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LONG-TERM EVOLUTION OF 1991 DA: A DYNAMICALLY EVOLVED EXTINCT HALLEY-TYPE COMET

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ABSTRACT

The long-term dynamical evolution of 21 variational orbits for the intermediate-period asteroid 1991 DA has been followed for up to $\pm 10^5$ years from the present. 1991 DA is close to the 2:7 resonance with Jupiter; it avoids close encounters, within 1 AU, with this planet for at least the past 30,000 years even at the node crossing. The future evolution typically shows no close encounters with Jupiter within at least 50,000 years. This corresponds to the mean time between node crossings with either Jupiter or Saturn. Close encounters with Saturn and Jupiter lead to a chaotic evolution for the whole ensemble, while secular perturbations cause large-amplitude swings in eccentricity and inclination (the latter covering the range $15° \lesssim i \lesssim 85°$) which correlate with deep excursions of the perihelion distance to values much less than 1 AU. These variations are similar to those found in P/Machholz and a variety of other high-inclination orbits, *e.g.* P/Hartley-IRAS. We emphasize the connexion between the orbital evolution of 1991 DA and that of Halley-type comets. If 1991 DA was once a comet, it is not surprising that it is now extinct.

INTRODUCTION

1991 DA is the only known asteroid which moves in an intermediate-period comet-like orbit of high inclination; its perihelion distance ($q \simeq 1.58$ AU) and inclination ($i \simeq 61°.9$) suggest that it should be classified as a Halley-type comet; but, despite deep imaging with CCD detectors (IAUC 5208), no outgassing has yet been reported. The evolution of 1991 DA is of exceptional interest, and in order to clarify the possible dynamical history we have carried out a long-term integration of an ensemble of 21 orbits with initial elements similar to those of the present object (*cf.* Hahn & Bailey 1990).

We consider initial orbits centred on the elements of 1991 DA as reported in March 1991. The variational elements were chosen so as to cover the expected uncertainty in this preliminary orbit, and a comparison with more recently published elements (MPC 18127 and MPC 18299) shows that this procedure was justified. The integrations covered $\pm 90,000$ years and $\pm 100,000$ years, the former using the orbit reported in IAUC 5208 and a 6-planet solar system (Earth+Moon through Neptune), the latter using the orbit reported in MPC 17971 and a 4-planet solar system (Jupiter through Neptune). The elements for 1991 DA and some representative test particles are shown in Table 1.

The integrations were carried out using the variable-step-size integrator RADAU to 15th order (RA 15) described by Everhart (1985). The 4-planet solar system model was calculated with an initial step size of 40 days and an internal accuracy parameter of 10^{-12}, and the 6-planet model with a smaller initial step size (1 day) and higher accuracy (10^{-13}). Details of all close encounters within 1 AU of the Jovian planets and 0.1 AU of the terrestrial planets were recorded, whilst away from close encounters the positions and velocities of each body were sampled every 2,500 days.

LONG-TERM EVOLUTION

Although 1991 DA crosses the orbit of Mars, Jupiter, Saturn and Uranus, suggesting that its orbital evolution (like that of many planet-crossing asteroids; Milani *et al.* 1989) should be strongly chaotic, a striking feature of our results is the orbit's extreme stability. This is illustrated in Figure 1 which shows the evolution of DA 06 (6) for $\pm 90,000$ yr. Although 1991 DA is now close to the 2/7 mean-motion resonance with Jupiter, most of the orbits in our ensemble are in associated higher-order resonances, sometimes jumping from one to another due to weak planetary perturbations. This situation persists for approximately the first $\pm 30,000$ years from the present; Jupiter is the controlling planet, but perturbations by Saturn, and to a lesser extent Uranus and Mars, also play a rôle.

