Rotation Rates of Recently Discovered Small Near-Earth Asteroids

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ABSTRACT

As part of an effort to obtain astrometric data on newly discovered Near-Earth Asteroids (NEAs) using the Magdalena Ridge Observatory's (MRO) 2.4-meter telescope, a program has also been implemented to obtain physical characterization information on some of the smallest objects in the asteroid population. Characterization studies that determine physical properties such as spin rates and orientations, shapes, material type and internal structure/strength are important for properly addressing and mitigating any potential threats from dangerous Earth-crossing objects. The rotation rate of an object can imply essential information about its internal composition (via deduction of strength boundary limits) and degree of fracture, and thereby its collisional history. In particular, the discovery of asteroids having sub-hour rotation periods is highly indicative of a non-negligible tensile strength. Previously, extensive work had been done to acquire rotation rates for asteroids greater than 200 meters in diameter, and although progress has been made extending this database to the less than 200 meter size-range, the data are still lacking. Therefore, our research has been focused toward collecting lightcurves of objects primarily smaller than 200 meters which have allowed the determination of rotation rates.

Rotation rates derived from the lightcurves collected to date indicate that the asteroids studied in this small size regime exhibit both slow (hours) and fast (minutes) rotation periods. With respect to superfast rotators, one object in our database of special note is asteroid 2009 BF2 (approximately 27 meters in diameter) which is the second fastest rotator yet discovered, with a rotation period of about 58 seconds (2008 HJ is the fastest rotator at 42.7 seconds). Additionally, this survey has collected three lightcurves for objects with absolute magnitudes H > 22 that have been observed to be rotating more slowly (greater than 7 hours) than the presumed strengthless body limit. In particular, asteroid 2008 UP100 exhibits an amplitude of ~1.2 magnitudes or greater even after correcting to zero phase. Recent modeling of rubble pile structures indicates that this borders on or exceeds the elongation limit of a slowly rotating strengthless object, implying the possible existence of tensile strength.

1. INTRODUCTION

Currently there exists only limited data on physical properties such as rotation rate for the very smallest Near-Earth Asteroids (NEAs) being discovered. The rotation rate of an object can imply important information about an asteroid's internal composition and degree of fracture, and thereby its collisional history. In particular, the discovery of objects with sub-hour rotation periods is highly indicative of a non-negligible tensile strength. Too little is known about this class of objects, and yet fundamental conclusions are being made about collisional processes that effect our core understanding of the dynamical evolution of small bodies in the solar system. For example, the current data suggest that for the most part, bodies smaller than 200 meters tend to rotate faster than 2.2 hours, while larger bodies have rotation rates longer than this. A more robust statistical sample is essential in the small size regime to either confirm this trend or see if there is possibly a higher percentage of slowly rotating small bodies than previously assumed.

We report here on our program to enhance the rotational database of very small NEAs by collecting and analyzing lightcurves on objects less primarily than ~200 meters in diameter (i.e., absolute magnitude H~22 and greater). We also investigate and characterize any peculiarities uncovered, including amplitude/shape effects, tumbling, binary systems, or other unexpected features.

This work has been done primarily at the Magdalena Ridge Observatory's (MRO) state-of-the-art 2.4-meter telescope (see Fig.1), which has as its primary mission to study small bodies in the solar system [1, 2]. The 2.4-meter telescope is located at 10,612 feet and is operated by the New Mexico Institute of Mining and Technology (NMT), a research and engineering university in Socorro, NM. In general, the 2.4-meter telescope can accommodate a wide variety of instrument systems, and support the fabrication, integration and operation of new instrumentation, as well as the development of innovative techniques in non-resolved characterization studies.

An unusual feature of the MRO 2.4-meter telescope is its rapid (10º per second) and precise slewing capability which permits efficient observations and tracking of even the fastest moving NEAs. We have focused on the NEA population of bodies instead of the Main Asteroid Belt (MBA) because NEAs come within such close proximity to the Earth that we can collect photometric data on objects as small as 10 meters in diameter with the 2.4-meter telescope. Our system is capable of doing ~5-10% photometry on bodies having an R magnitude of ~19-20 with 10-30 second exposures. Objects less than 200 meters in diameter are being discovered by survey programs on a routine basis, so the targets available for study are abundant. Pravec et al. [3] catalog spin rates for on the order of 12 or so asteroids 200 meters in diameter or smaller. The recently updated Asteroid Lightcurve Database (LCDB) [4] indicates that the sample of asteroid rotation rates derived for objects in this size regime now includes over 50 asteroids. Despite this increase, additional rotational data derived from lightcurves is very much needed.

