Description and justification of the grant proposal

Spins and orbit orientations of binary systems and pairs among small asteroids

P. Pravec[1], D. Vokrouhlický[2], P. Scheirich[1], D. Čapek[1]

[1] *Astronomical Institute AS CR, Ondřejov, Czech Republic*

[2] *Institute of Astronomy, Charles University, Prague, Czech Republic*

1. Binary systems and separated pairs among small asteroids

Asteroids with diameters about 10 km and smaller revolving in heliocentric orbits from near-Earth to main belt show a significant abundance of binary systems (Pravec and Harris, 2007, and references therein). In the same size range, pairs of asteroids in nearly identical heliocentric orbits have been found in the main belt (Vokrouhlický and Nesvorný, 2008). Binaries and asteroidal pairs may be products of same or related mechanisms working among small asteroids. We summarize below some known properties of the binary population and their proposed implications. We identify a few other features with which our understanding of properties of and mechanisms working in the binary population and of a possible relation between binaries and pairs would be significantly enhanced. To study them, we plan to run a program of photometric observations of binaries and pairs during 2009–2011 that will allow us to estimate distributions of some key properties in both binaries and pairs populations. Obtained results will provide constraints to theories of formation and evolution of both populations.

A fraction of binaries among near-Earth asteroids larger than 0.3 km is $15 \pm 4\%$ (Pravec et al. 2006). Recent observations of binaries among small main belt asteroids show that they are at least as abundant as NEA binaries. Studies of characteristics of binary systems have shown a few interesting common features and trends. The most significant common characteristic found in small close binaries in near-Earth as well as main belt orbits is that they have a total angular momentum very close to, but not generally exceeding, the critical limit for a single body in a gravity regime (Pravec and Harris, 2007). The common property of the small close (orbital periods < 100 h) binary systems is related to the fact that their primaries are mostly fast rotators, most of them lying just in front of the 2.2h spin barrier (see Pravec et al. 2007, and references therein). The observed amount of angular momentum suggests that close binaries with primary diameters of 10 km and smaller formed from parent bodies spinning at the critical rate (at the gravity spin limit for asteroids in the size range) by some sort of fission or mass shedding.

Three general binary formation mechanisms have been proposed. The mechanism of binary formation from ejecta from large asteroidal impacts (Durda et al. 2004) is supposed to form satellites of large asteroids, but its possible contribution to formation of close binaries among small asteroids is less clear. The mechanism of tidal disruptions of strengthless bodies during close encounters with terrestrial planets (see Walsh and Richardson 2006, and references therein) obviously does not work in the main belt so it cannot be a formation mechanism of small close main belt binaries, but it may contribute to the NEA part of the population (see below). The critical angular momentum content of small close binaries and their heliocentric orbit distribution ranging to the main belt favor the third proposed binary formation mechanism, which is a fission of or mass shedding by critically spinning parent bodies spun up by the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect (Bottke et al. 2006, and references therein; Ćuk 2007).

Some other features and trends seen in the NEA binary population observed by Pravec et al. (2006) may be explained by tidal interactions during close approaches to the terrestrial planets. Walsh and Richardson (2007) simulated a steady-state binary NEA population, and they found that tidal disruptions could account for only 1–2% of NEAs being binary. They estimated a lifetime of typical NEA binaries due to disruptions during close approaches to Earth and Venus to be only 1–2 Myr, and they found that it strongly depends on binary semi-major axis. The estimated binary survival lifetime is much shorter than the median lifetime of NEAs in their heliocentric orbits that is around 10 Myr (Gladman et al. 2000). This implies that binaries formed in and transported from the main belt may be only a small part of the NEA binary population, and that the NEA binaries mostly formed after their parents were transported from the main belt. The strong dependence of the lifetime of NEA binaries on separation of components may be an explanation for the fact that NEA binaries show a tendency to smaller separations (shorter periods). In any case, if binary NEAs are so short-living and they disrupt so frequently, the formation mechanism (presumably YORP) must form new NEA binaries on a shorter timescale so that the fraction of binaries among NEAs remains so high ($\sim 15\%$) as observed. Since the strength of the YORP effect is inversely proportional to the square of diameter, and a 1-km diameter near-Earth asteroid can be spun up to instability in about 1 Myr, the binary fraction in the NEA population may show a size dependence. Indeed, Pravec et al. (2006) found that binary systems concentrate among NEAs smaller than 2 km in diameter and that the fraction of binaries decreases significantly among larger NEAs. That "upper limit" on binary sizes is not being observed among small close MBA binaries. So, the data seem to be consistent with the short lifetime and its strong dependence on semi-major axis of NEA binaries found by Walsh and Richardson (2007).

