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Formation of the binary near-Earth object 1996 FG_3: Can binary NEOs be the source of short-CRE meteorites?

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Abstract–1996 FG_3 is a binary near-Earth object (NEO) that was likely formed during a tidal disruption event. Our results indicate that the formation of this binary object was unlikely to have occurred when the progenitor had a encounter velocity with the Earth significantly smaller than its current value (10.7 km/s); The formation of the binary object on an orbit similar to the present one is possible, and the survival of the satellite constrains this to have happened less than 1.6 Ma ago. However, the binary object could also have been formed when the progenitor's encounter velocity with Earth was >12 km/s, and in this case we cannot constrain its formation age. Our results indicate that tidal disruptions occurring among NEOs with low velocity encounters with Earth are unlikely to produce long-lasting NEO binaries. Thus, tidal disruption may not be able to completely re-supply the observed population. This would imply that a significant fraction of the observed NEO binaries evolved out of the main asteroid belt. Overall, our results suggest to us that the CM2 meteorites having cosmic ray exposure (CRE) ages of ~200,000 yr were likely liberated by the tidal disruption of a primitive NEO with a relative velocity with the Earth significantly smaller than that of 1996 FG_3. We propose a list of such objects, although as far as we know, none of the candidates is a binary for the reasons described above.

INTRODUCTION

Establishing a link between meteorites and their parent bodies is a key issue in planetary science because it bridges laboratory studies of solid extraterrestrial samples with astronomical observations of celestial bodies. Moreover, until we get data from sample return space missions (e.g., Stardust), meteorites are the primary means by which we can unravel the details of celestial bodies that are otherwise only known by their bulk, Earth-based, precision-limited telescopic observations. There are approximately 135 well-identified meteorite groups (Meibom and Clark 1999), each of them possibly corresponding to a unique parent body. Were we able to identify these parent bodies, we would considerably extend our knowledge of the solar system while placing strong constraints on models of its formation and evolution.

There are only few cases where it is possible to determine the relationship between a celestial body (planets, asteroids or comets) and a specific group of meteorites. Detailed comparisons between the mineralogy, chemical and isotopic composition of 32 lunar meteorites (January 2005, including paired ones) and the samples returned by the Apollo astronauts have established that they come from the Moon. A Martian origin has been attributed to more than 30 shergottite, nakhlite, and chassignite (SNC) meteorites (January 2005, including paired ones) on the basis of the similarity in abundance and isotopic composition of trapped noble gases with that of the atmosphere of Mars (e.g., McSween and Treiman 2000). The solid match between the infrared spectra of the howardite, eucrite, and diogenite (HED) meteorites and that of asteroid 4 Vesta has been used to suggest that HED meteorites come from this large asteroid (McCord et al. 1970). The identification of a dynamical route between fragments of Vesta (commonly called the Vestoids) and the Earth has strengthened that view (Binzel and Xu 1993; Migliorini et al. 1997).

Ideally, establishing the orbit of meteorites is a powerful way to link them with their parent bodies. Precise orbits have been determined for seven meteorites. Less precise orbits are known for a dozen or so more (see Gounelle et al. 2006 and references therein). Of these meteorites, all but three

(Murchison [CM2], Tagish Lake [C2-un] and Orgueil [CI1])—are high petrographic-type meteorites, coming from differentiated or metamorphosed asteroids. All meteorites with known orbits—with the possible exception of Orgueil—are consistent from the dynamical point of view with objects evolving out of the asteroid belt. Conversely, Orgueil might originate from beyond Jupiter's orbit (Gounelle et al. 2006). We have yet to find a meteorite, however, that can be orbitally linked to specific asteroid or comet.

Another powerful but less-explored way of connecting meteorites with parent bodies is to compare the measured cosmic ray exposure (CRE) ages of various meteorite groups with the time scales on which given asteroids can deliver fragments to the Earth (e.g., Eugster 2003). In this respect, we find it interesting that the CM2 chondrites (Van Schmus and Wood 1967) have a CRE age distribution with a peak near ~200,000 yr (Fig. 1). While it is plausible that this peak was produced by the fragile nature of these meteorites, we find that the very existence of meteorites with such short CRE ages is a puzzle all by itself. For example, the average CRE age for ordinary chondrites (85% of the falls) as well as most classes of carbonaceous chondrites is roughly 10 Ma (Eugster 2003); this makes any group of CRE ages with 200,000 yr rather exceptional. If CM2 chondrites with short CRE ages were produced by collisions of Main Belt asteroids, they would have to have been directly injected into a very powerful resonance capable of transporting them onto an Earth-crossing orbit over short time scales. Numerical experiments suggest the resonances capable of producing such short time scales tend to place the bodies on orbits where they are unlikely to strike the Earth (Morbidelli and Gladman 1998). Instead, we hypothesize that numerous meteorites with very short CRE ages are fragments of NEOs (Eugster et al. 2003). In fact, numerous NEOs are already on Earth-crossing orbits (or close to it), so that the liberated fragments can in principle hit the Earth after an arbitrarily short delay.

NEOs can eject meteoroids either upon collisions or during tidal stripping during low velocity close encounters with the planets (e.g., Bottke and Melosh 1996a). Concerning collisions, kilometer-size NEOs typically have dynamical lifetimes that are significantly shorter than their collisional lifetimes (e.g., Bottke et al. 2005), such that they are unlikely to be destroyed during their journey to the terrestrial planet region. There are enough NEOs (~1000 km-size bodies), however, that a few must disruption from time to time. These somewhat sporadic events may modify the meteorite flux reaching Earth. A second plausible means for producing meteoroids from NEOs is mass shedding produced by planetary tidal forces. The advantage here is that the orbits most favorable for tidal disruption are those where a large fraction of the material is likely to strike the Earth within short time scales (Bottke et al. 1997). We will concentrate on this mechanism for this paper.

Among the NEO population, about 15% of the objects are binary (Merline et al. 2002; Margot et al. 2002). Additional support for a significant binary NEO population comes from the 10% fraction of doublet craters found on Earth and Venus (Bottke and Melosh 1996a, 1996b). It is generally believed that many, if not most NEO binaries, were formed in tidal disruption events (Bottke and Melosh 1996a, 1996b; Richardson et al. 1998; Walsh and Richardson 2005), though the recent discovery of numerous binaries among smaller Main Belt asteroids may challenge this view (see the "Implications for Binary NEOs Formation Models" section for further information). If tidal disruption is an important means for producing binary asteroids, then C-type binary NEOs are reasonable candidate parent bodies of CM2 meteorites or, more generally, of any primitive meteorite with an exceptionally short CRE age. This means that by estimating the time of formation of these binaries, we may be able to make a plausible link between the formation of a specific binary asteroid and the CRE age of the CM2 meteorites.

In this paper, we focus on the binary NEO 1996 FG3. Its properties are detailed in "The Binary Near-Earth Object 1996 FG$_3$" section. Among all known C-type binaries, 1996 FG$_3$ is the one that currently encounters the Earth with the lowest relative velocity ($v_{\rm rel}$ = 10.7 km/s, where with $v_{\rm rel}$ we denote the encounter velocity at infinity, prior to the acceleration due to the gravitational action of the planet). Because tidal splitting is more likely at low $v_{\rm rel}$, this property makes 1996 FG3 the best candidate for having formed in recent times.

