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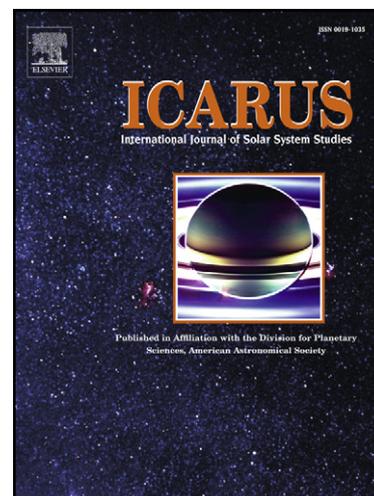
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Orbital and thermal evolutions of four
potential targets for a sample return space mission
to a primitive Near-Earth Asteroid

by

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Abstract

In this paper, we present our study of the orbital and thermal evolutions, due to solar radiative heating, of four near-Earth asteroids (NEAs) considered as potential target candidates for sample return space missions to primitive asteroids. We used a dynamical model of the NEA population to estimate the most likely source region and orbital history of these objects. Then, for each asteroid, we integrated numerically over their entire lifetime a set of 14 initially indistinguishable orbit (*clones*), obtained by small variations of the nominal initial conditions. Using a thermal model, we then computed surface and sub-surface temperatures of these bodies during their dynamical history. Our aim is to determine whether these bodies are likely to have experienced high temperature level, and whether great temperature changes can be expected due to the orbital changes as well as their maximum and minimum values. Such information is important in the framework of sample return space missions whose goal is to bring back pristine materials. The knowledge of the temperature range of materials at different depth over the orbital evolution of potential targets can help defining sampling strategies that ensure the likelihood that unaltered material will be brought back. Our results suggest that for all the considered potential targets, the surface has experienced for some time temperatures greater than 400 K and at most 500 K with 50% probability. This probability drops rapidly with increasing temperature. Sub-surface materials at a depth of only 3 cm are much more protected from high temperature and generally do not reach temperatures exceeding 450 K (with 50% probability). They should thus be unaltered at this depth at least from a sun-driven heating point of view. On the other hand, surface material for some of the considered objects can have a range of temperature which can make them less reliable as pristine materials. However, it is assumed here that the same material is constantly exposed to solar heat, while regolith turnover may occur. The latter can be caused by different processes such as seismic shaking and/or impact cratering. This would reduce the total time that materials are exposed to a certain temperature. Thus, it is very likely that a sample collected from any of the four considered targets, or any primitive NEA with similar dynamical properties, will have components that will be thermally unaltered as long as some of it comes from only 3 to 5 cm depth. Such a depth is not considered difficult to reach with some of the current designs of sampling devices.

Key Words: Asteroids, composition - Asteroids, dynamics - Near-Earth Objects - Resonances, orbital - Thermal histories

1 Introduction

Knowledge of physical and chemical properties of small bodies can provide important clues to the composition of the solar nebula in which planets formed. Indeed, most small bodies could neither experience high temperatures during their formation nor retain any atmosphere due to their small sizes. Impacts are also not likely to generate a lot of heat in the impact energy regime of the last 3.9 Gyr, except maybe very locally close to the impact point. As a consequence, most asteroids and comets are assumed to be relatively pristine objects, compared to the larger and differentiated planetary bodies, their satellites and the largest asteroids. This is believed to be even more true regarding low-albedo asteroids, generally related to taxonomic classes C, D, and other flat-spectrum types (e.g. B-types). Bodies belonging to these classes are usually thought of being the most primitive material remaining from the formation of the inner Solar System.

These arguments motivated to propose sample return missions to a primitive asteroid with the goal of bringing back pristine material for laboratory analysis. The Japanese mission Hayabusa was the first sample return mission launched to an asteroid (Fujiwara et al., 2006). It visited the 500 m-size Near-Earth Asteroid Itokawa during 3 months in fall 2005. Despite the great science results that it provided, the collect of a sample has not been confirmed and the re-entry capsule is expected to land on Earth in June 2010. In 2007, in response to a call for proposals to the scientific program Cosmic Vision 2015-2025 of the European Space Agency (ESA), a sample return mission, called Marco Polo, to a primitive asteroid was jointly proposed by a European-Japanese consortium (Barucci et al., 2009). The mission was then selected for an assessment study phase that ended in fall 2009.

In this paper, we investigate the orbital and thermal evolutions of the main current target candidates for a sample return mission. Our objectives are to study both their dynamics and thermal properties. In particular we determine whether we can link those objects to a potential source region from which they originate, and also determine their possible future evolutions. The knowledge of their potential origin can allow us to relate a sample in the laboratory to the asteroid from which it was taken and in turn to relate this body to its history and a source region, providing us a complete picture as never before.

Moreover, it has been shown (Marchi et al., 2009) that a large fraction of the NEA population has experienced in the past low perihelion distances: as a consequence these bodies have suffered considerable radiative heating from the Sun. Estimating the radiative heating due to the Sun that our potential sample

return mission targets may have suffered or may suffer during their past and future histories on their surface and at a few cm below, is very important for mission planning. This is because it allows us to determine whether a sample collected on either the surface or the subsurface from each target is likely to have undergone high temperature levels which may have altered its pristine properties. This can then help deciding also which of these targets is a better candidate for a sample return mission and interpreting the analysis of the sample. In this respect, it is important to consider the break-down temperatures of the organics thought to be present on the surface of primitive asteroids. We expect that at least part of the material at the surface (and subsurface) of the asteroids studied in this work bear a similar composition to carbonaceous meteorites, as suggested by their similarity in spectral properties. The latter are thus believed to be fragments of primitive asteroids that have remained relatively unprocessed since the formation of the Solar System 4.56 billion years ago. However, it is expected that a sample taken in-situ will contain information/material that is not present in meteorites, either because of contamination or due to the selection effect resulting from the passage through the atmosphere which can only be survived by the strongest materials. In these meteorites around 25% of the organics are present as solvent-soluble or free organic matter, but the majority is in the form of a complex solvent-insoluble macromolecular material (Sephton, 2002, and references therein). The combustion temperature of the free organic matter in carbonaceous meteorites such as Murchinson is $< 250\text{ C}^\circ$ ($\sim 520\text{ K}$; Sephton et al., 2004). The macromolecular matter can be divided operationally into a phase that breaks down under thermal stress (labile organic matter) and a phase that is more resistant to high temperatures (refractory organic matter; see Sephton et al., 2004). The labile and refractory phases of carbon- and nitrogen-bearing components observed in Murchison HF/HCl chondrites are dissociated for combustion at temperature between ~ 520 and $\sim 620\text{ K}$ and between ~ 620 and $\sim 770\text{ K}$, respectively (Sephton et al., 2003, 2004). Moreover, it is also known that the macromolecular phase in carbonaceous meteorites has a structure similar to refractory kerogen. This latter starts combustion and the production of oil and gas when heated above 420 K . On the other hand, the more primitive and volatile organics that we expect to find on carbonaceous asteroids have a structure similar to labile kerogens, which thermally decompose above 370 K (Franchi, personal communication).

In the following, we first present our method of investigation of the dynamics properties of the considered asteroids (Sec. 2). We then present the physical properties of the considered targets that make them suitable candidates for a sample return mission and their dynamical properties in Sec. 3. The method to

compute the thermal properties and the potential past and future thermal histories of the four considered objects are presented in Sec. 4. Implications for a sample return mission are discussed in Sec. 5 and conclusions are exposed in Sec. 6.

2 Method of investigation

The major difficulty to predict NEA evolutions, both backward and forward in time, is that the orbits of planet-crossing objects are very chaotic, with Lyapunov divergence times $t_L \approx 10^2$ yr (e.g., Whipple, 1995; Tancredi, 1995), owing to the sensitive dependence of the orbital changes caused by planetary encounters on the pre-encounter orbit. This time corresponds to the time beyond which two trajectories with nearby initial conditions diverge, on average, at an exponential rate. Consequently, computed evolutions are not deterministic predictions of the real evolutions over times much longer than the Lyapunov time t_L . Moreover, planet-crossing orbits are also sensitive to the assumed physical model of the Solar System, to the integration algorithm and to the round-off features of the computer. Small changes to any of these options imply that beyond a few times t_L , the computed orbits completely “lose memory” of their common origins. They are just “possible evolutions”, which are nonetheless very useful to identify the most important dynamical mechanisms which *may* affect the real orbit, or to make statistical estimates on the object’s lifetime, encounter rate and so on.

In our study, we are interested in both the past and future dynamical history of the considered objects. Indeed, the past dynamical behavior can tell us how much time the considered object may have spent at some given perihelion and aphelion distances, which in turn can provide information on the maximum and minimum temperatures it may have experienced at a given location on its surface or in sub-surface. This is an important information to determine whether a sample taken at a given surface location or depth might have been altered by strong Sun radiative heating or might have suffered large temperature stresses. Then, the future dynamical behavior is also interesting because these objects will continue to evolve for a long time; predicting their lifetime and future thermal properties is useful to characterize more or less typical physical and dynamical properties of the Near-Earth Object population.

2.1 Past history

Due to the chaotic properties of NEA orbits, the backward dynamical evolution of a NEA from its current orbit cannot be estimated in a deterministic way. Even using a negative time, the computed

evolution is just another occurrence of an evolution forward in time. Therefore, the only way to identify a potential source region and orbital history is to compute the evolution, forward in time, of thousands of particles from different potential source regions and see which of them reach the current orbit. Michel and Yoshikawa (2006) used this approach to estimate the most likely origin of the asteroid Itokawa, which was visited by the Japanese spacecraft Hayabusa.

In summary, to characterize the most likely source regions of the considered object, we use the following method. From the works by Michel et al. (2000a) and Bottke et al. (2002), a database of results of thousands of numerical integrations of particles starting from the main known sources of NEAs over their entire lifetime has been constructed. These main sources are the intermediate Mars-Crosser population (IMC, hereafter), the ν_6 secular resonance in the inner main belt, the 3/1 mean motion resonance with Jupiter at 2.5 AU, the outer belt and the Jupiter Family Comets. Considering the current orbital parameters of a NEA, we check in this database the fraction of particles from each source that reach this orbit and how much time the particles spend there; this allows us to estimate the probability that the considered object comes from each of these sources. Note that some of these sources are located so close to one another that they share overlapping orbital pathways. This is the case for the IMC and ν_6 sources, and also for IMC and 3/1 sources. An orbit having as identified source the ν_6 or the 3/1 resonance has also a chance to come from the IMC source, and this cannot be easily discriminated. Therefore, in the following, we will consider the three following sources: ν_6 , 3/1 and outer belt+Jupiter Family Comet. However, the first two ones will also include IMCs as a possibility.

As a by-product, one can also compute the probability that the object spent some time at or below a given perihelion distance, and how much time it spent there. This is a very interesting information because surface (and subsurface) temperatures of our objects mainly depend on their distance to the Sun. Thus, estimating the orbital history of an NEA provides strong information on its thermal one, which in turn provides strong constraints on the target's choice and design of a sample return space mission.