A pair of papers by Ostro et al. (2006) and Scheeres et al. (2006) provide the most detailed look at a near-Earth binary system available so far. They report a detailed radar imaging of the binary NEA (66391) 1999 KW_4, and a detailed dynamical description of the system. The images of the primary reveal a top-shaped object, with an equatorial profile that deviates no more than a few percent from circular. Indeed, the equatorial band appears as if it has been planed smooth by some process. Even more remarkable, the spin of the primary is only 1.3% slower than the critical rate at which a particle on the equator would levitate from the surface and go into orbit. The secondary, which rotates synchronously with the orbit period, is far more irregular, in fact with a shape roughly similar to the gravitational Roche lobe surrounding it.

Implications of the radar model of the binary NEA 1999 KW_4 were discussed by Pravec and Harris (2007). They pointed out that the characteristics of 1999 KW_4 appear pretty typical for the NEA binary population, so it may be the archetype for the class. They noted, however, that for the particular system that made close Earth approaches, it is difficult to distinguish what of its characteristics are due to the YORP effect and what have a tidal interaction origin.

One of the most important characteristics of the binary population that we will need to know is a distribution of their orbital poles. Čapek and Vokrouhlický (2004) have found that spin vectors of asteroids spun up by the YORP effect are changed towards asymptotic states with obliquities of 0/180 degrees. If small binary systems are formed by a fission of or mass shedding by critically spinning parent bodies spun up by the YORP effect and if normals of their orbits are aligned with spin vectors of their parent bodies, then a distribution of binary orbit poles reflects an (anisotropic) distrubution of spin vectors of YORP-evolved parent bodies.

A number of pairs of asteroids in nearly identical heliocentric orbits have been found in the main belt by Vokrouhlický and Nesvorný (2008). They have found that the identified pairs were formed during the last $\sim$ 1 Myr. They proposed three possible formation mechanisms: (1) disruptive catastrophic collision, (2) YORP-induced spin up and rotational fission, and (3) dissociation of asteroid binaries. The disruptive collision mechanism may have produced a part of the identified asteroid pairs that lie in young asteroidal families that have been formed during the last 1 Myr. The other two mechanisms (2 and 3) may have formed pairs found outside known asteroid families.

The different formation mechanisms may have left specific signatures in spin properties of pair asteroids. In the mechanisms 2 and 3, YORP-induced spin up and rotational fission and dissociation of asteroid binaries, parent bodies as well as primaries of precursor binary systems were fast rotators with spin rates not far from the cohesionless spin barrier (see above). If total angular momentum is conserved and kept at the amount we observe among known binary systems, ejected secondaries (smaller member of asteroid pairs) took away a part of angular momentum, i.e., they slowed down primaries (larger member of asteroid pairs), but a magnitude of the slow down could be significant only when the secondary is larger than about 1/3 of the primary in diameter; smaller bodies could be ejected with only a small amount of primary/parent body's angular momentum tranferred to the secondary's (orbital) angular momentum. It means that larger members of pairs with size ratios $>$ 3:1 produced by the mechanisms 2 and 3 are expected to be fast rotators with spin rates not much slower than observed for primaries of known asynchronous binary systems (which have spin periods concentrated in the range 2–4 hours). Members of asteroid pairs with size ratios closer to 1 may rotate with slower rates, unless the mechanism of dissociation of binaries caused an additional spin up of primaries. An additional specific feature of primaries of asteroid pairs is that they may be elongated. Estimated low equatorial elongations of primaries of known (non-separated) binaries with unequal sized components (see, e.g., Pravec and Harris 2007) may be actually a condition for their dynamical stability and systems with elongated primaries may be unstable (Scheeres 2002) and they may end as separated pairs in nearly identical heliocentric orbits. Distributions of spin rates and elongations of primaries and their possible dependence on sizes of pair members are therefore particularly interesting properties that will constrain the theories.

