Deduction of the possible excited spin states of 2P/Encke

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The determination of the spin state of an active cometary nucleus presents a somewhat different problem than the determination of the spin state of an asteroid — although there is also much in common in the two cases. To date the complete spin state has only been determined for two cometary nuclei — and at least one of them - 1P/Halley - remains controversial (Samarasinha et al. 2004). Partial information is available for about two-dozen more comets, but this information is mainly limited to the primary periodicity in the lightcurve and pole solutions are generally not available. This state of affairs is regrettable for those who wish to explore the implications of observable coma structures and global gas production rates for the properties of specific active regions on the surface. It is knowledge of the spin state that allows such phenomena to be traced back to particular localities on the cometary surface (e.g. Belton et al. 1991). 2P/Encke is a well-observed comet with a short orbital period that displays variable coma structure and also peculiarities in the production rates around perihelion. Its spin state is therefore of considerable interest. Several photometric studies in the late 80's seemed to indicate a fully relaxed spin state with a period near 15 hr, however not all workers agreed pointing out problems with the observed amplitudes of the lightcurves. More recently, observations in 2000 and 2001 have been reported with a period near 11 hr and all signs of a 15 hr period seem to have disappeared. In this paper I revisit these many data sets and show that the many periods latent in the data (not just the two mentioned above) can be consistently explained in terms of an excited spin state. I also show how the pole determinations of Sekanina (1988) and Festou and Barale (2000) can be generalized to give an estimate of the direction of the total angular momentum vector. More difficult is a choice between spin states in the short (SAM) or long (LAM) axis mode (both are allowed by the periodicities). A low-excitation SAM state is the preferred solution, although a highly excited LAM state with rather special properties is also a possibility. While not yet fully specified, four (possibly five) of the parameters describing the spin state are deduced. The rest could, in principle, be determined from radar observations and/or future high quality light curves in the thermal infrared.

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Searching for the Long Lost Precursors of the Primordial Earth

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It is frequently assumed that planetesimals formed at 1 AU, presumably the precursors of our heavily-evolved Earth, could not have survived to the present day. Dynamical models indicate that most objects on planetary crossing orbits have a very short dynamical lifetimes (<10 Myr) compared to the age of the solar system (Gladman et al. 1997; Icarus), while cosmochemical models suggest the Earth's bulk chemistry was unlikely to come from any combination of chondritic meteorites in our current collection (e.g., Burbine et al. 2003; LPSC). This is unfortunate, given that samples taken from planetesimals formed at 1 AU could help answer numerous unsolved questions about the formation and evolution of our Earth (e.g., did Earth's water come from 1 AU or was it delivered by primitive asteroids/comets).

Results from recent dynamical models, however, are somewhat less pessimistic; they hint at the possibility that a few Earth precursors may still be found, provided we know where to look. For example, Morbidelli et al. (2001; MAPS) showed that during the late stages of planet formation, perturbations with planetary embryos chased a few percent of the initial planetesimal population in the 1-2 AU zone onto highly-inclined orbits in the inner solar system. According to their dynamical model, these bodies could have been long-lived enough to cause an extended bombardment of all of the terrestrial planets for hundreds of Myr. We hypothesize that a very small fraction of this population may have survived all the way to today, provided that: (i) the initial population was large, (ii) the dynamical decay rate of this material was slow (i.e., some of this precursor material found its way into long-lived orbits within the inner solar system), and (iii) these survivors turn out to be protected from extensive comminution.

To test our hypothesis, we numerically integrated the known high-inclination NEOs (and their clones) using the code SWIFT-RMVS3 (Levison and Duncan 1994). In our simulation, whenever our initial population decays to less than 10% of the starting population, we clone the remnants and continue the integration. Our goal is to push out the integrations to several Gyr while searching for a long-lived tail to the original population. We believe our method has certain advantages over that used by Morbidelli et al. (2001) because we use the present-day orbital parameters of the planets; Morbidelli et al. (2001) integrated their particles using model-derived planetary parameters that do not match our current solar system.

Preliminary results suggest that some clones of our initial population reach orbits near the periphery of the modern-day Hungarias and Phocaeas populations, where their dynamical lifetimes can reach many hundreds of Myr, far longer than typical NEOs (Bottke et al. 2002; Icarus). Even so, it is not yet clear whether these lifetimes are long enough to be consistent with our hypothesis. Our latest results on this topic will be presented at the workshop.

Using Multi-Polarization Radar to Search for Regolith on Asteroids

Lynn M. Carter, Donald B. Campbell and Michael C. Nolan

The presence of regolith material will alter an asteroid's thermal properties and can affect its dynamical history via Yarkovsky forces [1]. It is not clear what sized asteroids have regolith; small asteroids have lower escape velocities, but internal strength and the presence of previously ejected material also determine how much volume is lost to space during an impact [2]. High resolution spacecraft images, such as the NEAR images of Eros, have confirmed that some asteroids possess regoliths [3]. Although many asteroids likely have a regolith, it is hard to detect such surface coverings at the resolutions typically achieved by ground-based optical imaging. At infrared wavelengths, thermal models can be used to extract a value for the thermal inertia, which is related to the density of the surface. However, shape, surface roughness, rotation state and thermal inertia are strongly connected in thermal models, and it is difficult to derive the thermal inertia from observed fluxes without some prior knowledge of the asteroid's physical properties.

