

Apollo asteroids (1566) Icarus and 2007 MK₆: Icarus family members?

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ABSTRACT

Although it is more complicated to search for near-Earth object (NEO) families than main belt asteroid (MBA) families, since differential orbital evolution within a NEO family can cause current orbital elements to drastically differ from each other, we have found that Apollo asteroids (1566) Icarus and the newly discovered 2007 MK₆ are almost certainly related. Specifically, their orbital evolutions show a similar profile, time shifted by only ~ 1000 yr, based on our time-lag theory. The dynamical relationship between Icarus and 2007 MK₆ along with a possible dust band, the Taurid-Perseid meteor swarm, implies the first detection of an asteroidal NEO family, namely the “Icarus asteroid family”.

Subject headings: minor planets, asteroids — comets: general — meteors, meteoroids

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1. Introduction

Near-Earth Apollo asteroid (1566) Icarus = 1949 MA was discovered by Baade (1949) as a 16th magnitude fast-moving object, on a plate taken using the 48-inch Palomar Schmidt on 1949 June 10, when Icarus approached the Earth to within 0.10 AU, near its descending node. Its orbital parameters were highly unusual: it had smaller semimajor axis ($a = 1.08$ AU), smaller perihelion distance ($q = 0.19$ AU), larger eccentricity ($e = 0.83$) than any other asteroid known at that time and relatively high inclination ($i = 23^\circ$). Icarus remained the record holder in having the smallest q among all asteroids until the discovery of (3200) Phaethon in 1983. Indeed, on account of its small q , Icarus was historically of particular interest as to whether the relativistic effects on its orbital motion are detectable (e.g., Shapiro et al. 1971).

In Icarus’ subsequent approaches to the Earth in 1968, 1987, and 1996, the following physical data were derived: absolute magnitude (H) = 15.95 and G -parameter = -0.04 (Tedesco 1989); rather high albedo ~ 0.33 and diameter ~ 1 km (e.g., Harris 1998); fast rotation period ~ 2.273 hr (e.g., Gehrels et al. 1970; De Angelis 1995) and others¹. Especially notable is that Icarus is spectrally classified as a Q-type in Tholen’s taxonomy. Q-type asteroids, which generally are spectroscopic analogues of ordinary chondrites (cf. McFadden et al. 1984; Hicks et al. 1998; Fevig & Fink 2007), are regarded as being less space-weathered S-complex asteroids, with a surface age ≤ 10 Myr owing to resurfacing effects (Marchi et al. 2006). Hence Icarus may represent the rather fresh internal structure of a precursor object broken up in recent history. Moreover, with $q \sim 0.19$ AU, the subsolar point on Icarus should reach a temperature of 800 K by solar heating, in which case the solar thermal stress may be a trigger to destroy the asteroid’s surface and subsurface. Resurfacing may alternatively be due to the tidal effects of the terrestrial planets (Nesvorný et al. 2005).

For the above reasons, we have expected some “Icarus Family Members” (hereafter “IFM(s)”) to exist in near-Earth space. We have therefore been searching for IFMs based on time-lag measurements (see below) between the orbital evolution of Icarus and any candidate IFM. This procedure was successful in finding the dynamical relationship between (3200) Phaethon and (155140) 2005 UD (Ohtsuka et al. 2006, hereafter Paper I). No certain IFMs had been found in the Apollo asteroid database² until very recently. However, we finally identified an extremely likely candidate from the latest MPECs (Minor Planet Electronic Circulars): a recently discovered Apollo asteroid 2007 MK₆.

¹<http://earn.dlr.de/nea/001566.htm>

²e.g., <http://cfa-www.harvard.edu/iau/lists/Apollosq.html>

2. Orbital integration of (1566) Icarus

As preliminary work for the IFM survey and for measuring the time-lags (detailed in the next section) between Icarus and unknown potential IFMs, we calculated the orbital evolution of Icarus. We performed a backward and forward numerical integration of the KS (Kustaanheimo–Stiefel) regularized equation of motion (cf. Arakida & Fukushima 2000, 2001), applying the 12th-order Adams method in double precision with a step size of 0.5 day. The integration covered 10000 BC to 10000 AD (JDT -1931503.5 to 5373520.5), and included terms of first order in the post-Newtonian approximation for the Sun’s gravitational field since relativistic effects advance the line of apsides of Icarus at a rate of $10''/\text{century}$.

