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Orbital Evolution of Příbram and Neuschwanstein

Leonard Kornoš · Juraj Tóth · Peter Vereš

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Abstract The orbital evolution of the two meteorites Příbram and Neuschwanstein on almost identical orbits and also several thousand clones were studied in the framework of the N-body problem for 5,000 years into the past. The meteorites moved on very similar orbits during the whole investigated interval. We have also searched for photographic meteors and asteroids moving on similar orbits. There were five meteors found in the IAU MDC database and six NEAs with currently similar orbits to Příbram and Neuschwanstein. However, only one meteor 161E1 and one asteroid 2002 QG46 had a similar orbital evolution over the last 2,000 years.

Keywords Meteorite · Meteoroid · Asteroid · Příbram · Neuschwanstein

1 Introduction

It is almost 50 years since the fall (April 7, 1959) and recovery of the Příbram meteorite (Ceplecha 1961), the first meteorite with a precisely known heliocentric orbit (Table 1). Later, the fall of the Neuschwanstein meteorite was observed on April 6, 2002 and it was successfully recovered (Oberst et al. 2004). It was shown that both meteorites were moving on similar orbits (Spurný et al. 2003), but the question about their origin remains unanswered. Moreover, their different meteoritic types, Příbram being an H5 ordinary chondrite (Ceplecha 1961) with cosmic-ray exposure age 12 Myr (Stauffer and Urey 1962) and Neuschwanstein an EL6 enstatite chondrite with cosmic-ray exposure age 48 Myr (Bishoff and Zipfel 2003; Zipfel et al. 2003), makes their common origin very problematic. It is a challenge for the scientific community to explain the dynamical and physical evolution of these two meteorites. Earlier, the existence of asteroidal-meteoritic streams was suggested by Halliday et al. (1990). Recently, the observation of Neuschwanstein led Spurný et al. (2003) to suggest a heterogeneous meteoritic stream in the orbit of Příbram. On the other

L. Kornoš · J. Tóth (✉) · P. Vereš
Department of Astronomy, Physics of the Earth and Meteorology, Faculty of Mathematics, Physics and Informatics, Comenius University, Mlynská dolina, 842 48 Bratislava, Slovak Republic
e-mail: toth@fmph.uniba.sk

Table 1 Orbital elements (eq. 2000.0) of Příbram and Neuschwanstein (Spurný et al. 2003)

	Příbram	Neuschwanstein
a	2.401 ± 0.002 AU	2.40 ± 0.02 AU
e	0.6711 ± 0.0003	0.670 ± 0.002
q	0.78951 ± 0.00006 AU	0.7929 ± 0.0004 AU
Q	4.012 ± 0.005 AU	4.01 ± 0.03 AU
ω	241.750° ± 0.013°	241.20°± 0.06°
Ω	17.79147°± 0.00001°	16.82664° ± 0.00001°
i	10.482° ± 0.004°	11.41° ± 0.03°

hand, a statistical analysis by Pauls and Gladman (2005) showed that the occurrence of pairs as close as Příbram and Neuschwanstein is at the 10% level, which is consistent with random chance. Recently, Jones and Williams (2007) studied the possible existence of meteoritic streams. Trigo-Rodríguez et al. (2007), performing orbital and spectral analyses, found three meteorite-dropping bolides, which may well be associated with the Near Earth Asteroid 2002 NY40. In the present paper, we analyze possible associations of meteors and NEAs with Příbram and Neuschwanstein and also their orbital evolutions on a time scale of 5,000 years. Also, we discuss the possible common origin of Příbram and Neuschwanstein.

2 Associations with Příbram and Neuschwanstein

The heliocentric orbits of Příbram and Neuschwanstein are almost identical (Table 1), but the errors in the orbital elements of Neuschwanstein are about 1 order of magnitude larger compared to Příbram. However, both orbits are relatively precise and the D-criterion of Southworth and Hawkins (1963), $D_{SH} = 0.03$, indicates a very close similarity.

