Physical Characterization Studies of Near-Earth Object Spacecraft Mission Targets

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ABSTRACT

Periodic asteroids and comets that come within a perihelion distance of 1.3 AU or less are defined as Near-Earth Objects (NEOs). These small bodies are in dynamically favorable positions as potential spacecraft mission targets. As a consequence, space missions to NEOs are underway or in development by several major agencies (e.g., NASA, ESA, JAXA), and recently, a manned mission to an NEO was announced as a NASA goal to be accomplished by the year 2025. Further, NASA has selected the OSIRIS-REx unmanned spacecraft mission for launch in 2016. The spacecraft will rendezvous with and collect samples from the near-Earth asteroid 1999 RQ36. Acquiring more information about the physical nature of NEOs not only contributes to general scientific pursuits and preparation for spacecraft missions, but is important to better address the threat from dangerous NEOs having Earth-crossing orbits.

We will present new data obtained by photometric, spectroscopic, and other techniques on the physical properties of several Earth-approaching asteroids that are potential mission candidates. We will discuss collaborative efforts with researchers using radar to characterize prospective targets, and outline the synergy and increased science return of such an endeavor. In addition, we will present characterization results of the photometric properties of asteroid 1999 RQ36 at visible wavelengths including its rotation rate. These data were collected during the 2011-2012 apparition of the asteroid, which is the last opportunity for ground-based studies before OSIRIS-REx is launched.

1. INTRODUCTION

Ground-based monitoring efforts to find and characterize suitable targets for planned and existing spacecraft missions require moderate to large-sized telescopes. Good candidate asteroids must have a well-defined orbit and be of a known composition. Knowledge of physical properties such as size, shape, internal structure, rotation rate (and whether the asteroid is tumbling) must also be derived. Acquiring more information about the physical nature of Near-Earth Objects (NEOs) not only contributes to general scientific pursuits (solar system formation) and preparation for spacecraft missions (as a precursor to manned missions to Mars), but is important to formulating mitigation plans to deal with potentially hazardous objects.

Choosing an appropriate potential mission candidate is not necessarily a straightforward process, however, since dynamical and physical parameters limit selection. Fortunately, new asteroids and comets are being discovered each night, so the target pool is continually growing. At present, the vast majority of NEA discoveries are being accomplished by the Catalina Sky Survey and Spacewatch survey near Tucson, AZ, the Pan-STARRS1 survey on Maui, HI, and the LINEAR survey near Socorro, NM. Researchers at the Magdalena Ridge Observatory's (MRO) 2.4-meter telescope facility (see Fig. 1) work in tandem with these discovery ventures, and have an ongoing, comprehensive program to determine orbital and physical characterization information of newly discovered objects in the near-Earth population. The approach of the program is to leverage nightly astrometric follow-up work (for orbit refinement) to obtain physical data (primarily rotation rates) on the most interesting, recently discovered NEOs, including promising spacecraft targets. This strategy allows one-of-a-kind, real-time access to the study of unique asteroids and comets before they leave the near-Earth vicinity.

The timing for asteroid follow-up and physical study is critical: when objects are first discovered they are in a prime location with respect to visibility from the Earth. Their synodic periods (when they will once again be in that same location) can otherwise be as much as decades long. At the first instant of discovery, however, all we know about these bodies is their rough orbits and absolute magnitudes. Since we need much more information to select a potential spacecraft target, efforts must be immediate to obtain data that will lead to size, composition, and rotation rate determinations. Researchers at the MRO 2.4-meter telescope routinely implement such an investigation of NEOs on a monthly basis throughout the year. Over the past 5 years that this program has been in operation, we have obtained spin rates for over 50 Near-Earth asteroids, quite a few of which are the fastest rotators in the Solar System. Several potential mission candidates have a rotation rate determination as a result of our work [1] as well.

Fig. 1. The Magdalena Ridge Observatory 2.4-meter fast-tracking telescope and support facility located outside of Socorro, NM on Magdalena Ridge. The observatory performs target-of-opportunity scientific research focusing on asteroids and comets along with work in the area of space situational awareness.