Below we consider various paradigms for the formation of 1996 FG3. In the "On Which Orbit Did 1996 FG$_3$ Form a Binary? First Case" section, we assume that at the time of the tidal disruption the relative encounter velocity with the Earth was smaller than the current one ($v_{\rm rel}$ ~6 km/s). Using constraints from the survivability of its satellite, we show this case is unlikely to have taken place. In the "Second Case" section, we assume that the relative velocity was similar to the current one ($v_{\rm rel}$ ~10.5 km/s). We show that this case is viable, and the short-term survivability of the satellite implies the disruption event occurred less than ~1.6 Ma ago. By considering the satellite eccentricity evolution, we also constrain the satellite's eccentricity damping time scale. In the "Third Case" section, we discuss the possibility that the tidal disruption occurred at larger $v_{\rm rel}$. In this case, we can only roughly constrain the time when $v_{\rm rel}$ decreased to its current value, and not the formation time of the binary itself. In the "Implications for Binary NEOs Formation Models" section, we review our results and their general implications on the NEO binary formation issue. In the "Binary NEO 1998 ST$_{27}$" section, we consider another C-type binary, NEO (1998 ST27), which has been recently proposed to be the parent body of metamorphosed CM and CI chondrites (Zolensky et al. 2005). General conclusions will follow in the "Discussions and Conclusions" section, where we come

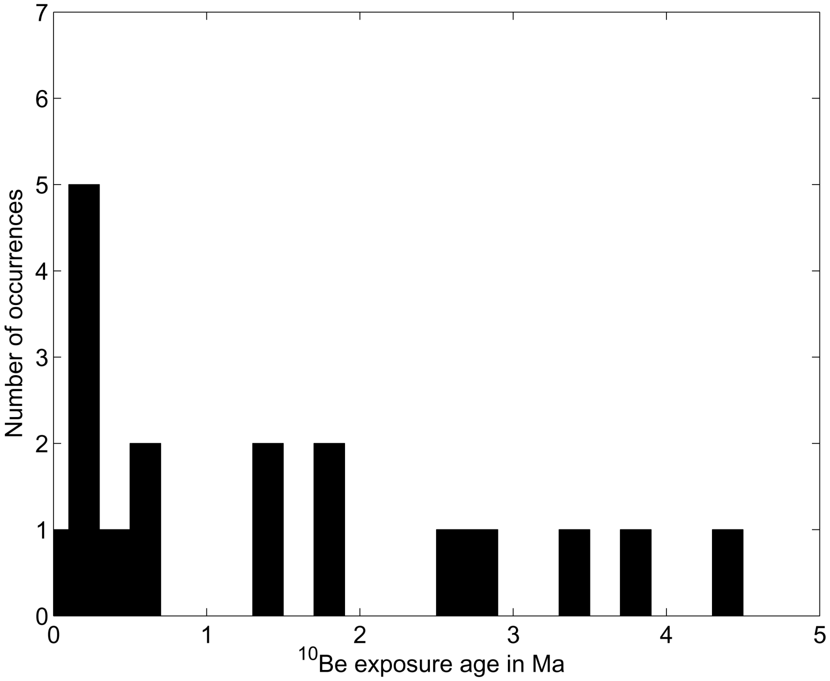

Fig. 1. The CRE ages distribution for CM2 chondrites (including the metamorphosed CM2s Belgica-7904 and Yamato-86720) from the formula $t_{\mathrm{CRE}}=1.44 \times T_{1/2} \times \log(N/N_{\mathrm{sat}})$, where t_{CRE} is the cosmic-ray exposure age, $T_{1/2}$ the ^{10}Be half-life (=1.5 Ma), N the number of ^{10}Be atoms measured in Nishiizumi et al. (1993), and N_{sat} the ^{10}Be saturation activity taken to be 24 dpm/kg (Kees Welten, personal communication). We have excluded the meteorites Elephant Moraine (EET) 90043 and MacAlpine Hills (MAC) 88107 from our data set because they are intermediary between CM and CO chondrites (Russell et al. 2000; Tonui et al. 2002). Off scale is Allan Hills (ALH) 84033 whose high ^{10}Be activity would lead to an infinite exposure age using the 24 dpm/kg saturation value.

back to the origin of the short CRE CM2 meteorites and propose a list of candidate parent bodies in addition to 1996 FG3.

The Binary Near-Earth Object 1996 FG$_3$

1996 FG$_3$ was discovered on March 24, 1996, by R. H. McNaught from the Siding Spring Observatory, New South Wales, Australia. Whiteley and Tholen (1999) later classified it as a C-type NEO with semimajor axis a = 1.054 AU, eccentricity e = 0.35, and inclination i = 1.98 degrees. Using light-curve data taken December 10–18, 1998 from the Ondrejov Observatory (Czech Republic), P. Pravec, L. Sarounova, and M. Wolf discovered that the asteroid has a satellite (see Pravec et al. 2000). Mottola and Lahulla (2000) observed mutual eclipse events in the system and determined the orbital and physical characteristics of the binary. The model that best fits their observations suggests the satellite has an orbital semi major axis around the primary of a = (1.7 +/– 0.3), D_1, where D_1 is the diameter of the primary, and an orbital eccentricity is e = 0.05 +/– 0.05. Assuming a geometric albedo of 0.065 (consistent with the spectral type of the asteroid), the diameters of the primary and satellite are D_1 ~1.4 km and D_2 ~430 m, respectively. The light curve also suggests that the primary is almost spherical, with normalized dimension axes of A = 1.05 +/– 0.02, B = 0.95 +/– 0.02 and C = 0.70 +/– 0.10. The orbital period of 16.135 +/– 0.005 h yields a primary bulk density of 1.4 +/– 0.3 g/cm^3.

Several groups have pointed out that 1996 FG$_3$ might be a target of choice for a NEO mission because the Hohmann-like transfer orbit from the Earth to the object requires maneuvers for a total V of only 5.16 km/s (Perozzi et al. 2001; Christou 2003; Binzel et al. 2004). The object's primitive physical nature and its binary nature also make this asteroid an interesting target for a scientific mission. In fact, in a joint phase-0 study for a NEO space mission, the French CNES, the Italian ASI, the German DLR, and the British BNSC, considered 1996 FG$_3$ their primary target.

The nearly spherical shape and fast rotation period (3.6 h) of 1996 FG$_3$ provides suggestive evidence of the binary's formation mechanism. Richardson et al. (1998) has shown that NEOs with rubble-pile-like internal structures making slow, close encounters with the Earth or Venus are likely to undergo tidal disruption. According to numerical modelling results, tidal forces can spin up the progenitor, often enough for it to shed mass. The remnant progenitor is left with a fast spin rate and, in many cases, a nearly spherical shape. At the same time, some of the material shed from the event may remain gravitationally bound to the remnant progenitor. Thus, objects on low-velocity encounters with the Earth can frequently be transformed into binary asteroids. If we assume this is what happened for 1996 FG_3, the question then becomes whether the object's orbit and binary status can be used to deduce its relatively recent orbital history.

On Which Orbit Did 1996 FG_3 Form a Binary? First Case: v_{rel} ~6 km/s

As described above, the asteroid 1996 FG_3 is currently on an orbit that encounters the Earth with v_{rel} = 10.7 km/s. According to our hypothesis, there are several possible modes where binary formation could have occurred: 1) the body experienced tidal disruption when it was on an orbit encountering the Earth at a lower speed (for instance, v_{rel} ~6–7 km/s), 2) it disrupted when its orbit was comparable to the current one (with encounter velocity v_{rel} ~10 km/s), 3) it disrupted when it was on a higher velocity orbit (e.g., v_{rel} ~15–20 km/s), or even 4) the binary was produced by a collision when the progenitor was still in the Main Belt. In this section, we consider case 1.

