3 and 5), and the Kholshevnikov's metrics (Kholshevnikov et al. 2016) (Fig. 2, 4 and 6) showed the possibility of close encounters of the orbits of the Phaeton group asteroids in the past.

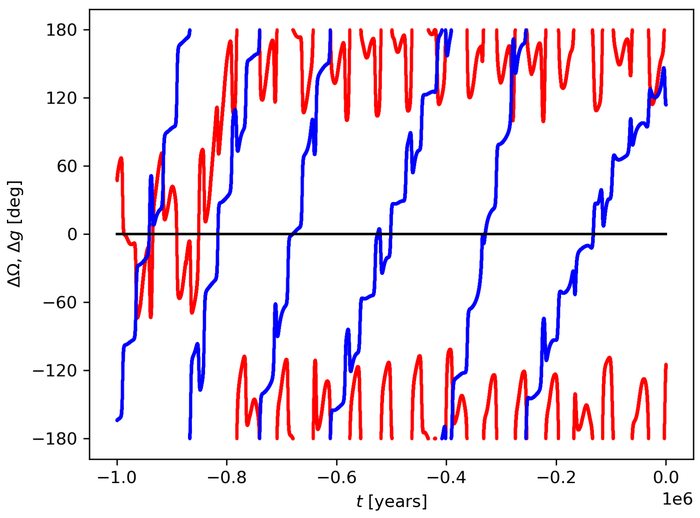

Figure 1. *Differences in the longitudes of the ascending nodes ΔΩ (blue) and the arguments of the pericenter Δg (red) for the pair* ***(3200) Phaethon – (155140) 2005 UD***

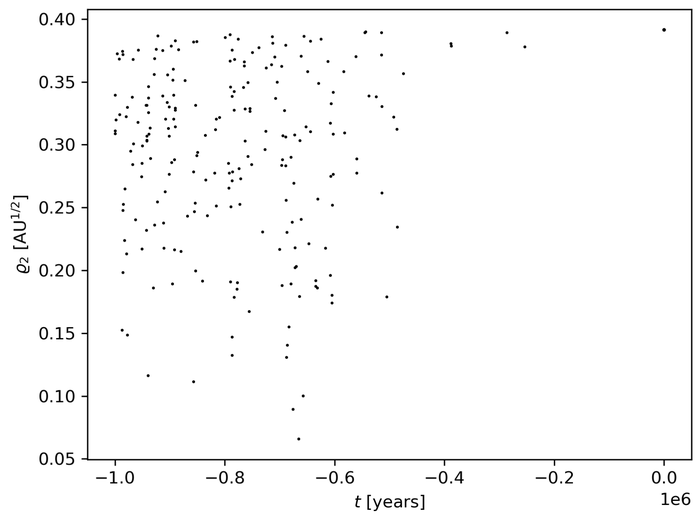

Figure 2. *Minimum values of the Kholshevnikov's metrics ρ_2 for the pair* ***(3200) Phaethon – (155140) 2005 UD***

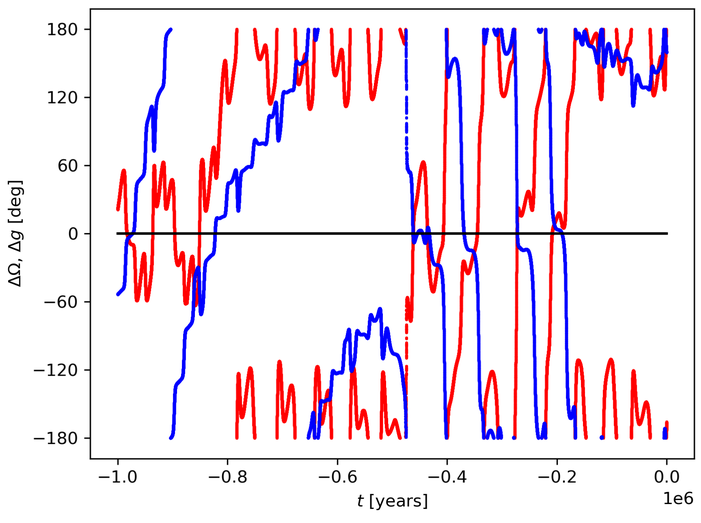

Figure 3. *Differences in the longitudes of the ascending nodes ΔΩ (blue) and the arguments of the pericenter Δg (red) for the pair* ***(3200) Phaethon – (225416) 1999 YC***

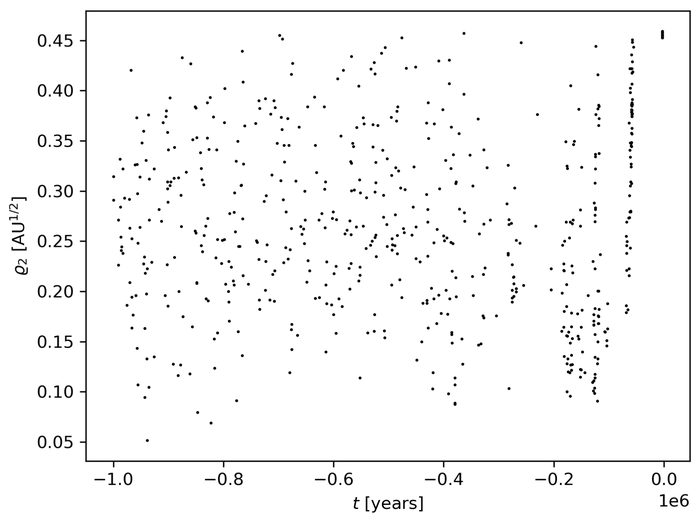

Figure 4. *Minimum values of the Kholshevnikov's metrics ρ_2 for the pair* ***(3200) Phaethon – (225416) 1999 YC***