Multi-polarization radar imaging provides a unique method to search for regolith. In radar experiments, an analysis of the degree of linear polarization in the received echo can be used to investigate whether there is a surface covering on an object. A circularly polarized wave, such as that transmitted by the Arecibo radar, can be thought of as a combination of two linearly polarized waves of equal magnitude, one perpendicular to the plane of incidence and one parallel to the plane of incidence. If a circularly polarized radar wave refracts into a surface that is smooth at wavelength scales and is reflected by embedded scatterers or by an underlying structure, the returned radar echo will have a net linearly polarized component (it will be elliptically polarized). The linear polarization is produced because the horizontally and vertically polarized components of the incident wave have different transmission coefficients into and out of the surface layer. This technique has been used by Stacy [4] to study the lunar regolith and by Carter et al. [5] to study surface deposits on Venus.

Benner et al. [6] used the Arecibo and Goldstone radars to observe the asteroid 1999 JM8 during its close approach to Earth. The asteroid is about 7 km in diameter, and delay-Doppler images from these radar runs have resolutions as small as 15 m/pixel, which gives thousands of pixels on the asteroid [6]. The Stokes parameter analysis reveals a significant linearly polarized echo component, which demonstrates that there is some penetration of the radar wave into a surface layer. JM8 has an irregular shape, and the resulting radar ambiguity makes it difficult to model physical properties, such as the dielectric constant and depth, of the regolith. However, the values of the degree of linear polarization also follow the incidence angle trend expected from the transmission coefficients: at near normal incidence angles, no linear polarized echo power is produced, and the values are higher elsewhere on the asteroid. This linear polarization technique can be used with other asteroids, provided that the radar data have sufficient signal-to-noise. We hope to compare the linear polarization properties of different size, shape and perhaps different composition asteroids.

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The First Direct Measurement of Yarkovsky Acceleration on an Asteroid

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Radar ranging at three apparitions over twelve years has unambiguously revealed the action of the Yarkovsky Effect on near-Earth asteroid 6489 Golevka. The most recent measurements, from Arecibo in May 2003, indicate a 15 km displacement that cannot be reconciled with a purely gravitational force model. This kind of detection requires careful consideration of astrometric uncertainties and potential mismodeling of gravitational perturbations. Indeed, uncertainty in the masses of perturbing asteroids has the potential to completely obscure Yarkovsky-induced deflections in some cases.

The magnitude of the displacement is consistent with the predictions from simplified Yarkovsky models, and thus many previous theoretical studies that relied on such models are substantially validated by this detection. Moreover, the Yarkovsky measurement permits us to place constraints on the mass and bulk density of the asteroid. However the quality of the mass estimate is degraded by uncertainty in the surface thermal characteristics. A Yarkovsky detection, along with independent measurement of the surface thermal conductivity would allow a much more precise estimate of the asteroid's mass. Conversely, if the mass can be independently determined, such as for a binary asteroid system, then a Yarkovsky detection would allow a precise estimate of the surface thermal properties.

YORP for Synchronous Asteroidal Satellites

that is an order of magnitude shorter than that for YORP acting on an ideal Ida. Of course, real asteroids have very different shapes; nevertheless this exercise demonstrates

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Many of the lesser components in binary asteroid pairs are expected to be in synchronous rotation. Geometrically, such satellites appear to be rigidly attached to their primaries, since they always keep the same orientations relative to their primary's center of mass (assuming the satellite's orbit is circular). Recently, YORP – the non-gravitational force affecting an asteroid's rotation – has received considerable attention (Rubincam 2000, Vokrouhlicky and Capek 2002, Vokrouhlicky et al. 2003). I argue that a similar effect should influence the orbits of at least some synchronous asteroidal satellites, owing to their similarity to promontories of the primary. To illustrate this mechanism, we visualize an irregularly shaped asteroid as a sphere with a wedge-shaped attachment (cf. Rubincam 2000, but we assume only a single attachment). This appendage is shaped like a prism with a right triangular base, which is attached to sphere's equator, with one of the smaller rectangular sides perpendicular to the sphere's rotation axis. This attachment reflects sunlight directly back off one side but out-of-plane off the other; each side has the same vertical cross-section. The infrared radiation re-emitted by the body itself has a similar distribution. Hence a torque, which can change spins, arises.

I now consider an identically shaped asteroidal satellite in synchronous rotation, with the prism glued to the satellite's long axis, which is assumed to point toward the primary. In this way one side of the prism is always facing forward relative to the satellite's orbital motion, while the other faces backwards. Depending on the prism's exact placement and its orientation, re-radiated energy from the prism can produce a positive or negative torque on the satellite's orbit. To estimate roughly the significance of this effect, we compare the timescales for YORP acting on the primary and "satellite YORP" acting on a secondary, assuming our "sphere-plus-wedge" shape and taking binary parameters like those of the Ida-Dactyl system. The YORP's magnitude varies with the prism's size, and therefore with radius squared, while the torque is the product of this force times the distance from the center of motion (the primary's radius for the usual YORP, but the binary's separation for the satellite YORP). The timescales for these two effects are estimated by dividing the relevant angular momenta by the respective torques. For YORP, the timescale

$$t_y = const * 2/5 * M * R^2 * W_{\rm rot}/(R * R^2) = const * R^2 * W_{\rm rot}$$

(where M, R and $W_{\rm rot}$ are the primary's mass, radius and rotation rate). For satellite YORP,

$$t_s = const * m * a^2 * W_{\rm orb}/(a * r^2) = const * a * r * W_{\rm orb}$$

(where m, r, a, $W_{\rm orb}$ are the satellite's mass, radius, semimajor axis and mean motion). Assuming identical densities, the ratio of timescales is:

$$(t_s)/(t_y) = 2.5 * (a/R) * (r/R) * (W_{\rm orb})/(W_{\rm rot})$$

For the Ida-Dactyl pair, $(a/R) = 7$, $(r/R) = 1/22$, $(W_{\rm orb}/W_{\rm rot}) = 1/8$, so the timescale ratio should be (t_s/t_y)= 0.1. Therefore, our ideal Dactyl would change its orbit on a timescale the potential importance of the satellite YORP. Since the orbital angular momentum varies as $\sqrt{a}$, and the satellite YORP torque is proportional to a, a satellite's outward migration is a runaway process (at least until the synchronous rotation is broken), quite unlike tidal evolution. Also, for some close binaries with similar-sized, mutually-synchronous components ("contact binaries"), YORP and satellite YORP should become indistinguishable.

