Proceedings for the 24th Annual Conference of the Society for Astronomical Science

Symposium on Telescope Science

Editors:
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May 25/26, 2005
Northwoods Resort, Big Bear Lake, CA

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Published by the Society for Astronomical Science, Inc.

First printed: May 2005

ISBN: 0-9714693-4-2

Photometric Survey for Asynchronous Binary Asteroids

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Abstract

Asynchronous binary asteroids have been found to be abundant among fast-spinning near-Earth asteroids (NEAs) smaller than 2 km in diameter; Pravec et al. (2005, Icarus, submitted) derived that 15 +/- 4 % of NEAs in the size range 0.3 to 2 km are binary with the secondary-to-primary mean diameter ratio >=0.18. The early results from the surveys of the Vesta family and the Hungaria group (Ryan et al., 2004, Planet. Space Sci. 42, 1093; 2004, Bull. Amer. Astron. Society 36, 1181; Warner et al., 2005, IAU Circ. 8511) suggest that the population extends beyond the region of terrestrial planets, but with characteristics shifted to larger sizes and longer periods; the four known binaries in the Vesta family/Hungaria group are 3 to 6 km large and they have primary rotation periods in a range of 3 to ~4 h, i.e., on the tail of the distribution of primary rotation periods of NEAs. The comparison suggests that formation and evolution mechanisms of asynchronous NEA and main-belt binaries may be similar and are related to their fast spins and rubble-pile structure. None of the current theories of their formation of evolution, however, explains the observed properties of both NEA and main-belt asynchronous binaries in full. We have established a collaborative observational program, called "Photometric Survey for Asynchronous Binary Asteroids" to discover and describe asynchronous binaries over a range of heliocentric distances from NEAs through Mars-crossers to inner main-belt asteroids. One new binary Amor asteroid, 2005 AB has been found during the first few months of the survey operation (Reddy et al., 2005, IAU Circ. 8483), and we have obtained follow-up data for two other binary systems. I outline the motivations, the technique, and the strategy of the Survey.

1. Introduction

Binary systems among small, especially Near-Earth Asteroids (NEAs) have been observed since mid-1990's by lightcurve photometry technique and since 2000 by radar (see Merline et al., 2002, and references therein). Most binary near-Earth asteroids are asynchronous systems; their primaries rotate with periods shorter than the mutual orbital periods. This property played a key role in establishing the efficient technique of their detection with lightcurve observations (Pravec et al., 2005b, and references therein, also outlined in Section 2). The up-to-date list of known binary NEAs is available on

http://www.asu.cas.cz/~asteroid/binneas.htm

A comparison of properties of the binary NEA population with those of binaries observed in other groups of asteroids lying outside the region of terrestrial planets is needed to understand relations between the different populations of binaries and to provide further data for constraining theories of their formation and evolution. Pravec et al. (2005b) have done some initial work on this. They compared the data on NEA binaries with data obtained by Ryan et al. (2004a, b) and Warner et al. (2005; personal communication) for two binary Vestoids and two binary Hungaria asteroids, respectively, and obtained a few interesting hints and constraints that suggest that the Vesta family/Hungaria group binaries (henceforth called "VH binaries") were formed and evolved by same or similar mechanisms as some or all binary NEAs.

Theories of formation and evolutionary processes of binary asteroids were summarized in Merline et al. (2002). None of the processes, however, explains the observed properties and abundance of binary NEAs as well as the VH binaries fully. Bottke and Melosh (1996a, b), Richardson et al. (1998), and Walsh and Richardson (2004) examined the tidal effect of planetary encounters on gravitationally bound aggregates and they proposed that Near-Earth Asteroids of a rubble pile structure (with zero global tensile strength) can evolve into co-orbiting binaries. While this mechanism may be responsible for some NEA binaries, it does not work in asteroid groups lying beyond the region of terrestrial planets.