2.2 Future evolutions

Future orbital evolutions cannot be computed in a deterministic way and each of them is just a possible evolution. Therefore, to increase the statistical significance of our study, we considered the *nominal object* defined with its measured orbital parameters listed in asteroid ephemerides, and also a sample of *clones*, i.e. initially “indistinguishable” orbits obtained by either adding or removing the last digit of one of the

orbital elements at a time. Hence, in addition to the nominal orbit, we defined 12 clones by changing each of the six orbital elements at a time (called e.g. object's name $a+$, $a-$, where a is the semimajor axis and the sign indicates if the last digit was increased or decreased by unity). In addition, we computed the evolution of the nominal orbit twice, using two computers having different round-off errors. In total, we thus obtained 14 clones and we computed their orbital evolutions over their entire lifetime, i.e. until they collided with a planet, the Sun or were ejected outside Saturn's orbit. We adopted a purely gravitational model of the Solar System, including all the planets. We did not take into account the Yarkovsky thermal effect that can also affect the orbital evolution of a small body. Indeed, for the level of accuracy targeted in this study, its contribution is negligible in the evolution of an NEA as close approaches to planets have the strongest influence on the orbital changes and do not allow this effect to accumulate over long enough time, as checked by Michel and Yoshikawa (2005) in the case of the small NEA Itokawa.

Using these initial conditions, we computed the long term possible evolution of these orbits by using a numerical integrator that already allowed us to study the evolutions of some NEAs (Michel et al. 1996a, b). It consists of a Bulirsch-Stoer variable step-size algorithm (Stoer and Bulirsch, 1980), optimized for dealing accurately with planetary close approaches, and adapted by us for recording accurately the miss distance corresponding to the encounters, despite the discrete time steps used to compute the orbits (Michel et al., 1996a). The accuracy of this integrator is computationally expensive but it is required to have enough confidence, particularly for orbits subjected to rapid changes. However, it limits the number of clones that can be integrated at reasonable computational expense.

Note that considering 14 clones for each object, we do not claim that our study is statistically robust as a much greater number of particles would be necessary to achieve this goal, which goes beyond the scope of this study. Here, we just want to analyse a few potential orbital paths that these objects may take and determine the resulting thermal properties. As we will see, the behaviors of the four targets are typical for Near-Earth Asteroids and therefore, our results may actually have some representative features for typical NEAs.

3 Orbital evolutions

Table 1 provides the physical properties that are known for the four considered objects. The choice of these bodies as potential targets of a sample return mission from a primitive object is based on several constraints. First, they must be reachable using a velocity impulse from Earth that is low enough to

be achievable at low cost. Then, targets are required to have a low albedo and a rather flat spectrum which makes them belong to C, D, B or T taxonomic type. Their size is constrained to be at least a few hundreds of meters, in order to have an accurate estimate of the mass by radio science. And finally, their rotation period should not be shorter than a few hours because this can cause navigation risks during approaches and touch-and-go manoeuvres when collecting a sample. Moreover, a fast spin may prevent regolith to be present on the surface, while it is interesting to have the possibility to collect regolith for analysis in laboratory.

The orbital behaviors computed forward in time for the four targets using clones and nominal conditions show some common trends which we indicate before describing them separately.

The four targets show typical orbital behaviors of NEAs that evolve deeply in the near-Earth space. Indeed, many small bodies are characterized as NEAs while they are transported through a resonance from the main belt directly into the Sun (e.g. the 3 : 1 mean motion one with Jupiter). Thus they never leave the resonance and their semimajor axis remains at main belt values (greater than 2 AU). For these objects, the dynamical lifetime as an NEA is rather short (typically less than a few Myr) and corresponds to the timescale necessary for the resonance to increase their eccentricity to one (Gladman et al., 1997; Bottke et al., 2002). Only the lucky ones are extracted from their transport mechanism by a planetary close approach which modifies their semimajor axis. These lucky objects can evolve deeper in the near-Earth space and then survive a longer time as only a planetary impact or a return in a major resonance as a result of close approaches can end their evolution.

Thus, it was already found that the observed NEA population (which is biased toward the latter objects) has a median lifetime of 9 Myr (Gladman et al., 2000). This is much longer than the median lifetime of a few Myr of objects staying in a resonance (Gladman et al., 1997). As can be seen in Tables 2 to 3, our four targets have lifetimes which are typical for objects evolving deeply in the near-Earth space. This is actually not surprising as these objects are qualified as space mission targets based on the low impulse necessary for an artificial satellite to reach them, and thus, they must evolve deep enough in the near-Earth space. However, contrary to what was found by Michel and Yoshikawa (2006) for the asteroid Itokawa, the target of the Japanese Hayabusa mission (Fujiwara et al., 2006), which may end its evolution with a collision with the Earth in a few Myr, the most probable fate of the four targets is a collision into the Sun, which is also found to be the case for 60% of the NEA population (Gladman et al., 1997, 2000; Bottke et al., 2002).

In the following, we analyse the potential past and future evolutions of each target separately, using the methods described in Sec. 2.

3.1 1989UQ

According to the model of Bottke et al. (2002), the most likely source of 1989UQ is the ν_6 resonance (see Table 4). Before reaching its current orbit, there is 50% chance that its perihelion distance was as small as 0.5 AU (Fig. 1), and the time spent at such a distance may have been as long as about 9 Myr (Fig. 2). Longer time may have been spent at even smaller perihelion distances but with less probability. This is considerably longer than the time spent by the three other targets, and as will be shown in Sec. 4, this can have some consequences on the temperature level that its surface and subsurface may have suffered.

As for its future evolution, this object starts as an asteroid belonging to the Aten group with a semimajor axis smaller than 1 AU. However, during most of the computed evolutions the asteroid becomes temporarily or definitively an Apollo object as close approaches increase its semimajor axis to a value greater than 1 AU. In some cases, it goes back in an Aten state until it collides with Venus or Mercury. In other cases, its eccentricity eventually reaches one due to the injection in a resonance.

The nominal case shows some interesting behavior (see Fig. 3), and demonstrates the findings of Michel and Froeschlé (1997) that secular resonances are present and effective in the region of semimajor axis less than 2 AU (Michel, 1997). The body first has its semimajor axis increased to a value close to 1 AU and it enters into the Kozai resonance with its argument of perihelion librating around 180° . This resonance serves as a protection mechanism against close approaches (Michel and Thomas, 1996), which allows the orbit to remain stable during a small period of time. Then, it eventually leaves this state and continues its evolution as a classical Apollo asteroid dominated by close approaches. After about 10 Myr of evolution it enters into the ν_2 secular resonance with Venus characterized by the libration of the critical angle $\sigma_2 = \varpi - g_2 \times t - \alpha_2$, where ϖ is the longitude of perihelion, $g_2 = 7.455$ arcsec/year is the fundamental frequency corresponding to the resonance and α_2 is the phase at time $t = 0$. The effect of this resonance is a fast increase of the eccentricity (see Fig. 3). Finally, the object is transported into the ν_5 secular resonance with Jupiter, characterized by the libration of its critical angle $\sigma_5 = \varpi - g_5 \times t - \alpha_5$, where $g_5 = 4.249$ arcsec/year and α_5 is the phase at time $t = 0$, which causes the final increase of the eccentricity to one.

Only in one case, we found an ejection from the inner Solar System due to a Jupiter close approach

at the aphelion while the body evolved in the 3/1 mean motion resonance with Jupiter at 2.5 AU.

From the 14 integrations, we find a median lifetime about 45.5 Myr (Table 3). Although a much greater number of clone integrations may be necessary to get a robust statistical estimate, this rather long lifetime compared to the median one of the observed NEA population (9 Myr; Gladman et al., 2000) is consistent with the state of this object which evolves very deeply in the Earth-crossing region and consequently rather far from a dangerous zone. Only a planetary impact could occur on a very short time, but for the six clones which end their evolution by a planetary impact, this occurs at least after 10 Myr.

3.2 1999JU₃

This target has been the baseline target of the space mission Marco Polo during the assessment study phase of the program Cosmic Vision 2015-2025 at the European Space Agency in 2007-2009 and of the Japanese Hayabusa 2 mission at JAXA Japanese Space Agency. It is a C-type asteroid and one of the currently most accessible targets for a space mission. As indicated in Table 4, its most likely source is the ν_6 resonance. Although its spectral type is the dominant one in the outer belt, our estimates indicate that the probability is zero that it comes directly from this zone. If this object was originally located in the outer belt, it must have undergone a diffusion of its semimajor axis due to the Yarkovsky effect until it reached one of the two transport mechanisms found to be able to send it on its current position. In that case, despite the lower probability associated to this source, the 3/1 resonance would be favored because this is the first one the object would encounter coming from the outer belt. However, being a C-type, our estimate of its source region is consistent with the possibility that it originates from a family with a similar spectral type and located close to this region. Bottke et al. (2007) identified the Baptistina family and characterized it as a C-type family, although some members have spectral types which may be different. According to these authors, most of the current NEA population is dominated by objects who belonged to this family (formed 200 Myr ago at $a=2.26$ AU, close to ν_6) and have been sent to NEA orbits through transport mechanisms such as the 3/1 or ν_6 . Jutzi et al. (2010) were able to match, at least qualitatively, the estimated size distribution of this family, by simulating the disruption of parent body, only if it consisted of porous material, in agreement with the dark taxonomic type of the family. Therefore, assuming that this scenario remains correct despite new observations indicating the Baptistina family may not be as well constrained as originally claimed (Carvano et al., 2009), we can speculate that

1999JU₃, due to its most likely source region, originally belonged to this family. This makes it an even more interesting target for a space mission, as it is not only easily accessible during a wide range of launch windows, but also, we have a potential scenario for its origin and age, which is obviously very useful for the interpretation of the space mission data (e.g. the number of craters) and sample analysis. Moreover, the time spent at small perihelion distances is rather short, with a maximum of 8 Myr at distances below 1 AU and about 1.4 Myr at distances below 0.5 AU (Fig. 2), which makes its thermal property history adapted for a sample return mission aimed at collecting thermally unaltered material (see Sec. 4).

As for its future evolution, 1999JU₃ evolves like a typical asteroid in the Near-Earth space. It is again found that it can enter into secular resonances while in the Earth-crossing zone with semimajor axis smaller than 2 AU (Michel and Froeschlé, 1997; Michel, 1997). Figure 4 shows the evolution of one of the clone orbits of 1999JU₃. The body first has its semimajor axis decreased down to values smaller than 1 AU, making it an Aten and even an Inner-Earth Object (IEO; Michel et al., 2000b). Then, close approaches increase again its semimajor axis and put it back into the Apollo group. After about 13 Myr of evolution it enters into the ν_5 secular resonance with Jupiter, characterized by the libration of its critical angle $\sigma_5 = \varpi - g_5 \times t - \alpha_5$, where ϖ is the longitude of perihelion of the small body, $g_5 = 4.249$ arcsec/year is the fundamental frequency corresponding to the resonance and α_5 is the phase at time $t = 0$. As one can see on Fig. 4 this resonance is correlated with large oscillations of the eccentricity, which amplitudes are large enough to make the body go into the Sun.

As for 1989UQ, the median lifetime of 1999JU₃ is long compared to the one of the NEA population (Table 3). This is again because the asteroid is initially deeply in the Earth-crossing space with a semimajor axis much smaller than 2 AU. Therefore, unless it collides with a planet, it can evolve a long time before reaching a resonance that can lead it into the Sun or outside the inner Solar System.

3.3 2001SG₂₈₆

The most probable source region of 2001SG₂₈₆ is the ν_6 secular resonance in the inner main belt (Table 4). Another less probable source is the 3/1 mean motion resonance with Jupiter at 2.5 AU. Although the D taxonomic type of this asteroid is usually found in the outer main belt, the Bottke et al.'s model finds a zero probability that its current position is reached from a transport mechanism located in this region or from the Jupiter Family Comets. However, the same arguments as those suggested for 1999JU₃ involving the Yarkovsky effect hold for 2001SG₂₈₆. Then, the probability that it reached small perihelion distances

increases regularly with the distance and is about 50% for a perihelion distance of 0.5 AU (Fig. 1). The time spent there is about 2 Myr (Fig. 2) and is smaller at smaller distances. As will be shown in the next section, this object is therefore not likely to have experienced high temperatures on its surface and subsurface, which is adapted to a sample return space mission.