The mechanism 1, formation of asteroid pairs in disruptive collisions has not been shown to produce a specific distribution of spin rates of outcoming fragments, so we do not have a hypothesis for a distribution of spin rates of members of asteroid pairs in young families. Nevertheless, we may expect that rotations of fragments produced by catastrophic disruptions were excited. Most smaller asteroids in pairs in young families may be still in non-principal axis (NPA) rotation states; a damping timescale of excited rotation for an asteroid with $D = 2$ km and $P = 2.8$ h is estimated to be about 1 Myr (Pravec et al. 2005). We may therefore see a dependence of PA vs NPA rotation states on sizes and spin rates of pair asteroids in the young families.

2. Proposed grant project

We plan to study spin and orbital properties of the population of binary systems and pairs among small asteroids. We will take photometric observations of selected systems and pairs with a standard photometric technique as described in, e.g., Pravec et al. (2005, 2006). Targeted systems and pairs will be selected from a sample of binary systems that have been discovered during past years (Pravec and Harris 2007, and references therein) and from a list of pairs identified by Vokrouhlický and Nesvorný (2008), respectively. To a sample of studied objects, we select all returning binaries/pairs from the above two publications that will occur in favorable conditions for our telescope and/or instruments of collaborating stations (see below). In addition to binaries/pairs known and published in the above two publications, we will select also favorable objects that will be discovered/identified during a course of this project within parallel projects run by us and collaborating researchers.

Photometric observations will be taken with the 0.65m telescope from Ondřejov Observatory that has been successfully used for our previous projects of photometric observations of asteroids and binaries. We will also continue our collaboration with a few stations around the world; they will take observations for returning binaries/pairs that will not be attainable from Ondřejov, e.g., because of their southern declinations. The collaborating stations will also cover orbital/rotational phases not observed by us (e.g., because of a commensurability of orbital/rotation period with Earth's rotation). We plan to collaborate with stations that have contributed to our previous studies (see, e.g., Pravec et al. 2005, 2006, 2008).

Obtained photometric data for targeted binary systems/pair members will be analysed with the standard technique (see the references above). It will give us data on spin rates for sampled pair members as well as constraints on their possible non-principal axis rotations. For binary systems, we will model obtained two/multiple opposition data on