Combining optical measurements of potential mission targets with radar observations significantly enhances characterization efforts and allows precise orbit determinations (optical observations measure object position; radar directly measures the distance to the object). Further, radar is the only ground-based technique capable of spatially resolving surface features (i.e., obtaining delay-Doppler "images") of near-Earth objects [2]. Therefore, radar observations, particularly at smaller sizes, directly provide shape, spin, and size data that complement the optically-derived physical information. However, radar shape and spin rate modeling is most effective in combination with optical lightcurve observations: radar imaging provides spatial resolution and the lightcurves provide a more accurate measurement of the asteroid's spin rate [3]. This synergy is invaluable to planning for robotic and manned spacecraft missions.

For one of the data collection opportunities described below, the MRO 2.4-meter telescope researchers worked with the Arecibo Observatory (Puerto Rico) and Goldstone Deep Space Network (CA) radar groups to characterized a newly discovered, close-approaching asteroid (2012 DW_{60}). We have subsequently worked together with radar astronomers on several occasions to characterize new NEA discoveries that could be future spacecraft targets. These collaborative efforts will continue since they have been very beneficial to refining a potential spacecraft target list, and have provided interesting and important scientific information about the population of bodies inhabiting the near-Earth vicinity.

2. ASTEROIDS AS TARGETS FOR SPACECRAFT MISSIONS

One of the most accessible and cost effective strategies to developing a spacecraft mission to an asteroid is to select a suitable target in close proximity to the Earth. A near-Earth Asteroid (NEA) is defined as an object that approaches the Sun to within 1.3 AU or less, bringing it to within 0.3 AU of the Earth's orbit. The largest known NEA is 1036 Ganymed, having a diameter of 31.7 km. An NEA is designated a "Potentially Hazardous Asteroid" (PHA) when its orbit comes to within 0.05 AU of the Earth's orbit. The largest known PHA is 4179 Toutatis, which has an average diameter of about 3 km. Since most NEAs are small, they do not have significant gravity associated with them as compared to the Moon or Mars.

Therefore, only a relatively small propulsive alteration is needed for a spacecraft to arrive and depart from a typical NEO.

Part of the official *National Space Policy of the United States of America* [4] as of June 28, 2010, includes the goal of sending astronauts to an NEA in the 2025 timeframe. Required propulsive change in velocity (delta-V, or impulse for departure/return) and roundtrip mission duration (less than a year) are the most critical factors in planning human spaceflight endeavors [5]. Therefore, the first human missions beyond the Earth-Moon system will necessarily target asteroids with orbits very similar to Earth's. Not only are these asteroids close, but their velocity relative to Earth is small, facilitating round trip journeys. Robotic missions could capitalize on such favorable trajectories as well to minimize overall cost, but are not limited by such constraints otherwise. As a precursor to developing either type of mission, suitable candidates must be identified, and their physical properties defined to a level that constrains scientific and engineering risk.

The first step in evaluating a target asteroid's suitability for spacecraft investigation is defining its orbit. After that, size, rotation rate and composition become critical. Table 1 has been derived via the NHATS initiative [5], and lists a sample of current potential candidates for human spaceflight missions. Spin rates are not available for most of these objects, which prevents mission planning from proceeding. Our program has thus far characterized 6 of the asteroids listed in the table (see Section 3). All of our derived rotation rates for the study asteroids are very fast, from minutes to tens of minutes. This suggests that these objects are likely to be solid, monolithic bodies and not rubble piles weakly held together by their self gravity.

