Near Earth Objects, our Celestial Neighbors: Opportunity and Risk
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Is the near-Earth asteroid 2000 PG$_3$ an extinct comet?

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Abstract. The existence of an observed meteor shower associated with some Near-Earth Asteroid (NEA) is one of the few useful criteria that can be used to indicate that such an object could be a candidate for being regarded as an extinct or dormant cometary nucleus. In order to identify possible new NEA-meteor showers associations, the secular variations of the orbital elements of the NEA 2000 PG$_3$, with comet-like albedo (0.02), and moving on a comet-like orbit, was investigated under the gravitational action of the Sun and six planets (Mercury to Saturn) over one cycle of variation of the argument of perihelion. The theoretical geocentric radiants and velocities of four possible meteor showers associated with this object are determined. Using published data, the theoretically predicted showers were identified with the night-time September Northern and Southern δ-Piscids fireball showers and several fireballs, and with the day-time meteor associations γ-Arietids and α-Piscids. The character of the orbit and low albedo of 2000 PG$_3$, and the existence of observed meteor showers associated with 2000 PG$_3$ provide evidence supporting the conjecture that this object may be of cometary nature.

Keywords. Near-Earth Asteroids, meteoroid streams, meteor showers

1. Introduction

The real distinction between comet and asteroid is in terms of composition, the first is dominated by ices and the second by rock and metals, which is determined by their location at the formation stage. Direct determination of the internal composition is however nearly impossible for most bodies and so other indirect methods have been used. In the past, the distinction between the orbits of comets and those of asteroids were regarded as an obvious discriminant, asteroids moved on near circular orbits located somewhere between Mars and Jupiter while comets moved on highly elliptical orbits possibly with high inclination and larger semimajor axis. Over recent years this distinction has become more blurred as it was realized that the dynamical lifetime of many orbits was much shorter than the age of the solar system. New observational discoveries, particularly of the Near-Earth Object (NEO) population, with the possibility that many asteroids, particularly in this NEO population are in reality dormant or dead cometary nuclei (see for example Williams 1997), re-enforced this conclusion.

An additional discriminant that has been used is the albedo. The albedo of comets generally lie in the range 0.02 to 0.12 (Jewitt 1992) while the albedos of asteroids are much higher. Of course, this is not an infallible test, the surface of a comet nucleus can become devoid of ices and thus take on an asteroidal appearance. Conversely collisions can cause resurfacing which exposes ices on asteroids that could have been burried for millenia.

Another indication of the cometary nature of an NEA is the existence of a related meteoroid stream produced during the period of cometary activity. At present about 1700 minor meteor showers and associations have been detected either optically or by radar. In the overwhelming majority of cases the parent comets of these showers have not been identified. There are two obvious reasons why the identification has not been made, either the parent and stream have experienced very different orbital evolution as Williams & Wu (1993) suggested for the comet of 1491 and the Quadrantids, or by the transformation of the parent comets into an asteroid-like body following the cessation of outgassing.

A meteor shower can only be produced from a meteoroid stream that intersects the Earth's orbit. Hence, the search for dead or dormant comet that is associated with a meteoroid stream can only be meaningful when conducted within the NEA population. Currently, there are several thousand known NEOs and the number is increasing very rapidly. Up to now only a dozen NEOs have been shown to have associated meteor showers, (3200) Phaethon and the Geminid shower (Fox *et al.*, 1984), the Taurid NEO complex and about 40 observable meteor showers (Babadzhanov 2001), 2003 EH_1 and the Quadrantid meteor shower (Jenniskens 2004; Williams *et al.* 2004), and 9 asteroid-fireball stream association (Porubčan *et al.* 2004).

From our general understanding of meteoroid stream formation (Babadzhanov & Obrubov 1992; Babadzhanov 1998, 2001; Williams 2002), the number of meteor showers produced by a meteoroid stream corresponds to the Earth-crossing class of the parent body orbit. During a year's orbiting around the Sun, the Earth collides with those stream meteoroids which have orbital nodes at a heliocentric distance close to 1 AU, i.e. satisfying the expression:

$$\omega = \pm \arccos\{[a(1-e^2)-1]/e\}. \tag{1.1}$$

For a given a and e the Earth's orbit may be intersected at four values of ω. As a result, one meteoroid stream may produce two night-time showers at the pre-perihelion intersections and two day-time showers at the post-perihelion intersections with the Earth. For example, asteroid (3200) Phaethon is a quadruple crosser of the Earth's orbit and the meteoroids of the stream that separated from Phaethon, having various values of the argument of perihelion, can form four meteor showers: the pre-perihelion Geminids and Canis Minorids, post-perihelion Daytime Sextantids and δ-Leonids (Babadzhanov & Obrubov 1992).