Does Microporosity or Macroporosity Dominate in Stone Asteroids?: Evidence from Stone Meteorites

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Comparison of the densities of asteroids with the densities of the minerals presumed to dominate their composition (based on reflection spectroscopy) indicates that most asteroids exhibit significant porosity (Flynn, 1994). The type of porosity ranging from microporosity to macroporosity (in the extreme case, a rubble pile) determines the physical behavior of the asteroids, e.g., the response to collisions, the maximum rotation rate, etc.

Since the meteorites are generally accepted to be samples of the asteroids, the study of porosity in meteorites can provide constraints on the type and amount of microporosity in the asteroids. Britt and Consolmagno (2003) reviewed the density and porosity measurements on stone meteorites obtained by several groups. The lowest bulk density in their tabulation is 1.5 gm/cc for a large (47.2 gm) sample of the hydrated CI carbonaceous chondrite Orgueil. Four of the hydrated CM carbonaceous chondrites in the tabulation have bulk density values < 2.0 gm/cc (ranging from 1.79 gm/cc for Santa Cruz to 1.96 gm/cc for Nogoya), but other hydrated CM meteorites Cold Bokkeveld, Kivesvaara, and Murchison have bulk densities ranging from 2.3 to 2.4 gm/cc. The lowest bulk density reported for an anhydrous meteorite is 2.38 gm/cc for the LL ordinary chondrite Y-75258. However, we might reasonably expect that the bulk density of the parent asteroid would be significantly lower than that of the meteorite derived from that parent since objects tend to break into their strongest subunits, thus minimizing their microporosity. This trend is evident in the Orgueil data (Britt and Consolmagno, 2003), where the sample having the lowest bulk density (1.5 gm/cc) is the largest one measured, while the smaller Orgueil samples have much higher bulk densities (averaging 2.1 gm/cc).

Recent asteroid flyby missions have permitted accurate determinations of the bulk densities of several asteroids: Mathilda at 1.3 gm/cc, Ida at 2.7 gm/cc, and Eros at 2.67 gm/cc. Each of these bulk densities is high enough to be explained entirely by microporosity, especially when the measured bulk densities of the meteorites are adjusted down to account for objects breaking into their strongest (most likely least porous) subunits.

The meteorites exhibit three distinct types of porosity on the microscale – cracks, vugs, and gaps or low density regions separating chondrules from the matrix (Flynn et al., 2000). But the dominant type of porosity is cracks, which, in some cases, may not reflect the condition of their parent body. Meteorites are believed to be ejected from their parent body by collisions, which can induce new cracks through shock or fill pre-existing cracks through injection of melted material into the interior of the rock. In addition, we have performed Computed MicroTomography (CMT) on several small whole stone meteorites. We found cracks that cut the fusion crust on two meteorites. Once the cracks were identified using CMT, we were able to locate these microscopic cracks on the exterior surface of these stones using a low-power magnifying lens. Thus, at least in some cases, the cracks in meteorites were either produced or significantly enlarged after production of the fusion crust.

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Asteroid Orbit Determination and Radar Astrometry: Small Forces and Long-Term Prediction

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Open-loop delay-Doppler measurements, accurate at the several meter and mm/s level, have been incorporated into orbit solutions for 138 asteroids and 5 comets over the last 30 years [1]. 70% of those cases have occurred in the last 10 years, being based on data from Arecibo and Goldstone. Closed-loop NASA Deep Space Network tracking data from the NEAR spacecraft was also transformed to produce 2-meter delay measurements of 433 Eros over a 1 year time-span [2]. Such meter-level measurements, coupled with modern solar system solutions, reduce statistical asteroid orbit uncertainties several orders of magnitude when compared to optical data solutions (whose angular resolution is accurate at the tens to thousands of km level). For objects observed only during their discovery apparition, radar increases the total planetary encounter predictability window by a factor of 8 on average; from a mean of 145 years when only optical data is available, to a mean of 1200 years, when both optical and radar are used in the solution [3]. On average, radar measurements extend the useful encounter prediction window by +370 years for single apparition cases. For multiple apparition cases, radar still reduces uncertainties, but rarely changes the predictability time-span.

When such small measurement-data uncertainties are present, prediction uncertainties over centuries are dominated by combinations of normally unmodelled small forces acting simultaneously. Small factors examined in precision numerical integration studies include: Yarkovsky, asteroid-asteroid perturbations, solar pressure, planetary mass uncertainties, relativity, solar oblateness, Poynting-Robertson drag, the decreasing mass of the Sun, numerical integration error control, galactic tides and Galilean satellites [4]. Trajectory deviation from n-body gravity predictions is the combined result of such factors acting over time, most of which depend on physical attributes of the object that are not well known, as well as dozens of other objects it gravitationally encounters.

When the primary discovery phase ends in 20-30 years, most potentially hazardous asteroids will have measurement covariances similar to radar cases now, in principle allowing prediction over many centuries. This increases by more than a magnitude the likelihood of impact risks being identified, with lead-times of centuries being the future norm, unlike now. This makes low-energy, low-technology mitigation methods such as Yarkovsky acceleration modification an available option. However, the accuracy of the prediction will ultimately depend on poorly known details, from future solar oblateness variations to the physical characteristics of the object itself, instead of measurement precision, as is the case at the present time.