Concerning its future evolution, 2001SG₂₈₆ starts on an Apollo orbit with a semimajor axis greater than 1 AU. All the clones except one end their evolution by a collision into the Sun. For most of them, this is due to their injection in the 3/1 mean motion resonance with Jupiter or the 4/1 mean motion resonance with Jupiter coupled with the ν_6 secular resonance. Because these resonances are located at a semimajor axis greater than 2 AU, a random walk of this orbital element due to planetary close approaches is necessary to increase its value beyond this limit, which explains the long median lifetime (22.19 Myr) found for this object based on the 14 computed evolutions, compared with the median lifetime of the NEA population (9 Myr). A few clones are also injected into the Sun while their semimajor axis is still smaller than 2 AU as a result of a secular resonance within this region, as found for 1989UQ (see Sec. 3.1).

3.4 2001SK₁₆₂

This asteroid has also a greater chance to come from the ν_6 resonance, but there is still a chance that it comes from the outer belt or the Jupiter Family Comets (see Table 4). Considering that it is a D-type asteroid, the latter source region is necessarily favored, although the same scenario as the one proposed for 1999JU₃ and 2001SG₂₈₆ involving the Yarkovsky effect can apply to this object. The probability that it reached a given perihelion distance is smaller than for all other targets, and for instance it only has a 18% chance of having reached a value of 0.5 AU and 50% chance of having reached 0.8 AU (Fig. 1). Similarly, the time spent at a given distance is smaller than for other targets, and remains smaller than 2 Myr at any distance up to 1 AU (Fig. 2). It is thus likely that it reached its current position on a timescale less than a few Myr from its injection in the transport mechanism in the main belt.

Concerning its future evolution, as for 2001SG₂₈₆, most of the clones evolve on an Earth-crossing orbit until their semimajor axis is driven back in a resonance (3/1, 4/1, ...) at main belt values. Then the eccentricity increases and they collide into the Sun or are ejected due to an encounter at aphelion with Jupiter. Only one clone collides with the Earth as it evolves as an Aten (semimajor axis smaller than 1 AU). Although one clone has the longest evolution (437.836 Myr) of all the computed orbits for the four targets, this asteroid has the shortest median lifetime (5.274), even compared with the median

lifetime of the NEA population (9 Myr). The reason is probably that its initial semimajor axis of 1.926 AU is already quite close to main belt values so that even a distant close approach can send it back in a powerful resonance.

Figure 5 shows the example of such a short evolution. The object is rapidly injected in a powerful resonance. It first undergoes close approaches which raise its semimajor axis and injects it in the 3/1 mean motion resonance at 2.5 AU. As already shown by Moons and Morbidelli (1995), this resonance becomes very effective when it is overlapped with the occurrence of the ν_6 resonance whose critical argument $\sigma_6 = \varpi - g_6 \times t - \alpha_6$, where ϖ is the longitude of perihelion, $g_6 = 28.22$ arcsec/year is the fundamental frequency corresponding to the resonance and α_6 is the phase at time $t = 0$. As shown on Fig. 5, when this argument starts librating while the object is in the 3/1 mean motion resonance at 2.5 AU, the eccentricity increases very rapidly from 0.6 to 1 and the body collides into the Sun.

4 Thermal evolutions

The primary goal of sample return missions is to return unaltered primordial material from the surface (or the subsurface) of asteroids for analysis in laboratory. It is thus crucial to study whether the temperatures at which these bodies have been exposed were high enough to cause loss of volatile components or thermal disgregation of the organic macromolecules thought to be present on these bodies. In the following we estimate the temperatures reached by 1989UQ, 1999JU₃, 2001SK₁₆₂, 2001SG₂₈₆ in their past and future dynamical life using the orbital evolutions described in the previous section. In order to do so, we follow the approach of Marchi et al. (2009): we consider that the only source of heat for an NEA is the radiative heating from the Sun. As a first step, we estimate an upper limit for the temperature at the surface of the body as a function of its orbital evolution. Then, we also evaluate what is the probability that at least 50% of the surface area of the body was heated to temperatures high enough to cause loss of volatiles and/or deeper alterations of the organics present on these primitive bodies. Finally we investigate the temperatures at a depth of 3 and 5 cm below the surface. These are reasonable penetration depths for a corer or a sample collecting device using a “touch and go” approach on board of an asteroid sample return mission.

The surface temperature depends on the body’s thermal and rotational properties, and of course on the heliocentric distance.

The rotation period is not known yet for 2001SG₂₈₆. As for the spin axis orientation, it is generally

assumed to be perpendicular to the orbital plane. However, in the case of 1999JU₃, there is a chance that it is parallel to the body's orbital plane (Abe et al., 2008). Obviously, the surface temperature distribution of an asteroid depends both on the spin period and axis orientation. In the following, to compute the thermal evolutions, for 2001SG₂₈₆ whose rotation period is not known, a period of 6 hours will be assumed, which corresponds to the average value of the asteroid population (Pravec et al., 2002), and for all the objects, the axis will be assumed perpendicular to the orbital plane.

Relevant thermal properties are the albedo, surface roughness and thermal inertia Γ . The latter parameter – the resistance of a material to temperature changes – is defined as $\Gamma = \sqrt{\rho\kappa c}$, where ρ is the density of the material, c is its specific heat content and κ is the thermal conductivity. The higher the thermal inertia the less a surface responds rapidly to changes in the radiative heating. It is expected that the thermal inertia varies with asteroid sizes: multi-100-km-sized main belt asteroids have thermal inertias around $10 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$ (equivalent to about $50 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$ at the higher temperatures found in the NEA region), multi-km-sized bodies have thermal inertia values around $100 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$, whereas thermal inertias around $500 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$ – $1000 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$ have been derived for NEAs smaller than 1 km (Harris et al., 2007; Mueller et al., 2004, 2005). Delbo et al. (2007) claim that the average thermal inertia of km-sized NEAs is around $200 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$. Hereafter, we will assume that our NEAs have the same thermal characteristics, namely a bolometric bond albedo of $A=0.02$ (corresponding to a geometric visible albedo, p_V , of 0.06 for the default phase integral $G=0.15$; Bowell et al., 1989). This value is believed to be typical for asteroids with primitive composition. For the thermal inertia, we will consider two values: $0 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$ and $500 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$. It is known that surface roughness increases the surface temperature (e.g. the bottom of a crater is warmer than the surrounding flat areas). These two values allow us to consider the case of a strong surface roughness and that of a perfectly smooth surface.

For an object without atmosphere, radiatively heated by the Sun light, the maximum surface temperature is at the equator (the surface is perpendicular to the direction to the Sun at local mid-day) and it can be easily estimated by the following expression derived from the equation of instantaneous thermal equilibrium with the Sun light:

$$T = [(1 - A)S_{\odot}q^{-2}\epsilon^{-1}\eta^{-1}\sigma^{-1}]^{0.25} \quad (1)$$

where A is the bolometric bond albedo, S_{\odot} is the solar constant at 1 AU (1329 Wm^{-2}), ϵ is the infrared

emissivity, σ is the constant of Stephan Boltzman and η is the so-called beaming parameter (see Harris and Lagerros, 2002, and references therein; Delbo and Harris, 2002, and references therein). The latter can be seen as a measure of the departure of the asteroid temperature distribution from that of a spherical, smooth body with all surface points in instantaneous thermal equilibrium with the Sun light (which would have $\eta = 1$). In particular, $\eta < 1$ is expected for a surface with significant roughness. The lowest measured value of η is 0.7 obtained by Wolters et al. (2005) for the NEA (6455) 1992 HE. The use of this value results in the highest possible temperature on the surface, corresponding to a surface with extreme roughness and no thermal inertia. We note that in the case of zero thermal inertia, the temperature on the surface is function of the actual heliocentric distance ($T \propto r^{-1/2}$). The maximum temperature is, therefore, reached at perihelion ($r = q$). The solid line of Fig. 6 shows the maximum temperature of a primitive asteroid as function of its heliocentric distance. This maximum temperature is reached at the equator.

However, for the planning and the engineering of asteroid sample return space missions, it is worth studying what fraction of the surface of a body has been heated above a certain temperature during its history. Thermophysical modeling is required to obtain this information. A thermophysical model (TPM; see Harris and Lagerros, 2002; Spencer et al., 1989; Spencer, 1990; Lagerros, 1996; Emery et al. 1998; Mueller, 2007, and references therein) uses a representation of an asteroid as a polyhedron made by a mesh of planar facets. The temperature of each facet is determined independently by numerically solving the one-dimensional heat diffusion equation into the subsurface: $\rho c (\partial T / \partial t) = \kappa (\partial^2 T / \partial z^2)$. The boundary conditions are given by: (1) the radiative heating by the Sun which varies according to the day and night cycle, (2) the energy irradiated away by each facet at the surface, and (3) by setting the heat flow at the deepest subsurface element to zero (see Marchi et al. 2009 for details). Here we use the same approach described by Marchi et al. (2009) in order to evaluate the temperature above which 50% of the surface of an NEA was heated as a function of its heliocentric distance. Namely, the areas of those facets the maximum temperatures of which are above a given temperature threshold (T_s) are added up. The ratio of their total area to the whole surface of the body is then calculated. This ratio is evaluated for different values of T_s from 0 up to 2000 K. The value of T_s for which the ratio of the surface whose maximum temperature is above T_s is equal to 0.5 is found by interpolation. In this work not only the surface temperature is estimated, but also the temperature of the facets at a depth $z=3$ cm and $z=5$ cm. The major differences with respect to the approach of Marchi et al. (2009) are: the thermal inertia is set

to $500 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$ and the bolometric bond albedo is 0.02. Moreover, the TPM was run on circular orbits with heliocentric distances ranging from 0.1 AU to 1 AU. Figure 6 shows the temperature above which 50% of the surface and subsurface (at 3 and 5 cm of depth) area of the asteroid is heated as a function of its distance to the Sun.

The curves of Fig. 6 represent a functional dependence between the heliocentric distance and the surface (and subsurface) temperature for an NEA with organic primitive composition. These curves can be used to estimate the temperatures of our targets during their orbital evolution.

4.1 Past thermal history

Our dynamical model allows us to calculate the probability that each asteroid spent a certain amount of time with a perihelion distance (q) smaller than any given threshold (q_S). The time spent with $q < q_S$ can also be estimated (see Fig. 2). The functions relating asteroid surface temperatures to the heliocentric distance of Fig. 6 allow us to directly transform the probability that our targets had $q < q_S$ into the probability that the temperature was above a certain threshold. The probabilities that 50% of the surface (and the subsurface) was heated above temperatures from ~ 350 to about ~ 1500 K are shown in Fig. 7.

4.2 Thermal evolution in the future

We also studied the evolution of the temperatures of our asteroids in the future. Temperature changes are due to the variation of the Sun radiative heating as a consequence of the evolution of the orbits of these bodies. We use the results of the orbital integrations described in Section 2.2. In particular, for each clone we tracked the variation of the perihelion distance q by recording its value every 500 years. We then used the curves plotted in Fig. 6 to estimate the maximum temperature and the temperatures above which 50% of the surface and of the subsurface at 3 and 5 cm depth was heated as a function of the perihelion distance. Figures 8 - 11 show the temperature evolutions of 14 clones for each considered asteroid. Four curves are displayed in each plot: namely the curve of maximum temperature as well as those of the temperatures above which 50% of the surface and subsurface of the asteroid have been heated as a function of time. Note that the dynamical lifetimes can be very different for different asteroids and respective clones.

