Orbital evolution of Příbram and Neuschwanstein

Leonard Kornoš · Juraj Tóth · Peter Vereš

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 5000 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 5 meteors found in the IAU MDC database and 6 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 2000 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 (Tab. 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 (Stauf-fer 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...
Table 1 Orbital elements (eq. 2000.0) of Příbram and Neuschwanstein (Spurný et al. 2003).

|       | Příbram                  | Neuschwanstein        |
|-------|--------------------------|-----------------------|
| $a$   | $2.401 \pm 0.002$ AU     | $2.40 \pm 0.02$ AU    |
| $e$   | $0.6711 \pm 0.0003$      | $0.670 \pm 0.002$     |
| $q$   | $0.78953 \pm 0.00006$ AU | $0.7929 \pm 0.0004$ AU|
| $Q$   | $4.012 \pm 0.005$ AU     | $4.01 \pm 0.03$ AU    |
| $\omega$ | $241.750^\circ \pm 0.013^\circ$ | $241.20^\circ \pm 0.06^\circ$ |
| $\Omega$ | $17.79147^\circ \pm 0.00001^\circ$ | $16.82664^\circ \pm 0.00001^\circ$ |
| $i$   | $10.482^\circ \pm 0.004^\circ$ | $11.41^\circ \pm 0.03^\circ$ |

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 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 5000 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 (Tab. 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 5 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 2100 g.

Also we have searched for a possible parent body among Near Earth Asteroids. We have found 6 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 5000 years. We have numerically integrated the motion of the Příbram and Neuschwanstein meteorites, the 5 meteoroids and 6 NEAs using the multi-step procedure of the Adams-Bashforth-Moulton 12th order method, with a variable step-
Table 2 Orbital elements (eq. 2000.0), geocentric velocity $V_g$, geocentric radiant ($RA$ and $DC$), magnitude and D-criterion of Príbram and Neuschwanstein meteorites (Spurný et al. 2003) as well as 5 meteoroids from the IAU Meteor Database (Lindblad et al. 2003).

| meteoroid | $q$ (AU) | $a$ (AU) | $e$ | $i$ (°) | $\omega$ (°) | $\Omega$ (°) | $\pi$ (°) | $V_g$ (km/s) | $RA$ (°) | $DC$ (°) | $mag$ | $D_{SH}$ |
|-----------|----------|----------|-----|--------|-------------|-------------|--------|-------------|--------|--------|-------|--------|
| Príbrm    | 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 Príbram (Spurný et al. 2003) as well as 6 objects from the NEA database (Bowell 2007). $H(1,0)$ is the absolute magnitude of NEAs and $D_{SH}$ is the D-criterion.

| name      | $q$ (AU) | $a$ (AU) | $e$ | $i$ (°) | $\omega$ (°) | $\Omega$ (°) | $\pi$ (°) | $H(1,0)$ | $D_{SH}$ |
|-----------|----------|----------|-----|--------|-------------|-------------|--------|----------|--------|
| Príbram   | 0.790    | 2.401    | 0.671 | 10.5   | 241.8       | 17.8        | 259.5  | 17.43       | 192.3  | 17.5   | -19.2 | -      |
| 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   |

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 Figure 1. The $D_{SH}$ between Príbram and Neuschwanstein is within 0.07 and also the difference in the longitude of perihelion is very small ($\Delta\pi \leq 3^\circ$) during the integration time of 5000 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 2000 years or so. However, the orbital evolution of asteroid 2002 QG46 is not so close to Príbram. So we prefer only the meteoroid 161E1 as a possible association.

3 Clones of Príbram and Neuschwanstein

Pauls and Gladman (2005) integrated Príbram’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 Príbram’s and Neuschwanstein’s orbital elements in order to check the stability of their orbital regions.

We have distributed 5 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 5 values in 5 orbital parameters, 3125 clones were obtained for each meteorite.
We have numerically integrated the clones of Příbram and Neuschwanstein over the past 5000 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 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 Figure 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 3000 years. The longitude of the ascending node is dispersed by about
10° after 5000 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 Figure 2. The possible stream could be active for at least ±5 days around the date
of the Příbram fall.

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 5000 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
caus’d a larger spread in the orbital elements at the end of the integration (Figure 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 5 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 \(2.75 \times 10^{-11}\).

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 \(2.5 \times 10^9\) (Stuart and Binzel, 2004) or \(1.4 \times 10^{11}\)
(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.
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.
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.