We also confirmed that the results of our numerical integration did not significantly change even when we adopted smaller step sizes or when we used other integration methods such as the extrapolation method. The initial orbital data of Icarus at osculation epoch 2007 Apr 10.0 TT = JDT 2454200.5 were taken from NASA JPL’s HORIZONS System ³ and are listed in Table 1. All the major planets from Mercury through Neptune and the quasi-planet, Pluto, were included as perturbing bodies (the Earth–Moon barycenter being one body, with the Moon’s mass added to the Earth’s). The coordinates of the major planets were taken from the JPL Planetary and Lunar Ephemeris DE408.

Over 20000 yr we found the orbital motion of Icarus to show a high degree of stability, with long-period secular changes according to the cycle in argument of perihelion ω , also known as the Kozai cycle (Kozai 1962). The corresponding large-amplitude oscillations in q and i , in antiphase with e , have period ~ 25000 yr, half that of the ω cycle. The ω period of ~ 50000 yr is somewhat larger than the ~ 40000 yr for Phaethon and 2005 UD (Paper I).

3. Time lag Δt of the orbital evolutions

In the first stage of the formation of an asteroid family, the orbital energies ($\propto 1/a$) of bodies or fragments are slightly different from that of the precursor, since the motions of the released objects are slightly accelerated or decelerated relative to the precursor. This results in differences in their evolutionary rates under gravitational perturbations (there may additionally be differential nongravitational perturbations): then a time-lag (which hereafter we call Δt) in the orbital evolutions arises. At the starting epoch, $\Delta t \approx 0$ yr, and it tends to increase with time. We note that Δt is not the time since separation, but rather quantifies how separated in phase two orbits have become in their respective (similar) secular

³<http://ssd.jpl.nasa.gov/horizons.html>

perturbation cycles. For measuring a difference in the evolutionary phase of two orbits, Δt is much more suitable than for example the difference in ω , since (for highly eccentric orbits particularly) $d\omega/dt$ is strongly dependent on the phase within the Kozai cycle (cf. Fig. 1 later). Any IFM should show a very close orbital similarity with Icarus when shifted by the appropriate Δt that brings both orbits to the same evolutionary phase.

The following successful studies applying this time-lag theory have been made so far: i) anticipation of the Marsden and Kracht comet groups’ periodicity and their return: Ohtsuka et al. (2003) anticipated these comet groups, which initially had parabolic orbit solutions, as being fragments of Periodic Comet 96P/Machholz. Their prediction was shown to be correct when Sekanina & Chodas (2005) linked orbits and found these comet groups to have orbital periods of 5–6 yr, corresponding to 96P’s ~ 5.2 yr. The Marsden and Kracht comet groups thus turned out to be decameter-size members of the 96P–Quadrantid stream complex. ii) genetic relationship of Phaethon and 2005 UD: Paper I revealed 2005 UD as being the most likely large fragment of Phaethon. This dynamical relationship was confirmed by the physical studies of Jewitt & Hsieh (2006) and Kinoshita et al. (2007), who classified both objects as F- or B-type. These taxonomic types are very rare, comprising only $\sim 5\%$ of NEOs that have been classified; combined with the dynamical evidence, the genetic relationship of Phaethon and 2005 UD is beyond doubt.

This time-lag theory is straightforward and is now well established as a technique to demonstrate the existence of cometary stream complexes or likely NEO families; so it should be a useful tool to survey for IFMs.

4. Survey

4.1. Procedure

The survey for IFMs in the Apollo asteroid database and latest MPECs uses the same procedure as in Paper I. We again applied the following three criteria as the retrieving engine for our IFM survey. The first is the traditional orbital similarity criterion D_{SH} of Southworth & Hawkins (1963), who defined D_{SH} as a distance between the orbits of two objects A and B in five-dimensional orbital element space $(e, q, \omega, \Omega, i)$, as follows:

$$D_{\text{SH}}^2 = \sum_{j=1}^5 f_j^2 (P_{A,j} - P_{B,j})^2, \quad (1)$$

where $P_{A \text{ or } B,j}$ are orbital elements and f_j are functions of the elements that ensure suitable weights are given to each term in (1). Thus we searched for potential IFMs on the basis of

Icarus’ orbital evolution from the integration described in Section 2. For each Near-Earth Apollo, we found the minimum D_{SH} between it and Icarus, as Icarus’ orbit evolves. A minimum $D_{\text{SH}} \leq 0.15$ means that Icarus and the given asteroid are within the probable association range.

