

Chaotic evolution of (719) Albert, the recently recovered minor planet

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Abstract. On May 9 the *Minor Planet Center* announced the re-discovery of the last ‘lost’ minor planet, (719) Albert. In this paper we study its orbital evolution. We show that Albert follows an extremely chaotic orbit, typical of near-Earth asteroids (NEAs) that are extracted from main belt resonances through close planetary encounters. It will become an Earth-crosser and, eventually, it will either be ejected from the solar system on a hyperbolic orbit or will become a Sun-grazer, most probably within the next 5 Myrs.

Key words: minor planets, asteroids – celestial mechanics, stellar dynamics – chaos

1. Introduction

The history of the asteroid (719) Albert is one of the most interesting examples of how systematic work can complement an adverse coincidence. Albert was originally discovered by J. Palisa of the Imperial Observatory of Vienna, during the night of October 3, 1911 as a 12.5 magnitude object with a fast direct motion. The next night three more observations of the newly discovered asteroid were made, one by Palisa himself and two by C.H. Pechüle from the Observatory of Copenhagen. Bad weather and a full moon prohibited follow-up observations in the following days and the asteroid was never observed visually for the next 89 years. Not having enough observations, the orbital elements of Albert could not be determined very accurately. For a more detailed account of the discovery and subsequent loss of Albert one may consult Ashbrook (1978).

Since 1911 six more photographic observations of the asteroid were identified; the plates of the three observations from Greenwich were lost, but the other three (two from Heidelberg and one from Johannesburg) enabled Kristensen and West (1989) to calculate much improved values for the orbital elements, classifying Albert as an Amor-type asteroid ($q = 1.19$ AU). However, since there existed an uncertainty in the orbital longitude, the authors concluded that recovery attempts could not be based on an ephemeris. The data of the original Greenwich plates were re-evaluated by Goffin (1995), without considerably improving the previous results.

The situation changed drastically during the first half of May 2000. On May 1 an object with unusual motion, presumably a near-Earth asteroid (NEA), later designated as 2000 JW8, was

photographed by J.A. Larsen during a routine observation within the *Spacewatch* program. The same object was re-observed on May 3 and 6 by R.S. McMillan and J.V. Scotti, and on May 9 with the 2.1 Kitt Peak reflector by M. Hicks and R. Fevig. G.V. Williams (2000), knowing Albert’s orbital elements by heart, identified 2000 JW8 with the last ‘lost’ numbered asteroid. An account of the events that led to its recovery can be found in Marsden (2000). The newly determined set of orbital elements are shown in Table 1. It is easy to imagine that such a highly-eccentric Mars-crossing orbit cannot be stable. Thus we decided to study, by means of numerical integration, the orbital evolution of (719) Albert, in an effort to understand more about the past and future history of this intriguing object.

2. The integrations

We use a solar system model that contains all planets except Pluto, interacting through Newtonian gravity; the Earth and the Moon are integrated as one object. A first 0.5 Myrs integration revealed the chaotic dynamical behavior of Albert. Thus, a single integration cannot be taken as a deterministic prediction of its long-term dynamical evolution. For this reason, the nominal orbit of (719) Albert was integrated **(i)** with a Bulirsch-Stoer (BS) integrator, **(ii)** with the RMVS3 integrator included in the SWIFT package (Levison & Duncan 1994) and **(iii)** with the hybrid symplectic/Bulirsch-Stoer integrator (Chambers 1999; hereafter HYBRID) included in the MERCURY package (Chambers & Migliorini 1997). The integration time was set to 5 Myrs in all cases.

In all these integrations Albert was found to evolve in a way typical of NEAs that are extracted from the main asteroid belt through close encounters with Mars (see Michel et al. 1996; Morbidelli 1999), namely it soon becomes an Earth-crosser and, finally, ends his life either by being ejected from the solar system or by falling onto the Sun (Farinella et al. 1994). Table 2 presents a summary of these integrations. The Lyapunov characteristic exponent, γ , which is the standard measure of chaos, was also calculated **(i)** by integrating the variational equations with a routine incorporated in SWIFT and **(ii)** by simultaneously integrating 3 more orbits in each of the integrations mentioned above, each of these 3 orbits being initially very close ($\sim 10^{-8}$) to Albert but having a different orientation of the deviation vector. The Lyapunov time was in all cases $T_L = 1/\gamma \approx 300\text{--}400$ years, a typical value for strongly chaotic orbits of minor bodies

Table 1. Orbital elements of (719) Albert (MPEC 2000-J37).