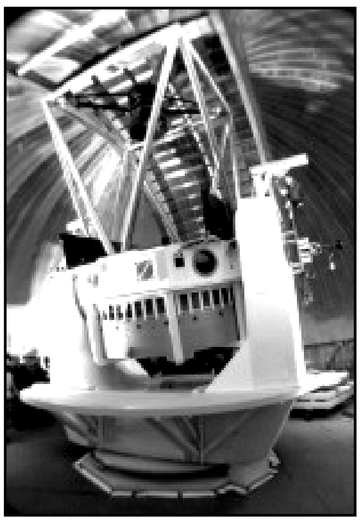

Fig.1. The Magdalena Ridge Observatory's 2.4-meter fast-tracking telescope. An instrument (an engineering CCD camera) is shown mounted to the right fork tine at the right Nasmyth port.

2. NEO ROTATION RATES

Excellent work has been done to date in acquiring asteroid rotation rates [3, 5] for asteroids greater than 200 meters in diameter by those in both the professional and amateur communities. Progress has also been made extending this database to the less than 200 meter size range [6, 7]. However, the data are still sparse at these very small sizes, as can be seen in Fig. 2, taken from Pravec et al. [3].

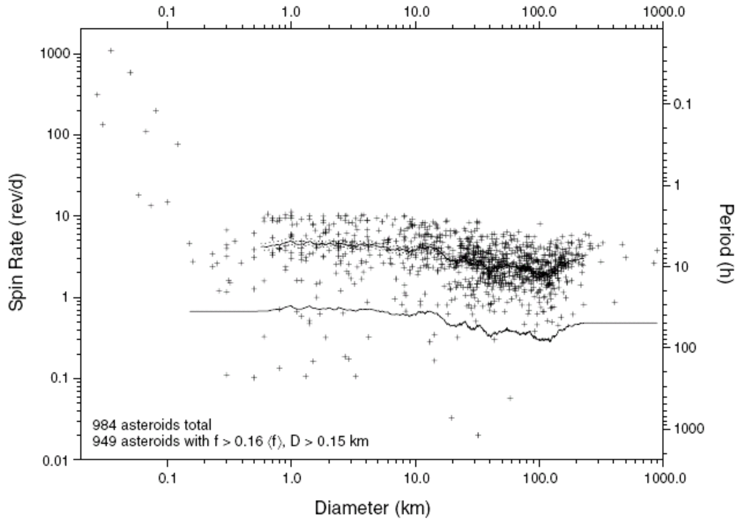

Fig. 2. Plot of asteroid spin rate *versus* diameter for the 984 asteroids for which this parameter is known. (Fig. 1 from Pravec et al. [3]).

Fig. 2 would seem to indicate that there is a strong spin rate dichotomy at diameters close to 200 meters, which corresponds to absolute magnitudes of H~22. That is, for the objects with known spin rates, those with sizes smaller than H~22 rotate faster than 2.2 hours, and those with sizes larger than H~22, slower. The period of 2.2 hours is the theoretically derived critical rotation limit for strengthless ellipsoids of realistic bulk densities [8, 9]. Further, for the very small objects depicted in Fig. 2, it would appear that there is a linear trend inversely linking size and spin rate (i.e., the smaller the object, the faster it rotates). Collisional evolution modeling done by Harris [10] predicted this dependence for an evolved population of rotating bodies dominated by material strength as opposed to gravity-dominated larger objects. But is this trend real or is it a consequence of limited data on the smallest asteroids? Recent data (not shown in Fig. 2) have already shown several exceptions to this general rule such that 1 or 2 asteroids smaller than 200 meters have been found to have periods slower than the critical limit [7]. Observing time on telescopes large enough to obtain photometric data on faint (e.g., small) objects is limited, so there may be a preferential bias towards small fast rotators being characterized, as opposed to small slow rotators whose lightcurves would take a good portion of the night to attain.

