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Efficient spin sense determination of Flora-region asteroids via the epoch method

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ABSTRACT

The Flora asteroid family's size and location on the inner edge of the main belt make it a likely source of NEOs and terrestrial planet impactors; however, reliable determination of Flora membership is inhibited by the family's age and the presence of a high density of background objects. Dykhuis et al. (Dykhuis et al. [2014]. Icarus 243, 111–128) identified the Flora family as the product of a 950-My-old collision dispersed in semimajor axis as a result of the Yarkovsky effect, and defined the family's membership and extent in orbital parameter space. The observed preponderance of prograde rotators at semimajor axes greater than that of (8) Flora is consistent with the predictions of the single-collision Yarkovsky dispersion model.

Here we extend the available rotational property data for the Flora family via a survey of 21 Flora-region asteroids, using a time-efficient modification of the "epoch method" to determine prograde/retrograde spin sense. Five of the survey asteroids are shown to be prograde; five are shown to be retrograde; six are shown to have spin axes in or near their orbital planes; and five represent other cases for which spin axis information was not determined. The high-semimajor axis component of the Flora family is found to have only prograde and in-plane rotators, consistent with model predictions of Yarkovsky dispersion. Moreover, we confirm a wide range of ecliptic latitudes of the spin axes among these prograde rotators, consistent with models of family evolution in which a significant fraction of the members are captured in spin–orbit resonance. Near the "center" of the family (near the semimajor axis location of (8) Flora), the spin directions are mixed, with a slight preference for retrograde rotators, placing constraints on the efficiency of YORP-cycle spin reorientation for the family.

In addition to our spin sense survey, we also report new measurements of the Sloan colors of a number of large inner main belt asteroids.

1. Introduction

The Flora region of the inner main belt is a prolific source of near-Earth objects (Vokrouhlický and Farinella, 2000; Bottke et al., 2001), and thus an important region for connections between main-belt asteroids and terrestrial planet impactors. The low semimajor axis edge of the Flora region is bounded by the strong ν_6 secular resonance, which, coupled with Yarkovsky semimajor axis mobility, provides an efficient dynamical pathway for main belt escape. Thorough characterization of the family membership and dynamical history of the Flora region is critical for understanding of the near-Earth asteroid population in the past, present and future.

The orbital and reflectance properties and age of the Flora family have been studied in detail by Dykhuis et al. (2014). The existence of the Flora family is evidenced by a preponderance of prograde-rotating objects at proper semimajor axis values greater than that of (8) Flora (Haegert and Molnar, 2009; Kryszczyńska, 2013; Hanuš et al., 2013a). These objects form half of the characteristic "V" shape in semimajor axis-size space (cf. Fig. 15 of Dykhuis et al., 2014), indicative of a collisional family dispersed by the Yarkovsky effect. The low-semimajor axis half of the family is absent, presumably removed via interactions with the ν_6

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Table 1
Orbital, reflectance and spin data for the 57 objects within the Flora family dynamical ranges for which spin information is available from the DAMIT database and Kryszczyńska (2013). Absolute magnitudes are taken from the Minor Planet Center (MPC). Proper orbital elements are calculated using the Orbit9 software from AstDyS as in Dykhuis et al. (2014). The a^* and $i-z$ color measurements are based on the data from the Sloan Digital Sky Survey (SDSS), excepting the cases of Asteroids 8, 43, and 951, which were measured in this work (see Table 4); the a^* parameter represents a linear combination of SDSS filters defined by Ivezić et al. (2001). The C parameter is defined in Eq. (1), with Δa_P referenced to the a_P of (8) Flora. The parameter β with error σ is the ecliptic latitude of the asteroid's north pole. The error σ, unless otherwise known, is estimated as 10% for models with combined dense and sparse data, and 20% for models with sparse data alone or uncertain model parameters. (In the cases where two or more pole solutions were reported in the DAMIT database, the value cited here is the mean of the ecliptic latitudes, as in Hanuš et al. (2013a); latitudes for ambiguous models are usually similar.) Reference key: 0 = Kaasalainen et al. (2002), 1 = Torppa et al. (2003), 2 = Ďurech et al. (2009), 3 = Vokrouhlický et al. (2009), 4 = Pilcher (2009), 5 = Ďurech et al. (2011), 6 = Hanuš et al. (2011), 7 = Hanuš et al. (2013c), 8 = Hanuš et al. (2013b), 9 = Hanuš et al. (2013a), 10 = Kryszczyńska (2013).