We have searched for possible members of a meteoroid stream, to be associated with the meteorites, in the IAU Meteor Database of Photographic Orbits (Lindblad et al. 2003) based on $D_{SH} \leq 0.2$ (cf. Jones et al. 2006). There were five meteoroids found, which are listed in Table 2 (for details of the designations see Neslušan 2003) and compared to the orbit of Příbram. While the Příbram and Neuschwanstein entry masses were several hundred kilograms, the other meteoroids mentioned in Table 2 are very small. The photometric mass of the largest one, 161E1, is about 2,100 g.

Table 2 Orbital elements (eq. 2000.0), geocentric velocity V_g, geocentric radiant (*RA* and *DC*), magnitude and D-criterion of Příbram and Neuschwanstein meteorites (Spurný et al. 2003) as well as five meteoroids from the IAU Meteor Database (Lindblad et al. 2003)

Meteoroid	q (AU)	a (AU)	e	i (°)	ω (°)	Ω (°)	π (°)	V_g (km/s)	*RA* (°)	*DC* (°)	Mag	D_{SH}
Příbr	0.790	2.401	0.671	10.5	241.8	17.8	259.5	17.43	192.3	17.5	−19.2	–
Neusch	0.793	2.400	0.670	11.4	241.2	16.8	258.0	17.51	192.3	19.5	−17.2	0.03
012F1	0.776	2.217	0.650	0.7	244.6	16.6	261.3	16.41	183.3	0.2	−6.7	0.17
161E1	0.817	2.696	0.697	9.6	236.5	18.9	255.4	16.95	189.5	17.8	−10.8	0.06
079H1	0.863	2.757	0.687	8.9	228.7	19.8	248.4	15.43	185.4	20.6	2.4	0.15
130F1	0.774	2.867	0.730	16.1	242.5	20.2	262.7	19.93	200.3	22.6	−10.7	0.12
083H1	0.821	2.582	0.682	4.9	236.5	21.7	258.1	16.01	186.9	8.6	2.0	0.10

Table 3 Orbital elements (eq. 2000.0) of Příbram (Spurný et al. 2003) as well as six objects from the NEA database (Bowell 2007)

Name	q	a	e	i	ω	Ω	π	$H(1,0)$	D_{SH}
Příbram	0.790	2.401	0.671	10.5	241.8	17.8	259.5		
1998 SJ70	0.656	2.236	0.706	7.4	244.4	23.8	268.2	18.3	0.18
2002 EU11	0.746	2.397	0.689	2.9	274.5	346.3	260.8	20.9	0.15
2002 QG46	0.905	2.434	0.628	8.3	268.2	346.0	254.2	19.6	0.17
2003 RM10	0.755	1.847	0.591	13.7	287.0	341.6	268.6	20.2	0.20
2005 GK141	0.938	2.735	0.657	14.0	218.2	34.2	252.5	22.1	0.19
2005 RW3	0.754	2.107	0.642	2.7	218.9	49.4	268.3	22.8	0.18

$H(1,0)$ is the absolute magnitude of NEAs and D_{SH} is the D-criterion

Also we have searched for a possible parent body among Near Earth Asteroids. We have found six NEAs from the current (April 2007) Bowell (2007) database, within $D_{SH} \leq 0.2$. The osculating orbital elements compared to Příbram are listed in Table 3.

Similarity of osculating orbits is not enough to prove any association among the orbits mentioned above. Therefore we have looked for similarity in orbital evolution over the past 5,000 years. We have numerically integrated the motion of the Příbram and Neuschwanstein meteorites, the five meteoroids and six NEAs using the multi-step procedure of the Adams–Bashforth–Moulton 12th order method, with a variable step-length. The positions of the perturbing major planets were obtained from the JPL Ephemeris DE406.

Only the orbital evolution of the best associations are presented in Fig. 1. The D_{SH} between Příbram and Neuschwanstein is within 0.07 and also the difference in the longitude of perihelion is very small ($\Delta\pi \leq 3°$) during the integration time of 5,000 years. This indicates a very close orbital evolution between the two meteorites. Only one meteoroid 161E1 and one asteroid 2002 QG46 were found with reasonably similar evolution to the meteorites in the last 2,000 years or so. However, the orbital evolution of asteroid 2002 QG46 is not so close to Příbram. So we prefer only the meteoroid 161E1 as a possible association.

