Spin axis of (2953) Vysheslavia and its implications

D. Vokrouhlický, M. Brož and J. Ďurech

Institute of Astronomy, Charles University, V Holešovičkách 2, CZ–18000 Prague 8, Czech Republic

E-mail: vokrouhl@mbox.cesnet.cz

T. Michałowski

Astronomical Observatory, Adam Mickiewicz University, ul. Słoneczna 36, P–60-286 Poznań, Poland

F. Colas

Institut de Mécanique Céleste, 77 Av. Denfert Rochereau, F–75014 Paris, France

L. Šarounová

Astronomical Institute, Czech Academy of Sciences, Fričova 298, CZ–25165 Ondřejov, Czech Republic

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ABSTRACT

Photometric observations taken during the last three years are used to determine pole orientation of (2953) Vysheslavia, about 15 km size member of the Koronis family. We find $\beta_{\rm p} = -62^\circ \pm 8^\circ$ and $\lambda_{\rm p} = 182^\circ \pm 3^\circ$ for the rotation pole position (ecliptic latitude and longitude), implying obliquity $\gamma = 151^\circ \pm 9^\circ$; sidereal rotation period is $P_{\rm sid} = 0.262267 \pm 0.000003$ day. This result is interesting for two reasons: (i) obliquity larger than 90° is consistent with prediction done by Vokrouhlický *et al.* (*Icarus* **150**, 78, 2001) that Vysheslavia might have been transported to its metastable orbit by the Yarkovsky effect, and (ii) with the obliquity close to 180°, Vysheslavia belongs to one of the two distinct groups in the Koronis family found recently by Slivan (*Nature* **419**, 49, 2002), further supporting the case of dichotomy in the spin axes distribution in this family. We also argue against the possibility that Vysheslavia has been placed on the current orbit by a recent collisional breakup in the family.

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Address:

David Vokrouhlický
Institute of Astronomy
Charles University, Prague
V Holešovičkách 2
CZ–18000 Prague 8
Czech Republic

Phone: (+420) 2 21 91 25 74
Fax: (+420) 2 688 50 95
E-mail: vokrouhl@mbox.cesnet.cz

1. Introduction

Vysheslavia, a moderately large asteroid in the zone of the Koronis family, received considerable attention after Milani and Farinella (1995) discovered its very short dynamical lifetime. According to these authors this asteroid will fall in the 5/2 mean motion resonance with Jupiter in about $10 - 20$ Myr (later confirmed by Vokrouhlický *et al.* 2001); as a result Vysheslavia must have been placed on its peculiar orbit a comparable time before the present. This is orders of magnitude shorter than any relevant timescale, collisional in particular, of an object of Vysheslavia's size and raises a question of its origin.

Milani and Farinella (1995) suggested that Vysheslavia may outcome of a recent secondary collision (disruptive or non-disruptive), though they pointed out that its probability is low (less than 5% in their estimate). Vokrouhlický *et al.* (2001) proposed a more robust scenario, namely they assumed that Vysheslavia underwent a slow transport due to the Yarkovsky effect from a dynamically more stable area further out from the 5/2 resonance (see also Brož and Vokrouhlický 2001). With a low value of the surface conductivity (the likely case), a specific orientation of the spin axis is needed, namely obliquity must be larger than 90°. Values closer to 180° are more favorable, since the relevant dynamical timescale of the Yarkovsky transport is shorter, and thus the whole hypothesis more robust.

Here we report photometric observations of Vysheslavia that allowed us to determine pole orientation, and thus obliquity, confirming the above scenario. Moreover, with a high obliquity of $151^\circ \pm 9^\circ$, Vysheslavia further strengthens conclusions from recent observations by Slivan (2002) and Slivan *et al.* (2003), who found a surprising dichotomy in the obliquity distribution of large Koronis members. Vysheslavia fits well the retrograde group. In the last Section, we collect additional arguments against the recent collisional origin of Vysheslavia with help of parameters derived for the Karin cluster (Nesvorný *et al.* 2002).

2. Observations

We have observed Vysheslavia on ten nights during the three last apparitions: January 2000, March–April 2001, and September 2002. The aspect data of the observations and other information are summarized in Table I.