Number	Name	H (mag)	a (AU)	e	$\sin i$	a^*	$i-z$	p_V	C (10^{-3} AU)	β (°)	σ	Ref
8	Flora	6.49	2.201	0.146	0.098	0.11	−0.01	0.23	0.00	−5	10	1; 4; 5; 8
43	Ariadne	7.93	2.203	0.142	0.071	0.11	−0.12	0.23	0.05	−15	10	0
281	Lucretia	11.95	2.188	0.131	0.077			0.20	−0.06	−75	9	10
291	Alice	11.45	2.222	0.143	0.035				0.11	56	6	10
352	Gisela	10.07	2.194	0.137	0.075			0.19	−0.07	−41	7	7; 10
367	Amicitia	10.5	2.219	0.147	0.041				0.14	53	7	6; 10
440	Theodora	11.46	2.210	0.153	0.038	0.15	−0.07		0.05	−88	10	6
540	Rosamunde	10.76	2.219	0.146	0.104			0.21	0.12	72	10	9
553	Kundry	12.1	2.231	0.130	0.085			0.28	0.11	69	10	9
685	Hermia	11.9	2.236	0.143	0.077				0.14	83	10	6
700	Auravictrix	11.0	2.230	0.154	0.112	0.19	−0.02	0.14	0.18	48	8	10
770	Bali	10.9	2.221	0.158	0.062			0.17	0.13	47	8	2; 6; 10
800	Kressmannia	11.23	2.193	0.140	0.075			0.15	−0.05	57	7	6; 10
810	Atossa	12.5	2.179	0.121	0.046			0.25	−0.07	68	10	6
819	Barnardiana	11.9	2.198	0.102	0.080	0.21	−0.06	0.34	−0.02	47	10	7
825	Tanina	11.5	2.226	0.114	0.053			0.21	0.12	52	8	6; 10
915	Cosette	11.5	2.228	0.132	0.088			0.29	0.13	56	6	2; 6; 10
937	Bethgea	11.7	2.232	0.164	0.078			0.19	0.14	74	10	10
951	Gaspra	11.48	2.210	0.148	0.089	0.14	0.00	0.33	0.04	19	10	9; 10
1056	Azalea	11.6	2.230	0.123	0.080			0.24	0.14	46	10	7
1088	Mitaka	11.39	2.201	0.148	0.115			0.19	0.00	−60	11	2; 6; 10
1130	Skuld	12	2.229	0.145	0.052			0.23	0.11	39	10	7
1188	Gothlandia	11.44	2.191	0.140	0.077			0.23	−0.06	−77	5	7; 10
1219	Britta	11.8	2.213	0.145	0.068				0.05	−79	5	10
1249	Rutherfordia	11.54	2.224	0.125	0.091			0.22	0.11	70	20	7
1270	Datura	12.4	2.235	0.153	0.092				0.11	76	5	3
1382	Gerti	12.01	2.220	0.147	0.027				0.07	25	10	6
1446	Sillanpaa	12.5	2.246	0.137	0.084	0.11	0.00	0.23	0.14	70	10	9
1472	Muonio	12.3	2.234	0.151	0.064			0.30	0.11	61	10	7
1514	Ricouxa	12.6	2.240	0.147	0.071			0.24	0.12	72	10	6; 10
1518	Rovaniemi	12.37	2.226	0.156	0.106			0.26	0.08	53	10	7
1527	Malmquista	12	2.227	0.144	0.088	0.18	−0.08	0.26	0.10	80	10	9
1634	Ndola	12.7	2.246	0.132	0.116				0.13	40	10	7
1675	Simonida	11.8	2.233	0.151	0.108				0.14	56	7	10
1682	Karel	12.7	2.239	0.141	0.076				0.11	37	10	6; 10
1703	Barry	12	2.215	0.113	0.067				0.05	−73	10	9
1704	Wachmann	12.84	2.223	0.137	0.028			0.18	0.06	40	10	7
1785	Wurm	13.2	2.236	0.122	0.075				0.08	47	10	7
1905	Ambartsumian	12.73	2.223	0.155	0.052				0.06	−66	10	7
1950	Wempe	13.07	2.178	0.149	0.066	0.14	−0.08		−0.06	−43	20	7
2017	Wesson	12.7	2.252	0.139	0.086			0.20	0.15	80	6	10
2094	Magnitka	11.9	2.232	0.145	0.094			0.21	0.13	53	10	7
2112	Ulyanov	12.3	2.254	0.124	0.071				0.18	61	20	7
2156	Kate	12.69	2.242	0.169	0.083	0.22	−0.06	0.21	0.12	68	8	6
2510	Shandong	12.6	2.253	0.150	0.077				0.16	27	10	7
2709	Sagan	13	2.195	0.128	0.064				−0.02	−24	10	7
2839	Annette	12.7	2.217	0.145	0.069			0.26	0.04	−42	10	7
3279	Solon	13	2.203	0.132	0.071				0.00	−70	10	9
3722	Urata	12.62	2.236	0.159	0.127			0.20	0.10	−15	10	7
4606	Saheki	12.9	2.252	0.148	0.058			0.27	0.13	64	10	9
5960	Wakkanai	13.6	2.189	0.114	0.061			0.29	−0.02	−65	20	7
6159	1991 YH	13.24	2.291	0.089	0.110			0.48	0.20	67	10	9
7043	Godart	13	2.245	0.147	0.106			0.34	0.11	71	10	9
7632	Stanislav	14	2.225	0.109	0.071	0.20	−0.07	0.21	0.04	−47	20	7
31,383	1998 XJ94	13.85	2.185	0.124	0.079			0.29	−0.03	−68	20	7
52,820	1998 RS2	15.59	2.213	0.174	0.030	−0.14	0.02	0.04	0.01	−57	10	7
57,394	2001 RD84	15.3	2.325	0.086	0.069	0.12	−0.24	0.30	0.11	63	20	7

resonance. The Yarkovsky dispersion in semimajor axis depends for each object on its spin sense; prograde-rotating objects drift to higher semimajor axes, while retrograde-rotating objects drift inward. Hence, the concentration of prograde rotators in the high-semimajor axis half of the Flora family supports the existence of the family as well as the single-collision Yarkovsky-dispersed model for the family's origin.

The amount of Yarkovsky dispersion in semimajor axis can be described by the following useful relation (Vokrouhlický et al., 2006a):