Epoch	a (AU)	e	i (deg)	Ω (deg)	ω (deg)	M (deg)
2000 Feb 26.0 TT	2.6366670	0.5482734	11.30945	184.93048	154.28850	235.16761

Table 2. Evolution of Albert’s nominal orbit, integrated with different techniques and levels of accuracy. δt is the time-step (in days) and ϵ the accuracy of the BS. T_R denotes the removal time and T_{cross} the time at which the orbit first crossed the orbit of the Earth (both in Myrs). The last column indicates the fate of the integrated orbit - *ejected* if the heliocentric distance became greater than $r \geq 100$ AU and *SUN* if the perihelion distance became smaller than the radius of the Sun, $q \leq 0.005$ AU.

Integrator	δt	ϵ	T_{cross}	T_R	End
BS		10^{-10}	1.479	2.725	SUN
RMVS3	1.83		1.683	3.867	SUN
RMVS3	0.36		0.658	3.718	ejected
HYBRID	1.83	10^{-15}	0.273	1.109	ejected
HYBRID	0.36	10^{-15}	1.243	1.907	ejected

evolving in a random-walk manner under the influence of close planetary encounters (Tancredi 1995; Whipple 1995).

Fig. 1 shows the evolution of Albert (HYBRID integration, $\delta t = 0.36$ days). In the beginning a random-walk in semi-major axis, around $a \approx 2.63$, is seen while the eccentricity remains practically unchanged, with a mean value of $e \approx 0.5$, and the inclination is also fairly constant at $i \approx 12^\circ$. The perihelion distance remains smaller than $q = 1.523$ AU, i.e. the mean semi-major axis of Mars, almost for all time. During this phase, Albert undergoes subsequent close encounters with Mars, the closest one being at a distance of $d = 2.9 \times 10^{-4}$ AU $\approx 44,000$ km at $t = 21,300$ years. Albert first crosses the orbit of the Earth at $t \approx 1.25$ Myrs, causing a visible ‘jump’ in a . Subsequent close encounters with our planet (the closest one being at $d = 0.0032$ AU $\approx 500,000$ km at $t = 1.65$ Myrs) inject the asteroid into a region where almost all linear secular resonances overlap (the arguments corresponding to ν_6^1 and ν_3 are shown in this figure). This leads to an increase of its eccentricity up to almost unity. Note that, at the end, anti-correlated oscillations of e and i reveal the presence of a Kozai resonance (Kozai 1962). The perihelion distance diminishes to $q \approx 0.005$ AU $\approx R_\odot$ but, in the case shown here, the asteroid encounters Jupiter just before it manages to fall onto the Sun. This leads to a ‘pinball-like’ evolution, the asteroid experiencing repeated close encounters with almost all planets, until it is ejected on a hyperbolic orbit (see also Fig. 2, below).

The evolution of the 4 Albert orbits on the (a, e) plane is shown in Fig. 2. Most of the time is spent in the interplanetary region between Mars and Earth. The objects do not evolve under the sole action of Martian encounters and the Tisserand parameter is poorly conserved, due to the close proximity of both planets

¹ The secular resonance ν_i occurs when the mean precession rate of the asteroid’s perihelion longitude, $\langle \dot{\varpi} \rangle$, is almost equal to that of planet i , $\langle \dot{\varpi}_i \rangle$.