Understanding Observed Rotation Rates

Investigations into asteroid collisional evolution have required researchers to combine experimental, analytical, observational, and numerical approaches to achieve progress toward a better understanding of this fundamental process [11]. Pravec et al. [3] suggests that sub-kilometer asteroids are collisionally derived fragments, having a negligible tensile strength (rubble-pile or shattered interior structure). Some very small asteroids (< 200 meters) are rotating so fast (having rotation periods on the order of minutes) that they would not be able to stay together in a rubble pile via self gravity, so the conclusion is that they must be monolithic or coherent bodies if they are rotating faster than 2.2 hours. Pravec et al. go on to suggest that these tiny asteroids are likely the individual fragments that must have once made up a rubble pile parent body, and have been disrupted by a catastrophic impact. Reality may be more complex, however, in that Holsapple [12] suggests refinements to the 2.2 hour rotation limit, such that rubble piles may be able to spin that fast or faster without breaking apart. He argues that there are cohesive forces that still exist (aside from self gravity) even in a rubble pile structure. By doing an analytical stress analysis for a rubble pile body that includes these forces, he finds a distribution (not a sharp transition) of critical spin states depending on degree of fracture, shape, and other factors.

To explain the high spin rates of very small NEAs, it has been suggested that post formation spin altering processes may be responsible. However, the importance of the usual suspects, processes such as the YORP effect (solar heating affecting spin rate and orientation) or tidal encounters, is not yet well understood [7]. Further, the existing rotational data base shows such a sharp transition diameter near ~200 meters for rotation rate that no known post-formation spin up mechanism could be so sensitive to size that it could explain such a dramatic change. This apparent threshold size agrees well with the results of hydrodynamic computations by Love and Ahrens [13], Melosh and Ryan [14], and Benz and Asphaug [15], who show that asteroids as small as a few hundred meters can be gravitationally bound, strengthless rubble piles if they have suffered a prior catastrophic collision. In assessing the collisional dynamics of the asteroid population, however, one should be able to find large monolithic asteroids rotating faster than the 2.2 hour critical rate, just as easily as one might find smaller asteroids rotating much slower than 2.2 hours—a sharp transition is counter intuitive considering the dynamic environment in question. This highlights once again the need for more data, as a large superfast rotator, asteroid 2001 OE84 (Whiteley et al. [7]), has been discovered, and is likely a coherent as opposed to rubble pile object, but is ~0.9 km in diameter. Is this object an exception to the rule, or just an example of what remains undiscovered and uncharacterized?

If we assume that the observed asteroid population has been significantly altered by experiencing catastrophic collisions, both numerical simulations of two-body impacts as well as laboratory impact experiments can be examined to shed light on what is currently being observed with respect to rotation rates. For laboratory-simulated collisions, the resulting post-impact velocity for a fragment depends on location within the target, not necessarily the size of the fragment, with surface fragments and fragments near the impact point having the highest velocities (Gault and Wedekind [16], Fujiwara and Tsukamoto [17], Davis and Ryan [18], Nakamura and Fujiwara [19], Giblin et al. [20]). Nakamura and Fujiwara [19] found no difference between normal and oblique impacts with respect to fragment rotation: fragments rotate away from the axis connecting the impact point to the target center, with small fragments near the impact site spinning the fastest. Specifically, ejection velocities, and thereby rotational energies, of collisional fragments were found to be related to their size, but also to their position within the parent body with respect to the impact point. Therefore, although there is a trend toward larger fragments having velocities slower than smaller fragments, to say that this is a definitive rule contradicts the data derived from laboratory studies.

The idea that a target body's internal structure can affect ejecta velocity distributions has also been tested in laboratory experiments. Love et al. [21] found that increasing a target's porosity had the effect of decreasing the impact speeds of the ejecta for a given specific energy collision event. This result contradicts with what was found by Ryan et al. [22], who constructed rubble pile analogs, i.e., weakly held together previously-shattered cement mortar targets, and impacted them with high-speed projectiles. They found that the mean ejecta speeds for these macroscopically porous bodies were higher than those measured for the strong homogeneous targets from which the preshattered structures were made. Additionally, the resultant fragment size distributions for the preshattered targets were not significantly different from their homogeneous counterparts-- they were not further fractured upon re-impact. Davis and Ryan [18] also noticed that the differentiated bodies (strong cement core, weak cement mantle) they were using in their experiment program had somewhat higher mean ejecta speeds associated with them, again pointing to the strong influence of target internal structure on collisional outcome.