5 Implications for a sample return mission

Table 5 indicates the thermal decomposition temperature of some carbon- and nitrogen-bearing components in carbonaceous chondrites and the perihelion distances at which such temperatures are reached derived from Fig. 6. This same figure shows that for low-albedo, primitive asteroids, the temperature of 370 K, corresponding to the thermal decomposition of labile kerogens, is always reached at perihelion distances < 1 AU. On the other hand, the subsurfaces at a depth of 3 and 5 cm remain below these temperatures as long as the perihelion distance of the asteroids is larger than ~ 0.7 AU. At about the same distance from the Sun, 50% of the whole surface is heated above 420 K, the temperature of pyrolysis of more refractory kerogens. However, the subsurface is still protected until the perihelion distance of the asteroid evolves down to distances of about 0.5 AU from the Sun. The labile organic matter in macromolecules starts to thermally decompose at the surface for distances between 0.7 and 0.5 AU from the Sun. The refractory organic matter is more resistant and requires heliocentric distances to lie between about 0.5 and 0.35 AU to decompose. The subsurface is protected from these temperatures until about 0.25 AU from the Sun.

Figure 7 shows the probability that each of the considered NEA was heated to above a given temperature during its past dynamical lifetime. Probability curves are plotted for temperatures at the surface and below the surface at depths of 3 and 5 cm. According to our model, all objects have a very high probability that the warmest regions on their surface were heated above 370 and 420 K. The latter is the temperature above which the macromolecular phase in carbonaceous meteorites starts to thermally decompose. If we require that at least 50% of the surface was heated above 420K, the probability drops and there are some differences amongst our targets. In particular, 2001SK₁₆₂ has a 40-50% probability that half of its surface was heated above 420K, whereas for the other targets, the probability is higher than 70%. The probability that 1989UQ, 1999JU₃, and 2000SG₂₈₆ had 50% of their surfaces heated above 520 K, the temperature of thermal decomposition of organic matter in macromolecules, is of about 40%, whereas in the case of 2001SK₁₆₂ this probability drops to below 20%. The probability that 50% of the surface of these bodies were heated above ~ 620 K (thermal decomposition of refractory organic matter in macromolecules) is of ~ 25 % for 1989UQ and 2000SG₂₈₆, but of about 10% for 1999JU₃ and 2001SK₁₆₂.

Figures 7 (C) and (D) show the likely subsurface temperature history of the four NEAs. We note that

1989UQ, 1999JU₃, and 2000SG₂₈₆ have a probability between 70 and 90% that half of their subsurface at 3 cm depth was heated above 370 K. On the other hand, for 2001SK₁₆₂ this probability is only of 40%. For a temperature of 420 K, the above probability drops to 50% for 1989UQ, 1999JU₃, and 2000SG₂₈₆, whereas 2001SK₁₆₂ has a probability of only 20% that 50% of its subsurface at 3cm depth was heated above 420 K. The probability that half of the subsurface was heated above 520 K (thermal decomposition of free organic matter in carbonaceous meteorites) is below 30% for 1989UQ and 2000SG₂₈₆ and of about 10% for 1999JU₃ and 2001SK₁₆₂. For temperatures above 600 K and 50% of the sub-surface at 3 cm depth, the probability is in general smaller than 20% for all targets.

At 5 cm depth, the surface is strongly protected from the Sun radiative heating. The probability that half of the subsurface was heated above 420 K is of about 50% (but less than 20% for 2001SK₁₆₂). The probability that the sub-surfaces of our targets were heated above higher temperatures, e.g. 520 K, drops to around 20% for 1989UQ and 2000SG₂₈₆ and to less than 10% for 1999JU₃ and 2001 SK₁₆₂.

The thermal evolution of our targets in the future confirms that heating above 420 K is very likely to occur at their surface. Moreover, the NEAs 1999JU₃ and 2001SK₁₆₂ look somewhat more protected from temperatures above 420 K than 1989UQ and 2000SG₂₈₆, for time scales of the order of a few million years.

Figure 6 shows that at about 420 K, the average temperature difference between 3 and 5 cm below the surface is of the order of only 10 K or smaller. This has important implication for the engineering of collecting devices of samples of pristine composition that has not been thermally altered by Sun radiative heating.

Note however, that it is assumed here that the same material is constantly exposed to solar heat, while regolith turnover may occur. The latter can be caused by different processes such as seismic shaking and/or impact cratering. This would reduce the total time that materials are exposed to a certain temperature. Therefore, our estimates can be considered as worse case scenarii.

6 Conclusions

We have studied the dynamical and thermal history of four potential primitive targets of sample return space missions, namely 1989UQ, 1999JU₃, 2001SG₂₈₆, and 2001SK₁₆₂.

Using a model of the NEA population (Bottke et al. 2002), we find that the most likely origin of our targets lies in the inner part of the main asteroid belt where they could be transported to the Earth-

crossing zone by the ν_6 resonance. Some of them may also come from the middle or outer belt but with much smaller probability. By integrating numerically the nominal and a few clone orbits of these targets, we then find that their evolutions are typical for NEAs evolving deeply in the Earth-crossing zone. The most probable fate for all of them is a collision with the Sun, which is also the fate of 60% of the NEA population (Gladman et al. 1997, 2000; Bottke et al. 2002). Their lifetime is a few tens of Myr (except for 2001SK₁₆₂ whose lifetime is about 5 Myr), which is greater than the 9 Myr median lifetime of the NEA population (Gladman et al. 2000). This can be easily explained by the fact that target candidates of sample return missions are required to be easily accessible (at low cost), and therefore they are located deeply in the Earth-crossing space, while most dangerous zones (i.e. resonances) where they can be eliminated rapidly are located at semimajor axis value greater than 2 AU. Therefore, unless a stochastic planetary collision occurs at any time, they can evolve a long time, only affected by planetary approaches and secular resonances with inner planet that will eventually send them back on a fast track to the Sun.

Using a simple thermal model and a more sophisticated thermophysical model (TPM), we have calculated the temperatures on the surface and subsurface of four potential sample return mission targets with primitive composition over their possible past and future evolutions. Our assumption is that the only source of energy is the radiative heating from the Sun. Our TPM allows also the temperature of the subsoil to be calculated as a function of the perihelion distance of the asteroid. Figure 6 shows temperature curves as a function of the asteroid perihelion distance for different thermal models.

Combining these results with our dynamical model, we estimated the probability that each asteroid had a perihelion distance smaller than a given threshold during its past thermal history. We then converted the perihelion distance in temperature using the curves of Fig. 6 in order to estimate the probability that each target was heated above a certain temperature in the course of its past dynamical evolution. We found that the surface of all targets is likely to have been heated above a temperature large enough to cause loss of volatiles and thermal decomposition of the most labile organic components thought to be present on primitive asteroids. On the other hand, the sub-surface at only 3 and 5 cm depths is much less heated. We then find that the least heated asteroid among our targets is (162998) 2001SK₁₆₂.

We point out that our temperature estimates are based on the simplistic assumption that the same material is constantly exposed to solar heat, while regolith turnover may occur. The latter can be caused by different processes such as seismic shaking and/or impact cratering. This would reduce the total time

that materials are exposed to a certain temperature and therefore our estimates can be considered as worse case scenarii. Also, spherical, smooth asteroids are unlikely to be representative of the expected rough, irregularly shaped objects. However, if the surface is rough, we expect the surface temperature, for instance inside craters, to be slightly higher, by about 10% relative value, than the temperature calculated from thermophysical modeling of a flat surface. So, this should not affect much our average estimates.

Combination of both dynamical and thermal computations can thus allow investigating the likelihood that the composition of a small body may be thermally altered during its evolution either on its surface or at given depths. Our present study indicates that it is very likely that a sample collected from any of the four considered targets, or any primitive NEA with similar dynamical properties, will have components that will be thermally unaltered as long as some of it comes from only 3 to 5 cm depth. Such a depth is not considered difficult to reach with some of the current designs of sampling devices.

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Figure 1: Probability of having spent some time on an orbit with perihelion distance q equal to or smaller than a given value qs for the four considered objects during their past evolution to their current location.

Figure 2: Time spent at a perihelion distance q equal to or smaller than a given value qs for the four considered objects before reaching their current orbit.

Figure 3: Orbital evolution of 1989UQ with initial conditions corresponding to the nominal orbit. Besides the semimajor axis and eccentricity, the critical arguments σ_2 and σ_5 of the ν_2 and ν_5 secular resonances are shown (see text for details).

Figure 4: Orbital evolution of 1999JU₃ $i+$ with initial conditions corresponding to the nominal orbit to which one digit was added to the initial orbital inclination. Besides the semimajor axis, eccentricity, and inclination, the critical argument σ_5 of the ν_5 secular resonance is shown (see text for details).

Figure 5: Orbital evolution of 2001SK₁₆₂ with initial conditions corresponding to the nominal orbit. Besides the semimajor axis, inclination and eccentricity, the critical arguments σ_6 of the ν_6 secular resonance is shown (see text for details).

Figure 6: Solid line: maximum surface temperature at the surface of a primitive asteroid as a function of the heliocentric distance. Other lines indicate the temperature above which 50% of the surface and the subsurface of an asteroid is heated as a function of the heliocentric distance: dotted line for the surface; dashed line for the subsurface at 3 cm depth; dashed-dotted line for the subsurface at 5 cm depth. Calculations have been performed using the thermophysical modeling (TPM) assuming $A=0.02$, $P=6$ h, $\Gamma = 500 \text{ J m}^{-2} \text{ s}^{-0.5} \text{ K}^{-1}$, smooth surface, and spherical shape. The spin-pole is assumed to be perpendicular to the orbital plane. Note that we also evaluated the temperature curves for bodies with different rotation periods than the assumed one of 6 h. In particular, for a rotation period of 3 hours the 3 curves below the black one would shift down by $\approx 5\%$ relative value. On the other hand, for a rotation period of 10 hours the 3 curves would shift up by $\approx 5\%$ relative value.