In accordance with these concept, to investigate possible genetic relationships between NEOs and meteor showers we need to include the following steps (Babadzhanov & Obrubov 1992; Babadzhanov 1998, 2001):

1) The calculation of the orbital evolutions of a near-Earth object for a time interval covering one cycle of the variation in the argument of perihelion.

2) The determination of the number of crossings of the Earth orbit during one cycle of variation of the perihelion argument. The number of crossings may be from one to eight.

3) The calculation of the theoretical geocentric radiants and velocities for the Earth-crossing orbits.

4) The search for theoretically predicted radiants in catalogues of observed meteor showers and of individual meteors.

In this paper we are concerned with asteroid 2000 PG_3.

2. Asteroid 2000 PG_3

The Near-Earth Asteroid 2000PG_3, discovered on August 1, 2000, has the following orbital elements (equinox 2000.0):

Semi-major axis	$a = 2.83$ AU
Eccentricity	$e = 0.859$
Perihelion distance	$q = 0.400$ AU
Inclination	$i = 20.5°$
Longitude of ascending node	$\Omega = 326.8°$
Argument of perihelion	$\omega = 138.5°$
Longitude of perihelion	$(\pi = \Omega + \omega)\, \pi = 105.3°$

By any definition this would be regarded as more of a comet-like than asteroid-like orbit with high eccentricity and inclination. Fernandez, Jewitt & Shepard (2001) have determined the visual geometric albedo and radiometric effective radius of $2000PG_3$. They give an effective radius R and geometrical albedo p in the range of $R = 3.08 - 3.49$ km and $p = 0.021 - 0.015$. Hence, based on both its albedo and orbit, the 2000 PG_3 appears as a good candidate for an extinct or dormant cometary nucleus.

We calculated the secular variations of the orbital elements of 2000 PG_3 using the Halphen-Goryachev integration method (Goryachev 1937). Gravitational perturbations from the six planets (Mercury-Saturn) were taken into account. The perturbations by other planets are very small, and are neglected. Results of calculations show that during the time interval embracing one cycle of variations of the argument of perihelion (~ 5.000 yrs) 2000 PG_3 intersects the Earth's orbit four times.

Figure 1 shows the secular variations of the heliocentric distance to the ascending node, R_a, and descending node, R_d, of the orbit of 2000 PG_3 plotted against the argument of perihelion ω. As can be seen, one or the other of R_a and R_d has a value of unity, so that the orbit of 2000 PG_3 crosses the Earth's orbit, at the values of ω equal to $69°, 111°, 246°$ and $294°$. It is therefore possible that any meteoroid stream associated with 2000 PG_3 might produce four meteor showers. The theoretical orbital elements and the theoretical geocentric coordinates of radiant (right ascension α and declination δ) and geocentric velocity V_g (km/s), the dates of activity (and the solar longitudes L. corresponding to these dates) of the meteor showers associated with asteroid 2000 PG_3 (denoted as A, B, C, D) are given in Table 1.

We undertook a search for the predicted showers in published catalogues of observed meteor showers: Cook (1973) (C), Kashcheev, Lebedinets & Lagutin (1967) (K), Lebedinets, Korpusov & Sosnova (1972) (L), Sekanina (1973), Sekanina (1976) (S1,S2), Terentyeva (1989) (T), Cannon (2001) (C1) and Halliday, Griffin & Blackwell (1996)(H) (note that we use Halliday's notation in Table 1). In this search we required the positions of the predicted and the observed radiant to be closer than ±10° in both right ascension an declination, the difference in geocentric velocity $\Delta V_g \leqslant 5$ km/s and the period of activity to be within ±15 days of each other. We also calculated D_{SH}, the Southworth & Hawkins (1963) criterion, which serves as a measure of similarity of two orbits, and required $D_{SH} \leqslant 0.3$.