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The January 2000 Vysheslavia observation was performed at Saint Veran Observatory (France) using a 0.62-m telescope equipped with a HiSys22 CCD camera (KAF400 chip) and a non-standard red filter. As a result, no transformation to the standard photometric system was possible. The data were processed with the software APHOT developed at Ondřejov Observatory. The aperture photometry was used as described by Pravec *et al.* (1996).

During the next two apparitions the asteroid was observed at Pic du Midi Observatory (France) using a 1.05-m reflector equipped with Thomson 7863 CCD camera and R filter. A standard reduction was performed with the ASTROL software developed at the Institut de Mécanique Céleste in Paris. The aperture photometry was obtained with the CCLRS STARLINK package (see also Michałowski *et al.* 2000). Due to non-photometric weather conditions the obtained data were not transformed to the standard system and only relative instrumental magnitudes are used.

In March 2001 Vysheslavia was also observed at the River Oaks Observatory, New Braunfels (Texas) using a 0.4-m Newtonian telescope equipped with a SBIG ST8E CCD camera. The standard dark substraction, flat fielding and differential photometry was performed using Mira software (http://www.axres.com).

EDITOR: PLACE FIGURE 1 HERE

The observations are reported as composite lightcurves (Fig. 1) all consistent with a synodic period of 6.293 ± 0.002 hours. The magnitude offset of each lightcurve was obtained by minimizing the dispersion of data points relative to their neighbors. The lightcurve amplitude varies from 0.20 magnitude in 2000 to 0.18 magnitude in 2002, with a value of 0.19 magnitude in 2001 (we estimate the error of the lightcurve amplitude to be $\simeq 0.02$ magnitude, while the error of the lightcurve maximum/minimum epoch is $\simeq 10$ minutes). We preliminarily note, that such a small variation during the three different oppositions, and phase angle ranging from $0°$ to nearly $15°$, already suggests a non-ecliptic pole for Vysheslavia (in March 2001 the phase angle was maximum and this is the reason why the secondary amplitude — see $0.5 - 0.8$ rotation phase in Fig. 1b — was slightly greater than that in April).

3. Shape and spin model of (2953) Vysheslavia

Orientation of the spin vector, sidereal period, and triaxial ellipsoid model of Vysheslavia have been determined by using the method described by Michałowski (1993). Since no absolute calibration was done, only the epochs of brightness maxima and amplitudes have been considered. This is basically the weighted *amplitude-aspect method* (see also Drummond *et al.* 1988) which models the asteroid as a triaxial ellipsoid of uniform surface reflectivity; to a good approximation the brightness variations are directly given by the changing cross-section of the asteroid as it rotates about the shortest axis of the inertia tensor. The orientation of the spin axis is thus obtained, but this method cannot by itself resolve the sense of rotation about the axis. To that end, we complemented the amplitude-aspect analysis by the *epoch method*, namely tracking in time a chosen "prominent feature" on the rotation curve assuming it corresponds to a pattern at fixed longitude on the asteroid. The amplitude-aspect-epoch analysis leads to a set of nonlinear equations for the pole position ($\lambda_{\rm p}$, $\beta_{\rm p}$), in ecliptic coordinates, the sidereal rotation period

$P_{\rm sid}$ and ratio a/b and b/c of the best-fit ellipsoid axes; Michałowski (1993) discusses the appropriate iterative method of their solution. At convergence, we obtained the following best-fit solution:

$$P_{\rm sid} = 0.262267 \pm 0.000003 \ \ \text{(days)}$$
$$\lambda_{\rm p} = 182^\circ \pm 3^\circ \ , \quad \beta_{\rm p} = -62^\circ \pm 8^\circ$$
$$a/b = 1.18 \pm 0.04 \ , \quad b/c = 1.0 \pm 0.1 \ ,$$

implying a retrograde sense of rotation and a pole far from ecliptic, in consistency with the above suggestion. This configuration is unfavourable to solve for the ratio b/c, and the above value of this parameter is only formal (see eqs. (3) and (5) in Michałowski 1993).

Because the pole aspect is close to 90°, further observations will keep reducing uncertainty in its determination but they will likely not improve the shape solution.