Of the other two mechanisms mentioned in Weidenschilling et al. (1989) and Merline et al. (2002), neither seems to fit with the observed properties and abundance of binary NEAs as well as VH asteroids. The cratering ejecta mechanism prefers irregularly shaped, elongated primaries. The disruptive capture mechanism predicts no initial preference for rapid rotation of primaries and no correlation with the primary's shape.

Recently it was proposed that binary systems with properties of the NEA as well as the VH binaries might be created by rotational fission of small rubble pile asteroids that were spun up by the YORP effect (Rubincam, 2000; Bottke et al., 2002).

To obtain a thorough understanding of the population of asynchronous binary asteroids over the range of heliocentric orbits and to constrain theories of their formation and evolution, we have established the project "Photometric Survey for Asynchronous Binary Asteroids".

2. Lightcurve technique for asynchronous binary detection

The technique for binary asteroid detection was reviewed in Pravec et al. (2005b). We outline its principles below.

An asynchronous binary asteroid is an object of two asteroidal bodies in a mutual orbit with at least one of them rotating with a period different from their orbital period. Photometric observations of such system can reveal signals with the two (or more) different periods. Each of the two bodies scatters sunlight that produces its own rotational lightcurve, and mutual events occur in favorable geometric conditions when the Earth or Sun is close enough to the mutual orbital plane of the system. The two rotational lightcurves add linearly into a combined lightcurve that can be represented as a linear addition of two Fourier series

$$F(t) = F_1\,(t) + F_2\,(t)$$

$$F_1\,(t) = C_1 + \sum_{k=1}^{m_1} \left[C_{1k} \cos\frac{2\pi k}{P_1}\,(t - t_o) + S_{1k} \sin\frac{2\pi k}{P_1}\,(t - t_o) \right]$$

$$F_2\,(t) = C_2 + \sum_{k=1}^{m_2} \left[C_{2k} \cos\frac{2\pi k}{P_2}\,(t - t_o) + S_{2k} \sin\frac{2\pi k}{P_2}\,(t - t_o) \right]$$

where

F(t)	is the total reduced light flux at time t
$F_j(t)$	are the reduced light fluxes of the components at time t
C_j	are the mean reduced light fluxes of the components
C_{jk} , S_{jk}	are the Fourier coefficients
P_j	are the rotation lightcurve periods
t_0	is the zero-point time (epoch)
m_j	are the maximum significant orders

(see also Pravec et al., 2000, and references therein).

The two constant terms are added to $C_0=C_1+C_2$ which is fitted in analysis. Note that using the representations with the above formulas, we assume a principal axis rotation for each of the components; a non-principal axis rotation would produce a complex lightcurve (see Pravec et al., 2005a).

Mutual events produce attenuations that are superposed to the combined rotational lightcurve of the two system's components. A shape of an individual attenuation event depends on instantaneous orientations, shapes, and surface brightness distributions of the two components as well as on illumination and viewing geometries of the system at the time of the event. Total events have, however, a few characteristic features:

- A plateau of constant brightness attenuation is seen during the total secondary event after the primary variation is subtracted from the lightcurve data.
- Slopes of increasing and decreasing branches (occuring during orbital phases where the bodies partially obscure one other) are steeper than slopes of the rotational lightcurve of the secondary. It is due to the fact that during the partial phases prior and after the total events, the rate of obscuration of the occulted/eclipsed body (in units of area per period) is greater than the rate at which parts of the secondary rotate into/out of view.

The features allow resolving between a rotational component feature (minimum) and a mutual event even in a binary system with the secondary rotating synchronously with the orbital motion. Onsets/offsets of the partial phases of the total events produce fast, large changes of the slope of the combined secondary's lightcurve and the mutual event attenuations.

The depth of the attenuation during the total secondary event provides an estimate of the constant term C_2, which leads to resolving the degeneration of the two constant terms in the fitted term C_0.