All four theoretically predicted showers associated with the asteroid 2000 PG_3 were identified. Two were identified with the real night-time September Southern and Northern δ-Piscids together with fireballs from the three fireball networks European (EN), Prairie (PN) (McCrosky *et al.* 1978) and MORP (Halliday *et al.* 1996). In the records of the IAU Meteor Orbit Data Center we find 11 orbits that are very close to the theoretical shower C and 15 orbits very close to the theoretical shower D. The mean orbital elements of these two meteor groups, which we will call the Daytime γ-Arietids and Daytime α-Piscids, because of the position of their mean radiant, are as follows:

Daytime γ-Arietids: $q = 0.355 \pm 0.016, e = 0.830 \pm 0.018, i = 12.1 \pm 1.4, \Omega = 40.5 \pm 1.9, \omega = 64.3 \pm 1.9, \alpha = 21.6 \pm 2.2, \delta = 19.2 \pm 1.3, V_g = 30.3 \pm 0.7$,

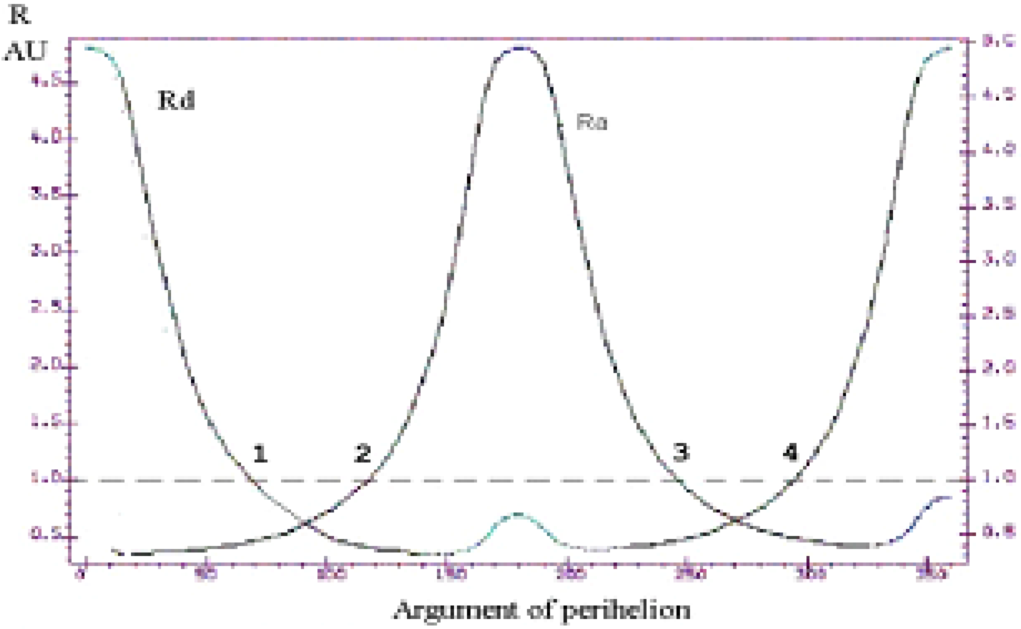

Figure 1. The heliocentric distance of the ascending R_a and descending R_d nodes of the asteroid 2000 PG$_3$ plotted against the argument of perihelion. Crossing 1 correspond to the association with the Daytime γ-Arietids; crossing 2 to that with the September Southern δ-Piscids; crossing 3 to that with the Daytime α-Piscids; crossing 4 to that with the September Northern δ-Piscids.

Daytime α-Piscids: $q = 0.372 \pm 0.008, e = 0.805 \pm 0.013, i = 7.2 \pm 1.1, \Omega = 222.3 \pm 1.6, \omega = 245.2 \pm 1.3, \alpha = 30.0 \pm 1.4, \delta = 5.6 \pm 1.0, V_g = 28.9 \pm 0.5,$

Period of activity of both these meteor association: April 25 − May 10.

Table 1 lists the observed (O) orbital elements, solar longitudes and corresponding dates of maximum activity, the geocentric coordinates of the radiants and velocities for all four showers. The values of D_{SH} given in Table 1 show satisfactory agreement between the theoretically predicted and the observed showers, i.e. all four possible meteor showers associated with 2000 PG$_3$ are active to date. The character of the orbit and low albedo of 2000 PG$_3$, and the existence of the meteor showers associated with 2000 PG$_3$ provide evidence supporting the conjecture that this asteroid may be of a cometary nature.