Using numerical simulations similar to those of Bottke et al. (2002), where synthetic asteroids evolving out of their main NEO sources in the asteroid belt have been followed all the way to their dynamical elimination, we selected a sample of three asteroids that had very close encounters with the Earth: in these cases, the perigee of the hyperbolic fly-by was <2 Earth radii and v_{rel}~6 km/s. The positions and velocities of these asteroids, as well as that of the planets at the time of the encounter, were recorded in these simulations. Each asteroid was then cloned 12 times, with its coordinates and velocity components modified by +/– 0.01%. We then tracked the dynamical evolution of these asteroids and their clones over a timespan of 2 Ma after their close approach with Earth. The goal of this study was to acquire a statistical understanding of how these orbits evolve in time. In particular, we monitored the encounter velocities of the test asteroids relative to the Earth as a function of time. Our results for the 36 integrated objects are shown in Fig. 2. Each object is represented by a solid curve. All curves are plotted with the same graphical style because, for our purposes, it is not important to distinguish one from the other. A horizontal line marks the threshold 10.7~km/s, which is the current encounter velocity of 1996 FG_3 relative to the Earth.

Although some objects quickly evolve to orbits that encounter the Earth at v_{rel} > 10.7 km/s, the bulk of the population preserves a low encounter velocity for the entire integration timespan. This is because the dynamics of these objects are dominated by encounters with the Earth, such that their Tisserand parameter relative to Earth:

$$T = 1/a + 2[a(1-e)^2]^{\frac{1}{2}} \cos i \tag{1}$$

is nearly preserved. The Tisserand parameter is related to the encounter velocity in units of the Earth's orbital velocity by the expression:

$$v_{rel} = (3-T)^{\frac{1}{2}} \tag{2}$$

This means that if T is nearly constant, v_{rel} will be nearly constant as well.

Recall that the 1996 FG_3 currently has v_{rel} = 10.7 km/s. According to Fig. 2, this implies that if the 1996 FG_3 binary formed when the progenitor encountered the Earth at ~6 km/s, the tidal disruption event most likely occurred more than 800,000 yr ago (and presumably several million years ago). In the interim, however, the binary would have repeatedly encountered the Earth at low velocity. The likely consequence is that the satellite would not have survived to the present epoch.

To illustrate this point, we recorded over the previous 2 Ma all the encounters where our test asteroids had passed within 1 Hill radius of the Earth or Venus. This produces data where, for each object and each encounter, the position and velocities of the object and of the encountered planet are recorded at moment of the object's entry into the planet's Hill sphere. For each object, we performed 20 simulations where the test asteroid was given a satellite with a semimajor axis matching that of observed for 1996 FG_3's satellite. The satellite's orbit was assumed to be circular and was given a random inclination. The orbit of the satellite was integrated using a Bulirsh-Stoer algorithm (Stoer and Bulirsh 1980) through the series of prerecorded encounters. More precisely, the evolution of the system (Sun-planet-primary-satellite) was tracked from the time when the binary enters the planet's Hill sphere to the time it leaves. The orbit of the satellite was then assumed not to change in the timespan between the two successive encounters. Thus, the orbit acquired by the satellite at the end of an encounter was used as initial orbit for the simulation of the next encounter. The satellite is considered lost if its pericenter becomes smaller than the primary's radius (assumed to be 0.7 km as for the 1996 FG_3 primary) or if its orbit becomes unbound (see also Bottke and Melosh 1996a, 1996b).

In total, we tracked the evolution of 720 satellites (20 satellites for 36 objects). All of them were lost within 46,000 years. According to Fig. 2, none of the objects acquire an orbit encountering the Earth at 10.7 km/s over this short time scale. The same simulations were performed a second time, although here we assumed that the satellite's eccentricity damps on a time scale of 10^5 yr (see the next section for a justification of this damping time scale and a description of the implementation algorithm). In this case, the mean time required to strip the satellite from the primary only increased to 58,000 yr.

These results imply that it was extremely unlikely that the satellite of 1996 FG_3 formed when the asteroid was on an orbit encountering the Earth at a velocity significantly smaller than the current one. Indeed, if these low-velocity encounters had occurred and a satellite had been formed, the latter would have been lost well before 1996 FG_3 reached its current orbit.

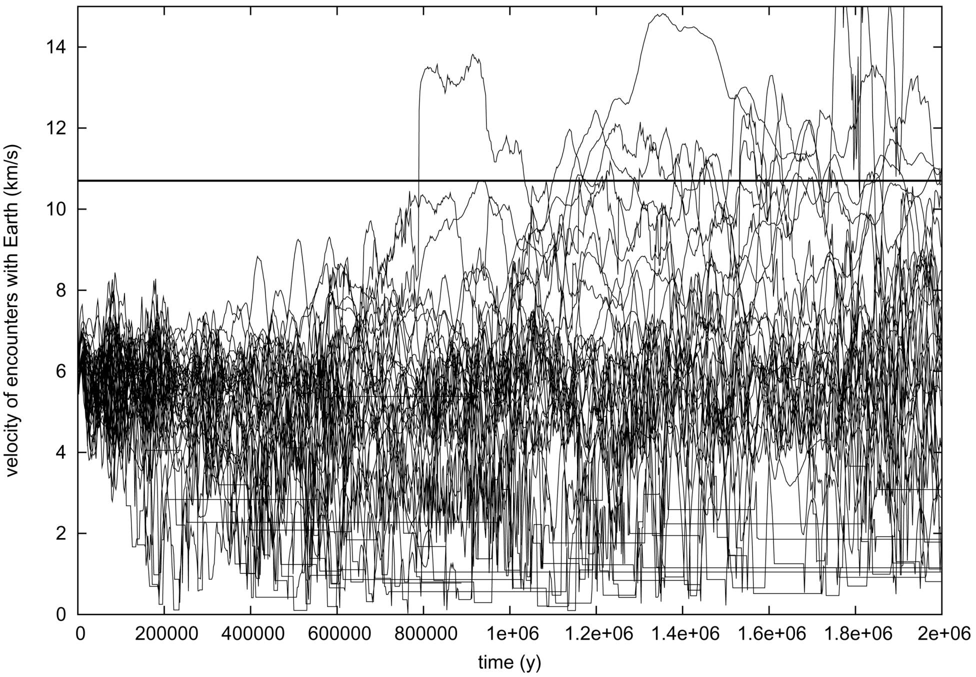

Fig. 2. The time evolution of the relative velocity of encounter with the Earth for 36 objects initially having close encounters at ~6 km/s. The horizontal line at 10.7 km/s mark the current value of the encounter velocity for 1996 FG$_3$. The horizontal segments at visible in the v_{rel} < 3 km/s mark the time intervals during which a considered object in not Earth-crossing.

On Which Orbit Did 1996 FG$_3$ Form a Binary? Second Case: v_{rel} ~10.5 km/s

Here we assume that the 1996 FG$_3$ binary formed by tidal disruption of a progenitor encountering the Earth with a relative velocity comparable to the present one (v_{rel} ~10–11 km/s).

Figure 3 is the equivalent of Fig. 2, but for 13 objects that were started from the current orbit of 1996 FG$_3$ or from similar orbits with position and velocity components changed by 0.01%. We find that some objects rapidly acquire orbits that encounter the Earth at high speeds, while others attain orbits with lower encounter velocities, and some keep encountering the Earth at ~10 km/s for an extended time.

Next, we address the survivability of the satellite. As in the previous section, we performed 20 simulations for each object. Each test asteroid was given a satellite with a circular orbit and a random inclination. The initial semimajor axis of the satellite was defined as that of 1996 FG$_3$'s satellite. The orbit of our test asteroid was then numerically integrated through the series of previously recorded encounters with the Earth and Venus.