4. Discussion

Our solution for the Vysheslavia pole has several interesting implications. First, it fits prediction by Vokrouhlický *et al.* (2001) and supports the Yarkovsky emplacement of Vysheslavia onto its unstable orbit. This agrees with a general model of dynamical evolution of asteroid families in which they continually spread in semimajor axis due to the Yarkovsky effect; their sharp termination at the prominent mean motion resonances (such as the 5/2 mean-motion resonance with Jupiter; Fig. 2) is one of strong arguments in favour of this view (Bottke *et al.* 2001, 2003). Vysheslavia is thus the largest member of the asteroid population "on the brink", continually resupplied by new objects (for other asteroids in the Koronis zone see Knežević *et al.* 1997, Brož and Vokrouhlický 2001, or Guillens *et al.* 2002 for asteroids in the vicinity of the 3/1 mean-motion resonance with Jupiter). In the Koronis family, another strong argument for the ongoing spreading in the semimajor axes is the existence of the Prometheus clan with a significantly higher eccentricity beyond the $g + 2g_5 - 3g_6$ secular resonance (Bottke *et al.* 2001).

An alternative possibility, discussed by Milani and Farinella (1995), is that Vysheslavia has a collisional origin, either as a result of a recent disruptive secondary break-up in the family or a non-disruptive impact on Vysheslavia that would shift its semimajor axis into the dynamically unstable region. A possible result of the collision could be a non-principal-axis rotation of Vysheslavia, provided the collision occurred recently so that the internal dissipation would not damp the wobble energy. For a 15 km size asteroid and 6.29 hr rotation period the charateristic damping timescale is $0.5 - 5$ My, depending on the physical parameters of the body (e.g. Vokrouhlický and Čapek 2002, Paolicchi *et al.* 2003). The higher value, if correct, is a non-negligible fraction of the dynamical lifetime of Vysheslavia's orbit. In this respect we note that our observations do not support non-principal-axis rotation and they are well fitted with the shortest axis rotation mode with a single rotation period over all three oppositions. This obviously does not rule out the recent collisional origin of Vysheslavia, but makes it less likely. We also note that collisional lifetime of a hypothetical $30 - 50$ km size parent body of Vysheslavia is likely $\gtrsim 10$ Gy (W.F. Bottke, personal communication), so that the likelihood of the recent secondary breakup in the Koronis family with Vysheslavia as one of the largest fragments is $\leq (0.5 - 1)\%$ (there might be less then ten objects of that size in the family close enough to the 5/2 resonance). Additionally, we note that reflectance spectrum of Vysheslavia is quite typical in the family (S-type; e.g. Chapman *et al.* 1989, Bus and Binzel 2002) and does not show any anomalous feature that would be related to its hypothetical younger age. To check this conclusion we used spectra of the 22 Koronis members, including Vysheslavia, available at the SMASSII web site http://smass.mit.edu.

EDITOR: PLACE FIGURE 2 HERE

Moreover, we can consider the well identified recent break-up in the Koronis family of a comparable size — the Karin cluster (Nesvorný *et al.* 2002) — as a "benchmark" and deduce what fraction of observable ejecta from a hypothetical secondary break-up event, for which Vysheslavia would be the largest fragment, would be still surviving. Assuming the same velocity distribution as observed in the Karin cluster and the central position of Vysheslavia, we predict that from initially $20-40$ fragments larger than $\simeq 3$ km (depending on steepness of the size distribution), some $8-16$ should survive 15 My. None of such objects is observed in the Vysheslavia vicinity (Fig. 2). Together with a very low probability of the secondary break-up of a large member in the family mentioned above, the absence of accompanying ejecta in the Vysheslavia neighborhood even lessens the probability of this case. On the other hand, we recall that a couple of multikilometer asteroids, unrelated to Vysheslavia, are also on unstable orbits (Brož and Vokrouhlický 2001); this makes more sense if we consider them to be members of the population fed by the Yarkovsky drift, rather then to be an outcome of several recent break-ups at the border of the 5/2 resonance.

Secondly, Slivan (2002) and Slivan *et al.* (2003) analyzed spin vectors of the largest members in the Koronis family. They found a markedly non-random distribution with two significant "clusters" having obliquity near 50° (prograde rotators) and between $150-180^\circ$ (retrograde rotators). Though Vysheslavia is little smaller than the asteroids observed by Slivan *et al.* (sizes of $20-40$ km), it still seems to support the bimodal distribution of the pole directions in the family, namely it matches characteristics of the retrograde rotators. Since it is very likely, that the pole bimodality is due to a so far unidentified dynamical process (Vokrouhlický *et al.* 2003), its extension to smaller asteroidal sizes may be an important key. Photometric observations of further $10-20$ km sized Koronis family members, with the goal to determine their pole, is thus an important project for the future.