Porubčan, Kornoš & Williams (2004) noted that if a relation between NEAs and meteoroid streams exist, it will be best recognized for fireball streams represented by larger meteoroids. As we see, the Southern and Northern δ-Piscides meteor showers, seen in September, described by Terentyeva (1989) from the data of the Prairie and MORP fireball networks, consist of fireballs brighter than −15 magnitude produced by bodies of decameter sizes. It was also shown (Babadzhanov 2003) that meteoroid streams may be populated as well by large bodies of several tens of meters in diameter. Porubčan, Kornoš & Williams (2004) found 26 asteroids associated with 20 different fireball streams. Therefore, it may be useful to search for small extinct comets along the orbits of meteoroid streams during periods of meteor shower activity. This inference is confirmed by the detection of 17 objects of some meters to some tens of meters, which passed within a few million km of the Earth. They were observed by Barabanov, Zenkovich, Mikisha, *et al.* (2001) during the period of activity of the Capricornids, Perseids, Leonids, and Coma Berenicids meteor showers, near the radiant positions of these showers, using 60-cm and 1-m telescopes with CCD-cameras ST-6, at the Zvenig-

Table 1.The theoretical (T) and observed (O) orbital elements, geocentric radiants and velocities of the meteor showers associated with the Near-Earth Asteroid 2000 PG_3. In the first column, EN stands for EN140977a, MORP for MORP841001, and PN for PN680912. For the type of shower (T), N denotes a night-time shower, and D a day-time shower; the catalogues (C) are described in the text, and in that column, M stands for IAU Meteor Orbit Data Center. Units: q is in AU, all the angles are in degrees, V_g is in km/s.

Shower	q	e	i	Ω	ω	π	$L_\odot$	Date	α	δ	V_g	D_{SH}	T	C
T ”A”	0.340	0.880	14.2	353.6	111.0	104.6	173.6	9/17	10.7	-7.2	31.0			
O δ-Psc^S	0.436	0.781	4.6	354.8	107.0	101.8	174.8	9/18	4.0	-3.0	25.6	0.22	N	T
O S Psc	0.420	0.820	2.0	357.0	107.0	104.0	177.0	9/20	6.0	0.0	26.3	0.23	N	C
O Psc	0.400	0.792	3.3	357.0	111.5	108.5	177.0	9/20	8.0	0.0	26.0	0.22	N	C1
O EN	0.388	0.830	2.4	351.5	112.2	103.7	171.5	9/14	2.7	-1.2	27.8	0.22	N	EN
T ”B”	0.342	0.879	11.6	170.9	293.7	104.6	170.9	9/14	359.4	9.5	30.5			
O δ-Psc^N	0.446	0.775	2.7	179.6	285.8	105.4	179.6	9/23	6.0	5.0	25.4	0.21	N	T
O Psc	0.344	0.816	3.8	167.6	298.5	106.1	167.6	9/10	0.2	3.6	27.4	0.15	N	S2
O 508	0.412	0.810	10.4	174.3	287.1	101.4	174.3	9/17	359.1	10.7	26.3	0.11	N	L
O MORP	0.435	0.855	11.3	187.8	283.1	110.9	187.8	10/01	9.7	15.9	27.8	0.15	N	H
O PN	0.270	0.860	5.1	169.0	305.3	114.3	169.0	9/12	4.1	5.6	30.5	0.20	N	PN
T ”C”	0.364	0.871	13.2	36.6	68.7	105.3	36.6	4/26	19.1	19.7	29.9			
O γ-Ari	0.355	0.830	12.1	40.5	64.3	104.8	40.5	5/01	21.6	19.2	30.3	0.05	D	M
T ”D”	0.342	0.879	10.6	219.0	246.3	105.3	39.0	4/29	27.9	2.6	30.4			
O α-Psc	0.372	0.805	7.2	222.3	245.2	107.5	42.3	5/03	30.0	5.6	28.9	0.10	D	M

orod (Moscow district) and Simeiz (Crimea) observatories of the Institute of Astronomy, Russian Academy of Sciences.