For same albedos and phase effects of the two bodies, the depth of the total secondary attenuation is related with the ratio of their mean projected diameters with the formula

$$\frac{C_2}{C_0} = \left[\left(\frac{D_s}{D_p}\right)^{-2} + 1\right]^{-1}$$

When only partial events occur, we do not see a plateau of constant brightness attenuation in the secondary event. Also, the slopes of increasing and decreasing branches of the events may not be distinctively greater than slopes of a rotational component of the secondary, making an immediate resolution between secondary's rotational component's minima and mutual events less certain in some cases. In such instances, further observations made in changing geometric conditions of the system with respect to Earth and Sun should bring an answer when the asteroid moves into a more favorable geometry that produces deeper events.

In a case where we see a two-periodic lightcurve that is well described with the additive two-period Fourier series but no clear mutual attenuation events (i.e., either the mutual events do not occur in the given geometric conditions, or they are too shallow so that we cannot distinguish them from the secondary's rotational lightcurve minima), we consider the asteroid as a probable binary system as well.

The possibility that it could be a tumbling asteroid has to be investigated but unless a significant signal in linear combinations of the two main frequencies is found, the lightcurve consisting of the two additive components favors the binary interpretation (see Pravec et al., 2005b).

An example of lightcurve data of asynchronous binary system is presented in Fig. 1 and 2 (reprinted from Pravec et al., 2005b). The two figures show the observational data obtained for (65803) Didymos during two different intervals. Both figures present the data in three different forms:

- The (a) part of each figure shows the original data folded with the orbital period, reduced to unit geo- and heliocentric distances and to a given phase angle using the H-G relation with the best fit value of G.
- The (b) part presents the data with the primary variation component removed; $(F_1(t)-C_1)$ was subtracted from each data point. The displayed data therefore represent the secondary lightcurve component with superposed mutual attenuation events, with the mean primary light flux C_1 present as well. (The full fitted constant term $C_0=C_1+C_2$ was left there and not subtracted from the data plotted in the figures.).
- The (c) part shows the primary rotation component; it presents data taken outside the mutual attenuation events with the secondary variation $(F_2(t)-C_2)$ subtracted and folded with the primary period.

We point out that while all the fits and subtractions of components were done in linear, flux units, the figures are plotted in magnitudes in order to present the data in the standard units.

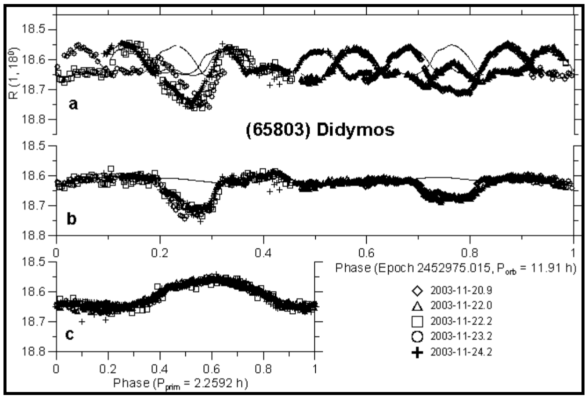

Fig. 1: Lightcurve data of (65803) Didymos of 2003-11-20.9 to 24.2 folded with the periods of 11.91 h (a, b) and 2.2592 h (c), and G=0.20. (a) The original data showing both lightcurve components. The additive Fourier series with the periods of 2.2592 h and 11.91 h was fitted to the primary and the secondary rotation data. (b) The long-period component showing the mutual events and the secondary rotation lightcurve. The primary lightcurve component was subtracted. (c) The primary lightcurve component. The epoch of the primary component's plot is the same as the epoch of the long period component's plot (all times are JD [UTC] light-time corrected).