Designation	*n*	Estimated Diameter (m)
2000 SG_{344}	3302638	27 - 85
1991 VG	2737751	5 - 16
2006 BZ_{147}	1674416	20 - 63
2001 FR_{85}	1618888	30 - 96
2008 EA_9	1597844	7 - 22
2010 VQ_{98}	1580174	6 - 18
2007 UN_{12}	1443703	4 - 14
2006 RH_{120}	1283817	3 - 10
2010 UE_{51}	1242487	5 - 17
2008 HU_4	1227757	6 - 17
2007 VU_6	1186902	12 - 38
2008 UA_{202}	1114827	3 - 10
2010 UJ	1082350	14 - 45
2011 BQ_{50}	1010896	5 - 16
2004 QA_{22}	1008597	6 - 20
2001 GP_2	980724	10 - 32
2009 HE_{60}	970582	18 - 56
2010 JR_{34}	960736	7 - 22
2009 BD	936904	5 - 16
2011 MD	936324	6 - 18
2010 TE_{55}	920319	6 - 20
2008 JL_{24}	904774	3 - 9
2011 BL_{45}	865199	9 - 28
2007 YF	791134	27 - 85
2010 JK_1	773964	32 - 100
2009 BF_2	205,531	11 – 51
2009 UD	431,711	7 – 29
2012 DW_{60}	113,217	9 – 40
2012 HM	15, 578	27-85

Table 1. Sample list of currently known NEAs that are compliant as assessed by the Human Space Flight Accessible Targets Study (NHATS). The number of viable trajectory solutions possible is denoted by the parameter *n,* which has been found to be useful for assessing which NEAs are the most accessible (adapted from Abell et al. 2012). The filter used in deriving this target list sorts by dynamical trajectory performance constraints (delta-V less than 12 km/s). Highlighted entries denote objects for which we have collected lightcurves or spectral data.

The inventory of NEAs shown in Table 1 are effective for evaluating opportunities for robotic missions, as well as for determining the most advantageous round trip trajectories for human spaceflight missions. The list also spotlights objects that can be prioritized for observation by ground-based telescopes (both optical and radar) for characterization studies and orbit refinement. Most of the asteroids in Table 1 are very small—less than 100 m. To date, only these very small objects (having negligible gravity, which prohibits a spacecraft from “landing”) have orbits with favorable trajectories. However, new discoveries are ongoing, which will add to the choice of possible candidates. Also, the NHATS list only includes near-Earth asteroids and not comets. Comets have higher eccentricities and longer orbital periods making rendezvous more difficult. Additionally, comets have active surfaces that could present a hazardous environment to both astronauts and the spacecraft itself.

3. LIGHTCURVES AND SPECTRA FOR POTENTIAL MISSION TARGETS

Researchers at the 2.4-meter facility have capitalized on opportunities to observe close-approaching, newly discovered NEAs to derive better orbits, calculate spin rates, and to determine composition. The section below details the data collected and analyzed for rotation rate and our beginning efforts to estimate asteroid composition.

LIGHTCURVES

A lightcurve is a graph that plots the intensity of light from an object as a function of time. Because asteroids are generally non-uniform in shape, when they rotate, their surface will reflect different amounts of light as different areas are oriented toward the Earth. Identifying a repeating pattern in the curve allows the determination of a rotation rate for the object.

Referring to Table 1 for targets suitable for human spaceflight missions, asteroids 2009 BD, 2011 MD, 2009 BF_2, 2009 UD, and 2012 DW_{60} have been studied by this research program to determine rotation rates. Fig,’s 2 and 3 show lightcurve plots and orbit diagrams for asteroids 2011 MD and 2012 DW_{60}; the spin rates derived were on the order of 10’s of minutes. Asteroid 2012 DW_{60} was also a radar target, and we worked together with the radar observers to physically characterize this object. Fig.’s 4 and 5 depict lightcurves for asteroids 2009 UD and 2009 BF_2; derived spin rates for these objects are on the order of one minute. A definitive rotation rate for asteroid 2009 BD could not be directly derived from its lightcurve under the observational conditions at the time of the data collection; implied from the data, however, is that it has a very fast spin rate as well.