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Asteroid Lightcurve Parameters Data File

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Beginning about the time of the first Asteroids conference in Tucson in 1979, I (AWH) began compiling data on asteroid rotations from literature reports of lightcurve observations. The first research based on that list was published that year (Harris and Burns, *Icarus* **40**, 115-144, 1979). Along with the statistical analysis of rotations, we published the entire list, which consisted of 304 entries referring to 191 different asteroids. Of these, 182 asteroids had some indication of rotational properties, and 151 had "reliable" rotation periods published. The entire list fit on six partial pages of the old small *Icarus* page layout. In following years, numerous papers have been published analyzing the data contained on various updates of the data file, and updates of the file itself have been published in the Asteroids II book, an Icarus paper in 1983, and in abridged form in the annual *Ephemeredes of Minor Planets* (EMP), and is posted on the MPC and CALL web sites. Here we present the latest revision, which has now grown to a file with 6,183 entries referring to 1,813 different asteroids, and including 1,371 reliable rotation periods. The current data file, if published in format similar to the original Icarus publication, would occupy a fair fraction of a single issue of the journal. Fortunately electronic publication has come to the rescue of the data explosion, so it is again possible to publish one's underlying data. This file, and updates thereof, will continue to be available on the CALL and MPC web sites, or available for download, or CD copy on request (to AWH). However, it is desirable from time to time to "freeze" a version of the data file so that analyses based on that set can be examined, checked and compared against other analyses using the same data. With that in mind, we offer the data set as used in the analyses presented at this conference (Pravec et al.; Harris and Pravec) and invite others to use the same data set for related analyses or checking of our results. This version of the data file will also be archived on the NASA Planetary Data System Small Bodies Node (http://pdssbn.astro.umd.edu/).