3 Clones of Příbram and Neuschwanstein

Pauls and Gladman (2005) integrated Příbram's orbit for several hundred thousand years and showed that the substantial decoherence of the modeled stream occurred in about 50,000 years. However, here we study the orbital evolution of clones covering the error intervals of Příbram's and Neuschwanstein's orbital elements in order to check the stability of their orbital regions.

We have distributed five values equidistantly within the error interval of each parameter (semimajor axis, eccentricity, inclination, argument of perihelion and mean anomaly). The sixth parameter, the longitude of node, remained fixed, being of two orders better precision. Using the combinations of five values in five orbital parameters, 3,125 clones were obtained for each meteorite.

We have numerically integrated the clones of Příbram and Neuschwanstein over the past 5,000 years. The orbital evolution of all clones is more or less similar and stable. The clones of Příbram are less spread at the end of integration due to the smaller initial dispersion. The largest dissimilarity in the orbital evolution is caused by different initial semimajor axes of

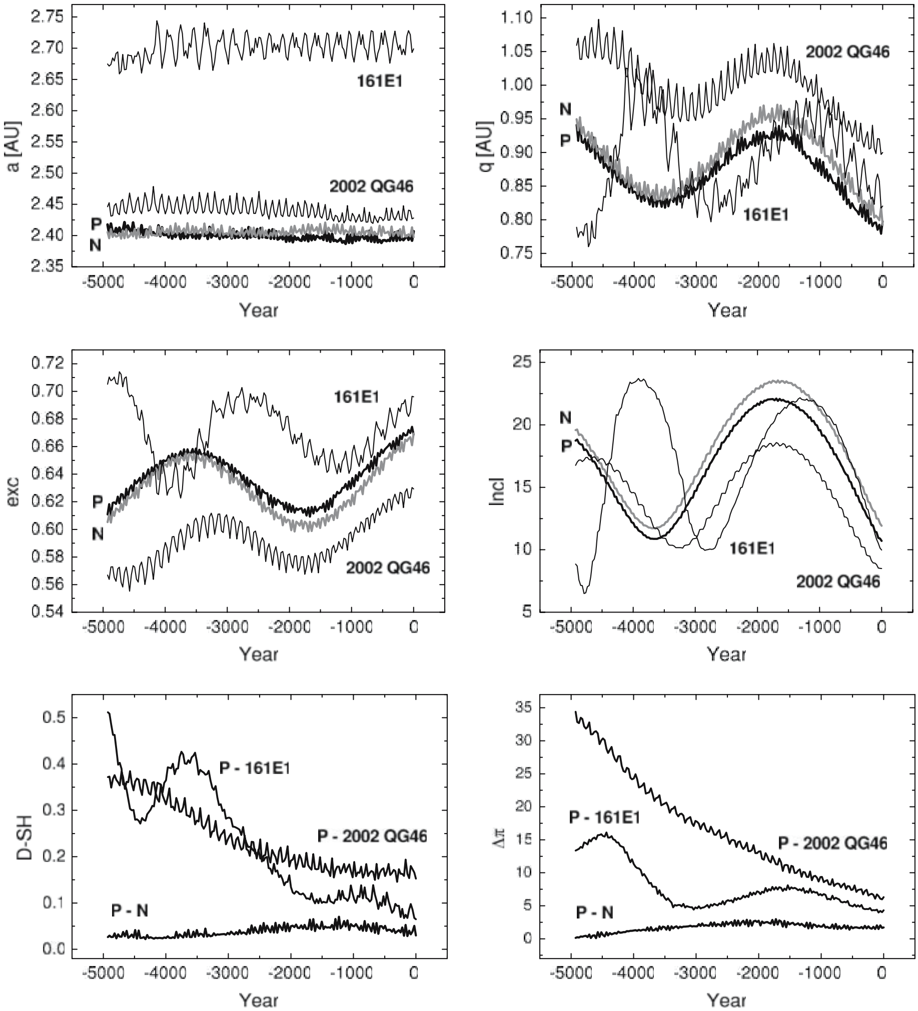

Fig. 1 The orbital evolution in semimajor axis a, perihelion distance q, eccentricity e, inclination i, D-criterion and difference in longitude of perihelion $\Delta\pi$ of Příbram (P), Neuschwanstein (N), meteor 161E1 and asteroid 2002 QG46