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Table 1. Aspect data of the (2953) Vysheslavia observations: date is the mean epoch of the observation, r and Δ are the heliocentric and geocentric distances, ϕ is the phase angle, (λ, β) are the ecliptic longitude and latitude, in the J2000.0 reference system and (α, δ) are the J2000.0 right ascension and declination.

Date (UT)	r (AU)	Δ (AU)	ϕ (°)	λ (°)	β (°)	α (°)	δ (°)	Observatory
				2000				
Jan 16.1	2.8822	1.9026	2.19	121.47	−1.20	123.41	18.66	Saint Veran
Jan 17.1	2.8821	1.9010	1.77	121.26	−1.21	123.19	18.70	Saint Veran
				2001				
Mar 16.4	2.7858	2.0021	14.92	221.93	−1.04	219.14	−16.40	River Oaks
Mar 20.3	2.7850	1.9632	13.83	221.69	−1.05	218.90	−16.33	River Oaks
Mar 21.3	2.7848	1.9538	13.54	221.61	−1.05	218.82	−16.31	River Oaks
Apr 26.1	2.7779	1.7717	0.37	215.64	−0.98	212.97	−14.32	Pic du Midi
Apr 27.0	2.7778	1.7715	0.60	215.44	−0.97	212.79	−14.25	Pic du Midi
Apr 28.0	2.7776	1.7715	0.98	215.22	−0.97	212.58	−14.17	Pic du Midi
				2002				
Sep 02.0	2.7951	1.8527	9.08	313.46	1.53	315.44	−15.33	Pic du Midi
Sep 03.0	2.7953	1.8588	9.43	313.32	1.52	315.29	−15.37	Pic du Midi