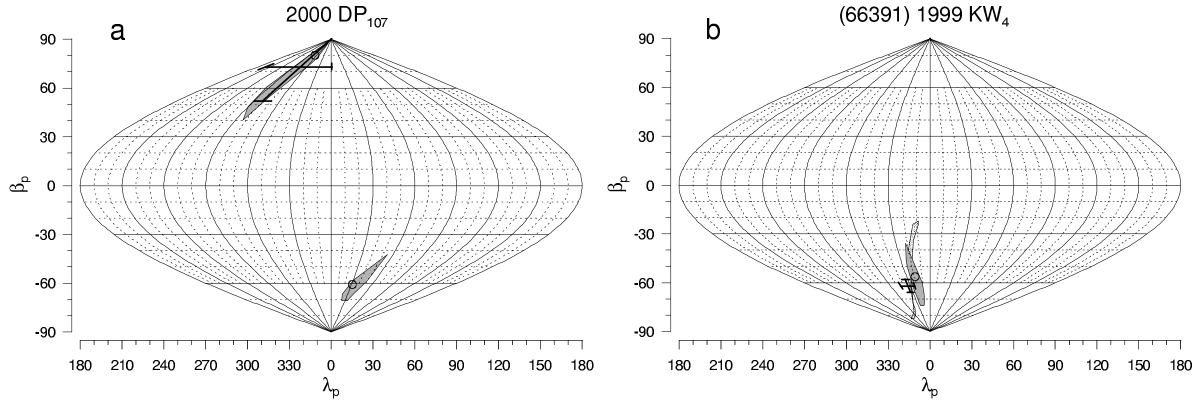

Figure 1: Examples of estimated binary orbit poles for asteroids (a) 2000 DP_{107} and (b) 66391 in ecliptic coordinates. The best-fit solutions obtained from photometric data are denoted with open circles with their 3-σ uncertainties plotted as grey areas. For 66391, results from two apparitions (2000 as light shaded area, 2001 as dark shaded area) are shown. For comparison, pole solutions obtained from radar observations (Margot el al. 2002 for 2000 DP_{107} and Ostro et al. 2006 for 66391) are denoted as crosses with their 3-σ formal error bars indicated.

mutual events between system components from past (discovery) and from observed return apparitions, that will provide estimates of orbit orientations of the binary systems. The modeling will be performed with a technique developed by P. Scheirich (PhD thesis, 2008). Examples of estimated binary orbit poles for two near-Earth asteroid binaries for which we have obtained data in the past see Fig. 1.

Using obtained data on binary orbit orientations, we will model observational (discovery) biases present in the observed population of small main-belt binary systems using a method analogous to that we used for estimating properties of a binary population among near-Earth asteroids in Pravec et al. (2006). With obtained model of observational biases, we will analyze/de-bias observed distribution of binary orbital poles and compare it with theoretical predictions (see Sect. 1).

For targeted members of asteroid pairs, we will analyze obtained distribution of their spin rates and principal/non-principal axis rotation states, estimate their dependence on sizes of pair components, and compare the distributions with hypotheses mentioned in Sect. 1.

2.1 Project phases and time schedule

During 2009 to mid-2011, as many as 28 small main-belt binary systems discovered during previous years (see Pravec and Harris 2007) will return to favorable conditions for photometric observations from Ondřejov or our collaborating stations. Their list is given in Table 1. It means that we will have one returning binary in almost every month. We will take photometric observations for them from Ondřejov and collaborating stations from the beginning of 2009 to mid-2011.

Table 1: Dates of oppositions for planned binary targets during 2009 to mid-2011

Designation	Opposition Date(s)		Designation	Opposition Date(s)	
(1338) Duponta	2009Dec	2011May	(4951) Iwamoto	2009Oct	2011Apr
(1453) Fennia	2009Jul	2011Feb	(5477) 1989 UH2	2009Jan	2010Aug
(1717) Arlon	2010May		(5905) Johnson	2010Feb	
(1830) Pogson	2010Mar		(6084) Bascom	2010Mar	2011Jul
(2006) Polonskaya	2010Jan	2011May	(6244) Okamoto	2009Aug	2011Mar
(2044) Wirt	2010Mar		(6265) 1985 TW3	2009Jan	2010May
(2478) Tokai	2009Dec	2011Jun	(7225) Huntress	2009Jun	2010Sep
(2754) Efimov	2009Jun	2011Feb	(8116) Jeanperrin	2010Jul	
(3073) Kursk	2009Sep	2011Mar	(9069) Hovland	2009Aug	
(3309) Brorfelde	2009Feb	2010Nov	(9617) Grahamchapman	(2009Jan)	
(3673) Levy	2009May	2010Aug	(10208) 1997 QN1	2010May	
(3982) Kastel	2009Dec	2011Mar	(17260) 2000 JQ58	(2009Jan)	
(4029) Bridges	2010Apr		(32008) 2000 HM53	2010Jun	
(4786) Tatianina	2010Jul		(76818) 2000 RG79	(2009Jan)	2010Jun

Oppositions of objects with parenthesized dates occur in 2008 Dec, but the objects are still observable in 2009 January.

Observational windows of returning binary systems last typically for a few weeks up to a couple months centered at the given opposition dates.

As two or multiple opposition data will gradually accumulate for individual binaries over the two and half years of observations, we will analyze obtained data, model observed mutual events, and estimate their orbit poles. Derived models will be published in two papers in a peer-reviewed journal, one in the 2nd and another one in the 3rd year of the project. In the third year when we will complete the observations, we will model observational biases present in the sample of binary systems, analyze/de-bias observed distribution of binary orbital poles, and compare it with theoretical predictions. We will submit a paper on derived properties of the population of small main belt binary asteroids and their implications to theories of their formation and evolution before the end of the 3rd year.