3. Conclusions

Investigation of the orbital evolution of 2000 PG_3 shows that this object is a quadruple Earth-crosser and, therefore, its hypothetical meteoroid stream might produce four meteor showers observable from Earth in April and September. A search of the theoretically predicted radiants in the catalogues of observed meteor showers show that all these showers, namely, the night-time September Southern and Northern δ-Piscides meteor showers, and the day-time meteor associations γ-Arietid and α-Piscids are active at present. The existence of the meteor showers associated with 2000 PG_3 provides evidence supporting the conjecture that this asteroid may be of a cometary nature.

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References

Babadzhanov, P.B. 1998, *Celest. Mech. & Dynam. Astron.* 69, 221

Babadzhanov, P.B. 2001, *A&A* 373, 329

Babadzhanov, P.B. 2003, *A&A* 397, 319

Babadzhanov, P.B. & Obrubov, Yu.V. 1987, in: Z. Ceplecha, P. Pecina (eds.) *Interplanetary matter*, Proc. 10th European Regional Astronomy Meeting of the IAU 2, p. 141

Babadzhanov, P.B. & Obrubov, Yu.V. 1992, *Celest. Mech. & Dynam. Astron.* 54, 111

Barabanov, S.I., Zenkovich, A.D., Mikisha, A.M., Smirnov, M.A 2001, in: Near-Earth Astronomy of the XXI Century, Proceedings of Conference, Zvenigorod 2001, May 21-25, Moscow, GEOS, p. 158

Cannon, E. 2001, *Visual Meteor Showers, http://web.austin.utexas.edu/edcannon/aka-date.htm*

Cook, A.F. 1973, in: Hemenway C.L., Millman P.M., Cook A.F. (eds.), *Evolutionary and Physical Properties of Meteoroids*, NASA SP-319, Washington, D.C., p. 183

Fernandez, Y.R., Jewitt, D.C. & Shepard, S.S. 2001, *Ap J* 553: L197

Fox, K., Williams, I.P. & Hughes, D.W. 1984, *MNRAS* 2108, 11P

Goryachev, N.N. 1937, Halphen's Method for Calculation of Planetary Secular Perturbations and its Application to Ceres. Krasnoe znamya, Tomsk

Halliday, I., Griffin, A.A. & Blackwell, A.T. 1971, MORP network fireball data (1971-84). The IAU Meteor Data Center in Lund, Sweden

Halliday, I., Griffin, A.A. & Blackwell, A.T. 1996, *Meteor & Planet. Sci.* 31, 185

Jenniskens, P. 2004, *WGN, The Journal of the IMO* 32:1, 7

Jewitt, D.C. 1992, in: R.L. Newburn *et al.* (eds.), Comets in the Post-Halley Era (Dordrecht: Kluwer), p. 19

Kashcheev, B.L., Lebedinets, V.N. & Lagutin, M.F. 1967, Meteoric Phenomena in the Earth atmosphere, Nauka. Moscow

Lebedinets, V.N., Korpusov, V.N. & Sosnova, A.K. 1972, *Trudy Inst. Eksper. Meteorol.* No 1 (34), 88

McCrosky, R.E., Shao, C.Y. & Posen, A. 1978, Prairie network fireball data (1963-75). *Meteoritika (Russian)* 37, 44

Porubčan, V., Kornoš, L. & Williams, I.P. 2004, *Earth, Moon & Planets* 95, 697

Sekanina, Z. 1973, *Icarus* 18, 253

Sekanina, Z. 1976, *Icarus* 27, 265

Southworth, R.B. & Hawkins, G.S. 1963, *Smit. Contrib. Astrophys.* 7, 261

Terentyeva, A.K. 1989, in: C.-I. Lagerkvist, H. Rickman, B.A. Lindblad, M. Lindgren (eds.) Asteroids, Comets, Meteors III, (Uppsala Universitet, Reprocentralen HSC), Uppsala, p. 579

Williams, I.P. 1997, *Astronomy & Geophysics* 38, 23

Williams, I.P. 2002, The Evolution of Meteoroid Streams, in: E. Murad and I.P. Williams (eds.), Meteors in the Earth's Atmosphere, Cambridge University Press, p. 13

Williams, I.P., Ryabova, G.O., Baturin, A.P. & Chernitsov, A.M. 2004, *MNRAS* 355, p. 1171

Williams, I.P. & Wu, Z. 1993, *MNRAS* 264, 659