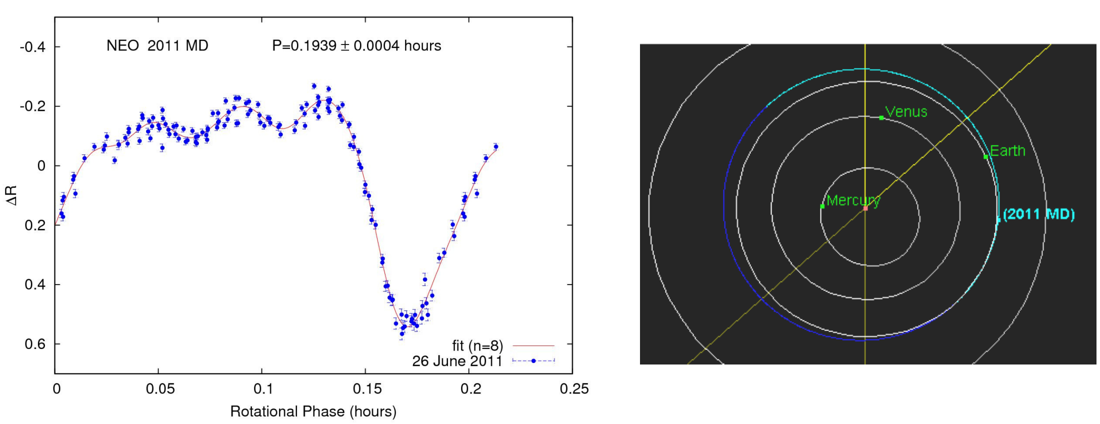

Fig 2. Lightcurve (left) and orbit diagram (right) of close Earth-approaching asteroid 2011 MD; the asteroid’s diameter is about 11 meters, and its rotation period was determined to be 0.194 hours. Data was collected for the lightcurve in June, 2011 using the MRO 2.4-meter telescope; the visual magnitude of the asteroid was V~17. The object/Earth orbital positions were calculated using the JPL Small-Body Database Browser (http://ssd.jpl.nasa.gov) for September 4, 2012.

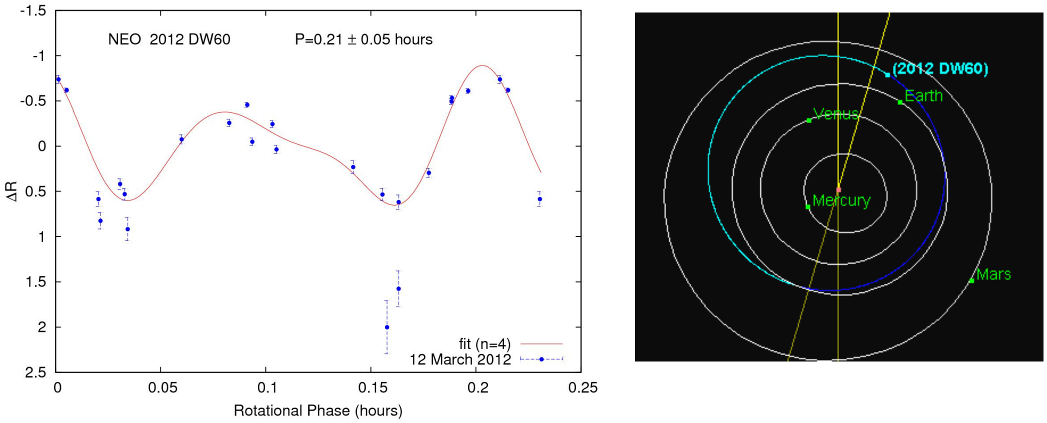

Fig 3. Lightcurve (left) and orbit diagram (right) of close Earth-approaching asteroid 2012 DW_{60}; the asteroid's diameter is about 18 meters, and its rotation period was determined to be 0.21 hours. Data was collected for the lightcurve in March, 2012 using the MRO 2.4-meter telescope; the visual magnitude of the asteroid was V~19. The object/Earth orbital positions were calculated using the JPL Small-Body Database Browser (http://ssd.jpl.nasa.gov) for September 4, 2012. This target was also under study by radar groups.