A further use of this data file is for observation planning, particularly for radar or other complimentary physical observations, or to identify targets in need of confirmation or further study. With that in mind the data file contains entries indicating unpublished results and identifying the observers who have made those observations so that one can inquire directly with other observers to determine what further observations are needed. These unpublished entries are not listed in the EMP or MPC versions of the list, but are indicated in the compressed files on the CALL website (http://www.minorplanetobserver.com/astlc/default.htm). Following is a brief non-random sample from the file:

```
     Asteroid          Class    dia.    H    Alb.   Per.     Ampl.  Rel Com

2921 Sophocles           C*     12.1  13.3 *.058    4.778       0.16  2
     Birlan 96                                      4.778       0.16  2

2929 Harris              T      26.4  11.6 *.058                      2 *
     Harris                                                           2 *

2945*Zanstra                    21.12 12.2  .0522  19.414       0.20  1
    *Behrend 03w                                   19.414       0.20  1
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The first entry is a published result, with the full journal citation given in a companion file; the third entry refers to a result posted on a web page (indicated by a "03w" citation). The second entry is of an unpublished observation. You'll have to ask the observer for numerical results relating to this object.

Fast and Slow Spins Revisited: YORP alteration

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At the ACM 2002 meeting in Berlin, I (AWH) congratulated Bottke et al. for finding the "smoking gun" of the Yarkovsky Effect, in the form of the odd orbital structure of the Koronis family, and challenged them to find a similar "smoking gun" of the claimed YORP effect. Less than a year later, they obliged with the evidence of spin alteration of the members of the Koronis family (Vokrouhlicky et al, 2003). The compelling aspect of this evidence is not only the dispersion of spin rates, but also most strikingly the clustering of spin axis orientations, leaving little doubt that the YORP effect is capable of altering th spin states of asteroids up to a size of 30-40 km in diameter. With this new insight in hand, and utilizin the new compilation of asteroid rotation rates of nearly 1400 asteroids (Harris et al, this conference), we return to the problem of slow rotators among asteroids, which has been an unsolved mystery for two decades, since the discovery of the record slow rotator, 288 Glauke, with a rotation period exceeding 1000 hours. The hypothesis that slow rotators are the result of YORP despinning is supported by the fa that most slow rotators are also very irregular bodies with large amplitudes of lightcurve variation (but that could also be in part a selection effect of what can be observed). It is further supported by the absence of slow rotators at larger sizes: 253 Mathilde is the largest at nearly 60 km diameter. Howeve the numbers of yet larger asteroids decreases rapidly so that one can't be sure if there is a real cutoff w larger size, or if there are just too few asteroids for a chance outlier. Nevertheless, it can be noted that rate of YORP despinning is inversely proportional to diameter squared, so the difference from ~30 km where we see clear evidence in the Koronis family, and Mathilde is only a factor of about four in rate of spin evolution. Furthermore, the spin evolution looks more like "sliding friction" than "aerodynamic drag" (cf., evolution plots in Vokrouhlicky et al, 2003, where we see that rotation rates simply "skid to a halt," rather than slowing exponentially), thus if an asteroid like Mathilde happened to start out with a somewhat slow rotation rate, say 20-30 hours, it could plausibly be brought to a near halt by YORP dra in the same time as a 30-km diameter asteroid starting from an average spin rate.

Turning to the smaller end of the size distribution, it has long been apparent that the spin distribution of asteroids becomes increasingly dispersed with decreasing size. This is even more apparent in the "hig resolution" view of the new data set. YORP is a suitable explanation for the ever-increasing numbers o slow rotators as we go to smaller sizes, as the inverse-square with diameter power of the effect allows less irregular bodies to evolve to greater degrees. The slow trend toward faster rotation among the bul of asteroids may also be due to YORP effect in the opposite direction. As we have noted previously, th "spin barrier" for rubble pile asteroids sets an upper limit to spin rate, but YORP could lead to mass shedding leading to binary formation as objects are spun up to the barrier. The statistics of small (most NEA) binaries are consistent with splitting of bodies rotating at nearly critical rates, then evolving by tidal evolution to stable end states. An important observational test is whether NEAs are unusual in the spin states and fraction of binaries, compared to main-belt asteroids where tidal disruptions by close planetary encounters are not a viable mode of spin alteration or binary formation.

Hungaria asteroids provide a possibility to compare spin statistics of non-planet crossers with planet crossing asteroids. Hungarias are extreme inner main-belt objects just beyond Mars, and also high albedo, thus typically very small for their apparent brightness. These asteroids offer an opportunity to study main-belt asteroids nearly as small as NEAs to compare rotation statistics, pole orientations, and incidence of binaries to see if planet-crossing (tidal interactions) significantly alter these properties.

Near-Earth orbital distribution of asteroid fragments coming from the ν_6 resonance zone

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We have begun a numerical investigation on the orbital evolution of asteroid fragments originated by a disruption event in the main belt. Our final purpose is to compare the collisional probability of those fragments on the Moon and the lunar crater records which is regarded as a consequence of the possible cataclysmic heavy bombardment about 4 Gyr ago. The framework of our work consists of three parts: (1) Numerical integrations of test particles originally injected into some resonance area in the main belt. This will enable us to calculate the orbital distribution and the decay rate of the asteroid fragments which come close to the Earth–Moon system. (2) Estimation of the impact ratio of the fragments on the Moon. This procedure includes a gravitational four-body problem containing Earth, Moon, Sun, and a fragment. (3) Creating a synthetic crater record assuming some size distribution of the asteroid fragments. This leads us to the comparison of the numerical results with the real lunar crater record.

In this meeting we will present our preliminary result of the stage (1) about the fragments coming from ν_6 resonance. Although our result is still a reproduction of previous researches such as Gladman et al (1997, *Science,* **277**, 197–201), Morbidelli & Gladman (1998, *Meteor. Planet. Sci.,* **33**, 999–1016), or Bottke et al (2002, *Icarus,* **156**, 399–433) at this point, we have found a few interesting points in the dynamical behavior of the asteroids.

We assume that an isotropic disruption event happens near the ν_6 resonance, creating many small asteroid fragments. Then we numerically integrate the orbits of each fragment over ~ 100 Myr, treating asteroids as test particles. Starting from several initial disruption points and using about ten thousand test particles in total, we found that the NEO collision rate with the Earth typically reaches maximum in 2–3 Myr after the disruption, with a half-decay time of 10–20 Myr. The longest tail of the incoming asteroid flux can be as long as 50–100 Myr, depending on the initial position of disruption and the initial ejection velocity of the asteroid fragments after the disruption.