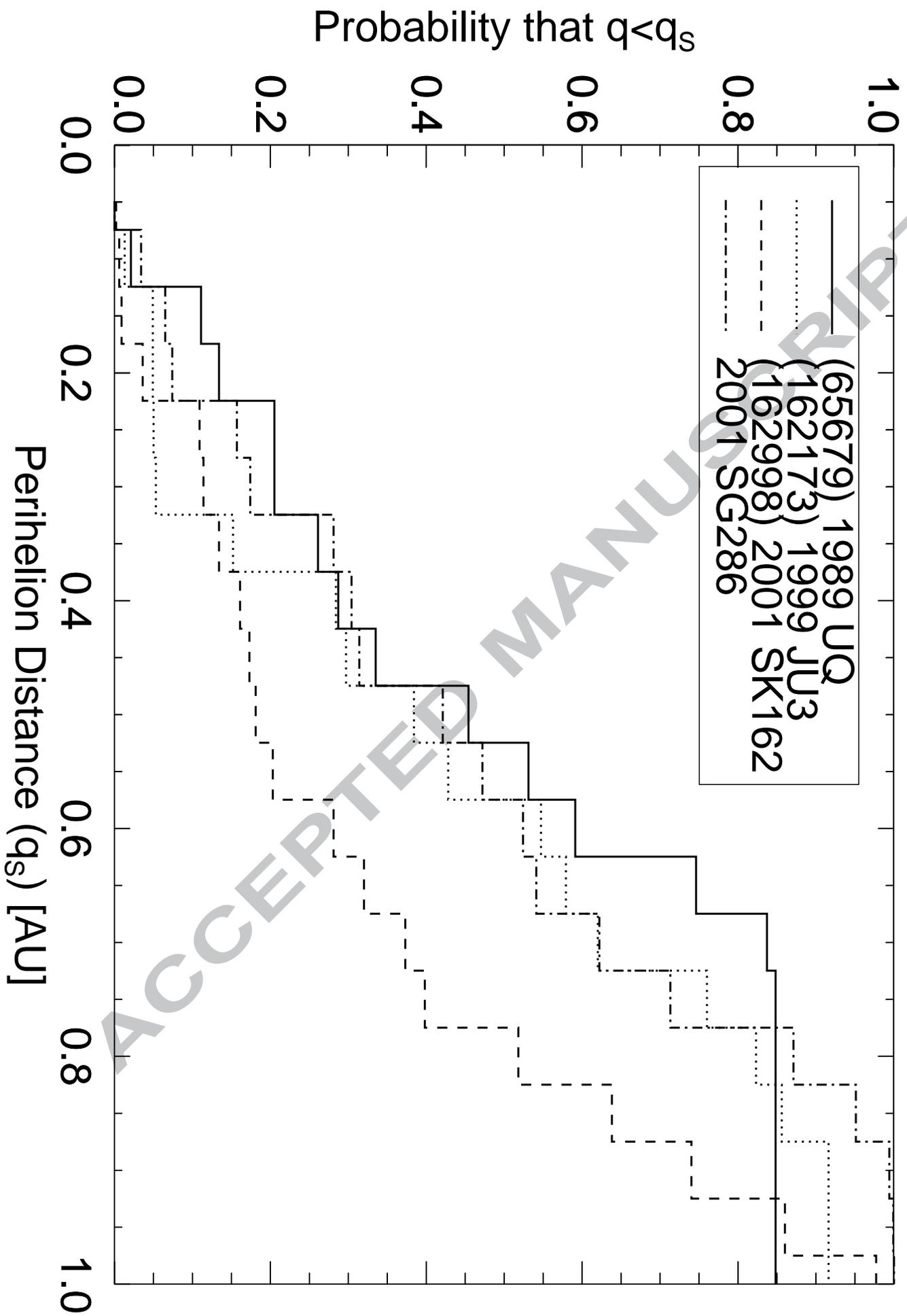
Figure 7: Probability that each NEA was heated to a temperature greater than a given temperature (abscissa) during its past dynamical lifetime. (A): maximum surface temperature. This plot represents the probability that the warmest area on the surface of an object (bottom of a crater or topographic depression, at the equator) was heated above a given temperature. (B): Probability that 50% of the surface of each asteroid was heated above a given temperature during its past dynamical lifetime. (C) same as (B) but for the subsurface at a depth of 3cm. (D) same as (C) but for a depth of 5 cm.

Figure 8: Possible evolutions of the temperature in the future of 14 clones of the NEA 1989UQ. The labels indicated on the plot for the different curves have the same meaning as those on Fig. 6.

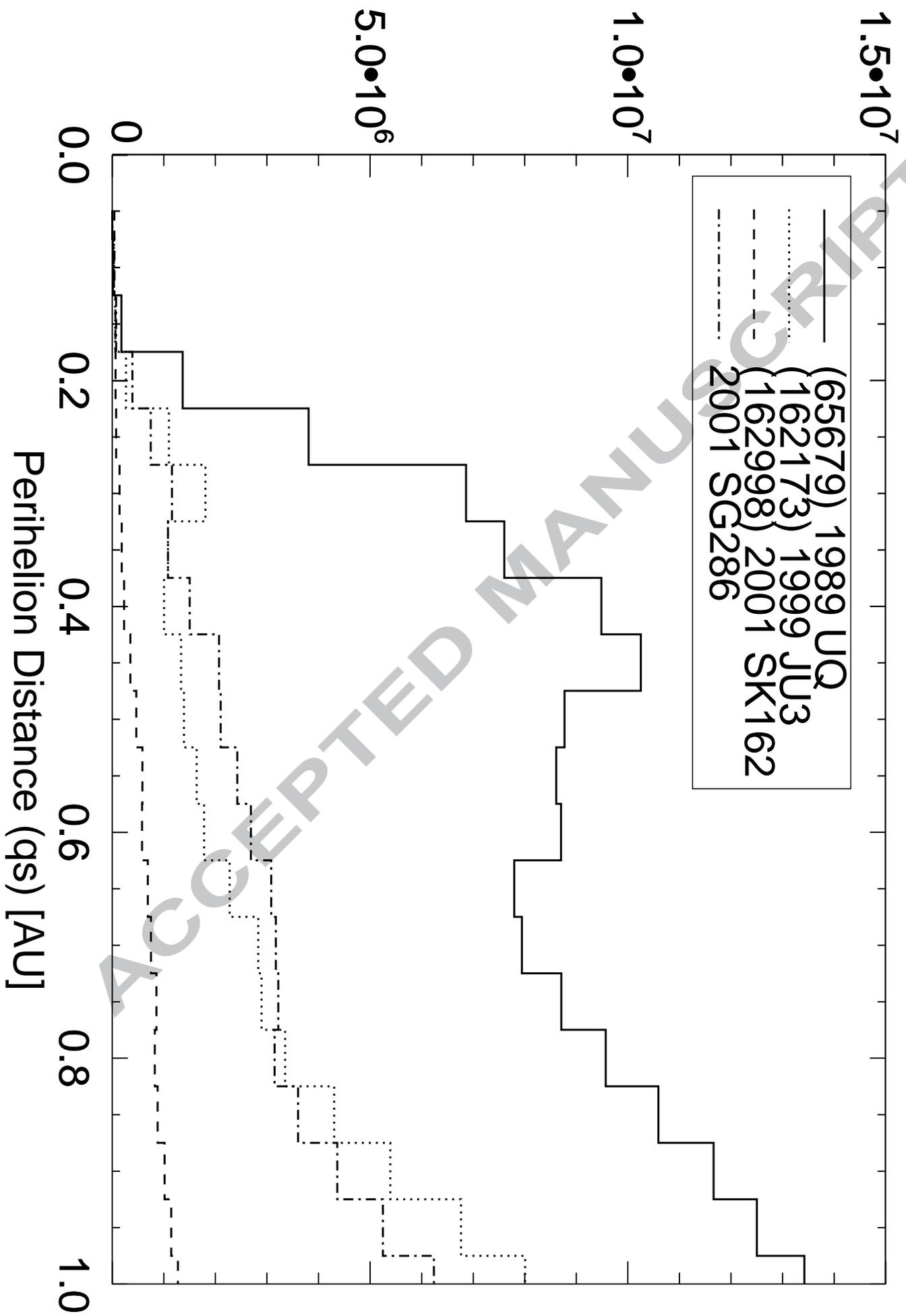
Figure 9: Same as Fig. 8 for 1999JU₃.

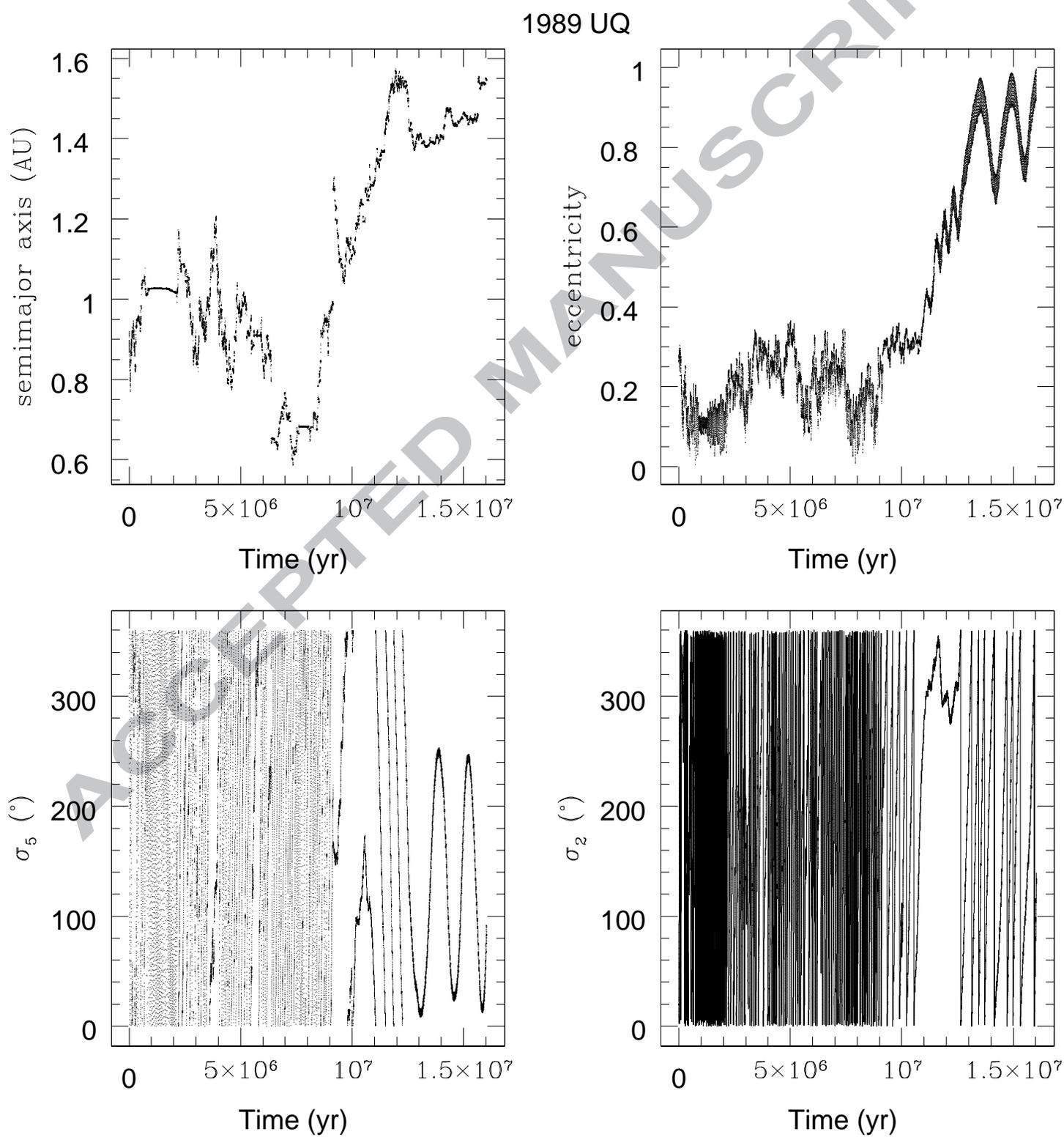
Figure 10: Same as Fig. 8 for 2001SG₂₈₆.