The second and third criteria are the C_1 and C_2 integrals derived by Moiseev (1945) and Lidov (1961) respectively, which we calculate for candidates selected by D_{SH} :

$$C_1 = (1 - e^2) \cos^2 i, \tag{2}$$

$$C_2 = e^2 (0.4 - \sin^2 i \sin^2 \omega). \tag{3}$$

These integrals describe the secular orbital variations well. Both C_1 and C_2 are almost invariant for the orbital motions of Phaethon and 2005 UD (Paper I), and should also be useful criteria to distinguish IFMs.

4.2. Detection of the IFM candidate: Near-Earth Apollo asteroid 2007 MK₆

In this way, we finally detected a very likely IFM candidate from the latest MPECs: Near-Earth Apollo asteroid 2007 MK₆, which was recently discovered in the Catalina sky survey, on 2007 June 21.2 (Hill et al. 2007). Soon after, Ohtsuka (2007) made the identification of 2007 MK₆ with another Apollo, 2006 KT₂₇, so 2007 MK₆ = 2006 KT₂₇; the latter was both discovered (on 2006 May 26) and observed only (12 positions over a 1 day arc) by the Mt. Lemmon survey. This extended the arc to more than one year. Nakano successfully linked their orbits, based on 54 positions at two oppositions (covering 2006 May 26 to 2007 June 27) with an RMS residual of 0".74. The absolute magnitude $H \sim 19.9$ corresponds to an object a few hundred meters in size at most, if we assume 2007 MK₆ is a high-albedo object such as an S-type.

Using Nakano’s data, listed in Table 1, we integrated 2007 MK₆ using the same method as for Icarus. The dynamical evolutions of both asteroids are illustrated in Fig. 1. Icarus and 2007 MK₆ sometimes encounter the terrestrial planets. Encounters with Venus or Earth can cause changes in a but these are small enough that the other elements display a stable secular evolution, as with Phaethon and 2005 UD (Paper I). Neither asteroid has a nodal intersection epoch with Venus or Earth in the past 10000 yr, hence the interval of constant a in Fig. 1.

Comparing the orbital elements of 2007 MK₆ at the current epoch with the changing orbit of Icarus over time, as described in Section 4.1, we found a strikingly good match with Icarus at around 1034 AD (Table 1); thus $\Delta t \sim 1000$ yr. The corresponding minimum value

of D_{SH} is only 0.0098. Both Δt and D_{SH} are fairly small compared to the respective values ~ 4600 yr and 0.04 between Phaethon–2005 UD (Paper I). The C_1 and C_2 parameters are almost constant, within the ranges 0.26–0.28 and 0.24–0.25 respectively. Therefore 2007 MK₆ is a very strong candidate IFM.

The two orbital evolutions show a similar profile, with quasi-sinusoidal changes, simply shifted by $\Delta t \sim 1000$ yr. Their smaller Δt than Phaethon–2005 UD suggests a younger separation age, but D_{SH} between Icarus–2007 MK₆ at the same osculation epoch has never been below 0.03 in our integration timespan. Only in quite rare cases (such as the Karin cluster in the main belt; Nesvorný et al. 2002) can an exact separation age be found unambiguously, although we may certainly expect D_{SH} to have been smaller around the time that Icarus and 2007 MK₆ separated. Some test integrations back 10^5 yr tentatively show Δt decreasing back in time but random small changes in a due to close encounters make it hard to reach a precise quantitative conclusion about the separation age. However, this age is clearly within 10 Myr, the resurfacing age of Q-type NEOs, possibly two orders of magnitude shorter. The Icarus–2007 MK₆ parent may well have been injected into the near-Earth environment of the order of 10 Ma (cf. Bottke et al. 2002), but with the separation occurring much more recently.