Acknowledgements This work was supported by VEGA - the Slovak Grant Agency for Science (grant No. 1/3067/06) and by Comenius University grant UK/401/2007. The authors are grateful to reviewers I.P. Williams and D. Asher for valuable suggestions.

References

1. Bishoff A, Zipfel J (2003) Mineralogy of the Neuschwanstein (EL6) Chondrite - First Results (abstract 1212) 34th Lunar and Planetary Science Conference
2. Bottke WF, Jedicke R, Morbidelli A, Gladman B, Petit J-M (2000) Understanding the distribution of near-Earth objects Science 288:2190–2194
3. Bowell T (2007) Asteroid Orbital Element Database [http://alumnus.caltech.edu/~nolan/astorb.html]
4. Brown P, Spalding RE, ReVelle DO, Tagliaferri E, Worden SP (2002) The flux of small near-Earth objects colliding with the Earth Nature 420:294–296
5. Ceplecha Z (1961) Multiple fall of Příbram meteorites photographed. I. Double-station photographs of the fireball and their relations to the found meteorites Bull. Astron. Inst. Czech. 12:21–47
6. Halliday I, Blackwell AT, Griffin AA (1990) Evidence for the existence of groups of meteorite-producing asteroidal fragments Meteoritics 25:93–99
7. Jones DC, Williams IP, Porubčan V (2006) The Kappa Cygnid meteoroid complex Mon. Not. R. Astron. Soc. 371:684–694
8. Jones DC, Williams IP (2007) High Inclination Meteorite Streams can Exist Earth Moon Planets (This volume)
9. Lindblad BA, Neslušan L, Svoreň J, Porubčan V (2003) IAU Meteor Database of photographic orbits version 2003 Earth Moon Planets 95:249–260
10. Neslušan L (2003) IAU Meteor Database of Photographic Orbits [http://www.astro.sk/~ne/IAUMDC/Ph2003/DATA2003/document.txt]
11. Oberst J, Heinlein D, Köhler U, Spurný P (2004) Meteorit. Planet. Sci. 39:1627–1641
12. Pauls A, Gladman, B (2005) Decoherence time scales for "meteoroid streams" Meteorit. Planet. Sci. 40(8):1241–1256
13. Porubčan V, Williams IP, Kornoš L (2004) Associations Between Asteroids and Meteoroid Streams Earth Moon Planets 95:697–712
14. ReVelle DO, Brown PG, Spurný P (2004) Entry dynamics and acoustics/infrasonic/seismic analysis for the Neuschwanstein meteorite fall Meteorit. Planet. Sci. 39(10):1605–1626
15. Southworth RB, Hawkins GS (1963) Statistics of meteor streams Smithsonian. Contr. Astrophys. 7:261–285
16. Spurný P, Oberst J, Heinlein D (2003) Photographic observations of Neuschwanstein, a second meteorite from the orbit of the Příbram chondrite Nature 423:151–153
17. Stauffer H, Urey HC (1962) Multiple fall of Příbram meteorites photographed. III. Rare gas isotopes in the Velká stone meteorite Bull. Astron. Inst. Czech. 13:106–109
18. Stuart JS, Binzel RP (2004) Bias-corrected population, size distribution, and impact hazard for the near-Earth objects Icarus 170(2):295–311
19. Trigo-Rodríguez JM, Lytton E, Jones DC, Madiedo JM, Castro-Tirado AJ, Williams IP, Lloca J, Viték S, Jelínek M, Troughton B, Gálvez F (2007) Asteroid 2002NY40 as a source of meteorite-dropping bolides Mon. Not. R. Astron. Soc. doi: 10.1111/j.1365-2966.2007.12503.x
20. Vereš P, Kornoš L, Tóth J (2006) Search for very close approaching NEAs Contrib. Astron. Obs. Skalnaté Pleso 36:171–180
21. Vereš P, Klachka J, Kómar L, Tóth J (2007) Motion of a meteoroid released from an asteroid Earth Moon Planets (This volume)
22. Wu Z, Williams IP (1992) On the Quadrantid meteoroid stream complex Mon. Not. R. Astron. Soc. 259:617–628
23. Zipfel J, Spettel B, Schnbeck T, Palme H, Bischoff A (2003) Bulk chemistry of the Neuschwanstein (EL6) chondrite - First results (abstract 1640) 34th Lunar and Planetary Science Conference