When we look at the orbital evolution of each asteroid fragment, we notice that there are three typical stages in the dynamical evolution of their orbits. At first, the eccentricities of the asteroid fragments are pumped up by the resonance ν_6 with the timescale of ~ 1 Myr. The enhanced eccentricities cause the close encounter between the asteroids and planets, which changes the semimajor axes of the asteroids and removes them from the resonance. The average timescale of this removal is nearly equivalent to the typical timescale that the collision rate of the asteroid fragments reaches maximum, i.e. 10–20 Myr. Meanwhile, many of the asteroids show so-called Kozai behavior (Kozai oscillation). The Kozai behavior seen in our numerical result is mostly circulation-type, but it is effective enough to increase the eccentricities of the asteroids nearly to 1, creating many sun-grazers. This is one of the reasons why more than 60% of the test particles are removed from the system through the collision with the Sun.

In addition to these result, our calculation indicates that the existence of Mercury might not be negligible in this kind of numerical simulation. Mercury deflects certain number of sun-grazers, which can end up in the increase of the collision ratio of asteroids on the Earth and Venus.

The Properties of Main-belt Asteroids Measured by the Sloan Digital Sky Survey

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Abstract.

I will discuss five-band (UV to IR) measurements of ∼134,000 main-belt asteroids obtained by the Sloan Digital Sky Survey (SDSS). Only about a third of these asteroids have been previously observed, and usually in just one band. The SDSS data allow a measurement of the main-belt asteroid size distribution to a significantly smaller size limit (< 1 km) than possible before, and suggest that the size distribution resembles a broken power-law independent of the heliocentric distance: $D^{-2.3}$ for 0.4 km $\lesssim D \lesssim$ 5 km, and D^{-4} for 5 km $\lesssim D \lesssim$ 40 km. The overall normalization implies that there are about 750,000 objects with $D > 1$ km in the main asteroid belt.

Accurate photometric measurements for a large sample of objects vividly demonstrate that asteroid families have distinctive optical colors, and strongly support suggestions that asteroids belonging to a particular family have a common origin. The properties of asteroid color variability indicate that the space weathering effects significantly change the surface reflectance of main-belt asteroids.

Asteroid spins and shapes from multidatainversion: the big picture

Mikko Kaasalainen (1,2), Markku Lehtinen (2), Daniel Hestroffer (3),
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A large set of comprehensive physical asteroid models can be and is now being built with combined analysis of photo- and interferometric and radar observations, occultation timings, and other data. In addition to optimizing the models to fit the data, it is useful to optimize the data acquisition events themselves (timing, design of radar experiments, etc.). This is a joint effort with several observers and research groups. We have now compiled a population sample of nearly 100 targets, including MBAs, NEAs, and Jupiter Trojans. This group displays a wide variety of shapes, spin states, and structures. It is possible to obtain hundreds of such models in the relatively near future.

This sample can be analyzed in the collective sense by investigating cross-correlations between quantities such as size, rotation period, pole latitude, shape irregularity, deviation from an equilibrium shape, etc. This should provide us with new insights into asteroid structures and evolution. Potential trends such as YORP spin clustering will also provide information for choosing the objects that should be targeted for observations (Koronis/Hungarias/NEAs/slow rotators/etc.).

Instead of professing to give answers, we present a list of open questions on which we hope to evoke lively discussion:

1. What should we observe (especially for fewer biasing effects)?
2. How should we observe (for maximal information)?
3. How should we analyze the ensemble?
4. Should we be looking for something (en masse or á la Itokawa)?
5. Should we not be looking for anything?
6. Should we have something to drink?

References and links: `www.astro.helsinki.fi/∼kaselain`

Topics in asteroid dynamics

Donald Korycansky, CODEP, UC Santa Cruz

I discuss some recent and ongoing work by our group (CODEP) at UC Santa Cruz. The first two topics concern the role played by impacts and secondary ejecta in determining the regolith distribution on asteroids such as 433 Eros, and the possible effect of the same in determining their shape. Finally I present work on the dynamics of rigid bodies and the application to modeling the structure and dynamics of gravitational aggregates ("rubble piles").

For the first two areas, we used many-faced polyhedral models and their gravitational potentials as calculated by the "polyhedron gravity" algorithm of Werner and Scheeres (Werner 1994, Werner and Scheeres 1996). In 2003 we published a study (Korycansky and Asphaug, Icarus v. 163, 374-288) of the role that small impacts might play in reshaping asteroids. In this paper, we modeled small impacts, the craters that they produced, and their ejecta, to see how the cumulative effect of many such impacts might change the shape of an initially-spherical asteroid. We found that oblate shapes dominated the outcomes of this process for rotating bodies, unlike the prolate or irregular shapes that are often seen. More recent work (Korycansky and Asphaug, submitted to Icarus) is a study of the ejecta blanket produced by small impacts on Eros. Here we integrated the orbits of test particles produced at the locations of primary impacts and mapped the distribution of those particles that re-impacted the asteroid. We found that ejecta tend to "pile up" in low-lying regions such as the craters Psyche, Himeros, and in Shoemaker Regio. Conversely, high spots, (the two long ends of the asteroid) were net losers of ejecta.

Both of our studies suggest that small impacts (and resulting ejecta) act to smooth or "round down" asteroids toward quasi-spherical or oblate shapes. In turn, this suggests that asteroid shapes, in particular the often rather extreme shapes of many small objects, are determined by catastrophic events such as large impacts or tidal encounters.

Some recently completed work (Korycansky, Astrophysics and Space Science in press) focuses on rigid body dynamics of self-gravitating polyhedra (of arbitrary shape). Mutual forces and torques exerted by bodies are calculated by means of appropriate surface integrals, and collisions are included as well. Collisions can be elastic, inelastic, or frictional, depending on the specification of coefficients of restitution. Our ongoing work is aimed at modeling "rubble pile" asteroids made of individual sub-components of general shapes and sizes. We hope to test some ideas in the literature about rubble-piles and arrive at predictions for the internal structure of asteroids.

Yarkovsky Effect Measured for Main-Belt Asteroids

David Nesvorny, William F. Bottke, Jr., Southwest Research Institute

The Karin cluster is a remarkably young asteroid family. Using N-body gravitational models and backward numerical integrations, we showed that all family members had nearly identical orbits at 5.8 ± 0.2 My ago. To make the orbits converge exactly, the orbital histories of the family members must be corrected for thermal effects. Using this novel method, we measured, for the first time, the semimajor axis drift that 2 to 6-km-diameter asteroids experience in the main belt due to the Yarkovsky effect. As a by-product, we determined obliquities for ~ 100 members of the Karin cluster which gives us an insight into physics of the 5.8-Ma impact event that produced the family.