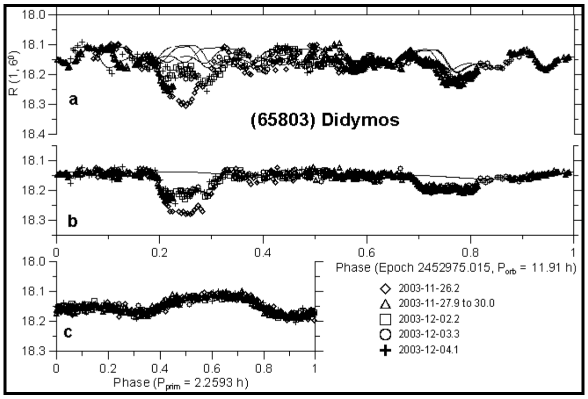

Fig. 2: Lightcurves of (65803) Didymos of 2003-11-26.2 to 12-04.1. See caption to Fig. 1. The best-fit synodic primary period was 2.2593 h.

3. Properties of the Population of Binary NEAs

Pravec et al. (2005b) analyzed observational selection effects of their survey for binary NEAs and derived characteristic properties of their population. A few figures from the Pravec et al. (2005b) are reprinted below.

I summarize their conclusions in following.

- Binary systems with D_s/D_p>0.18 concentrate among NEAs smaller than 2 km in diameter; the abundance of binaries decreases among larger NEAs. See Fig. 3.
- Secondaries show an apparent upper size limit of D_s=0.5-1 km. Systems with the secondary-to-primary mean diameter ratios $D_s/D_p <= 0.5$ are abundant while larger satellites are less frequent. See Figs. 3 and 4.
- Primaries have spheroidal shapes and they rotate fast, concentrating in the range of periods 2.2-2.8 h and with the tail of the distribution in the range 2.8 to ~4 h. The fast rotators are close to the critical spin for rubble piles with bulk densities about 2 g/cm^3. See Fig. 5 and 6.
- Orbital periods show a cut-off at P_{orb} ~ 11 h; closer systems with shorter orbital periods are rare or non-existent, which is apparently consistent with the Roche's limit for strengthless satellites. See Fig. 4.
- On average, secondary shapes are more elongated than primaries. Their rotations appear to be mostly synchronized with the orbital motion in close systems with P_{orb} < 20 h, but it appears that some systems with larger separations have unsynchronous secondary rotations.
- The available data do not provide evidence on whether the asynchronous binary population remains the same or changes, in abundance or in formation mechanism(s), with perihelion distance beyond q=1.05 AU. A comparison with the four binaries known in the Vesta family and the Hungaria group suggests that the population extends beyond the region of terrestrial planets, but with characteristics shifted a bit to larger sizes and greater periods.

The characteristics of the binary NEA population indicate a formation mechanism closely related to their fast spins and rubble pile structure. However, neither the observational data nor predictions from the theories are detailed or thorough enough to distinguish whether the NEA binaries were created by a mechanism related to their near-Earth orbits (e.g., by tidal splitting during planetary encounters) or by some other mechanism that also works in more distant orbits (e.g., the spin-up YORP effect).

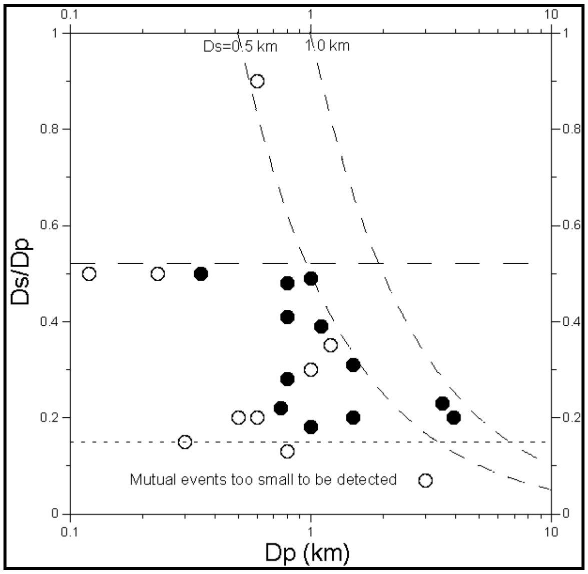

Fig. 3: Secondary-to-primary mean-diameter ratio vs. primary diameter for the 12 regularly detected binary NEAs (filled circles) within the photometric survey, and for 10 additional systems detected primarily or exclusively by radar (see Pravec et al., 2005b). Secondaries concentrate at and below D_s = 0.5 km.