clones. A comparison of the orbital evolution of Neuschwanstein clones that have semimajor axes at the edges of the error interval ($a = 2.38$ AU and $a = 2.42$ AU) is presented in Fig. 2. As can be seen, the evolution of both sets of clones is very similar. Essentially the only difference is that the period of the variations in perihelion, eccentricity and inclination for the clones with $a = 2.42$ AU is shorter than for the clones with $a = 2.38$ AU. This is caused by the distance of the orbit from the orbit of Jupiter being smaller, as shown by Wu and Williams (1992). The descending nodes of almost all clones are stable and close to the Earth's orbit during the last 3,000 years. The longitude of the ascending node is dispersed by about 10° after 5,000 years of evolution. If we suppose that our clones represent a meteoroid stream, then it would have a similar dispersion of the orbital elements as that depicted in Fig. 2. The possible stream could be active for at least ±5 days around the date of the Příbram fall.

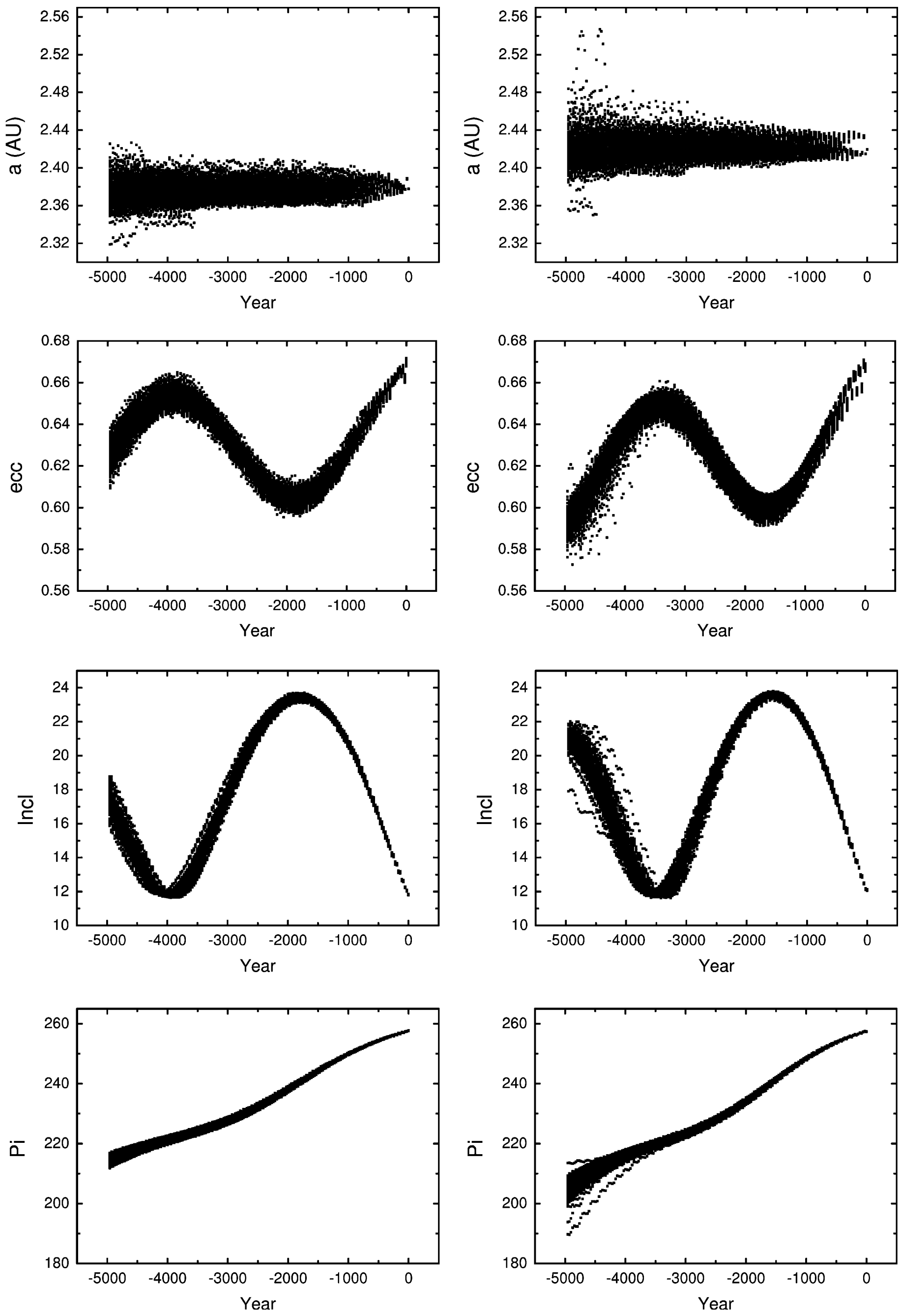

Fig. 2 The orbital evolution in semimajor axis, eccentricity, inclination and longitude of perihelion of clones of Neuschwanstein. The left set of graphs presents the clones for the initial semimajor axis $a = 2.38$ AU and the right set for $a = 2.42$ AU

Analysis of the orbital evolution has shown that 75% of the clones of Příbram and 84% of Neuschwanstein experienced close encounters with the Earth within 0.028 AU in the last 5,000 years. This distance is equivalent to a gravitational perturbation by Jupiter from a distance of 0.5 AU with respect to the perturbed body. Closer approaches caused a larger spread in the orbital elements at the end of the integration (Fig. 2). Some of the clones undergo more than one close approach to the Earth. Only a few clones encountered Mars also.

The results of the orbital integration of the clones of Příbram and Neuschwanstein show that the orbits are rather stable over several thousand years. A body with slightly different orbital elements from Příbram would then also have a similar evolution. Is it possible that Příbram and Neuschwanstein have such close orbits by chance?

We are interested in an occurrence of orbits of Příbram type in a five dimensional space of orbital elements. In our previous paper (Vereš et al. 2006), we generated and modeled 10^7 synthetic orbits of 10 m size bodies according to the NEA orbit distribution of Bottke et al. (2000) and population distribution of Stuart and Binzel (2004). A probability was found for the occurrence of each orbital element $(a, e, i, \omega, \Omega)$ within the error boundaries of Příbram and Neuschwanstein. Then the overall chance of this type of orbit occurring at random is the product of the probabilities in each element. The resultant probability is very small, only 2.75×10^{-11}.