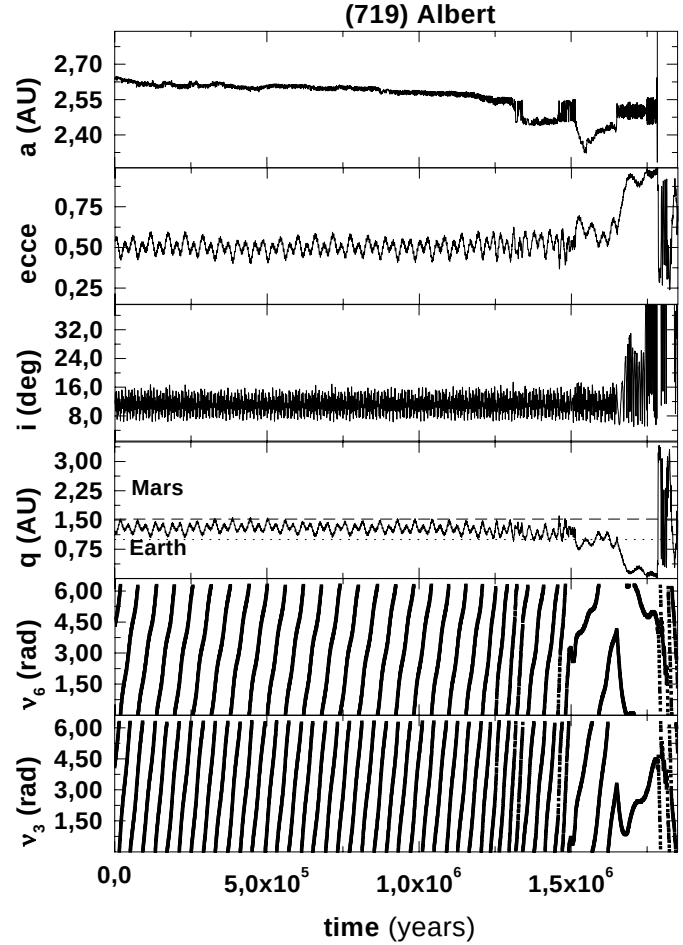


Fig. 1. Evolution of (719) Albert in the HYBRID integration with $\delta t = 0.36$ and $\epsilon = 10^{-15}$. The elements shown are (from top to bottom) the semi-major axis a , eccentricity e , inclination i and perihelion distance $q = a(1 - e)$. The last two panels are the arguments related to the secular resonances $\nu_6 = \varpi - \varpi_6$ and $\nu_3 = \varpi - \varpi_3$ with Saturn and Earth, respectively (see text for a discussion).

(see Morbidelli 1999). The orbits cannot become Earth-crossing easily, since the small mass of Mars cannot provide the ‘kicks’ required for the orbit to jump across the resonances. However, as also indicated by horizontal crossings in the (a, e) plane, brief periods of ‘trapping’ in mean motion resonances (Michel et al. 1996), including three-body resonances of the Jupiter-Saturn-asteroid type (Morbidelli & Nesvorný 1999), can compensate the inefficient Martian encounters. Fig. 3 shows some examples of resonance-trapping for the same orbit as in Fig. 1.

In order to obtain statistically improved estimates of the dynamical lifetime of Albert, two groups of ‘clone’ orbits were integrated: (i) 10 orbits were integrated with the HYBRID integrator for 5 Myrs, their initial conditions taken by adding