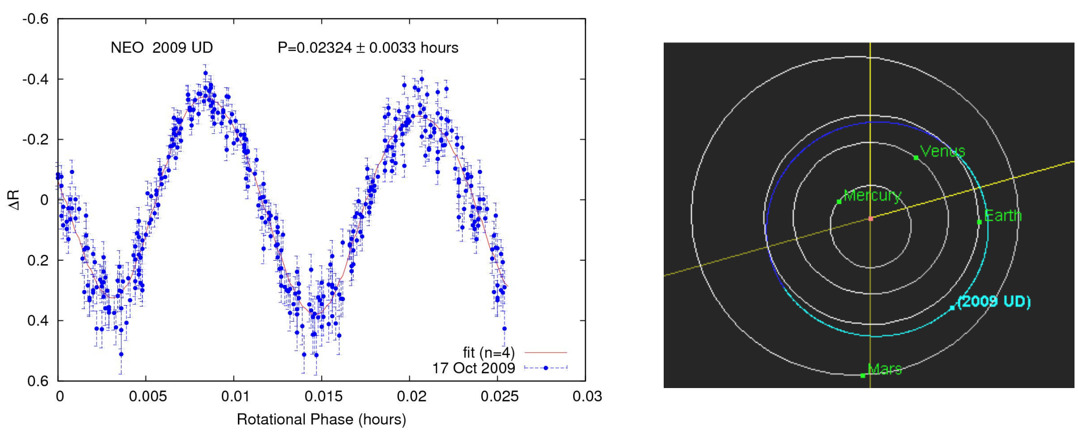

Fig 4. Lightcurve (left) and orbit diagram (right) of close Earth-approaching asteroid 2009 UD; the asteroid's diameter is about 18 meters, and its rotation period was determined to be 0.023 hours. Data was collected for the lightcurve in October, 2009 using the MRO 2.4-meter telescope; the visual magnitude of the asteroid was V~18. The object/Earth orbital positions were calculated using the JPL Small-Body Database Browser (http://ssd.jpl.nasa.gov) for September 4, 2012.

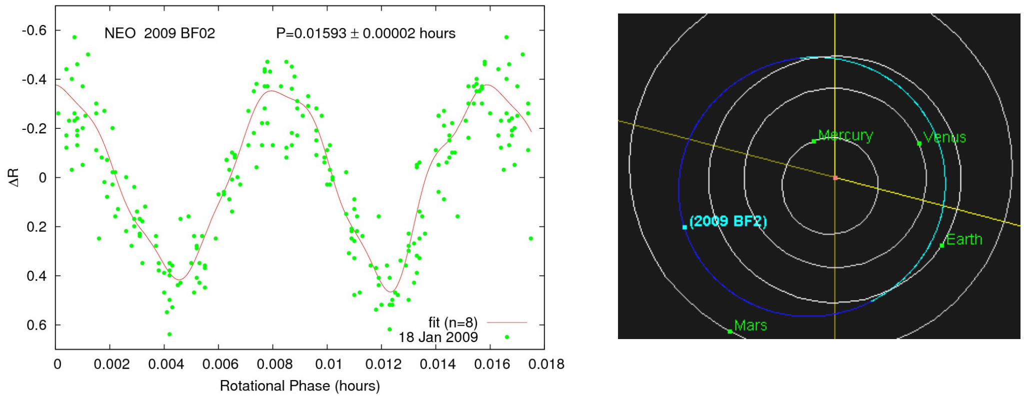

Fig. 5. Lightcurve (left) and orbit diagram (right) of close Earth-approaching asteroid 2009 BF_2; the asteroid’s diameter is about 27 meters, and its rotation period was determined to be 0.0159 hours. Data was collected for the lightcurve in January, 2009 using the MRO 2.4-meter telescope; the visual magnitude of the asteroid was V~18.5. The object/Earth orbital positions were calculated using the JPL Small-Body Database Browser (http://ssd.jpl.nasa.gov) for September 4, 2012.

What challenges do fast spin rates present for spacecraft mission planning? Rapid rotation periods for small asteroids would likely mean solid, non-rubble pile internal structures; but without loose gravel or regolith, this may make sample collection, even by a human crew, difficult. Fast spins would also mean that astronauts at a particular site of interest on the asteroid surface would tend to be carried away from their spacecraft. If the asteroid rotated quickly enough, astronauts might transition out of sight/communication of the spacecraft during any extra-vehicular activities (EVAs), making these operations difficult (loss of radio and visual contact between spacecraft and “surface” crew would be unwelcome). As an alternative, the spacecraft could be maneuvered to match a target asteroid’s rotation during EVAs. In any event, spin rates such as these shown above would present considerable obstacles to overcome.