Additionally, numerical simulations are consistent with what has been observed in the laboratory with respect to fragment velocities post impact. The smooth-particle hydrodynamics (SPH) simulation performed in Asphaug and Scheeres [23] focused on the post-impact state of fragments derived from a collision into a model contact-binary asteroid, relying on the Hudson and Ostro [24] radar-derived data for (4769) Castalia. The general result was that the small fragments had a wide distribution of spin periods, with some of the very smallest asteroids having spin periods comparable to the fast rotators observed in the current asteroid population, but some rotating much slower. Once again, this discrepancy between modeling results and what is observed in the measured distribution of spin rates again could vanish with the acquisition of more rotation periods for asteroids near the 200 meter transition zone and smaller.

3. BASIC APPROACH

To best interpret the current data base of rotation rates as a function of size, more observational data is needed on asteroids in the regime separating strength-dominated from gravity dominated asteroids. Specific attention needs to be paid to establishing whether or not there are monolithic fast-rotating asteroids larger than 200 meter in diameter, as well as discerning what percentage of asteroids with absolute magnitude $H > 22$ rotate more slowly than the critical threshold for strengthless bodies. The latter is the motivation of this current effort. With better statistics, more definitive conclusions regarding the observed distribution of small asteroid spin rates can be made.

Observing Strategy

In our program, lightcurve observations are obtained for target-of-opportunity objects with limited observing windows (i.e., those which have been recently discovered). This naturally leads us to examine the smaller objects that have brighter apparent magnitudes as they make a close approach and pass the Earth.

Examination of Fig. 3 shows that the recently discovered objects most likely to possess material strength are truly targets-of-opportunity. We can generally expect to be capable of ~5% photometry of asteroids with V~19 with 10 second exposures. Recognizing typical NEA speeds to be 5 - 20 km/sec, traveling ~ 0.003-0.011 A.U./day, we discern that the observing window for the H=27 objects is one to a few days. For the brighter H=23.5 targets, this extends to a few weeks. However, it is important to note that, in practice, these times are shortened since discovery does not always occur immediately and the full observable window can not always be utilized.

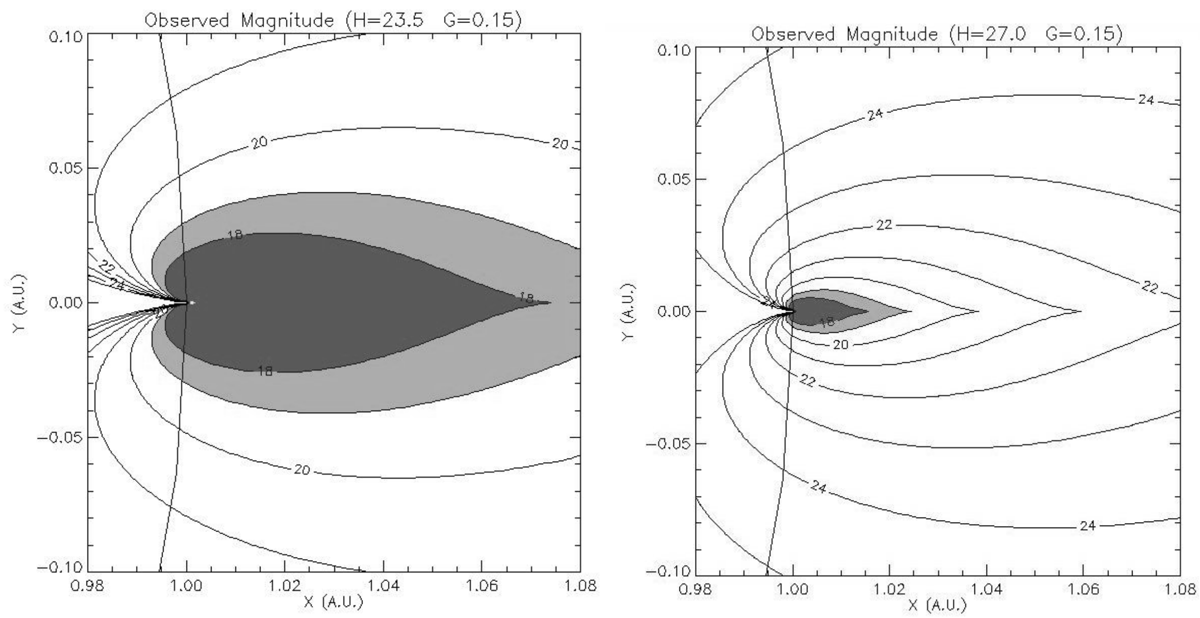

Fig. 3. Contour plots showing the apparent visual magnitude of an H=23.5 (diameter ~50-120m) and an H=27.0 (diameter ~10-25m) NEA as a function of position in the near-Earth vicinity. The Earth's location is at (1, 0) and the partial circle represents the Earth's orbit. The shadings represent the regions where V<18 (darker inner most shade) and V < 19 (lighter middle shade). For reference, a typical relative NEA speed range is 5-20 km/sec and ~ 0.003-0.011 A.U./day.