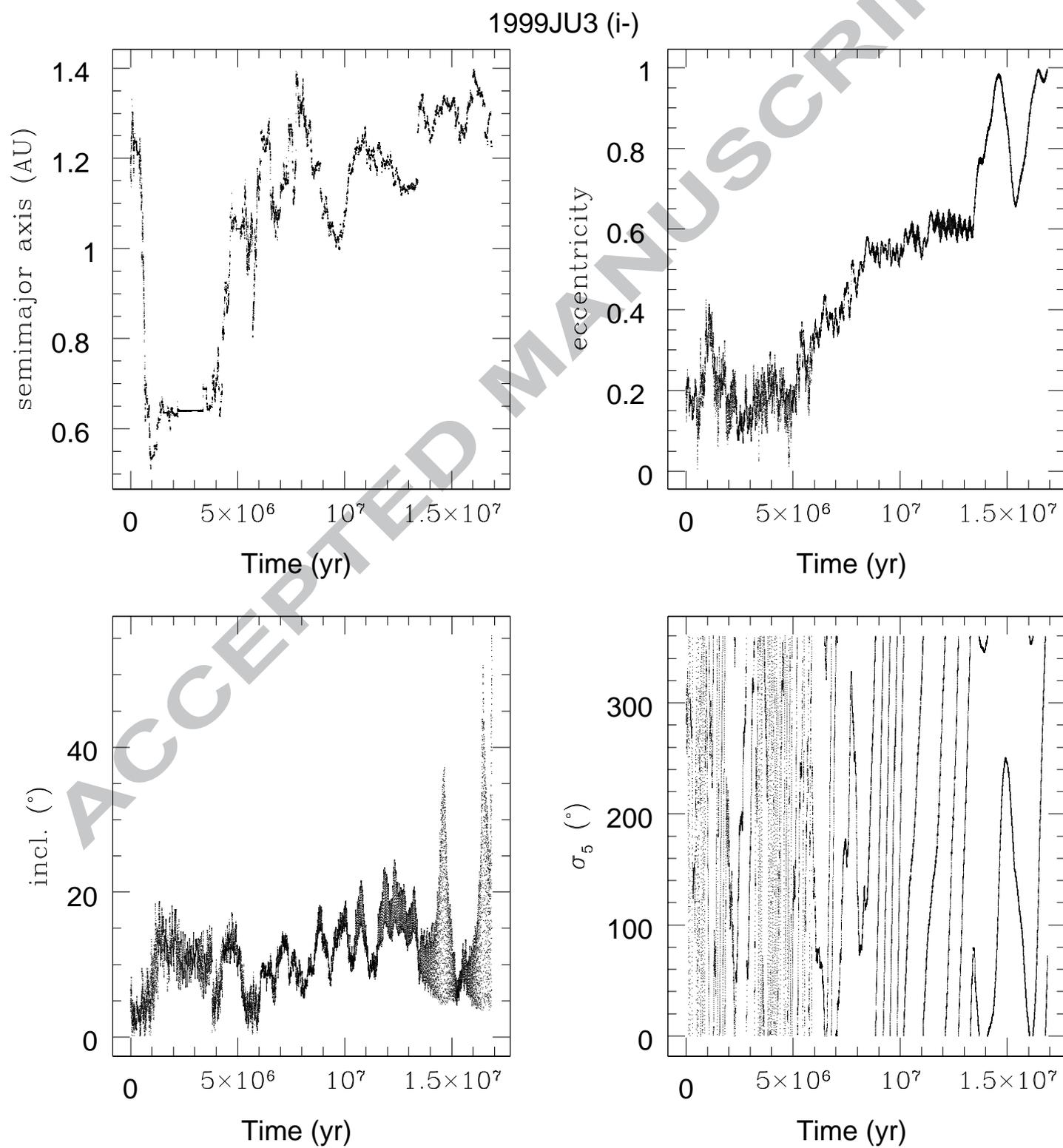
Figure 11: Same as Fig. 8 for 2001SK₁₆₂.

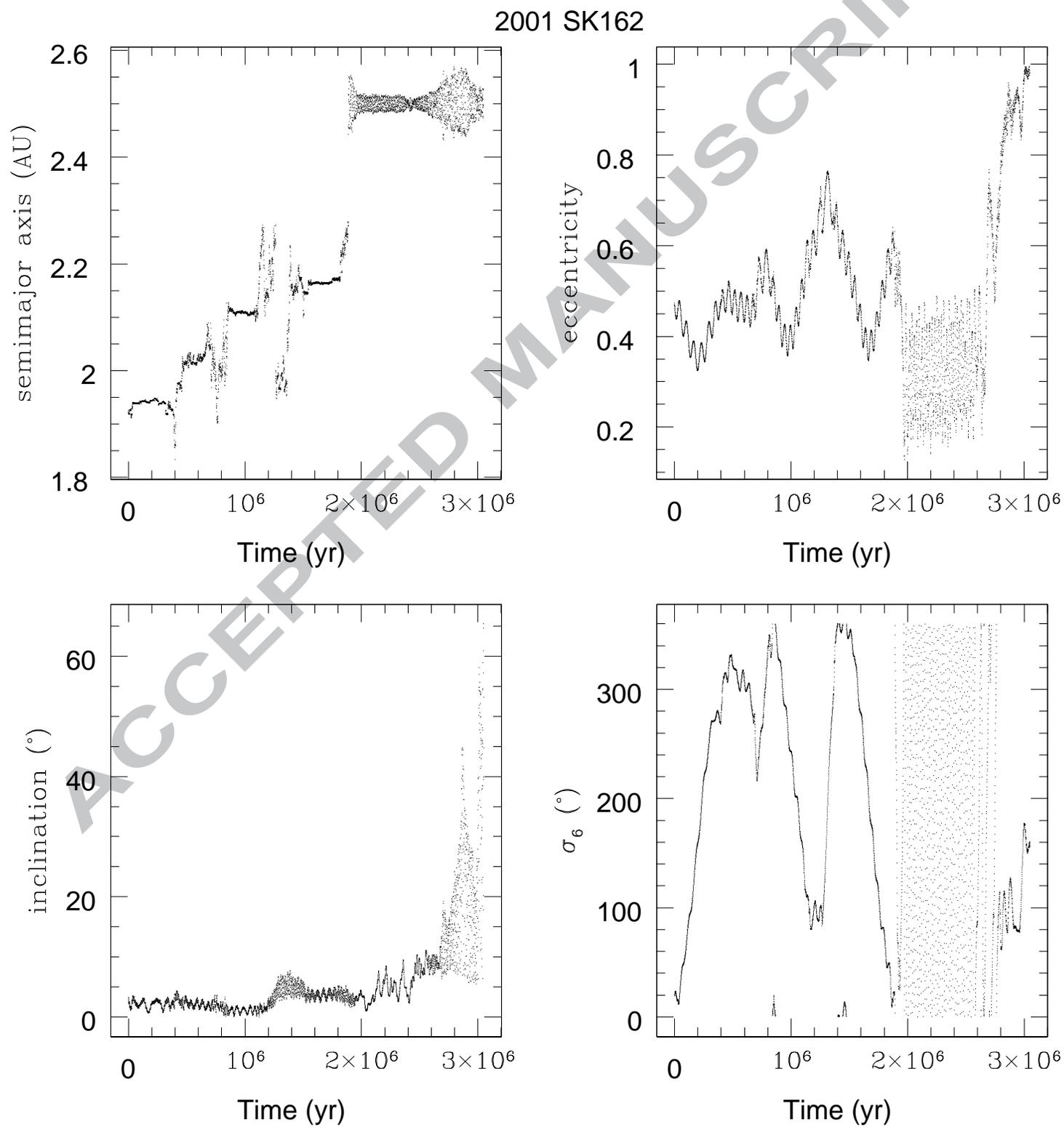


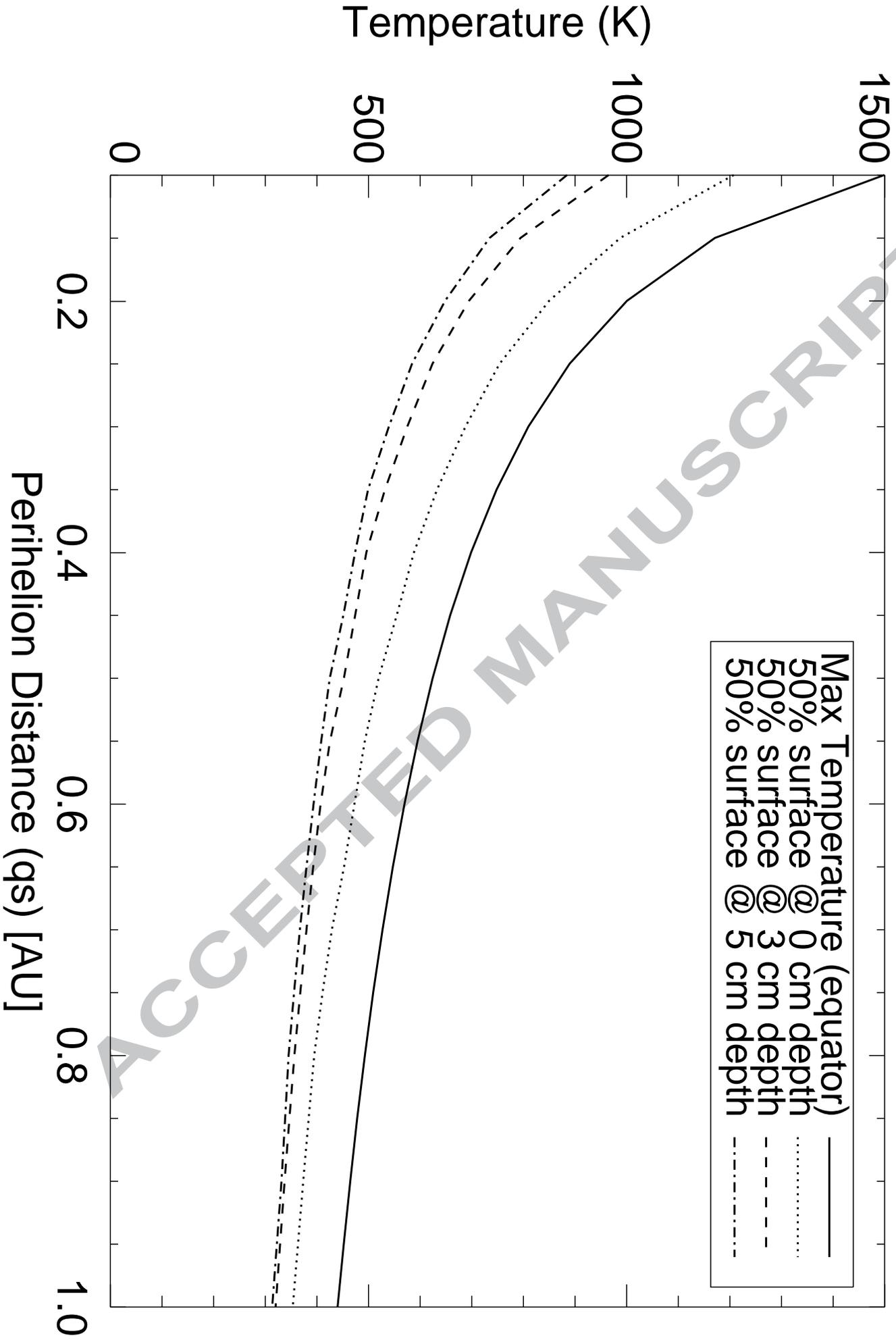
Time spent with $q < q_s$ [year]