SPECTRA

Composition information aids in the determination of the size/mass of the asteroid by constraining possible albedo (reflectivity) ranges. An object's absolute magnitude determined at discovery can be converted to a specific size only if its albedo is known. However, the albedos of near-Earth asteroids vary considerably. Therefore, an asteroid's diameter can only be estimated to within about a factor of two from its absolute magnitude in the absence of composition data. Spectral measurements are consequently a desirable component of characterization studies.

For practical purposes, it is also helpful to know exactly what an asteroid’s surface roughness and composition might be, for example, to properly design anchors or tools that can easily burrow under the upper layers. Carbonaceous asteroids are the most compositionally diverse and contain a rich mixture of volatile material (e.g., water), complex organic molecules, rock, and metals. They make up about 20% of the known population, and would be desirable mission targets.

Our program, through a collaborative with JPL and Edwards Air Force Base, has access to a visible wavelength spectrometer mounted on the 2.4-meter telescope to characterize artificial satellites in Earth orbit. In 2012, we began to extend this instrumentation beyond its space situational awareness applications to the study of asteroids. Fig. 6 is one of the first spectra we have taken of a potential mission target: asteroid 2012 HM (see Table 1). The spectral information indicates that this asteroid is an S-type, or of silicate composition. Asteroids that are S-type have spectra displaying a moderately steep slope at wavelengths shorter than 0.7 µm, and an absorption feature centered near 0.63 µm. S-Types also have moderate to weak absorption features around 1 µm that indicate the presence of silicates (stony minerals);

the wavelength range of our spectrometer unfortunately did not extend that far red. We have not yet determined a rotation rate for this object.

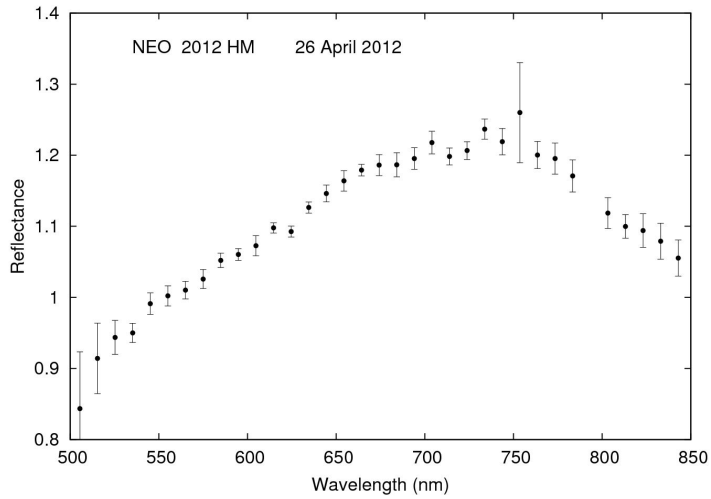

Fig. 6. Spectral characteristics (visible wavelengths) of potential mission target 2012 HM; the spectrum indicates that it is likely an S-type asteroid: characteristic steep slope shortward of 0.7 µm, and a small dip at 0.63 µm. This object was also extensively studied by radar groups.

The spectrum shown in Fig. 6 (resolution R~70 and 0.7 µm) was taken when 2012 HM was making a close approach to the Earth (~0.009 AU), and the asteroid had a visual magnitude V~ 16.6. Average exposures were 3 - 10 minutes, and the object spectrum was divided by the solar analog star 16 Cygni B to yield surface reflectance. Relative reflectance was normalized to 0.55 µm. The large error bar near 0.76 µm is due to the atmospheric oxygen (O_2) line not faultlessly corrected.

4. LIGHTCURVES FOR ACTUAL MISSION TARGET 1999 RQ_{36}

Scheduled for launch in 2016, the OSIRIS-REx spacecraft mission will collect and send back the first samples ever taken of a carbon-rich near-Earth asteroid, 1999 RQ_{36}. The asteroid was discovered in 1999 by the LINEAR survey at MIT's Lincoln Laboratory. 1999 RQ_{36} has an average diameter of approximately 500 meters. The mission aims to reveal valuable insights regarding the origin of life on Earth by studying this object and later the regolith it will capture and return for analysis. Asteroid 1999 RQ_{36} is also a potentially hazardous object, with a small probability (currently a 1-in-1000 chance) of impacting the Earth in the year 2182 [6].