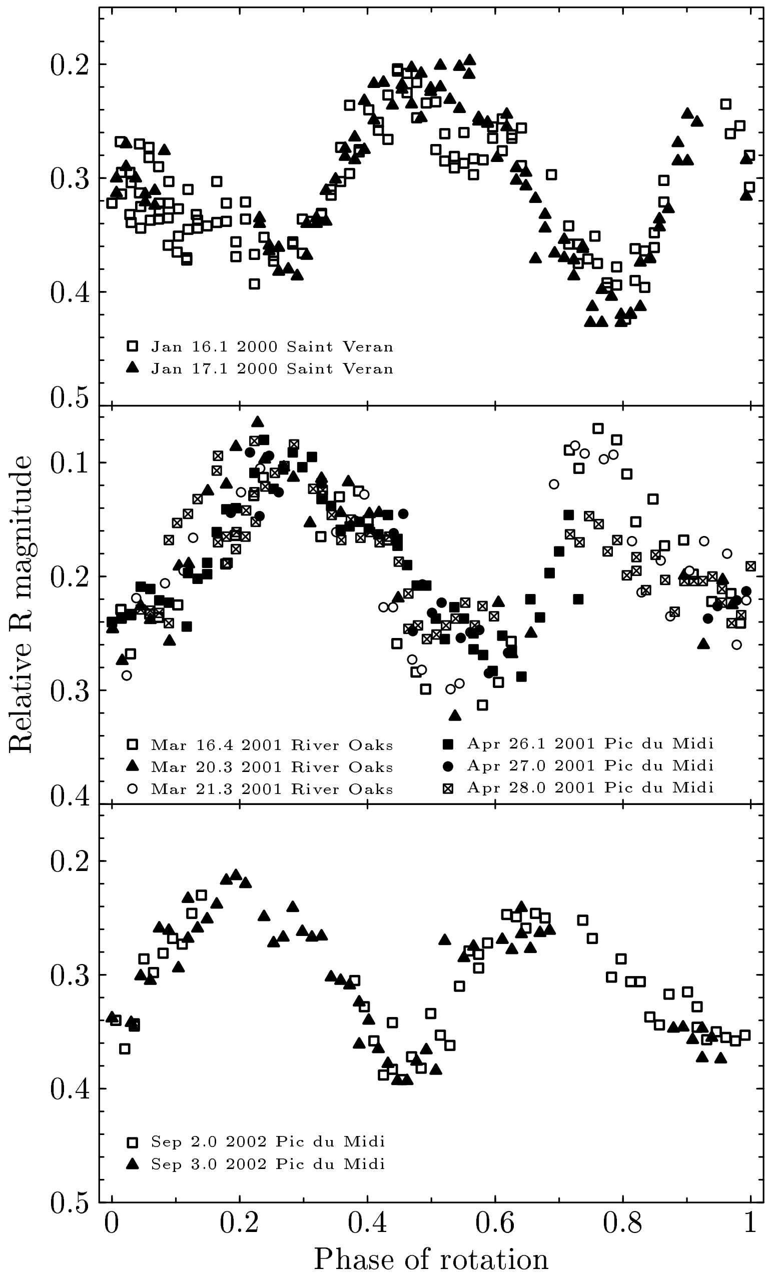

Fig. 1.— Composite rotation lightcurves of 2953 Vysheslavia in three consecutive oppositions: January 2000, March–April 2001 and September 2002. The abscissa is the rotational phase with zero points corrected for light-time and corresponding to: 2000, Jan 15.9179 UT, 2001, Apr 25.9550 UT, and 2002, Sep 2.8146 UT, respectively; on ordinate, relative instrumental magnitudes adjusted so that dispersion with respect to the neighbors is minimized.

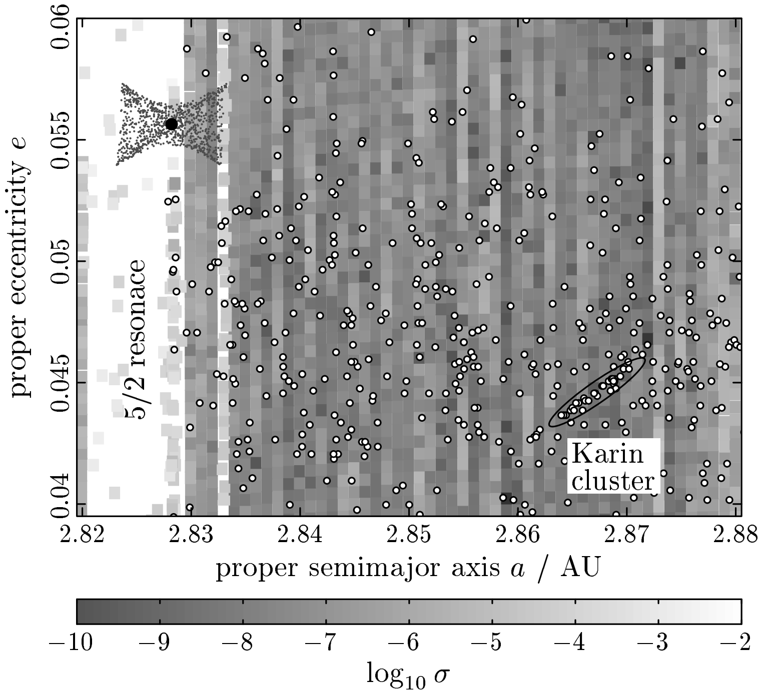

Fig. 2.— Koronis family members (dots) projected on the plane of proper semimajor axis and proper eccentricity (Knežević *et al.* 2003); Karin cluster is indicated in the lower right corner. For an isotropic velocity field, and different values orbital parameters, ejecta from a hypothetical secondary collision near Vysheslavia (full circle) would fall in the region indicated by dots. None of the observed Koronis asteroids falls in this zone, notably in its stable part above the 5/2 mean motion resonance with Jupiter. Orbital stability is indicated by grey shading obtained with a parameter $\sigma = 1 - n^{(2)}/n^{(1)}$, where $n^{(1)}$ and $n^{(2)}$ are proper mean motions of test particles calculated in the two consequtive time intervals, each spanning 1.2 Myr (dark zones of small σ mean stability, white areas of high σ value, such as the 5/2 resonance, are unstable); this is based of frequency map analysis by Robutel and Laskar (2001). The family members were identified using the hierarchical clustering method and the velocity cutoff of 60 m/s, e.g. Zappalà *et al.* (1995), Bottke *et al.* (2001). We first used a catalogue of proper elements at http://newton.dm.unipi.it computed analytically for identification; at a second step, we selected (and plotted here) only those asteroids for which synthetic proper elements have been computed.