When we extend this NEA synthetic population to smaller objects, of the initial radius of the Neuschwanstein meteoroid 0.3 m (ReVelle et al. 2004), we obtain a population with a cumulative number of 2.5×10^9 (Stuart and Binzel 2004) or 1.4×10^{11} (Brown et al. 2002) bodies. Then the expected occurrence of orbits within the error interval of Příbram and Neuschwanstein could be from 0.07 to 4 orbits depending on the real cumulative number in the NEA population.

4 Conclusions

If the real number of meteorite producing bodies of size $\sim$0.6 m in the NEA population is about 10^{11}, we would expect at least one very close pair in the Příbram region. This is in good agreement with conclusions of Pauls and Gladman (2005) that the occurrence of such close orbits is by chance. On the other hand, considering a more conservative assessment of 10^9 bodies in the NEA population, the probability of the existence of the Příbram and Neuschwanstein pair is very low. Moreover, this probability seems to be even smaller when we take into account the fact that both bodies entered the Earth's atmosphere within a time interval of 43 years, as was mentioned by Spurný et al. (2003).

Based on our dynamical investigation described above, we are in favour of the hypothesis of a common origin of the Příbram and Neuschwanstein meteorites from a heterogeneous parent asteroid. The close evolution of the two orbits over several thousand years is not a proof (e.g., Porubčan et al. 2004; Jones et al. 2006; Trigo-Rodríguez et al. 2007), but it does give significant support to suspicions about their common origin. The parent body of these meteorites could be a rubble pile asteroid which can possess heterogeneous material gravitationally aggregated after collisions. In another paper (Vereš et al. 2007) it has been proposed that relatively recent release of meteoroids from a parent asteroid by the Earth's tidal force is possible at substantially larger distances than the Roche limit. At such distances the differential gravitational influence would be insufficient to disperse the orbits of released meteoroids from the parent body. That is why we expect similar orbits of the parent body and Příbram and Neuschwanstein. We suppose that the different cosmic-ray ages of the meteorites are affected by having different cosmic radiation exposure times during which they were exposed on the surface of the “parent” body.

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