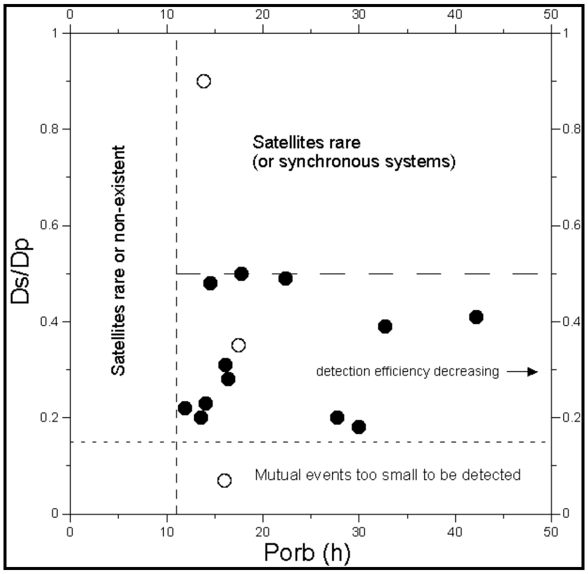

Fig. 4: Secondary-to-primary mean-diameter ratio vs orbital period for the 12 regularly detected binary NEAs (filled circles) within the survey by Pravec et al. (2005b). Three other systems with D_p>0.3 km are included, (66391) 1999 KW$_4$, (69230) Hermes and 2002 CE$_{26}$. They were measured mostly with radar. The horizontal dashed lines at D_s/D_p= 0.15 and 0.5, respectively, in this as well as in Fig. 3, indicate the photometric detection lower limit and the apparent upper limit of the range of concentration of the secondaries. The vertical dashed line at P_{orb}= 11 h indicates the apparent cut-off in the orbital periods.

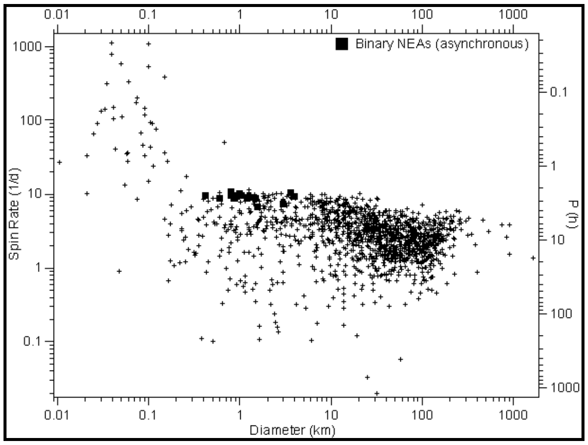

Fig. 5: Asteroids' spin rate vs. diameter plot. Primary periods of asynchronous binary NEAs are marked with filled squares.