Acquired Lightcurves

Below we describe a sample of small NEA lightcurves recently obtained (September 2008 - March 2009) from which we have derived rotation rates. Fig. 4a, b shows lightcurves for near-Earth asteroids 2008 TY09 and 2009 BF2 collected using the MRO 2.4-meter telescope. NEO 2008 TY09, which has a diameter of 25 - 75 meters (depending on spectral class), had a visual magnitude of V~19.5 when observed and was moving at 10.42"/min. Its rotation period was ~11.5 minutes. 2009 BF2, with a diameter of 20-50m, displayed a period of only 57 seconds. Both asteroids were imaged with 10 sec integrations while tracking on the asteroid. These objects follow the general trend that asteroids with diameters less than 200 meters have rotation periods which indicate that they possess material strength.

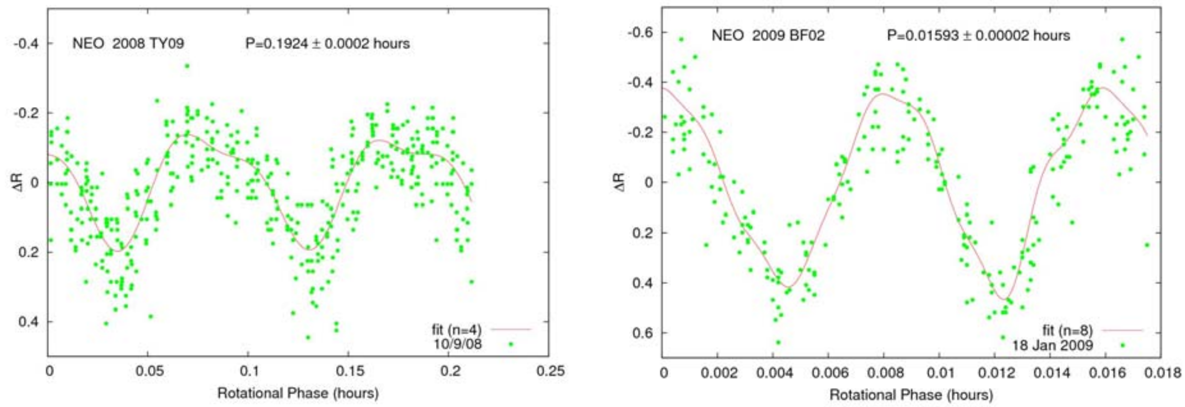

Fig. 4 a,b. Lightcurves acquired for near-Earth asteroids 2008 TY09 (left) and 2009 BF2 (right).

Additionally, however, the MRO 2.4-meter survey has collected three lightcurves to date for objects with H > 22 that have been observed to be rotating more slowly than the presumed strengthless body limit. The lightcurves for two of these asteroids having periods greater than 7 hours are shown in Fig. 5a, b. The large amplitude of 2008 UP100 shown on Fig. 5b is of particular interest. Even after correcting to zero phase, the amplitude is still ~1.2 magnitudes or greater. Recent modeling efforts of rubble piles done by Harris et al. [25] indicate that this borders on or exceeds the elongation limit of a more slowly rotating strengthless object, implying the possible existence of a tensile strength. Given that this survey has only recently been initiated, we expect that the continued photometric observation of faint NEA targets-of-opportunity will increase our sample of studied objects and result in a better understanding of the structure of these small bodies.