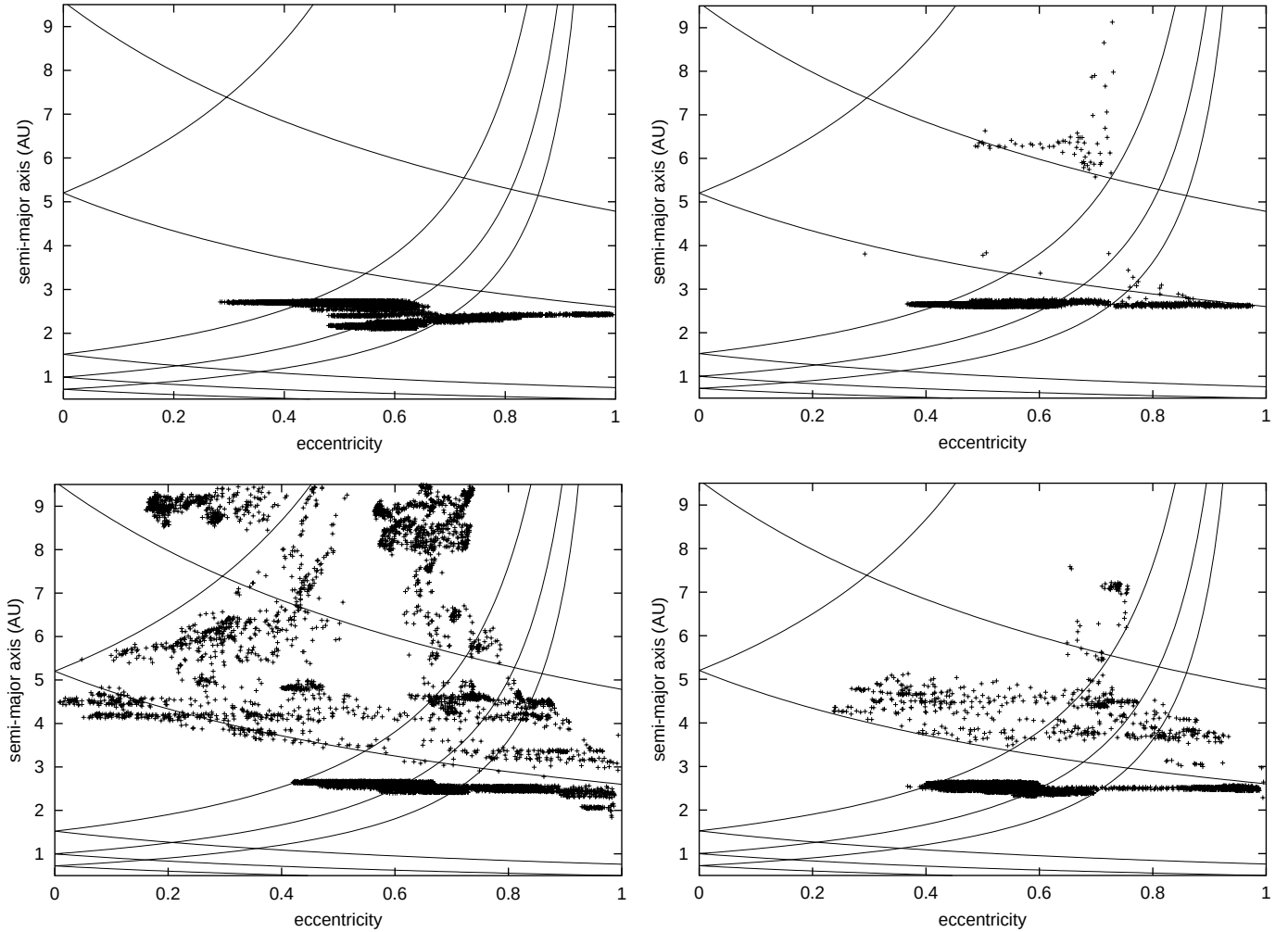


Fig. 2. Evolution of (719) Albert on the (a, e) plane. The solid lines drawn in the figures are lines at which the perihelion ($q = a(1 - e)$) or aphelion ($Q = a(1 + e)$) distances are equal to the mean semi-major axes of the planets. The top-left panel is the outcome of the BS integration; Albert falls onto the Sun. The top-right panel is the RMVS3 ($\delta t = 0.36$) integration. The bottom-left panel is just another representation of the orbit shown in Fig. 1 and the bottom-right panel is the result of the other HYBRID integration ($\delta t = 1.83$). Note that in all cases, except the BS integration, the asteroid encounters Jupiter at the apocenter of its orbit, right before falling onto the Sun. This leads to a random-walk on the (a, e) plane and, eventually, to the ejection from the solar system.

Table 3. Summary of the integration results for the two groups of clone-orbits. The integration time-step was 3 days in both integrations and the accuracy parameter of the BS used in HYBRID was again set to 10^{-15} . The percentage of *SUN*-grazers and *ejected* bodies are given along with the mean removal time, $\langle T_R \rangle$, and the mean Earth-crossing time, $\langle T_{cross} \rangle$ (both in Myrs).