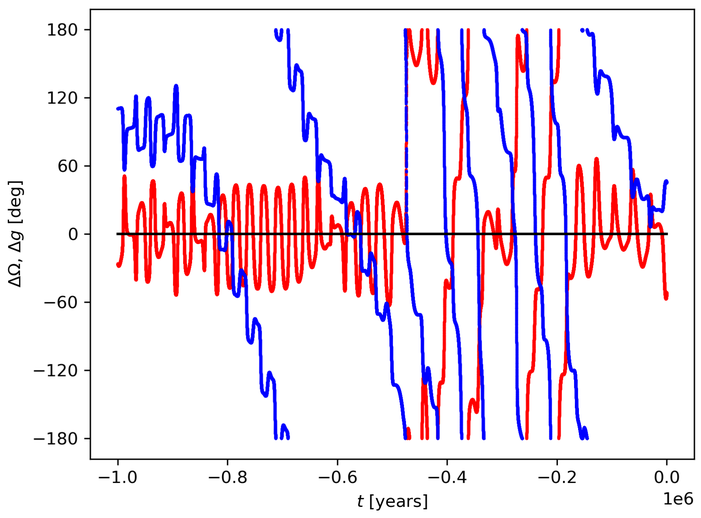

Figure 5. *Differences in the longitudes of the ascending nodes ΔΩ (blue) and the arguments of the pericenter Δg (red) for the pair* ***(155140) 2005 UD – (225416) 1999 YC***

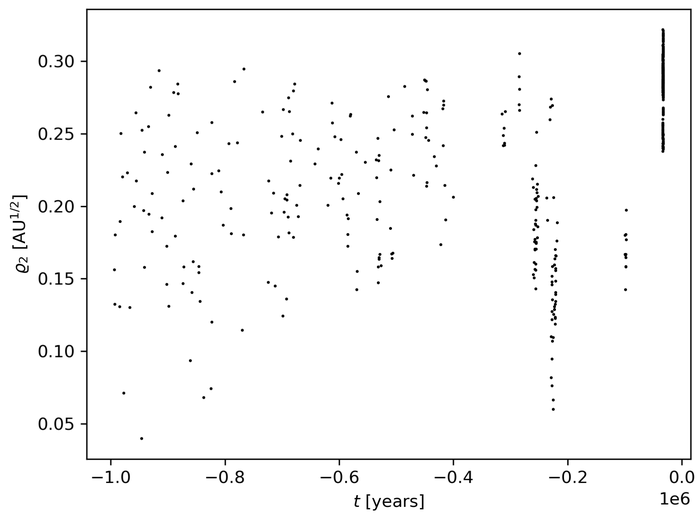

Figure 6. *Minimum values of the Kholshevnikov's metrics ρ_2 for the pair* ***(155140) 2005 UD – (225416) 1999 YC***

- The **orbital convergence condition is fulfilled** for the pair **(3200) Phaethon – (155140) 2005 UD** after **0.9 Myr** in the past.
- The difference in the perihelion arguments **Δ*g* librates** relative to the values of **180°** and **0°** with an amplitude of 60° (Fig. 1).
- The libration Δ*g* to 180° is since both asteroids are in **the metastable Lidov–Kozai resonance** (Michel and Thomas 1996), which protects asteroids from very close encounters with planets.
- The perihelion argument is librated to 0° for (3200) Phaethon and 180° in the case of (155140) 2005 UD over 0.8 Myr in the past. This behavior of the perihelion arguments **excludes the orbits convergence for (3200) Phaethon and (155140) 2005 UD over 0.8 Myr in the past**.
- Asteroid **(225416) 1999 YC** is also in **the metastable Lidov–Kozai resonance**.
- Unlike (3200) Phaethon and (155140) 2005 UD, the perihelion argument of (225416) 1999 YC **changes the libration center position** between 0° and 180°, which makes it possible to converge the orbit of (225416) 1999 YC as with the orbit (3200) Phaethon, and with the orbit (155140) 2005 UD.
- If the asteroid **(225416) 1999 YC** results from the fragmentation of the asteroid **(155140) 2005 UD**, **the age of the pair may be 200 kyr and more** (Fig. 5 and 6).
- If **(225416) 1999 YC** is a fragment of **(3200) Phaethon**, then the age of the pair **exceeds 100 kyr**, which is consistent with the conclusions of Hanuš et al. (2016).
- The results of **probabilistic evolution** do not allow us to reliably estimate the age of pairs (Fig. 2, 4 and 6).
- The minimum values of the metric make it possible to distinguish **the intervals** of close encounters of the orbits when **a pair could have formed**.

Discussion

- The results indicate the complex resonance dynamics of the Phaeton cluster.
- To obtain reliable estimates of the ages of pairs, an **intensive study of probabilistic evolution of the Phaethon cluster** is required.
- A separate consideration is required for the problem of the close encounter of asteroids (155140) 2005 UD and (225416) 1999 YC in 1422.
- The solution of these problems is planned to be carried out during further research.

Acknowledgements

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