A detailed description of our results is given by Bailey & Hahn (1992), but it is clear from Figure 1 that the orbit's remarkable stability is due to the lack of close encounters with Jupiter and Saturn. The first

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Object	a (AU)	e	i (deg)	M (deg)	Epoch (JD)
1991 DA (6)	11.863912	0.866923	61.8932	0.000	2448228.4579
DA 01 (6)	11.863	0.8668	61.89	0.000	2448228.5000
DA 02 (6)	11.863	0.8669	61.89	0.000	2448228.5000
DA 03 (6)	11.863	0.8670	61.89	0.000	2448228.5000
DA 05 (6)	11.864	0.8669	61.89	0.000	2448228.5000
DA 09 (6)	11.865	0.8670	61.89	0.000	2448228.5000
1991 DA (4)	11.8639121	0.8669226	61.89324	1.72553	2448300.0000
DA 00 (4)	11.863912	0.866923	61.8932	0.000	2448228.4579
DA 01 (4)	11.75	0.866	61.89	1.73	2448300.0000
DA 02 (4)	11.75	0.867	61.89	1.73	2448300.0000
DA 03 (4)	11.75	0.868	61.89	1.73	2448300.0000
DA 05 (4)	11.85	0.867	61.89	1.73	2448300.0000
DA 09 (4)	11.95	0.868	61.89	1.73	2448300.0000

Table 1: Orbital elements for 1991 DA and test particles DAnn. Those marked (6) were integrated in a 6-planet model solar system with angular elements $\Omega = 313^\circ.4108$ (1991 DA), rounded to $313^\circ.41$ (DAnn), and $\omega = 191^\circ.2467$ (1991 DA), rounded to $191^\circ.25$ (DAnn). Those marked (4) were integrated in a 4-planet model solar system with angular elements $\Omega = 313^\circ.41077$ (1991 DA) and $313^\circ.4108$ (DA 00), rounded to $313^\circ.41$ (DAnn), and $\omega = 191^\circ.24673$ (1991 DA) and $191^\circ.2467$ (DA 00), rounded to $191^\circ.25$ (DAnn).

Saturn encounters (at $t \lesssim -20,000$ yr and $t \gtrsim 40,000$ yr) cause small orbital changes which may or may not break the mean-motion resonance with Jupiter, while some particles remain protected from close encounters with Jupiter at the first node crossing.

Figure 1 also shows libration of the critical argument σ for DA 06 (6), in which the semi-major axis is close to one or another mean-motion resonance with Jupiter for almost the whole time considered. The critical argument σ is defined, for an asteroid in the the $(p+q)/p$ resonance, by $\sigma = (p+q)\lambda_J - p\lambda - q\varpi$