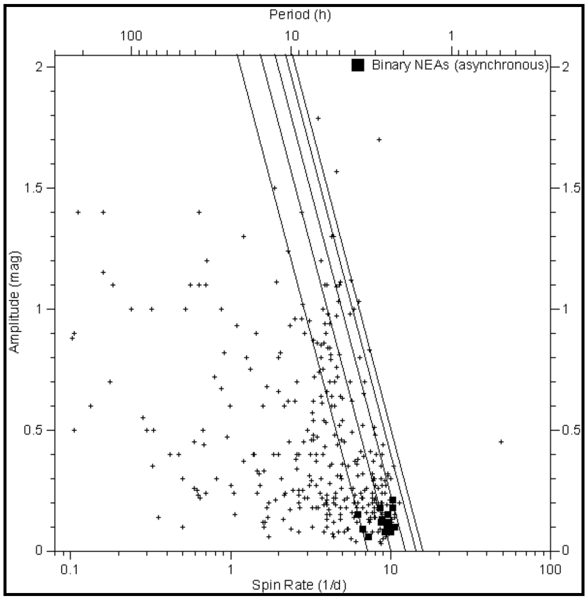

Fig. 6: Observed lightcurve amplitude vs. spin rate plot for asteroids with 0.3 km < D < 10 km. Primaries of asynchronous binary NEAs are marked with filled squares. The lines are approximate limits of spin rates of prolate spheroids (a >= b = c) held together by self-gravitation only, with bulk densities of 1, 2, 3, 4, and 5 g/cm^3 (from left to right, respectively), and observed at zero phase angle. The formula is A = log (P^2 rho/10.9) / 0.8 (P in hours and rho in g/cm^3). A few objects to the right of the line are either not rubble piles or their lightcurve amplitudes were increased by the amplitude-phase effect at non-zero solar phase angles.

4. Photometric Survey for Asynchronous Binary Asteroids

Since December 2004 we have run an extended survey looking for binary asteroids. A group of interested and devoted asteroid photometrists that work in a coordinated way and use a strategy as outlined below was established. They coordinate their observations internally; some more general information has been placed on the www pages

http://www.asu.cas.cz/~asteroid/binastphotsurvey.htm

The observational strategy used in this Survey is an enhanced version of the strategy that Pravec et al. (2005b) used for detection of NEA binaries during 1994-2004 and that allowed them to model selection effects of their survey.

A central point of the strategy is to cover a targeted asteroid thoroughly on a few nearby nights so that its (primary) period can be estimated uniquely and a potential attenuation feature, or a secondary period, resolved immediately. A fast reduction and analysis of the observations, basically before beginning of following night, is a necessary condition to achieve the goal.

When an attenuation feature or a second period is found in the data, a few other stations participating in the Survey are asked to collaborate on taking further data needed to describe the binary system.

4.1. Targeted asteroids

While binary NEAs concentrate in the size range below 2 km and their abudnance decreases significantly above 2 km (though a small fraction of them may be as large as ~4 km), the VH binaries appear to have the apparent upper limit shifted to larger sizes. The four known VH binaries are 3 to 6 km in size. We therefore extended the Survey to asteroids with sizes up to 10 km. Since an actual size and albedo of such small asteroids are usually unknown, we have to estimate the size from the absolute magnitude using an albedo value assumed according to a typical albedo in the given group of asteroids. For example, most asteroids in the Vesta family as well as in the Hungaria group of asteroids have a high albedo of p_V= 0.3 to 0.4, so the size limit of 10 km converts to a limit in H of ~11.8. In other groups of asteroids (NEAs, Mars-crossers, other inner main-belt asteroids), a typical albedo is about p_v = 0.2, which converts the 10-km size limit to H~12.4. Given the uncertainties of a few tenths of magnitude in the majority of available H estimates, we use a practical limit for selecting targets for the Survey of H > 12.

The selection procedure takes into account observational conditions of the asteroid for the given station during a few weeks. Observational windows lasting for a week or less are too narrow, as it might be difficult to get sufficient follow-up for the asteroid, if discovered to be binary, in the narrow window.

During the observational window, the asteroid should be observable at airmass lower than 2 for at least a few hours on each night. The brightness and motion of the asteroid should allow the observer's system to obtain photometric errors of 0.03 mag or less during the observational window.

Ideally, the selection procedure should not consider previous lightcurve observations of the given asteroid. In practice, it suffices to check whether the asteroid has been covered thoroughly on at least one past apparition. If it was not, the asteroid might be targeted within the Survey again so that a sufficient coverage is obtained during the new apparition.