Group/particles	<i>SUN</i>	<i>Ejected</i>	$\langle T_{cross} \rangle$	$\langle T_R \rangle$
HYBRID / 10	10%	70%	0.664	3.045
RMVS3 / 30	33%	34%	0.637	2.291

small random deviations to the nominal elements, within the intervals $\Delta a = 10^{-3}$ AU, $\Delta e = 0.01$, $\Delta i = 0^\circ.05$ and $\Delta \Omega = \Delta \omega = \Delta M = 0^\circ.01$, and (ii) 30 orbits, with the initial elements varying within the same intervals as before except for $\Delta a = 10^{-2}$ AU this time, were integrated with the RMVS3

method again for 5 Myrs into the future. The dynamical evolution of these fictitious objects is similar to the one described above. The mean removal time is, in both cases, of the order of 2–3 Myrs (see Table 3 for a summary). We note the fact that clones that are not removed within the integration time-span either do not cross the orbit of the Earth at all or they cross its orbit but do not undergo a significant close encounter with our planet within these 5 Myrs.

3. Conclusions

Based on the integrations performed, we can conclude that the orbit of (719) Albert is very chaotic, following an evolution typical of NEAs that are extracted from main-belt resonances by close encounters with the inner planets, and will most probably become an Earth-crosser within the next 2 Myrs. In fact, its current orbit ($a \approx 2.6$ AU) indicates that this asteroid most prob-

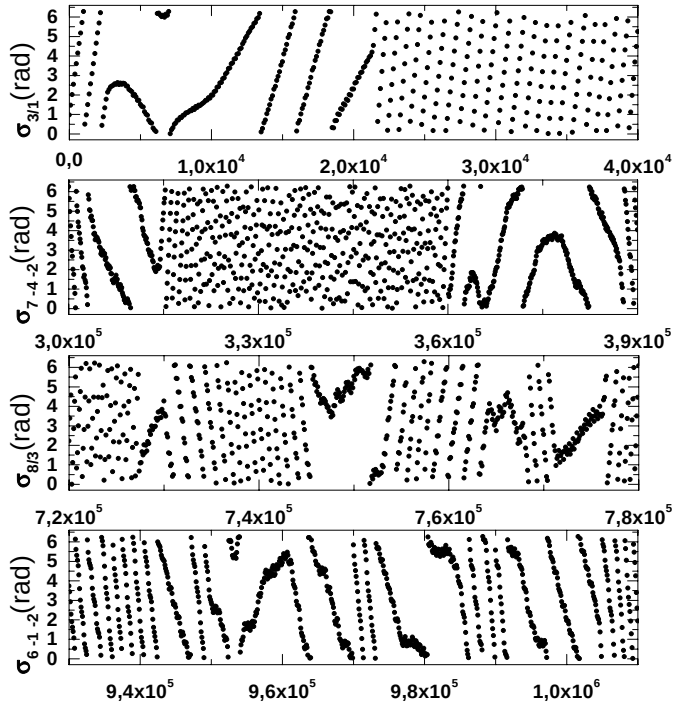


Fig. 3. The critical arguments corresponding to resonances in which Albert (the same orbit as in Fig. 1) is briefly trapped. Alternation between libration and circulation implies the crossing of the separatrix of the respective resonance. Time increases from top to bottom (note the different time-scale in each plot). The arguments shown here are related to the 3/1 mean motion resonance with Jupiter, the 7 -4 -2 three-body resonance (Jupiter-Saturn-asteroid), the 8/3 mean motion resonance with Jupiter and the 6 -1 -2 three-body resonance, respectively.

ably originated from the region covered by the 3/1 mean motion or the ν_6 secular resonance, two dynamical mechanisms that are

most efficient in delivering NEAs. Performing an integration of the 10-clone orbits' group (HYBRID) for 5 Myrs into the past, 9 (of 10) clones were seen to enter these two resonances; brief periods of trapping in other secular resonances (including Kozai resonance) where also found.

No collision was recorded in our integrations, but the possibility of such a hazardous event to occur, in the far future, cannot be ruled out - the extreme chaoticity of Albert preventing us from making orbit predictions even for times of the order of 1000 years. However, as our results indicate, the most probable fate of this object is that, in accordance with the presently accepted scenario for NEAs, it will either fall onto the Sun or be ejected from the solar system on a hyperbolic orbit.

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