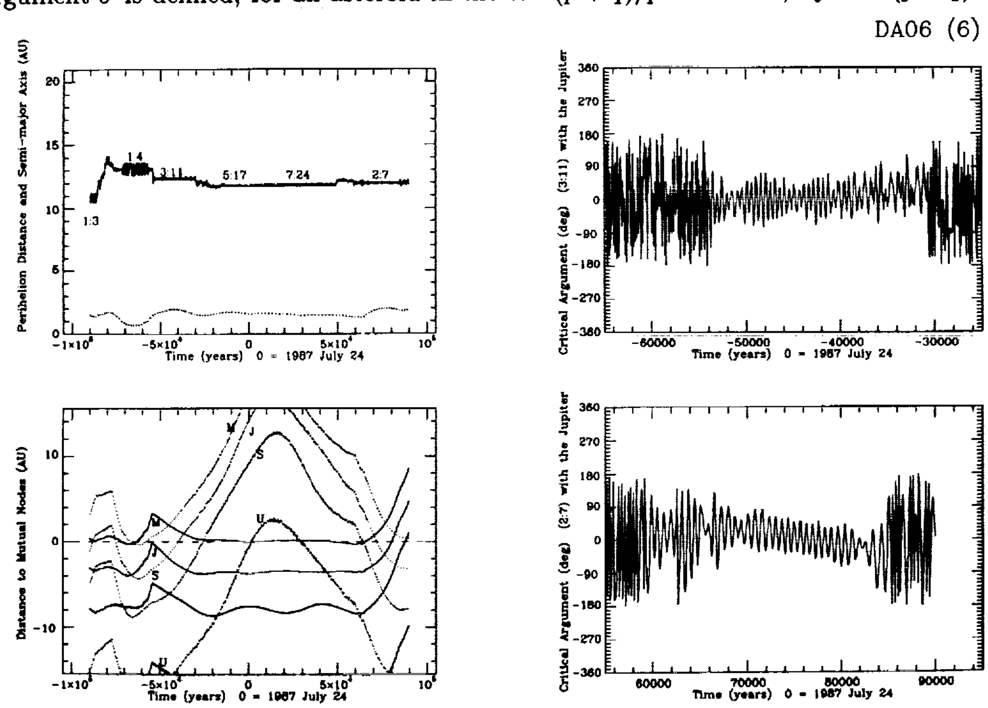

Figure 1: Evolution of DA 06 (6) for $\pm 90,000$ yr in a 6-planet model solar system, showing extreme stability of the present orbit and mean-motion resonances. The distances to the mutual nodes with respect to Mars, Jupiter, Saturn and Uranus are also shown, as too are the librations of the critical argument σ.

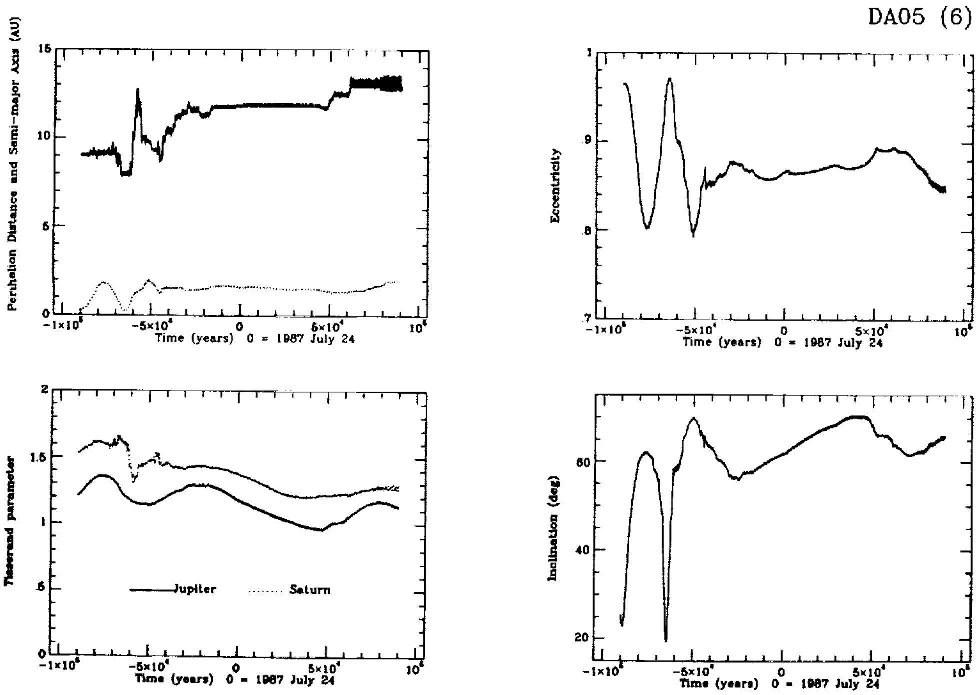

Figure 2: Evolution of DA 05 (6) for $\pm 90,000$ yr from the present, showing the semi-major axis and perihelion distance, the Tisserand parameters with respect to Jupiter and Saturn, and the deep surges in eccentricity and perihelion distance correlating with large swings in inclination.

(Yoshikawa 1989), where λ and λ_J are the mean longitudes of the asteroid and Jupiter respectively, and ϖ denotes the longitude of perihelion of the asteroid. p and q are integers; *e.g.* $p = 7$ and $q = -5$ for the 2/7 resonance. A qualitatively similar behaviour was observed for other orbits in the ensemble, though following close encounters with Saturn most did not remain protected against close encounters with Jupiter.