We also surveyed meteor data related to the IFMs. Consequently, we noticed a likely meteor swarm found by Sekanina (1973) in the Harvard (Havana) radar meteor orbit survey: the daytime Taurid-Perseid meteor swarm, recorded around June 18 in the radar’s 1961–1965 term of operation. The orbital parameters are in good agreement with those of Icarus, as presented in Table 2. Their $D_{\text{SH}} \sim 0.08$ is in the probable association range. Although we cannot accurately measure their Δt , both the current orbits look to be at almost the same evolutionary phase. No further orbital data were found in the radar meteor orbit database. We may therefore regard the Taurids-Perseids as a transient Earth-crossing IFM dust band rather than a cometary meteor stream.

5. Discussion and Conclusions

There have been numerous studies on the formation of main belt asteroid (MBA) families, and also some on NEO families. Statistical studies using NEO orbit data, based on orbital similarity, often generate positive results on the existence of NEO families. However, Fu et al. (2005) concluded that it is unlikely that these results are anything more than random fluctuations in the NEO orbit population. In a past IFM study, Steel et al. (1992) noted an orbital similarity between (5786) Talos = 1991 RC and Icarus. Their orbital elements, except for ω and Ω , indeed coincide well with each other. However, Talos’ longitude

of perihelion remains widely separated (by $\sim 50^\circ$) from that of Icarus over the past 11000 yr integrated by Steel et al., so that it is difficult to verify a genetic relationship. If there exist NEO families having high-eccentricity and rather highly inclined orbits, then unless their origin is extremely recent, their differential orbital evolutions, shifted by Δt , will lead to their current orbital elements being drastically different. For this reason it is more complicated to search for NEO families than MBA families.

Nevertheless, we found Near-Earth Apollo asteroids Icarus and 2007 MK₆ to be very likely candidates for IFMs, based on our time-lag theory. Their $\Delta t \sim 1000$ yr and minimized $D_{\text{SH}} \sim 0.0098$ are even smaller than those, ~ 4600 yr and 0.04, of the well-established Phaethon–2005 UD relationship. Since Phaethon and 2005 UD may have a cometary origin (Paper I), therefore, the dynamical relationship between Icarus and 2007 MK₆ along with a possible IFM dust band may constitute the first detection of an asteroidal NEO family, namely the “Icarus asteroid family”. In this case, Icarus should be the parent body, but as it is only a 1-km size object, the Icarus family is on a smaller scale than MBA families.

The next Earth approaches of Icarus and 2007 MK₆ will occur respectively on 2015 June 17 to 0.05 AU and 2016 June 15 to 0.10 AU, providing good opportunities to determine additional physical parameters and to further study their common origin. It is possible that further accurate astrometry and advances in the numerical analysis will eventually resolve the separation age.

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Table 1: Orbital parameters of (1566) Icarus and 2007 MK₆ (equinox J2000)

object	(1566) Icarus		2007 MK ₆
osculation epoch (TT)	2007 Apr. 10.0	1034 Jul. 03.0	2007 Apr. 10.0
mean anomaly M	285°.14414	161°.45243	336°.75725
perihelion distance q (AU)	0.1866177	0.1930133	0.1959358
semimajor axis a (AU)	1.0778849	1.0776443	1.0807494
eccentricity e	0.8268668	0.8208933	0.8187038
argument of perihelion ω	31°.29236	25°.37252	25°.38152
longitude of ascending node Ω	88°.08105	93°.55925	92°.94672
inclination i	22°.85385	25°.07805	25°.15553
# of observations	711		54
arc (oppositions)	1949–2006 (14)		2006–2007 (2)
RMS residual	1".12		0".74
absolute mag. H	15.95		19.9
reference	JPL	this work	Nakano

Table 2: (1566) Icarus and the Taurids-Perseids (Sekanina 1973) at almost the same evolutionary phase

object	epoch (TT)	q (AU)	a (AU)	e	ω	Ω (2000.0)	i
Icarus	1963 Jul. 3.0	0.18697	1.07791	0.82655	31°.032	88°.337	22°.940
Tau-Per	1961–1965	0.163	1.268	0.871	36°.3	86°.7	23°.3