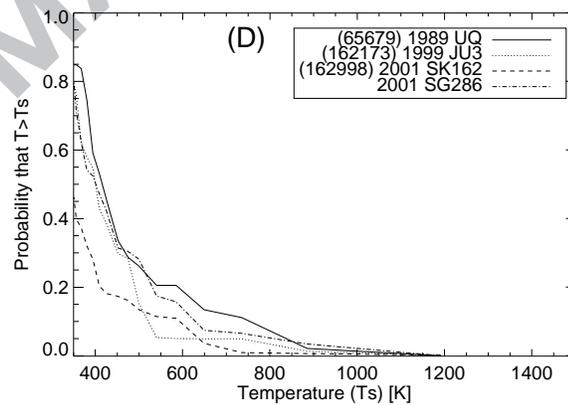
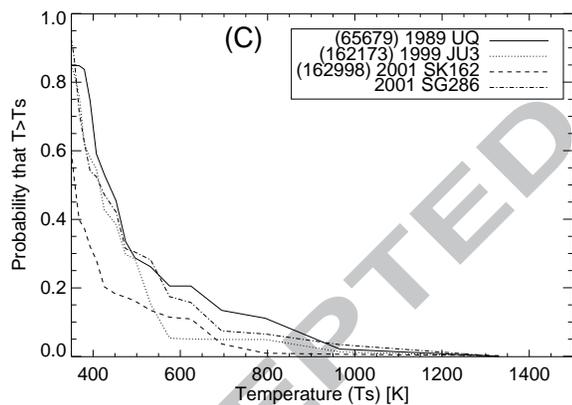
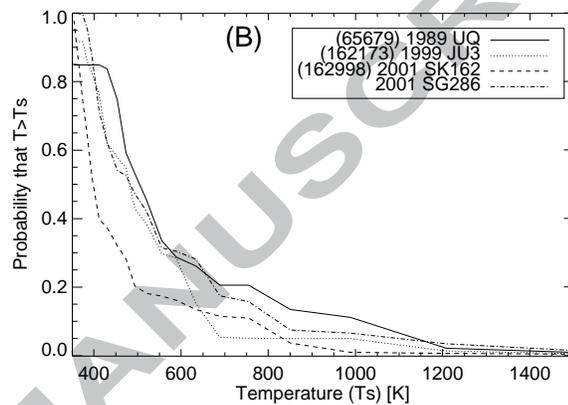
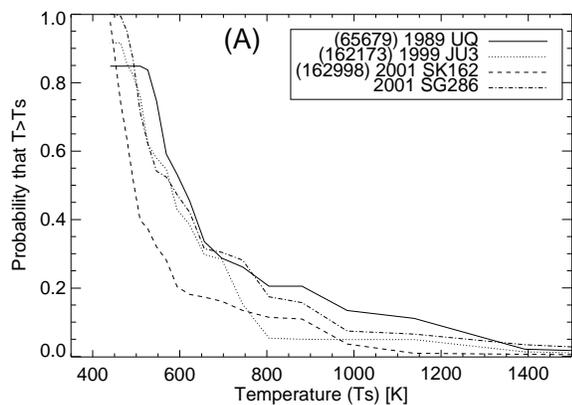