Figure 4 shows the combined probability that, at time T after the disruption event, our test asteroid fulfills the two following conditions: 1) it still has an orbit encountering the Earth at v_{rel} < 12 km/s, and 2) it has preserved its satellite. Notice that the curve does not decay monotonically. In fact, as shown in Fig. 3, some objects can temporarily exceed the threshold v_{rel} = 12 km/s and then return to a low encounter velocity orbit. Thus, unlike condition (2), condition (1) does not give a monotonically decaying probability function. The threshold of ~12 km/s is, of course, arbitrary; we chose it because it is similar to the current reference encounter velocity and because binaries on orbits encountering the planets at v_{rel} > 12 km/s are much more likely to preserve their satellites (see next section).

Data from Fig. 4 implies that, if the 1996 FG$_3$ binary formed on an orbit comparable to the current one, it is unlikely that the formation event occurred more than ~1.6 Ma ago. Over longer timespans, 1996 FG$_3$ either would have lost its satellite or would have evolved onto an orbit encountering the Earth at significantly larger speed. Therefore, in this scenario, the putative meteorites liberated by the 1996 FG$_3$ tidal disruption event should have CRE <1.6 Ma.

Additional Constraints From the Satellite's Eccentricity

The analysis described above (Fig. 4) does not consider the evolution of the satellite's orbital eccentricity and assumed initial circular orbits. This assumption could be incorrect, considering that the best available tidal disruption model indicates that most newly formed satellites have eccentricities in the range 0.2–1.0 (Walsh and Richardson 2005). On the other hand, these results may not be representative of real binaries; Walsh and Richardson (2005) restricted their analysis to progenitors made up of 500 equal-

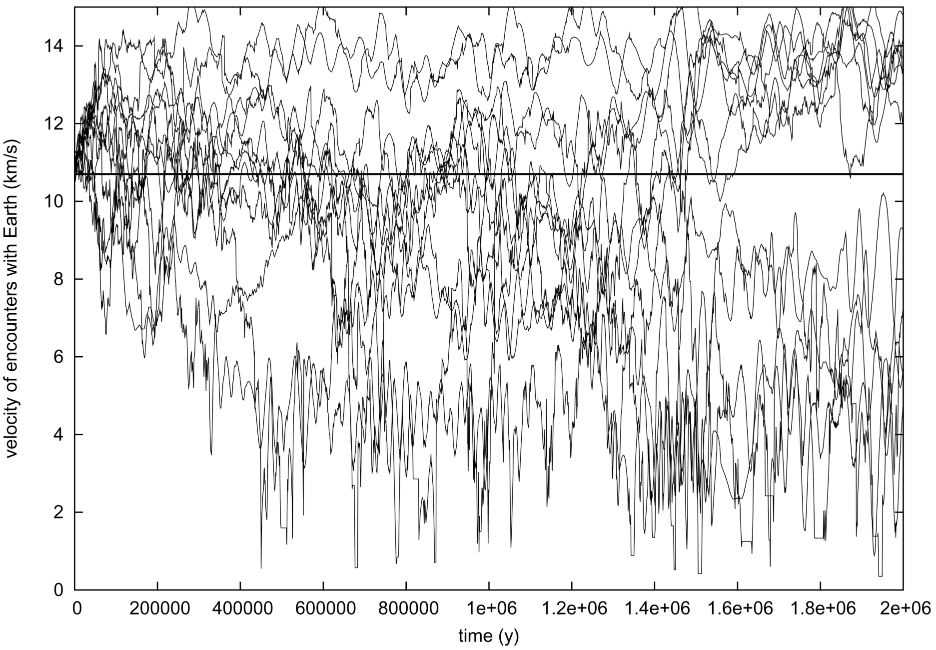

Fig. 3. The same as Fig. 2, but for 13 objects initially encountering the Earth at the current speed of 1996 FG_3.

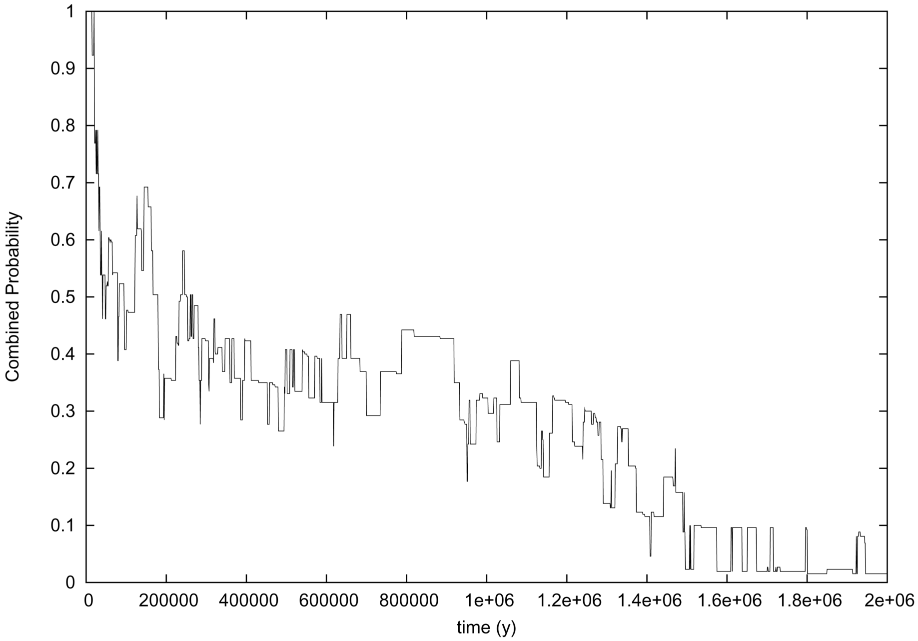

Fig. 4. The first estimate of the age of 1996 FG_3. The plot shows the probability that an object that disrupted during an encounter at 10.7 km/s at a given time from the disruption event, 1) has an orbit with encounter velocity lower than 12 km/s and 2) has preserved its satellite. This plot argues that, if the 1996 FG_3 binary formed on an orbit with an encounter velocity with the Earth similar to the current one, the formation event should not have formed more than 1.6 Ma ago.

sized particles. Preliminary work suggests that increasing the number of particles can significantly change the nature of the tidal disruption outcome (D. Richardson, personal communication). Still, we note that, with one exception (1998 ST_{27}), all observed satellites of NEOs (including 1996 FG_3) have quasi-circular orbits around the primary. This difference with respect to the initial orbit inferred from the tidal disruption model is usually explained by invoking eccentricity damping, presumably produced by tidal forces acting between the primary and secondary. We will return to this issue below.