Of 60 asteroid pairs identified by Vokrouhlický and Nesvorný (2008), 19 primaries (larger members of the pairs) will occur in favorable conditions (around opposition and with $V < 17.5$) for photometric observations with accuracy sufficient for estimating their spin rates and constraining possible non-principal axis (NPA) rotation states by July 2011. Of the 19 primaries, 16 are not members of known young asteroid families, and we will use obtained data for the sample to do first estimates of distributions of spin rates and rotation states for primaries of non-family asteroid pairs. The sample size of 16 may be sufficient to provide good constraints to theories if the spin rate distribution is highly non-uniform, e.g., if their spin rates concentrate in a fast spin range not far the cohesionless spin barrier (see Sect. 1). In a case of a broader distribution, however, the sample size of 16 may turn out insufficient for obtaining meaningful constraints. Therefore, to increase the sample size, we will develop a method of establishing significances of identifications of pairs with components more distant than the limit of $d = 10\,\mathrm{m/s}$ used in Vokrouhlický and Nesvorný (2008). It will allow us to identify and observe several more asteroid pairs that will be still statistically significant, i.e., probabilities for that they are spurious (random) pairs will be sufficiently low, not greater than a few percent for each of such additional pairs. Photometric observations for such enlarged sample of asteroid pairs will improve statsitical significance of obtained results for the population of asteroid pairs, e.g., a dependence of spin rate distribution on size ratio between pair components. We will therefore develop the pair significance estimation method right after the start of the project, and we will publish it during the 1st year of the project.

Results obtained within the project will also be presented at meetings and conferences; we plan to attend to 2–3 conferences each year.

3. The team and collaborations

The team is led by Dr. Petr Pravec who has obtained or contributed to a number of significant results on physical properties of asteroids over the past ten years. His major role in this project will be to plan and coordinate photometric observations, to analyze and interpret obtained data, to develop (together with D. Vokrouhlický) a pair significance estimation method, to model biases in the sample of binaries, and (together with other team members) to compare obtained data with theoretical predictions.

Dr. David Vokrouhlický of the Institute of Astronomy of the Charles University Prague is an expert on dynamics of asteroids. He will contribute to the project with interpretations and comparison of obtained data with theoretical predictions, and he will develop (together with P. Pravec) the pair significance estimation method.

Peter Scheirich has finished his PhD thesis "Modeling of binary asteroids" in February 2008, a defense is planned in spring 2008. He will apply for a postdoc position at the Astronomical Institute in Ondřejov in June 2008. In this project, he will use a technique of modeling binary asteroids that he developed in his PhD thesis to create models of observed binary systems, and he will also contribute to interpretation of obtained results and comparison with theoretical predictions.

Dr. David Čapek has obtained the PhD degree with a thesis on YORP effect in 2007 and currently he is at a postdoc position at the Astronomical Institute in Ondřejov. He will contribute to interpretations of data obtained within the project and their comparison with theoretical predictions.

Dr. Adrián Galád will contribute to the project with coordinating and analyzing additional observations from collaborating stations in the world and he will assist with maintaining our binary database.

Peter Kušnirák is the primary observer at the Ondřejov 0.65m telescope. He will do photometric observations and data reduction with the telescope. He will also assist with coordinating and analyzing observations of collaborating stations in the world.

Kamil Hornoch is the second observer and a telescope system specialist for the 0.65m telescope. He will do photometric observations and will maintain the telescope system.

Miroslav Velen will maintain the reduction software system and contribute to development of our analytical software.

We will use the 0.65m telescope located at Ondřejov Observatory as our primary instrument. The telescope has been equipped with a new CCD camera in Fall 2007 and with a new coma corrector in February 2008, and it will be ready for photometric observations right from the beginning of the project. During the project 2009–2011, basically just a maintenance of the telescope, its mount, and the control system will be needed.