Radar Observations of Binary Near-Earth Asteroid 66391 (1999 KW4)

Steven J. Ostro, Lance A. M. Benner, Jon D. Giorgini, Raymond F. Jurgens (JPL/Caltech),
Jean-Luc Margot (UCLA), Michael C. Nolan (Arecibo Observatory),
Petr Pravec (Astronomical Institute, Academy of Sciences of the Czech Republic),
and Daniel J. Scheeres (U. Michigan)

The Mercury crosser 66391 (1999 KW4) has an orbit (a,e,i = 0.64 AU, 0.69, 39°) that is unique among known asteroids for its combination of small perihelion distance (q = 0.200 AU) and high inclination.

Only four known objects, all comets, have both a smaller perihelion distance and a larger inclination. The asteroid's 2001 approach to within 0.032 AU from Earth was its closest until 2036, and we conducted extended observations using the Goldstone X-band (8560-MHz, 3.5-cm) and Arecibo S-band (2380-MHz, 13-cm) radar systems. The Goldstone sequences revealed the binary nature of this asteroid and provide our longest continuous imaging coverage, while the Arecibo images are much stronger and have finer resolution.

I'll describe the state of our analyses.

Tumbling Asteroids

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We present both a review of earlier data and new results on non-principal axis rotators (tumblers) among asteroids. Among new tumblers found, the best data we have are for 2002 TD60, 2000 WL107 and 54789 2001 MZ7 — each of them shows a lightcurve with two frequencies (full terms with linear combinations of the two frequencies are present in the lightcurve). For 2002 TD60, we will present a physical model of the NPA rotation. Other recent objects which have been found to be likely tumblers based on their lightcurves that don't fit with a single periodicity are 2002 NY40, 16067 1999 RH27, and 5645 1990 SP. Among observational conditions and selection effects affecting detections of NPA rotations, there is a bias against detection of lower-amplitude (less elongated) tumblers. High amplitude tumblers are easy to recognize when data covering at least a few rotation cycles repeatedly in about constant geometric conditions are obtained.

We present a statistical analysis of the population of NPA rotators. We have found an evidence that most asteroids larger than 0.5 km with estimated damping timescales of 4.5 b.y. and longer (according to the formula by Harris 1994) are NPA rotators. The statistic of two tumblers (D=0.04 and 0.4 km) among monolithic asteroids suggests that they have $\mu * Q/T$, where μ is the mechanical rigidity, Q is the elastic dissipation factor, and T is the age of the object, greater by two to three orders of magnitude than the larger, rubble-pile tumblers.

Equilibrium Shapes of Rubble Piles

Derek C. Richardson (U Maryland), Pradeep Elankumaran (U Maryland), Keith A. Holsapple (U Washington)

With increasing interest in the notion that many asteroids may be gravitational aggregates, that is, loose collections of solid material held together mainly by gravity, it is important to characterize the range of allowable equilibrium shapes such bodies may have in response to properties like their spin states. These shapes may act as diagnostics of the internal structure of the bodies. We have begun an investigation of the supportable configurations of spinning rubble piles as a first step toward this goal. Our rubble piles are collections of identical smooth spheres, representing idealizations of a medium-porosity gravitational aggregates with low tensile strength. We find that even in this ideal case, which might be construed as a good analog for a fluid, deviations from the classical limits described by Maclaurin spheroids and Jacobi ellipsoids can be large. We report on the dependence of equilibrium shape on the number of particles in the rubble pile (the "resolution"), and whether shape approaches the fluid limit as the resolution is increased. We also determine the maximum spin rate of the rubble piles before mass loss begins and compare the results to recent observations of NEA spin periods. Future work will include a study of the effect of interlocking between non-spherical particles.

Constraining NEA albedos using near-infrared spectroscopy

A. S. Rivkin and R. P. Binzel (MIT)

Albedo is one of the fundamental physical properties for asteroids, knowledge of which is important for interpreting spectra and determining sizes. This is particularly true for near-Earth asteroids, which show a large range of albedos in a number of spectral types (Harris and Lagerros 2001). For near-Earth asteroids, however, albedo measurements are often not available due to the short periods for which these objects are available and the "catch as catch can" nature of observations. Knowing the albedo, as well as the presence or absence of a regolith, are critical to understanding the thermal properties of an object, which in turn is critical to determining how large a part the Yarkovsky effect will play in its orbital evolution.

Because NEAs are close to the sun, and their temperatures are warm (relative to their main-belt cousins), observations in the 1-2.5 μm region can constrain albedos for NEAs. For some objects, thermal emission can in fact be detected and measured at 2.5 μm, allowing a model fit to determine or constrain the albedo value. For example: an object at 1.2 AU with an albedo of 0.1 will have an "excess" flux of roughly 10-15%. For others, a lower limit for albedo can be calculated based on the lack of thermal emission.

Furthermore, there is the potential for determining (or at least making a good guess) about fundamental surface properties other than albedo, based on the presence or absence of a thermal tail. Delbo et al. (2003) showed that for the majority of NEAs, the "beaming parameter" (η) is near 1.0, much lower than expected for bare rock and suggestive of the presence of regolith on these bodies. However, there are some objects with very high values of η, closer to 3.0 (which is what would be expected for bedrock, if not higher). Given a known spectral class, and a typical range of albedos for that class, an anomalously high model albedo may be indicative of a regolith-free surface. Conversely, objects showing a thermal contribution will almost always be bearing regolith.

We will present a set of NEA albedos determined from 1-2.5 μm spectra taken with SpeX on the IRTF over the past two years.

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Dynamics of Deformable Asteroids

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Abstract

Recent observations suggest that most asteroids might be granular aggregates. Compared to solid objects, granular ones tend to deform more and, possibly, to dissipate more energy. Both these facts might have a significant influence on the dynamics and shape of granular asteroids. To study the dynamics of a granular asteroid, we begin by assuming that the asteroid deforms homogeneously. We then consider different kinds of material behaviours. For example, we model the asteroid as a collection of colliding, inelastic, rigid spheres or as a dense packing of frictional spheres. In both cases the asteroid is held together by gravity. The type of dynamical situations we consider include free Eulerian precession and planetary fly-by's. In these, we determine the position and velocity of the center of mass and/or the homogeneous deformation as functions of time.

Accurate ephemerides of Eros' rotation

Jean Souchay (Observatoire de Paris)

To compute with precision the rotation of any celestial body as an asteroid, requires a deep knowledge of physical and astrometrical parameters related to this body, as its moments of inertia and its angular speed of rotation. This is now available in the case of the asteroid Eros 433, which was recently abundantly observed by the NEAR (Near Earth Asteroid Rendez-Vous) probe mission. After describing in some details the two components of the motion (free and forced rotations) we show how very accurate ephemerides of Eros'rotation could be obtained.