Planetary encounters act against eccentricity damping by exciting the satellite's orbital eccentricity at every flyby. Hence, by using the encounter statistics of 1996 FG_3 with the

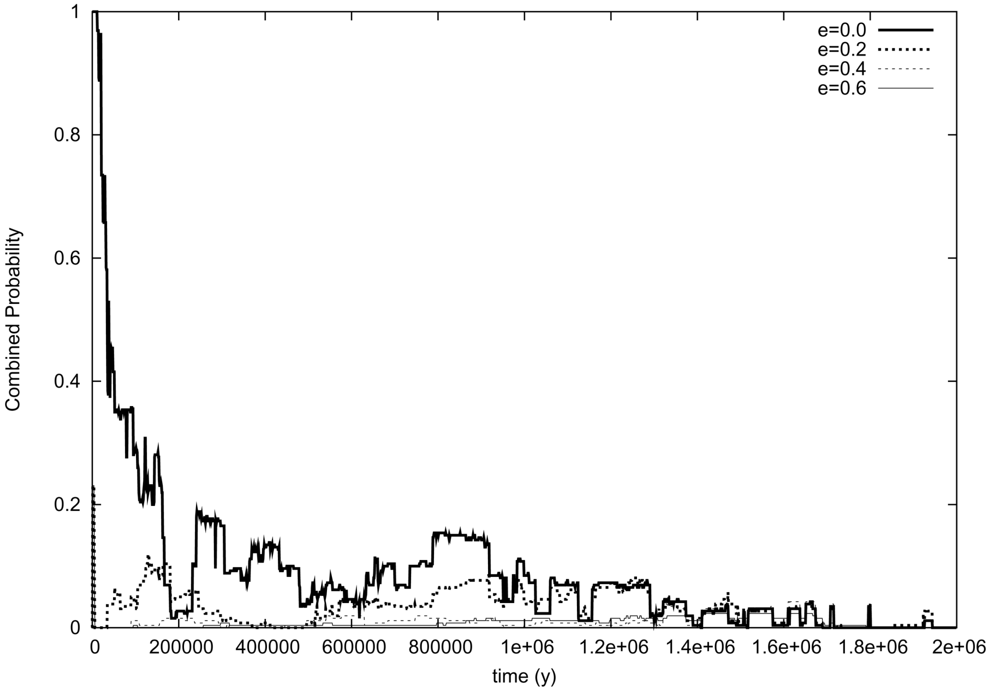

Fig 5. The same as Fig. 4, but combined with the probability that the satellite has an orbit with eccentricity smaller than 0.1. The four curves correspond to initial satellite eccentricity of 0.0, 0.2, 0.4, and 0.6. A damping time scale of 1 Ma is assumed.

planets obtained in the previous section, we can use the quasi-circular orbit of the satellite to derive tighter constraints on the age of the binary and on the strength of any putative eccentricity damping mechanism.

To model the damping of the satellite's orbital eccentricity, we implemented the following procedure. Close encounters between binaries and planets were modelled as before, with e_f, q_f, and i_f the final eccentricity, pericenter distance, and inclination of the satellite's orbit at the end of the encounter and δT the time interval until the next encounter. In previous sections, we assumed that, at the beginning of the next encounter, the satellite was on an orbit with $e = e_f$, $q = q_f$, and $i = i_f$. In this case, however, we assume that the satellite orbit has $e = e_f\,(1/2)^{\delta T/\tau}$, where is the assumed damping time scale. The other parameters remain the same as before. For each of the 13 bodies representing 1996 FG$_3$ we performed four series of 20 satellite simulations, with initial satellite orbital eccentricities equal to 0.0, 0.2, 0.4, and 0.6, respectively. In addition to conditions 1 and 2 used in Fig. 4, we also added a third one: the satellite orbit has $e < 0.1$ at time T.

Figure 5 shows the probability that conditions 1, 2, and 3 are simultaneously fulfilled at time T after tidal disruption for the different simulations. Here we used a damping time scale $\tau = 1$ Ma. As one can see, if the initial eccentricity is zero (an unlikely situation according to the tidal disruption simulations by Walsh and Richardson), the probability that a satellite exists on a quasi-circular orbit quickly decreases. For example, at T ~200,000 yr, it is down to ~20%. Note that the sudden drop at T = 200,000 yr is caused by the test binaries temporarily failing to meet condition 1; it should not be interpreted as an indication that the binaries could not form 200,000 years ago. For $T > 1$ Ma, the probability reaches <10%.

The situation, however, is completely different if the satellites have an initial eccentricity. In these cases, at any time in the 0–1.5 Ma interval, the probability to have a satellite with $e < 0.1$ does not exceed a few percent. Thus, if the damping time scale adopted in this simulation were correct, 1996 FG$_3$ would, dynamically speaking, be an exceptional object.

To check this, we repeated the same computation as before, using a damping time scale reduced by an order of magnitude (τ = 100,000 yr). The results are illustrated in Fig. 6. The damping is now strong enough to produce a quasi-circular orbit for most of the surviving satellites, even if their initial eccentricities were large. The probability of preserving a satellite with $e < 0.1$ is now non-negligible (>10%) for time as large as ~1.6 Ma. The probability peaks at ~50% in the 500,000 < T < 1,200,000 a interval, independent of the satellite's initial eccentricity.

These results may indicate that the real eccentricity damping time scale for 1996 FG$_3$ is ~100,000 yr rather than ~1 Ma. What mechanism could produce such a strong eccentricity damping? As described above, eccentricity damping is usually thought to be a by-product of tidal forces between the primary and secondary component. One of the most important parameters affecting the tidal damping time scale is the so-called rigidity of the bodies. Margot et al. (2002) addressed this question by examining the binary NEO

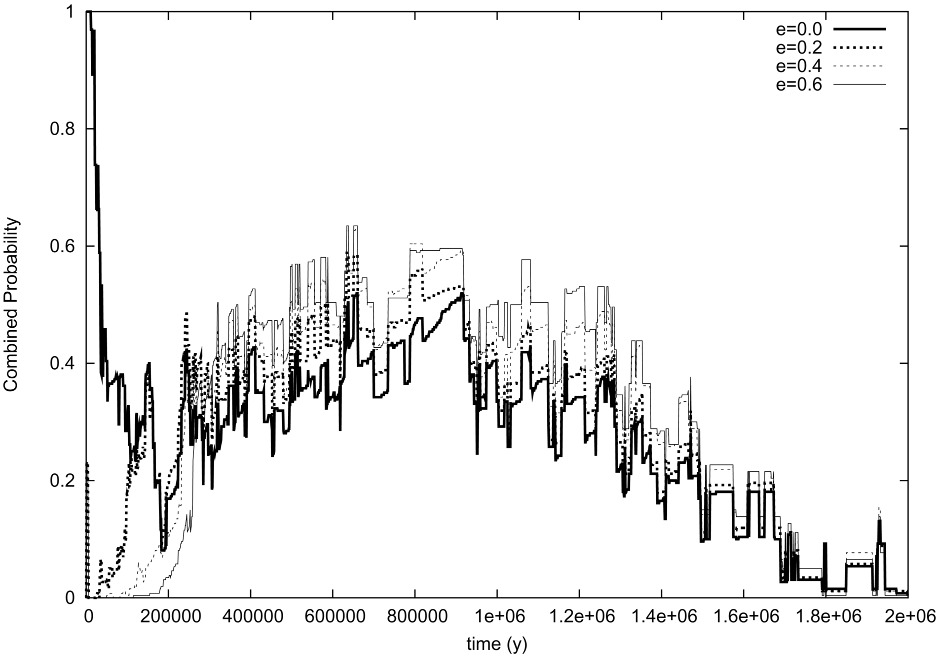

Fig. 6. The same as Fig. 5, but assuming a damping time scale of 0.1 Ma.

2000 DP_{107}. By examining the strength of the tidal forces needed to move the secondary from near-contact with its primary to its current separation, all within the median NEO lifetime of ~10 Ma, Margot et al. (2002) estimated that the rigidity of 2000 DP_{107} would need to be 10^5 times less rigid than rock and 10^4 times less rigid than Phobos (Yoder 1982). According to Walsh and Richardson (2005), this leads to a tidal damping time scale of 10^5 yr for 1996 FG_3.