4.2. Time coverage

Generally, long nightly runs are much more preferred than short ones. This is due to the fact that the orbital periods are all relatively long (with the lower limit of ~11 hours but some have orbital periods in a range of tens of hours), so long nightly runs increase the probability of catching a mutual event. Shorter runs may be usable as well, but runs with durations below 2 hours are of little use.

A minimum requirement on the coverage of primary rotation period is that each rotation phase has to be covered twice. Gaps in the coverage of primary period shorter than ~0.5 hour can be tolerated as mutual events of significant depths last typically for 1 or 2 hours, but any longer gap needs to be covered with further data on another night. Since the required minimal double coverage of the primary rotation period would mean an extensive length of observations for longer periods, and considering that the known asynchronous binary NEAs and VH asteroids have $P_{\mathrm{prim}} < 5$ h, we established a practical upper limit for the double coverage to be applied only to asteroids with rotation periods shorter than 10 hours.

So, the strategy actually is: 1) establish a unique period solution for the targeted asteroid, 2) complete the double coverage of the derived rotation period if it is less than 10 hours.

A minimum number of nights that will be needed for the particular asteroid therefore cannot be well planned until data on the first night, sometimes several, are obtained. The requirement to obtain a unique solution of the rotation period is sometimes fulfilled in a single night (if it is long enough so that more than one cycle is observed), but more typically it takes 2 or 3 nights. The requirement to cover each primary period phase twice means that the total length is always at least $2P_{\mathrm{prim}}$, but it usually takes about $3P_{\mathrm{prim}}$ due to overlaps and an "interference" between P_{prim} and one day. So, the station that targets the particular asteroid has to plan to 20 to 30 hours total coverage during at least 3 nights, though it may turn out that the object is finished sooner if its rotation period is significantly shorter that 10 hours.

If the station participating in the Survey cannot complete the coverage of the targeted asteroid for any reason, or if the station gets less than two full observing nights, it may still contribute usefully to the Survey. This can be either by collaborating on an asteroid observed from another station so that the unique solution and/or the double coverage of the asteroid's rotation period is obtained faster, or by targeting a binary asteroid discovered earlier for which further follow-up observations are needed.

4.3. Calibrated vs. Uncalibrated data

Data calibrated on the standard system (Cousins R band is preferred) or mutually linked to a level of 0.02 mag or better are most useful. Relative (differential) measurements are useful as well if they cover features that allow solving for the magnitude zero point. In practice, it turns out that relative runs longer than 4 hours are almost always usable while runs shorter than 2 hours are rarely useful.

5. Concluding remarks

The estimated abundance of asynchronous binaries among NEAs of 15 +/- 4% and their estimated detection probability of the Survey of about 0.40 (Pravec et al., 2005b) means that about 6% of NEAs targeted within the Survey will actually be resolved as binary. The early data for VH binaries suggest that the abundance of binaries among them is similar to that of NEAs. So, we may expect to detect a binary in 1 of ~20 asteroids targeted within the Survey. Since we run the observations in a way that allows modeling the selection effects of the Survey, nondetections are as important as binary detections.

After we cover a few hundred targets during the Survey and discover more than 10 new binary systems over a range of heliocentric distances from NEAs to inner main-belt asteroids, it will be the right time to do a thorough analysis of the selection effects of the Survey. This will be done using methods similar to those used by Pravec et al. (2005b) for their survey of NEA binaries, yielding an estimate of the properties of the population of asynchronous binary asteroids over the range of heliocentric orbits.

In the meantime, publications for individual resolved binaries as well as interesting non-detections may be done as found suitable by the principal observer/station for each individual case. A summary of the results for each targeted asteroid can be placed on dedicated web pages after finishing the target within the Survey. And, of course, each discovered binary is published on the IAU Circular immediately after the discovery.

6. Acknowledgements

The work has been supported by the Grant Agency of the Czech Republic, Grant 205/05/0604.

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