1999 RQ36 is on a low delta-V orbit with respect to Earth, and comes close enough for favorable observations once every six years; this cadence dictates the timescales for ground-based data collection. During the 2011 closest approach in early September, 1999 RQ_{36} was 10.9 million miles away from the Earth. This apparition was the last chance to study this target asteroid from Earth before the OSIRIS-REx spacecraft launches in 2016. High precision in the lightcurve period is needed to enhance sample return success (a technically challenging maneuver) and many astronomers around the world studied the asteroid to acquire the necessary data.

MRO 2.4-meter telescope researchers also participated in the observing campaign: we collected data from late September 2011 through April 2012. Fig. 7 shows a plot of the lightcurve with the derived period of 4.295 hours for the asteroid for a subset of data taken in the Fall of 2011. At the time these observations were made, conditions were somewhat challenging for our moderate-sized telescope: visual magnitude varied from V~ 20.5 – 21, so optimizing signal-to-noise was a primary concern. The object was also extensively studied by the Arecibo and Goldstone radar groups, and we once again worked in concert with researchers from this community to maximize the science return possible from the asteroid's last favorable alignment before spacecraft launch.

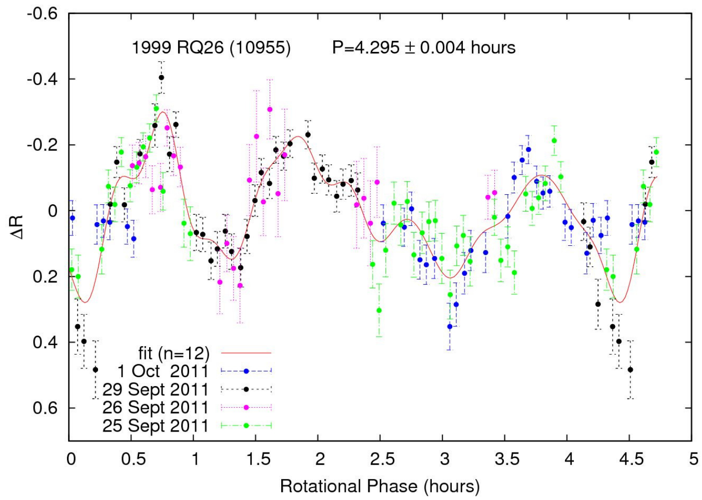

Fig. 7. Lightcurve for NEA 1999 RQ_{36} acquired in September and October, 2011 using the MRO 2.4-meter telescope. The spin period is 4.295 hours. Approximate visual magnitude for the asteroid at the time the observations were taken was V~21.

4. FUTURE TARGETS: POTENTIALLY HAZARDOUS OBJECTS

To best assess and plan for mitigation of an asteroid impact with the Earth, an improved understanding of the physical parameters (impact strength, size, spin rate, shape) that characterize the near-Earth population of objects that are potentially hazardous (PHAs) is required. Further, sometimes small asteroids can come very close to the Earth without hitting it, but instead pass through the geosynchronous satellite zone (this occurred several times in 2011). Studying such bodies can have implications for the health and safety of man-made objects in orbit around the Earth.

Mitigation planning for PHAs that have a high probability of Earth collision would almost certainly require a precursor spacecraft mission. Therefore, the same approach to planning and executing ground-based observational campaigns for potential human spacecraft mission targets is taken in addressing the threat of PHAs. Presently there are two asteroids, 2011 AG_5 and 2002 GT, which have generated some concern regarding their future impact probability.