An additional eccentricity damping mechanism may be provided by the so-called B-YORP effect (Cuk and Burns 2005). This effect, which is caused by the re-emission of thermal radiation by the primary and the satellite, can synchronize secondaries and circularizing orbits in less than 10^5 yr. If the B-YORP effect dominates the dynamics of the 2000 DP_{107} binary, then the rigidity deduced by Margot et al. (2002) has no validity; we believe this may explain why its value is so much lower than that of Phobos. The B-YORP effect, however, also poses an unsolved hazard for the survivability of the binary because it forces the satellite to undergo radial migration. Either way, both eccentricity damping mechanisms support a time scale of 10^5 yr, which is consistent with the one that we have found (on a purely dynamical basis) to be necessary in order to explain the circular orbit of the satellite of 1996 FG_3.

Assuming a damping time scale of 10^5 yr, our results still imply that the 1996 FG_3 binary should not have formed more than 1.6 Ma ago. Beyond this threshold, it is unlikely that the satellite can survive if the binary remains on a low encounter velocity orbit. In particular, an age of 200,000 a, consistent with the CRE ages of CM2 meteorites, cannot be excluded, especially if the initial satellite had a moderate eccentricity ($e < 0.2$). It is more unlikely if the initial satellite's eccentricity was large ($e > 0.4$) because, in this case, there would not have been enough time to circularize the satellite's orbit. Of course these conclusions only hold if the starting assumption used in this section (i.e., that the binary formed when its v_{rel} was similar to the current one) is fulfilled.

On Which Orbit Did 1996 FG_3 Form a Binary? Third Case: v_{rel} ~12 km/s

Among the simulations presented in the previous section (clones of 1996 FG_3 and satellite dynamics simulated with 100,000 yr damping time scales), 10 of the 13 clones had at least some encounters with our planet with relative velocity v_{rel} exceeding 12 km/s, for a total of slightly more than 2,000 "fast" encounters within a distance less than one Earth Hill radius. On average, each of the clones carried 18 satellites when these fast encounters happened. Thus, we have a statistics of 36,000 data on the effects of $v_{\mathrm{rel}} > 12$ km/s encounters on satellites. In only 5 cases, the satellite was stripped away, corresponding to a 0.014% probability. Given that the typical interval between encounters is ~2,000 yr, this means that the probability to lose a satellite is only ~7% per Ma when the binary is on an orbit with $v_{\mathrm{rel}} > 12$ km/s.

From these estimates, we can conclude that, for a binary object like 1996 FG_3, if the encounters with Earth occur at $v_{\mathrm{rel}} > 12$ km/s, the satellite is generally "safe." Thus, if 1996 FG_3 formed its binary when it was on a $v_{\mathrm{rel}} > 12$ km/s orbit (for a discussion of this possibility, see below), the satellite could survive as long as the encounter velocity remained above this threshold. Given the weakness of the encounters in this configuration and the putative short eccentricity damping time scale, the satellite's orbit was presumably quasi-circular most of this time. When the relative encounter velocity decreased below 12 km/s, however, planetary encounters became increasingly effective. In this scenario, the curve corresponding to initial $e = 0$ in Fig. 6 indicates that the orbit of 1996 FG_3 probably decreased v_{rel} below 12 km/s no more than 1.6 Ma ago. On the other hand, it does not constrain the formation time of the binary, which can be significantly older.

From Fig. 3, we see that for some clones, v_{rel} increased from the initial value to above 12 km/s in a few 100,000 yr. Because the dynamics are reversible, it is possible that the relative velocity of 1996 FG_3 decreased below 12 km/s in recent times, so that the binary stayed on a "dangerous" orbit for a shorter time than the maximum of 1.6 Ma found in Fig. 6. Another way to see this is that in the simulation of Fig. 3, 7 out of 13 clones had v_{rel}>12 km/s after 2 Ma. Of these, 4 had all their original satellites, and 6 had at least 50% of them. Again, by a reversibility argument, this shows that, from the dynamical point of view, it is possible that 1996 FG_3 had its satellite from at least 2 Ma ago.

While the dynamical considerations discussed above indicate that some evolutionary pathways are possible, it does not address their likelihood. An important issue to be considered is the likelihood that a binary forms by tidal disruption if v_{rel} > 12 km/s. Richardson et al. (1998) defined three types of tidal disruption end-states: S-class, where the mass of the NEO after a planetary encounter is less than 50% that of the progenitor, B-class, where this fraction is between 50 and 90%, and M-class, where the mass fraction is >90%. Given that 97.7% of the mass of 1996 FG_3 is in the primary, this binary most likely belongs to the M-class, although we cannot be certain because we have no way to estimate how much mass was dispersed in space. Walsh and Richardson (2005) showed that binaries produced by S-class disruptions are unlikely to form if v_{rel}>10 km/s. For binaries produced by M-class disruptions, however, the formation probability for larger v_{rel} is non-negligible (see Fig. 11 in Walsh and Richardson 2005). Normalizing to unity the probability to form a binary from an M-class disruption in an encounter with v_{rel} between 6 and 10 km/s, the probability decreases to 0.6 for $10 < v_{rel} < 14$ km/s, 0.3 for $14 < v_{rel} < 18$ km/s, and 0.15 for $18 < v_{rel} < 22$ km/s. For binaries from B-class disruptions, the outcome is intermediate between that of S-class and M-class binaries. Thus, we cannot exclude the possibility that 1996 FG_3 formed when it encountered the Earth at v_{rel} > 12 km/s and then only recently acquired its low-encounter velocity orbit.

Taking these considerations to an extreme, we also cannot exclude the possibility that the 1996 FG_3 binary formed in the Main Belt in a collision event (Durda et al. 2004) and then dynamically evolved to NEO space. For example, if the binary had only fast velocity encounters with the terrestrial planets during the beginning of its evolution as an NEO, and only then experienced a decrease in its encounter velocity below 12 km/s (say, in the last million years), the satellite could probably survive. The shape, spin rate, and orbit of 1996 FG_3, however, suggest this scenario probably did not occur for this binary.

In conclusion, if the 1996 FG_3 binary formed when the progenitor body was on an orbit with relative Earth encounter velocity significantly larger than the current one, the binary formation event could be much older than 200,000 yr, with no possible connection with the CM2 meteorites of similar CRE age.

Implications for Binary NEOs Formation Models

The results illustrated in the previous sections are relevant for the general issue of NEO binary formation. Numerical simulations (Bottke and Melosh 1996a, 1996b; Richardson et al. 1998; Walsh and Richardson 2005) show that the lower the relative encounter velocity with a planet, the easier it is for tidal disruption (and binary formation) to take place. These studies, however, have not considered the issue of the long-term survivability of the satellite in the context of the realistic NEO dynamical model. We have shown that the relative encounter velocity of an NEO with a planet evolves slowly. Thus, orbits with low-encounter velocity suffer frequent, slow, and strong planetary encounters that are generally fatal for the survivability of the satellite. Thus, the orbits that are most likely to produce binaries are also the most likely to disperse the satellites after a short timespan. In reality, there is a trade-off between the probability of forming a binary (which decreases with v_{rel}) and the probability of keeping the satellite (which increases with v_{rel}). Although a specific study of these two competing effects remains to be done, from our simulations we expect that the orbits that are the most efficient in producing observable, long-lasting binaries are probably those with a moderate v_{rel} of 10–15 km/s. This implies that binaries from S-class disruptions, which according to Walsh and Richardson (2005) can be produced only at v_{rel} < 10 km/s, should be extremely rare among the observed binary NEO population.

The next step is to evaluate this issue in a self-consistent model that accounts for both accurate tidal disruption over a range of spin, shapes, internal structures, and so forth, as well as accurate NEO dynamical evolution. Until that time, we can only speculate about the implications of the results described above. Given what we have learned, we believe that overall efficiency of binary production from tidal disruption may be insufficient to maintain the predicted steady-state binary fraction of 15% for the NEO population.