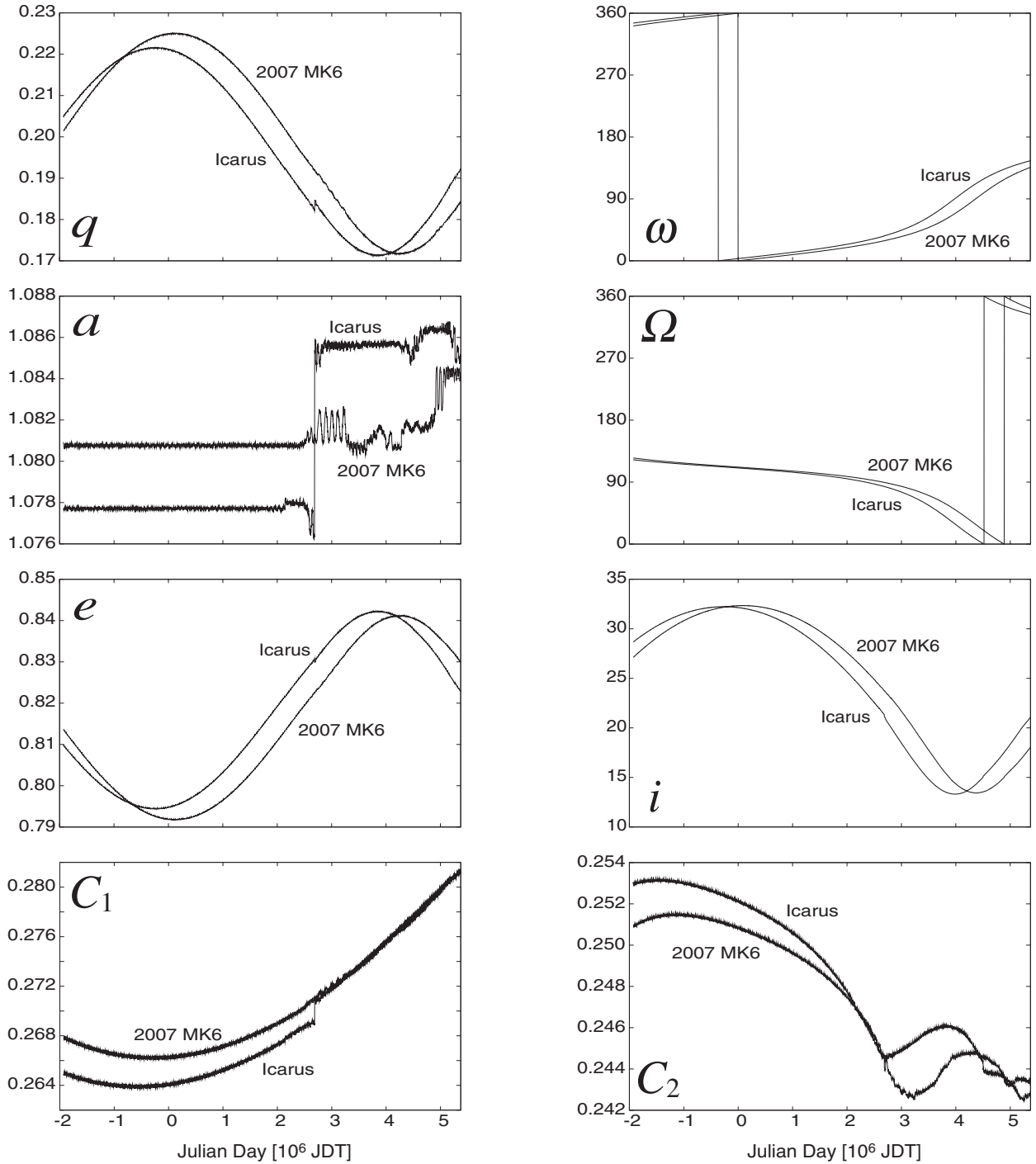


Fig. 1.— Orbital evolution of (1566) Icarus and 2007 MK₆. The eight graphs show: q = perihelion distance in AU; a = semimajor axis in AU; e = eccentricity; ω = argument of perihelion in degrees; Ω = longitude of ascending node in degrees; i = inclination in degrees; and the C_1 and C_2 integrals. The abscissa of all is time (Julian Terrestrial Date, JDT).