We will do absolutely calibrated R photometry of returning binary systems and primaries of separated asteroid pairs brighter than $V = 17.5$ and at declinations greater than -10° with a required accuracy (0.01 to 0.05 mag, depending on target brightness and parameters). The telescope will be available for the project for 50% of time, and we expect that there will be about 60 observational nights per year for the project, i.e., on average 5 nights each month. With the available telescope time and at latitude 50° N, we will cover 21 returning binaries and more than half of returning pair primaries given in Sect. 2.

A part of the observations will be conveniently done in collaboration with stations in the world. Similar collaborations have been quite successfull in our earlier projects (Pravec et al. 2005, 2006, 2008), and we plan to maintain the collaboration also for this project. A list of regularly participating stations is available on web page http://www.asu.cas.cz/∼asteroid/binastphotsurvey.htm With contribution from the collaborating stations, we will obtain more abundant data faster, both because of an advantage to observe at different times of the day (night) from different longitudes, and also because of different weather patterns on different stations. Moreover, the southern stations in Australia and in the US Southwest will be needed to cover binaries when they will be too south for Ondřejov and other collaborating northern hemisphere stations. So, while a main part of the observational work will be done from Ondřejov, we will keep the collaboration on a high level so that our sample grows faster.

References

Bottke, W.F. Jr., Vokrouhlický, D., Rubincam, D.P., Nesvorný, D., 2006. The Yarkovsky and YORP effects: Implications for asteroid dynamics. Ann. Rev. Earth Planet. Sci. 34, 157-191.

Čapek D., Vokrouhlický D., 2004. The YORP effect with finite thermal conductivity. Icarus 172, 526-536.

Ćuk, M., 2007. Formation and Destruction of Small Binary Asteroids. Astroph. Journal, 659, L57–L60

Durda, D.D., Bottke, W.F. Jr., Enke, B.L., Merline, W.J., Asphaug, E., Richardson, D.C., Leinhardt, Z.M., 2004. The formation of asteroid satellites in large impacts: results from numerical simulations. Icarus 170, 243-257.

Gladman, B., Michel, P., Froeschlé, C., 2000. The near-Earth object population. Icarus 146, 176-189.

Margot, J.-L., Nolan, M.C., Benner, L.A.M., Ostro, S.J., Jurgens, R.F., Giorgini, J.D., Slade, M.A., Campbell, D.B., 2002. Binary asteroids in the near-Earth object population. Science 296, 1445-1448.

Ostro, S.J., and 15 colleagues, 2006. Radar imaging of binary near-Earth asteroid (66391) 1999 KW4. Science 314, 1276-1280.

Pravec, P., Harris, A.W., 2007. Binary asteroid population. 1. Angular momentum content. Icarus 190, 250-259.

Pravec, P., and 19 colleagues, 2005. Tumbling asteroids. Icarus 173, 108-131.

Pravec, P., and 56 colleagues, 2006. Photometric survey of binary near-Earth asteroids. Icarus 181, 63-93.

Pravec, P., Harris, A.W., Warner, B., 2007. NEA rotations and binaries. In: Milani, A., Valsecchi, G.B., Vokrouhlický, D. (Eds.), Proceedings of the IAU Symposium 236, in press.

Pravec, P., and 30 colleagues, 2008. Spin rate distribution of small asteroids. Icarus, submitted, manuscript available on http://www.asu.cas.cz/ ppravec/

Scheeres, D. J., 2002. Stability of Binary Asteroids. Icarus, 159, 271–283

Scheeres, D.J., and 15 colleagues, 2006. Dynamical configuration of binary near-Earth asteroid (66391) 1999 KW4. Science 314, 1280-1283.

Vokrouhlický, D., Nesvorný, D., 2008. Pairs of asteroids probably of common origin. Astron. J., submitted.

Walsh, K.J., Richardson, D.C., 2006. Binary near-Earth asteroid formation: Rubble pile model of tidal disruptions. Icarus 180, 201-216.

Walsh, K.J., Richardson, D.C., 2007. A steady-state model of NEA binaries formed by tidal disruption of gravitational aggregates. Icarus, submitted.