An alternative scenario for the origin of binary NEOs is that they were initially formed in the Main Belt by collisions (e.g., escaping ejecta binaries, or EEBs) (Durda et al. 2004) or YORP-induced spin-up and fission (Rubincam 2000). Recent satellite searches for binaries among smaller Main Belt asteroids in the Koronis family (Merline et al. 2005), showed that the fraction of binary Main Belt asteroids can be as large as 20%. If EEBs are indeed common in the Main Belt among km-size asteroids, it is probable that some remained gravitationally bound long enough to reach a Main Belt resonance capable of taking them to the terrestrial planet region. Note that NEOs come from the asteroid belt via a two-step dynamical process that involves Yarkovsky thermal forces and gravitational resonances. Asteroids first drift in semi-major axis in the Main Belt under the Yarkovsky effect until they are captured into a resonance with a planet (mostly a resonance with Jupiter or Saturn), which decreases the perihelion distance of the body below the terrestrial planet encounter limit (Morbidelli et al. 2002; Bottke et al. 2002; Morbidelli and Vokrouhlicky 2003). This two-step process has no reason to discriminate binary Main Belt asteroids from single asteroids of the same size (Vokrouhlicky et al. 2005). Thus, if about 10–20% of small Main Belt asteroids are binary, a comparable proportion of asteroids that become NEOs should be binary as well. The fact that the estimated binary fraction in the NEO population is 15% suggests that the Main Belt might be a sufficient source for many NEO binaries. In fact, one cannot rule out the possibility a priori that all binary NEOs are from the Main Belt and that no tidal disruption binary-formation mechanisms are needed at all.

While this scenario is appealing for its simplicity, we believe it is unlikely to represent the true answer. Instead, we suspect the NEO population is a 50-50 mixture of binaries formed "locally" and those that have evolved out of the Main Belt. Supporting evidence that some NEOs were formed by tidal disruption can be found in the nearly spherical shapes and very fast rotation rates of binaries observed by radar or deduced from light curve studies (Merline et al. 2002; Ostro et al. 2002; Pravec et al. 2002). Richardson et al. (1998) and Walsh and Richardson (2005) have shown that these outcomes are common by-products of close encounters between "rubble-pile" NEOs and the Earth/Venus. On the other hand, the available numerical modeling work of Main Belt binaries produced by escaping ejecta fragments during collisions suggests their primaries would most likely have irregular shapes (e.g., Ida/Dactyl) and a wide range of rotation periods (Durda et al. 2004). Thus, while additional work on this topic is needed, we argue that a substantial fraction of the observed NEO binaries, particularly those with the lowest encounter velocities with Earth and Venus, were formed by tidal disruption.

The Binary NEO 1998 ST$_{27}$ and Metamorphosed CM and CI Chondrites

In this section, we digress to consider the orbital dynamics of binary NEO 1998 ST$_{27}$ and, more generally, on the possibility that tidal disruption of an NEO can lead to meteorite shower on Earth after a time scale of a few 10^5 yr.

1998 ST$_{27}$ is also a C-type binary NEO. It has been suggested by Zolensky et al. (2005) as a possible parent body candidate for a subgroup of CM and CI meteorites that have experienced thermal metamorphism in the same parent body. All of these meteorites were found in Antarctica, with the majority coming from the Yamato Mountains site. After ruling out the possibility that these meteorites were paired, Zolensky et al. (2005) argued from recovery statistics that these meteorites fell in a shower at a time corresponding to the age of the Yamato Mountain recovery surface. Because these meteorites also have short CRE ages compared to ordinary chondrites, the authors speculated that they might have been released during a binary NEO formation event. 1998 ST$_{27}$ was preferred by Zolensky et al. over other primitive NEO binaries because the observation (Benner et al. 2003) that the spin of the satellite is not synchronous with the orbital period and that the satellite's orbital eccentricity is large (~0.3, the only eccentric case among all NEO binaries) suggests that this binary might be very young. These properties, however, may also be the consequence of a recent encounter that perturbed the binary's motion. In fact, notice from the bottom panel of Fig. 7 that 1998 ST$_{27}$ has currently one nodal distance at 1 AU. This implies that the asteroid can have very close approaches to the Earth at the present, or very recent time (this is the reason for which its binary nature could be discovered by radar observations). Thus, it is plausible that the satellite eccentricity has been excited during a recent close encounter. On the other hand, 1998 ST$_{27}$ currently encounters the Earth with a relative velocity of 17.6 km/s, which makes a recent tidal disruption improbable (but not impossible) (Walsh and Richardson 2005).

If the origin of metamorphosed CM meteorites from 1998 ST$_{27}$ cannot be ruled out from chronology considerations, the idea that objects liberated by this asteroid could fall on Earth in a meteorite shower, however, is more suspect.

A necessary condition for a meteorite shower to occur, after time T from the disruption event recorded by the CRE age, is that the nodal distances of the meteoroid stream are still confined within a narrow range. Tidally disrupted NEOs, which are likely to have low-velocity encounters with a planet, can have an extremely chaotic evolution due to the effectiveness of planetary encounters at changing their orbit. A consequence of these encounters are that the nodal distances of a putative meteoroid stream disperse quickly.

To illustrate this fact, we shown in the upper panel of Fig. 7 the nodal distances of the members of a putative stream generated by 1996 FG$_3$ from its current orbit (v_{rel} = 10.7 km/s). We find that in this case, the nodal distances only retain coherence for ~10,000 yr. If a meteorite shower were generated by this asteroid during a tidal disruption, it would have to fall in the first 10,000 yr after the tidal disruption event. Thus, all the meteorites in the shower would have CRE < 10,000 yr. The bottom panel of Fig. 7 shows the nodal distances for fragments coming from 1998 ST$_{27}$. Here the situation is better because the progenitor encounters the Earth at higher speed (v_{rel} = 17.6 km/s) and therefore the stream of orbits is less perturbed. Nevertheless, even in this case, the