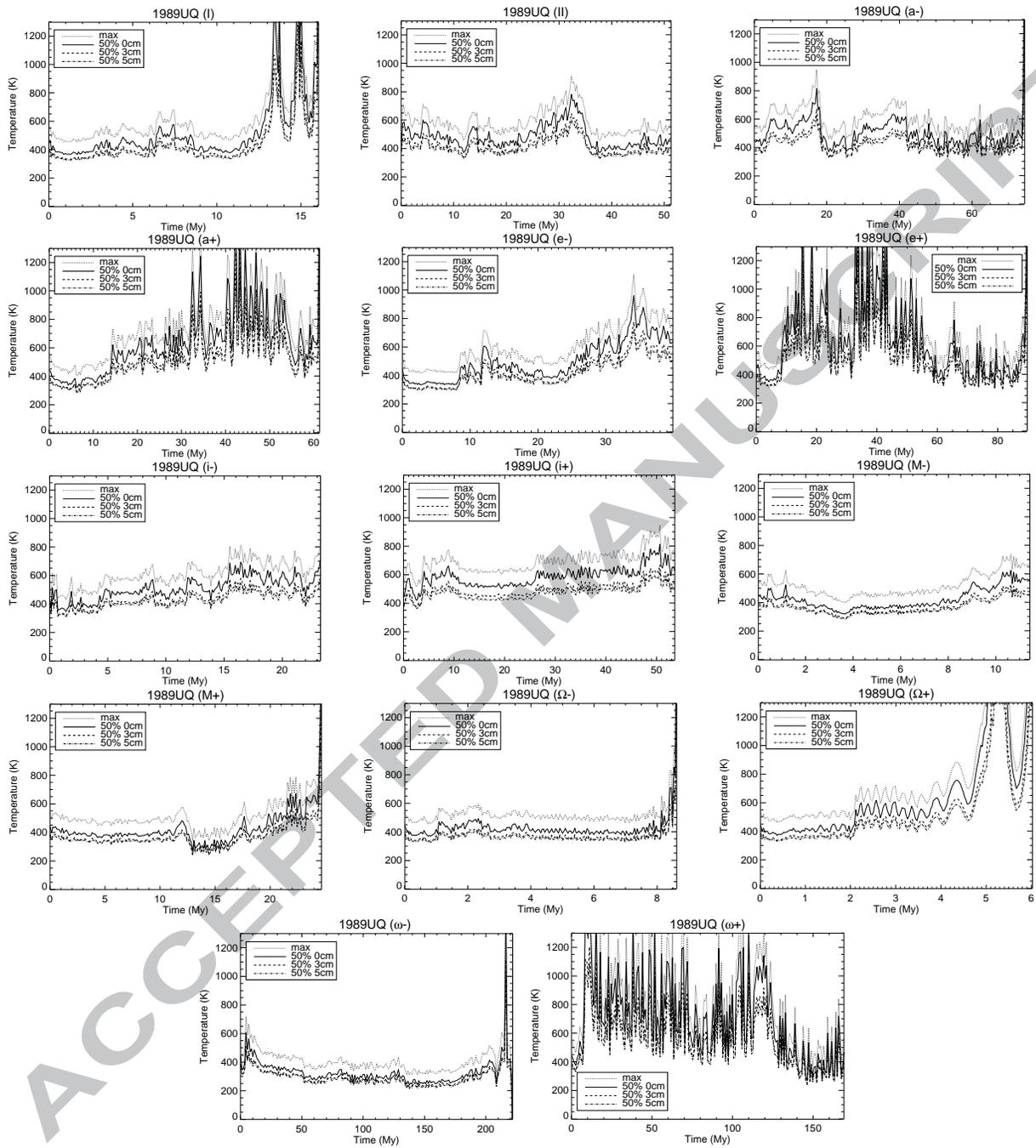


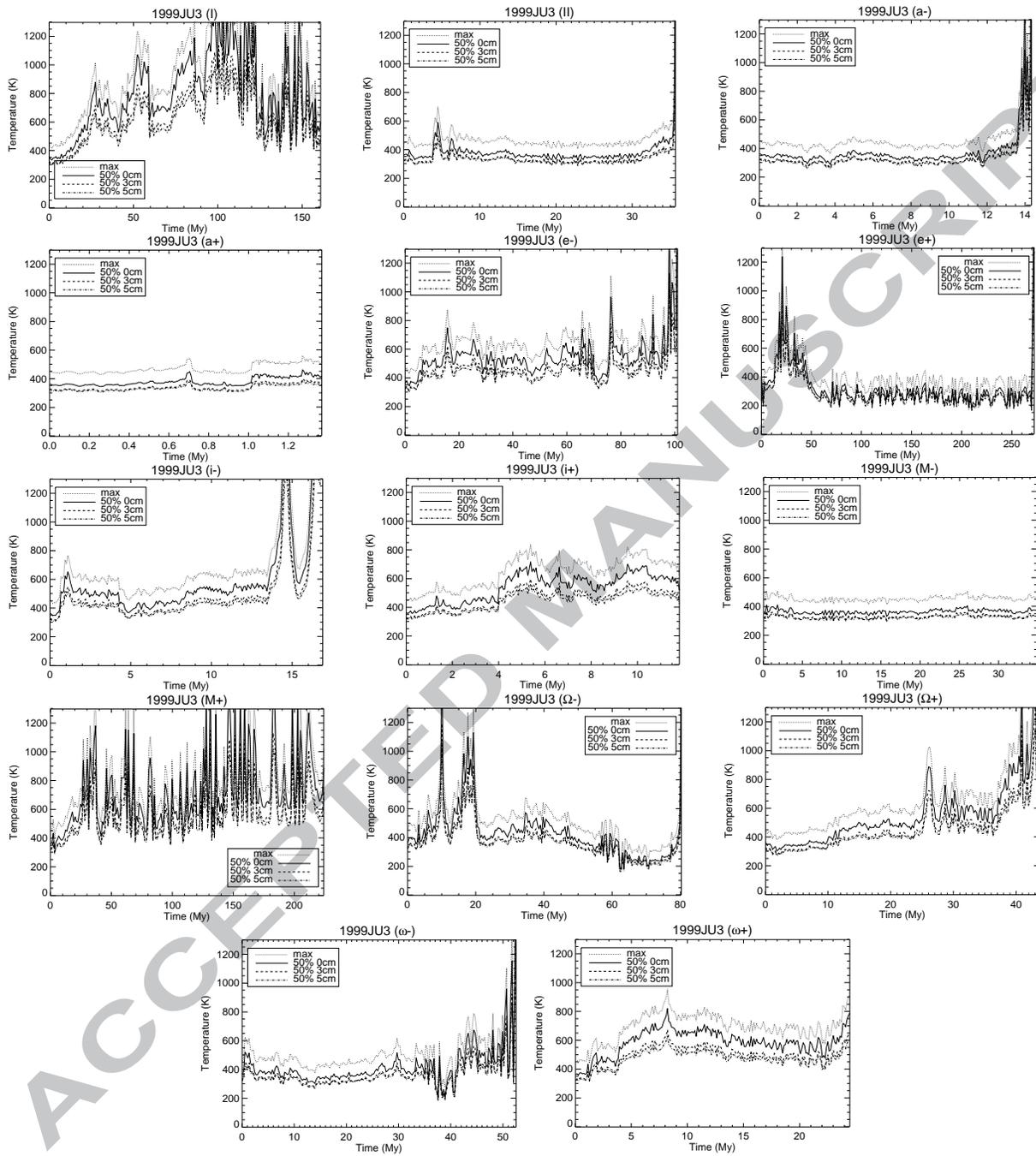


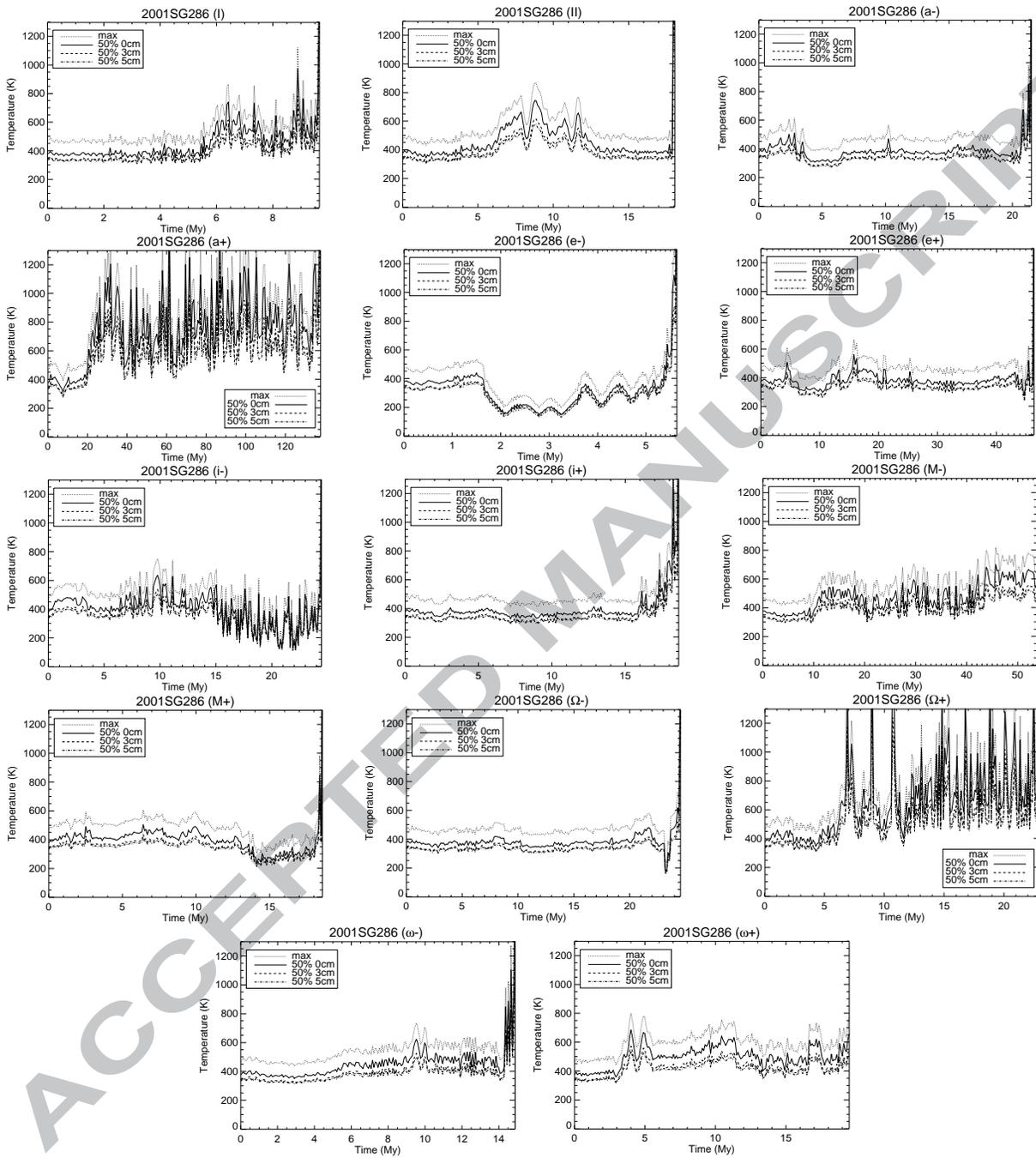


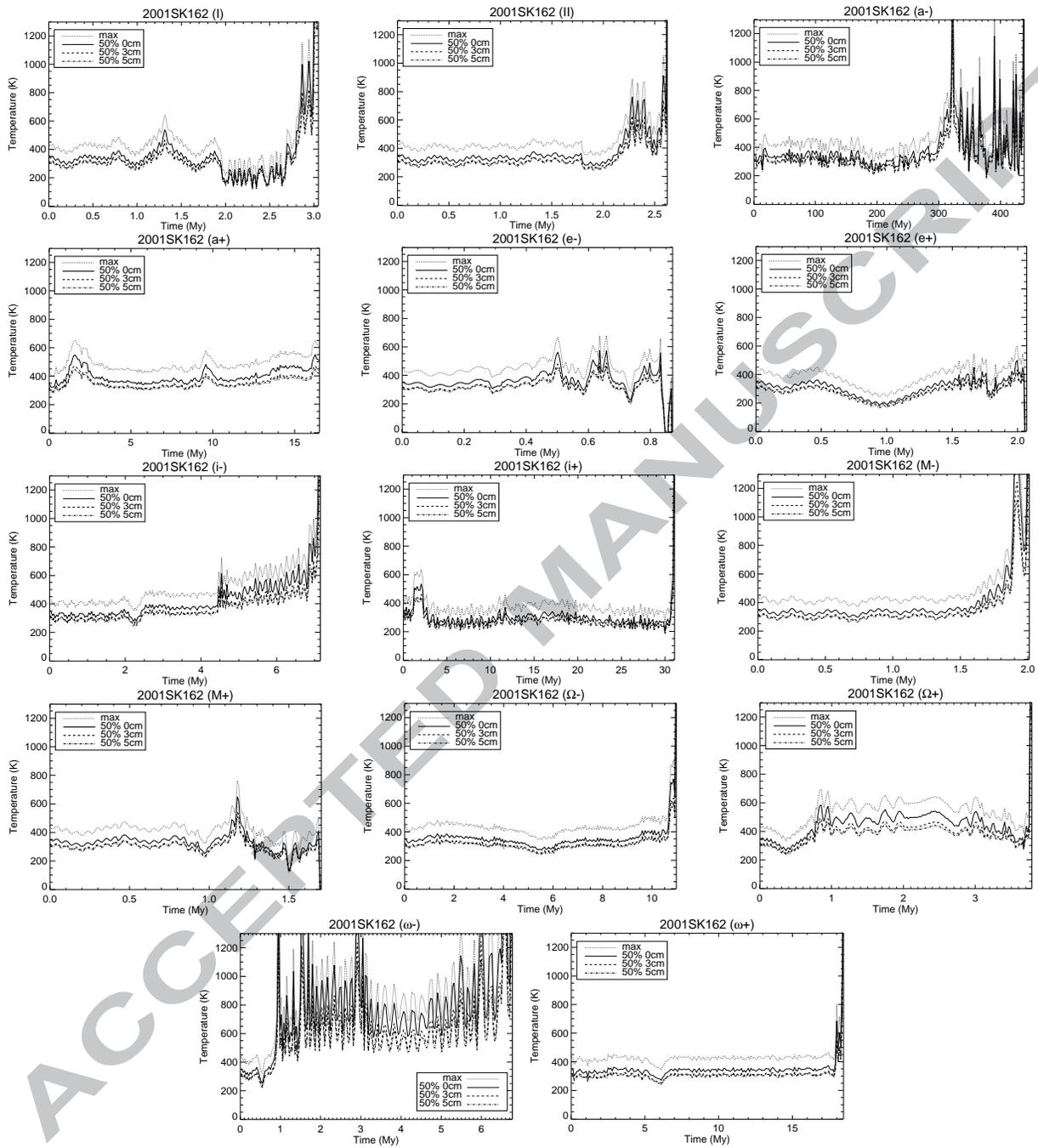
ACCEPTED MANUSCRIPT











Body	Taxonomic type	Diameter (m)	Rotation period (hr)
(65679) 1989UQ	B	760	7.73
(162173) 1999JU ₃	C	900 ± 140	7.67
2001SG ₂₈₆	D	350	Not known
(162998) 2001SK ₁₆₂	T	1520	68

Table 1: Physical properties of the four considered targets of a sample return space mission. The size (and the albedo) of (162173) 1999 JU₃ is known from Spitzer radiometric observations by Campins et al. (2009). The sizes of the others NEAs are estimated from their absolute magnitudes, assuming an albedo of 0.06 (typical for these objects' taxonomic classes), and a spherical shape.

UQ	L	F	JU ₃	L	F	SG ₂₈₆	L	F	SK ₁₆₂	L	F
	(Myr)			(Myr)			(Myr)			(Myr)	
I	16.039	Sun	I	160.878	Mercury	I	9.651	Sun	I	3.049	Sun
<i>a</i> +	61.292	Sun	<i>a</i> +	1.371	Venus	<i>a</i> +	137.677	Sun	<i>a</i> +	16.505	Earth
<i>a</i> -	74.348	Sun	<i>a</i> -	14.312	Sun	<i>a</i> -	21.461	Sun	<i>a</i> -	437.836	Sun
<i>e</i> +	89.618	Sun	<i>e</i> +	271.955	Sun	<i>e</i> +	46.332	Sun	<i>e</i> +	2.066	Ejected
<i>e</i> -	39.847	Venus	<i>e</i> -	100.901	Sun	<i>e</i> -	5.631	Sun	<i>e</i> -	0.871	Ejected
<i>i</i> +	53.553	Mercury	<i>i</i> +	11.800	Earth	<i>i</i> +	18.618	Sun	<i>i</i> +	31.046	Sun
<i>i</i> -	23.274	Venus	<i>i</i> -	16.879	Sun	<i>i</i> -	24.438	Sun	<i>i</i> -	7.150	Sun
II	51.251	Venus	II	35.646	Sun	II	18.061	Sun	II	2.620	Sun
<i>M</i> +	24.656	Sun	<i>M</i> +	224.001	Mercury	<i>M</i> +	18.572	Sun	<i>M</i> +	1.704	Ejected
<i>M</i> -	11.419	Earth	<i>M</i> -	34.828	Earth	<i>M</i> -	194.626	Sun	<i>M</i> -	2.008	Sun
ω +	169.030	Venus	ω +	24.452	Mercury	ω +	19.468	Mercury	ω +	18.446	Sun
ω -	221.622	Ejected	ω -	52.494	Sun	ω -	14.875	Sun	ω -	6.765	Sun
Ω +	6.017	Sun	Ω +	43.670	Sun	Ω +	22.920	Sun	Ω +	3.782	Sun
Ω -	8.610	Sun	Ω -	80.180	Sun	Ω -	24.517	Sun	Ω -	10.964	Sun

Table 2: Lifetimes (L) and Fates (F) of the nominal and *clone* orbits of the four considered asteroids over their whole lifetime. The name of each target is only indicated by letters to reduce the table width and their full names are indicated in Table 1. The label indicates which orbital parameter has been changed initially from the nominal one (see text for details). In the column F, the name of the planet onto which the asteroid collides is indicated, or Sun means a Solar collision, and Ejection means that the object has been ejected beyond Saturn's orbit.

Body	Median lifetime (Myr)	Most probable fate
1989UQ	45.549	Sun
1999JU ₃	39.658	Sun
2001SG ₂₈₆	22.190	Sun
2001SK ₁₆₂	5.274	Sun

Table 3: Median lifetime and most probable fate of the four considered potential targets based on the data of Table 2. The most probable fate is considered as the one occurring for at least 50% of the computed evolutions.

Body	P_{ν_6}	$P_{3/1}$	P_{OB-JFC}
1989UQ	84.8	15.2	0
1999JU ₃	91.6	8.4	0
2001SG ₂₈₆	89.6	10.4	0
2001SK ₁₆₂	82.6	7.6	9.8

Table 4: Probability of coming from one of the main NEA sources, namely the ν_6 resonance (P_{ν_6}), the 3/1 mean motion resonance with Jupiter ($P_{3/1}$) and the outer belt or Jupiter Family Comets (P_{OB-JFC}). See Sec. 2.1 for details.

Temperature (K)	thermal dissociation of	q_0 (AU)	q_3 (AU)	q_5 (AU)
370	Labile kerogens	0.9	0.75	0.7
420	Refractory kerogens	0.7	0.55	0.5
520	Free organic matter in carbonaceous meteorites	0.5	0.35	0.3
520-620	Labile organic matter in macromolecules	0.50-0.35	0.35-0.25	0.3-0.20
620-770	Refractory organic matter in macromolecules	0.35-0.25	0.25-0.20	0.2-0.15

Table 5: Thermal decomposition temperature of some carbon- and nitrogen-bearing components in carbonaceous chondrites. These compounds are also thought to be present on the surfaces and sub-surfaces of primitive asteroids. q_0 , q_3 , and q_5 are the perihelion distances below which 50% of the surface and sub-surface at 3 and 5 cm depth, respectively, is heated above the corresponding temperature values indicated in the first column. See text for details.

Figure 1: Probability of having spent some time on an orbit with perihelion distance q equal to or smaller than a given value q_s for the four considered objects during their past evolution to their current location.

Figure 2: Time spent at a perihelion distance q equal to or smaller than a given value q_s for the four considered objects before reaching their current orbit.

Figure 3: Orbital evolution of 1989UQ with initial conditions corresponding to the nominal orbit. Besides the semimajor axis and eccentricity, the critical arguments σ_2 and σ_5 of the ν_2 and ν_5 secular resonances are shown (see text for details).

Figure 4: Orbital evolution of 1999JU₃ $i+$ with initial conditions corresponding to the nominal orbit to which one digit was added to the initial orbital inclination. Besides the semimajor axis, eccentricity, and inclination, the critical argument σ_5 of the ν_5 secular resonance is shown (see text for details).