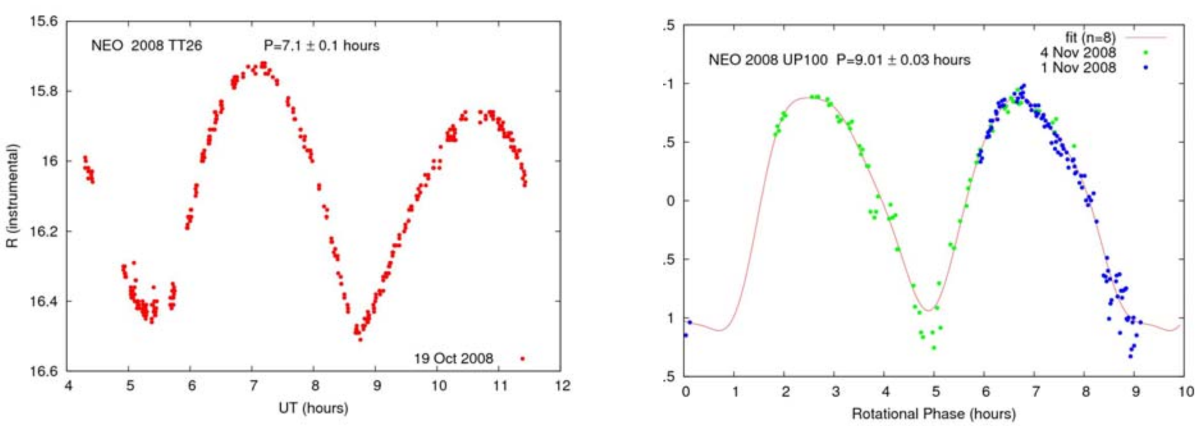

Figure 5 a,b. A preliminary lightcurves of NEO 2008 TT26 (left) and 2008 UP100 (right, with only two of four night's data shown) indicating long rotation periods of over 7 hours for small bodies having a diameter of only ~50 - 100 meters.

4. SUMMARY

We take the data collated by Warner, Harris, and Pravec [4] from the Asteroid Lightcurve Database (Fig. 2), and plot only those objects in the near-Earth zone in Fig. 6. The 11 new asteroids (one asteroid is larger than the 200 meter diameter) for which we have acquired enough lightcurve data to definitively solve for a rotation rate are also shown in Fig. 6. Three of the 10 small asteroids (H~22 and greater) that we studied show spin rate periods longer than the expected 2.2 hours or shorter rotational barrier domain. Statistically speaking, this is indicative that we should expect to find a larger number of very small, slow rotators in the future.

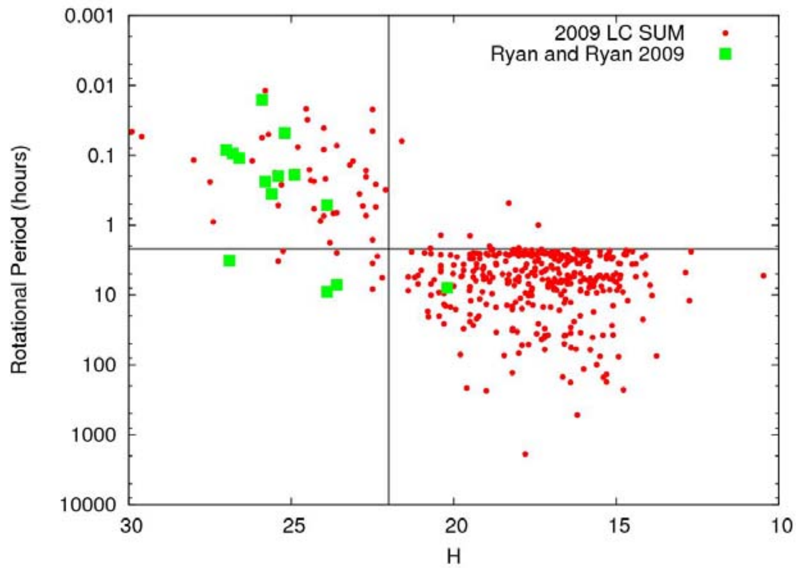

Fig. 6. A plot of rotation period versus absolute magnitude (H), where the filled (red) circles are all NEAs from the 2009 Asteroid Lightcurve Database (Warner et al.), and the green squares are the new data acquired via this current work. The horizontal line corresponds to a rotation period of P~2.2 hours, which is the hypothesized rubble pile rotational barrier. The vertical line denotes absolute magnitude H=22.

The goal of our program is to increase the sample of known rotation periods for very small asteroids, and to determine whether the existing trends in the current data base are real or the victim of under sampling. Since many of the asteroids we would need to study are targets-of-opportunity, this work is best done with a large telescope already routinely observing newly discovered objects in real time (i.e., such observing time would be difficult to "schedule" in advance). Therefore, the MRO 2.4m telescope observational program is uniquely qualified to continue this rotational characterization program of the smallest NEAs being discovered by the ongoing survey projects.

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