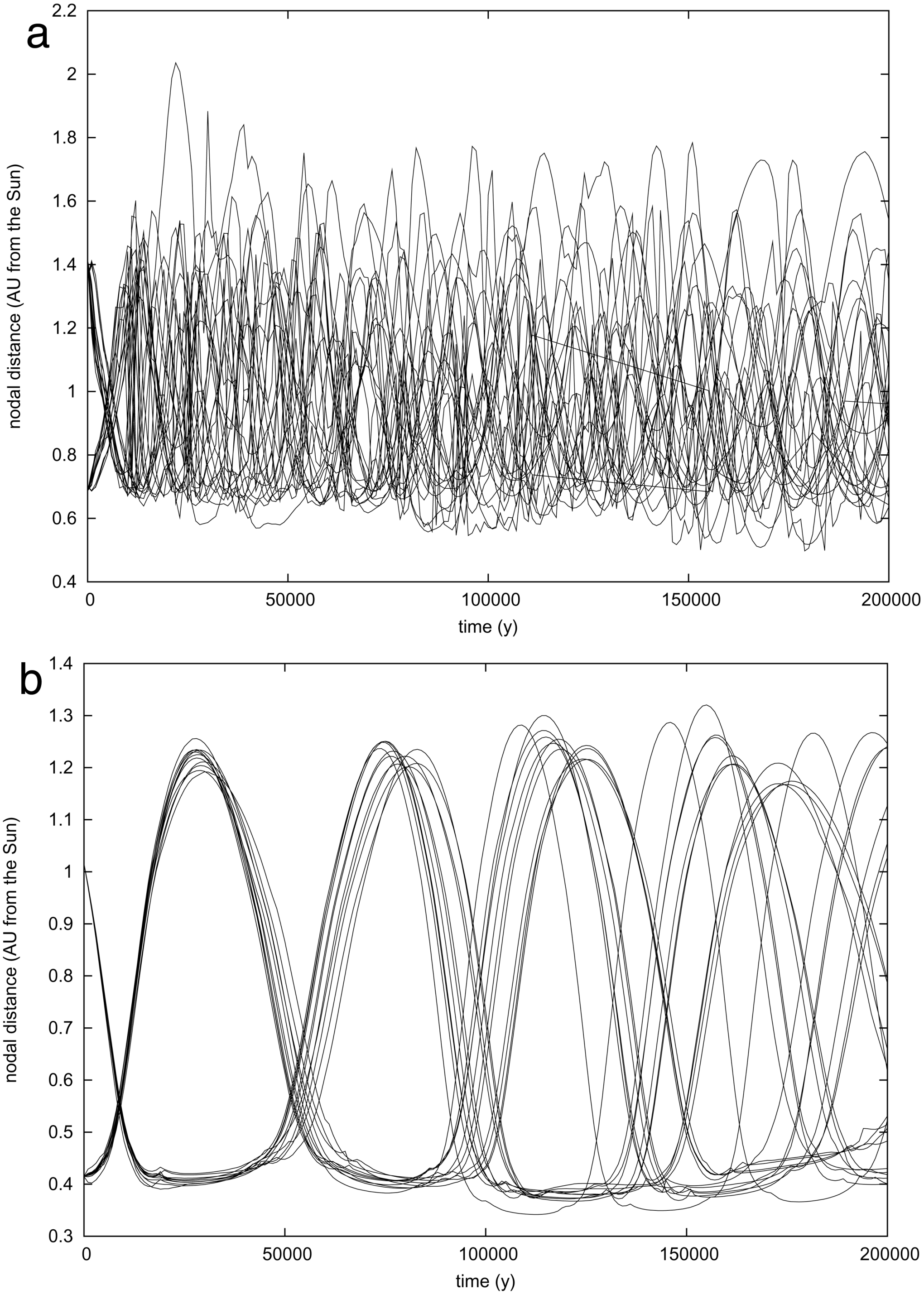

Fig. 7. The distribution of nodal distances for a stream of 13 bodies initially departing from the current orbit of 1996 FG3 (top panel) or of 1998 ST$_{27}$ (bottom panel).

nodal distances only remain coherent for ~100,000 yr. If metamorphosed CM meteorites really fell in a shower and were generated by this asteroid, the formation age of the binary and the CRE age of these meteorites should be ~100,000 yr or less. This is not observed. In fact, the two C chondrites with measured CRE ages have values of (from Nishiizumi et al.'s [1993] data) have CRE = 1.82 Ma (Belgica-7904) and CRE = 0.44 Ma (Yamato-86720).

The comparison between the two panels of Fig. 7 suggests that, if the Earth really experienced a shower of meteorite falls with CRE ages <200,000 yr, then these meteorites were most likely liberated from a NEO encountering the Earth orbit at a larger speed ($v_{\mathrm{rel}} > 20$ km/s). High-velocity encounters, which are less susceptible to gravitational perturbations from Earth, tend to retain the coherence of the nodal distances for longer time scales. Such high velocities, however, are less likely to produce a meteoroid stream via tidal disruption (unless the object has a fast spin rate and/or is very elongated).

DISCUSSION AND CONCLUSIONS

In this paper, we investigated the origin of 1996 FG_3, a binary asteroid on an NEO orbit. We hypothesized that the event producing a binary, presumed to be tidal disruption, may have also be responsible for the CM2 meteorites with CRE ages near 200,000 yr. Because NEOs can be disrupted by tides during low-velocity encounters with terrestrial planets more frequently than by collisions, and because binary NEOs are thought to be the by-product of re-accumulation after such tidal disruptions events, we focused our attention on 1996 FG_3. This object has the lowest encounter velocity relative to the Earth of all of the known C-type binaries.

We showed that 1996 FG_3 is unlikely to have formed into a binary when it had relative velocities with Earth significantly lower than its current one. Indeed, if this were the case, it would have likely lost its satellite well before acquiring the current Earth encounter velocity of 10.7 km/s. We then showed that if the binary formation event occurred during an Earth encounter with a relative velocity comparable to the current one, 1996 FG_3 could have preserved its satellite and have remained on an orbit with a similar encounter velocity for about 1.6 Ma. In this case, the tidal formation of the 1996 FG3 binary likely occurred <1.6 Ma. Finally, we showed that if the binary formation occurred at significantly larger encounter velocity, we cannot easily determine its formation age. The only (weak) constraint that remains is the one that tells us when 1996 FG_3 decreased its encounter velocity below ~12 km/s.

These results have general implications on NEO binary formation models. They show that the orbits which are more likely to form binaries by tidal disruption (i.e., those with the lowest encounter velocities relative to planets) are also the orbits that are less likely to preserve the satellites. This decreases the probability that tidal disruption forms long lasting binaries.

It is possible that many of the observed binary NEOs formed during encounters at moderate velocities (15–20 km/s). These encounters can produce tidal disruption outcomes capable of shedding mass, provided the progenitor makes a very close approach distance to Earth or Venus. These orbits give the binary increased odds of surviving for an extended period. We also speculate that a substantial fraction of the binary NEO population may have formed in the Main Belt before evolving to the NEO region. This possibility requires further investigation.

Overall, we argue that 1996 FG_3 is a possible but not likely candidate parent body for the CM2 meteorites. More in general, we find that NEOs that undergo tidal disruption at moderate encounter velocities with Earth should not deliver a large number of meteorites to the Earth. In fact, if the relative encounter velocity with the Earth is of order of the Earth's escape velocity (~11 km/s), the Earth's "gravitational focusing factor" is of order unity, Consequently, the collision probability with Earth of the liberated meteoroids is not abnormally high compared to the background population.

Thus, we believe that the parent body of the short CRE age CM2 meteorites is likely a primitive, non-binary NEO that encountered the Earth at much lower velocity than 1996 FG_3. It is likely that a body with these characteristics underwent tidal disruption recently (e.g., ~200,000 yr ago), given the favorable relative velocity. Moreover, the fragments that it liberated would have a greater chance of striking the Earth than the background population, again because of their slow relative velocities with the Earth. As shown in the "First Case" section, the fact that these NEOs do not appear as binaries is not necessarily an indication that they never suffered tidal disruption, but simply the result of the short dynamical lifetime of their putative satellites.

For reference, the known primitive-type Earth-crossing NEOs with the lowest encounter velocities with the Earth are: 1999 JU_3 ($v_{\mathrm{rel}} = 5.10$ km/s), Nereus ($v_{\mathrm{rel}} = 6.84$ km/s), 1989 UQ ($v_{\mathrm{rel}} = 7.49$ km/s) and 1992 BF ($v_{\mathrm{rel}} = 8.42$ km/s). Any of them may be a good parent body candidate for the CM2 meteorites. Still others may be waiting to be discovered. Finally, our numerical results indicate that the tidal disruption of a NEO most likely leads to meteorite showers, but only in the first few 10,000 yr after the disruption event. Low-encounter velocities are so effective in dispersing meteoroid streams that showers quickly become impossible. Nevertheless, meteorites liberated during a given tidal disruption event may continue to fall on Earth for millions of years, although not in the form of showers.

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