An important feature of the evolution is the length of time in which only slight changes in semi-major axis occur. The semi-major axis stays close to a mean-motion resonance with Jupiter for a time comparable with the period between node crossings with Jupiter or Saturn, and during these relatively stable periods large excursions in the perihelion distance, eccentricity and inclination occur (Figure 2). This behaviour is characteristic of the evolution of high-inclination, intermediate-period orbits with small perihelion distance, and is seen in P/Machholz (Green *et al.* 1990, McIntosh 1990), and also in long-term integrations of P/Hartley-IRAS and the sungrazers (Bailey *et al.* 1991a).

Although several bodies were briefly captured to or from longer periods, there was only one case of ejection to a parabolic orbit. This indicates a dynamical half-life for 1991 DA on the order of 1–3 Myr. Since this is probably much shorter than the time necessary for evolution of a mainbelt asteroid into an orbit with the inclination and eccentricity observed in 1991 DA we conclude that a cometary source for 1991 DA is the more likely. During a dynamical lifetime on the order of 2 Myr, it presents itself to Jupiter and Saturn many times (*i.e.* at intervals on the order of the node-crossing period, $\approx 5 \times 10^4$ yr), suffering close encounters at each node crossing, and eventually undergoes a chaotic orbital evolution.

DISCUSSION

These arguments suggest that 1991 DA is indeed an extinct comet, probably captured by Jupiter within the past 1 Myr from a nearly parabolic orbit of originally small perihelion distance ($\lesssim 2$ AU) and inclination on the order of 45° or more. There is an important link between 1991 DA and active comets of the Halley family, and with orbits such as those of P/Machholz and P/Hartley-IRAS, and our calculations provide firm evidence that 1991 DA has been circulating in more or less its present orbit for at least the past 25,000 yr — and will probably continue to do so for another 50,000 yr. With a period close to 40 yr, it has already made at least 600 revolutions with a perihelion distance on the order of 1 AU, some of which may have included episodes of even smaller q. From this point of view it is not surprising that 1991 DA is inactive, though observations should be continued in order to detect residual outgassing.

With a near-parabolic flux of comets with perihelion distances $q \lesssim 2$ AU on the order of $1\,\mathrm{yr}^{-1}$ (Bailey *et al.* 1991b) and an inclination-averaged capture probability to periods less than 200 yr on the order of $(1\text{–}3)\times10^{-3}$ (*cf.* Stagg & Bailey 1989), Halley-type comets are produced at a rate on the order of 1–3 per 10^3 years. If the active physical lifetime is about 10^4 yr, the steady-state number of Halley-type comets should be around 20, in reasonable agreement with observations. Subsequent evolution of the cometary core leads either to total disintegration of the nucleus or to ejection of the remaining body after a time on the order of 1–3 Myr, most of which is presumably spent as an inert asteroid-like body. Unless the cometary nucleus is extremely fragile (with a physical lifetime comparable to the active cometary phase), one would expect many such extinct cometary cores to be circulating in high-inclination orbits similar to 1991 DA. These undiscovered bodies may be an important source of dust in the inner solar system and would represent a significant 'cometary' source for craters on the terrestrial planets. The source would be time-dependent (since it responds within about 1 Myr to variations in the near-parabolic flux), with important implications for mechanisms aimed at explaining possible cyclicity in the terrestrial cratering rate (Bailey *et al.* 1987, Clube & Napier 1990, Bailey *et al.* 1990).

Finally, we emphasize that close planetary encounters or strong non-gravitational forces during the small-q phases of evolution may allow some high-inclination near-earth asteroids such as 1973 NA or 1982 YA (see Milani *et al.* 1989 for their dynamical evolution) to be produced from orbits like that of 1991 DA (*cf.* Nakamura 1983). Further observations of 1991 DA should be encouraged, as too should searches to discover other 'unexpected asteroids' far from the ecliptic plane.

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