Outlier detection

J. Virtanen, K. Muinonen, M. Granvik (Observatory, University of Helsinki)

We discuss the problem of identifying outlier observations in the case of sparse/exiguous data. Outlier rejection is an important part of the orbit computation process, in particular, in applications such as the linking of asteroid observations, evaluation of impact probability, and analysis of high-precision data (e.g. the GAIA mission). Although algorithms exist for identifying outliers in multiapparition data sets, the case of short observational arcs and small numbers of observations has not been studied in detail. We propose a new outlier detection algorithm, which makes use of the technique of statistical ranging.

Next Yark Candidates

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The first successful detection of the Yarkovsky effect acting on the orbit of a near-Earth Asteroid (6489 Golevka) not only validated current models, but also demonstrated a unique means of estimating an asteroid's mass. We provide an overview of further candidates for which the Yarkovsky effect is likely to be detected within next decade or two. In all cases radar ranging to these targets during their next Earth close approaches is crucial, and in some cases accurate pre-encounter optical astrometry is also needed.

Tidal Reshaping of the Near Earth Asteroid Population

Kevin J. Walsh (U. of Maryland), Derek C. Richardson (U. of Maryland), William F. Bottke (SwRI), Douglas P. Hamilton (U. of Maryland)

Radar observations show a surprising number of near-Earth asteroids (NEAs) have nearly spherical shapes. While it is possible some of these objects were produced by the reaccretion of debris after a catastrophic collision, collisional modeling work suggests such outcomes should be relatively rare (e.g., Michel et al. 2004; Durda et al. 2004). We suggest a different mechanism to explain these unusually-shaped objects.

NEAs are known to have numerous close encounters with terrestrial planets during their dynamical lifetimes. Together with evidence suggesting that most of the NEAs above 150 meters in diameter are gravitational aggregates, it is likely that many NEAs have been distorted or disrupted via planetary tidal forces (Richardson et al. 1998). Accordingly, we believe that many nearly-spherical NEAs may in fact be by-products of these same processes.

To test this scenario we used an N-body code to numerically model close encounters between rubble pile asteroids and the Earth. Our progenitor was constructed of identical rigid spheres and held together by self-gravity rather than tensile strength. For a large number of cases our results indicate that tidal forces can reshape elongated into nearly spherical bodies. This mechanism relies on the tidal forces stretching the body and having it collapse back on itself. Our plan is to compare these results with NEA lightcurve amplitudes (to estimate elongation) and spin rates. Continuing efforts on this project includes simulations towards the creation of a steady-state shape distribution for NEAs as affected by tidal disruption.

Amateur Contributions to the Study of Asteroid Lightcurves

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The past few years has seen a dramatic increase in the number of quality asteroid lightcurves produced by amateur observers. This has been clearly demonstrated in the number of curves submitted to the *Minor Planet Bulletin*, which jumped from 3 in 1985 to 78 in 2003. It's also reflected in the number of curves in the list maintained by Alan Harris and the author, which now has more than 1800 objects represented with almost 1400 of those having reliable curves.

The increased involvement by amateur observers, proven very capable of quality work, and who are not under the telescope time constraints of professional astronomers, i.e., being able to respond to situations on demand and/or work a given target for extended periods, is invaluable. The increasing output of this pool provides the opportunity for more rapid development of asteroid dynamics theories that center on spin axis rate and orientation or shape modeling. The Collaborative Asteroid Lightcurve Link web site, maintained by the author since early 2000 (http://www.MinorPlanetObserver.com/astlc/default.htm), helps coordinate programs among observers by providing a "reservation" system so that unnecessary duplication of effort is avoided and allows results to be publicly posted prior to formal publication. It also provides links to other observing programs such as the shape and spin axis modeling programs being conducted by Mikko Kaasalainen and Steven Slivan.

The efforts at the Palmer Divide Observatory and others will be used as an example of how amateurs go about developing a lightcurve program, including measuring images and analyzing results and working with professionals, optical and radar, to help build the statistical pool required for ongoing studies in asteroid dynamics. Some specific case studies of successful pro-am collaborations will be included to demonstrate their effectiveness and see how they might be improved.

Photometric Observation of Karin Family Asteroids

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In 2002, a very young asteroid family, the Karin family, was discovered by Nesvorny et al (2002). This family consists of 39 members (their diameter range is between 1.5-20km) , and is estimated to have been created by an asteroid breakup event only 5.8 Myr ago, while most known asteroid families are considered very old (about a few Gyr), so the latter have undergone significant collisional and dynamical evolution which mask the property of the original collisional events. Meanwhile, the members of the young Karin family seem to still preserve properties of the original collision. A part of collisional properties seems to appear in the non-principal axis rotation and/or the wide-range distribution of their rotational period, which possibly reflect the rotational status of asteroid fragments just after the breakup event. The distribution of shape of the Karin family members is also interesting. If we assume the spherical shape indicate a rubble pile asteroids and the elongate shape is interpreted by the monolithic fragments, we can estimate the production rate of rubble pile asteroids, monolithic asteroids on one breakup event. The YORP effect can alter the orientation of asteroids' spin axes to a specific direction. This phenomenon was discovered in Koronis family asteroids (their diameter range is between 20-40km) by Slivan (2003). Just after a catastrophic collision, the orientation of their spin axes must be random. We expect to estimate the time scale that the YORP effect arranges the asteroids' spin axes by the Karin members. And also color distribution of their surface is important. We guess the largest member "(832) Karin" has old region and fresh region which was exposed by excavation of the collision on its surface.

So, based on the above view points, we intend to grasp the insight of the collisional properties through the observations of their lightcurves.

We report here the results of the lightcurve observation for six Karin family asteroids. The observations were performed from November 2002 to September 2003. We determined their rotational periods and show the possibility of their non-principal axis rotation. Asteroid (4507) 1990FV (main rotational period (MRP)) is 6.576 hr) doesn't have the non-principal axis rotation probably. Asteroids (832) Karin (MRP is 18.348 hr), (28271) 1999CK16 (MRP:5.640 hr), 2000VE21 (MRP:3.912 hr), and (16706) Svojsik (MRP:5.880 hr) likely have multi-period rotation. However, we need more observations.

Our observation must be a unique opportunity to understand an asteroid disruption event. We believe that our observation could be essentially important for the dynamical study of the asteroid fragments formed by a family-forming collisional event, though the observations are still in progress.