ASTEROIDS 2011 AG_5 and 2002 GT

Asteroid 2011 AG_5 was discovered by the Catalina Sky Survey, and has a diameter of about 140 meters. Observations to date indicate there is a slight chance that 2011 AG_5 could impact Earth in 2040, making it a PHA. If it hit, damage from an asteroid this size could affect a local region at least a hundred miles wide. Possible mitigation planning is contingent on whether AG_5 passes through a 227-mile-wide keyhole in early February 2023. If it does, Earth's gravitational pull could divert its orbital path enough to align it for an impact with the Earth on February 5, 2040. If the asteroid misses the keyhole, an impact in 2040 will not occur.

In the next four years, analysis of space and ground-based observations will likely show that 2011 AG_5 will miss the Earth. However, if the above keyhole scenario comes to pass, NASA will probably prepare an investigatory spacecraft mission after 2023. However, ground-based observations between now and then are crucial to pin down the asteroid's orbit in anticipation of risk assessment. Several observatories (including our team) monitored 2011 AG_5 during its discovery apparition (near January 2011) before it moved too far away and became too faint. Observations have since been limited because of its present location beyond the orbit of Mars and in the daytime sky on the other side of the Sun (see Fig. 8). In 2013, conditions will improve to allow ground-based telescopes to better track the asteroid's path. MRO 2.4-meter researchers will be participating in the data collection efforts to help constrain the risk.

Another potentially hazardous object under study is 2002 GT. The *Deep Impact* spacecraft is on course for a January 2020 flyby of this PHA. Plans for a characterization campaign to support and enhance the flyby science are underway. 2002 GT is not observable at the moment (see orbit schematic in Fig. 8) but will make a relatively close pass near the Earth in June 2013, reaching visual magnitude V~16. The MRO 2.4-meter telescope researchers will join the collaboration since a significant focus will be to get lightcurves periodically through the entire apparition to support the determination of a rotation rate, which is as yet unknown. Radar observations will also be desirable, and may help reveal whether the object is a binary asteroid.

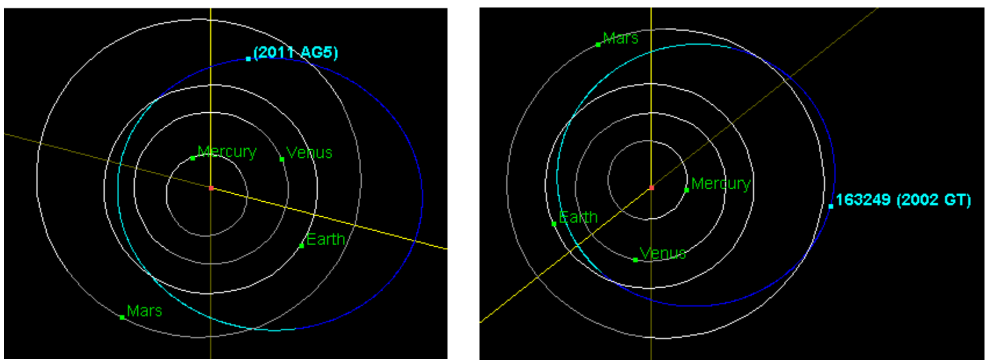

Fig. 8. The object/Earth orbital positions for PHAs 2011 AG_5 (left) and 2002 GT (right) were calculated using the JPL Small-Body Database Browser (http://ssd.jpl.nasa.gov) for September 4, 2012.

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6. SUMMARY

Researchers at the Magdalena Ridge Observatory's 2.4-meter telescope are investigating various methods to enhance and improve existing capabilities for characterizing potential and actual spacecraft mission targets in the near-Earth zone. Included in the exercise is collaborating with radar groups to enhance the science information that can be acquired.

Physical characterization (including spectral studies) of Near-Earth asteroids that are potential spacecraft targets enhances our knowledge of the formation and history of our solar system, contributes to hazard mitigation planning for PHAs, and provides a mechanism for a shorter, simpler, dry-run for astronauts traveling to Mars. Planning and development for future spacecraft missions is made possible by ground-based efforts to detect and characterize small, near-Earth asteroids, however timing is crucial. Observational efforts must commence at or near the time of discovery for the objects to ensure favorable parameters for data collection. Subsequent optimal apparitions for an asteroid may be decades away. 2.4-meter telescope researchers are well positioned to acquire such data since their ongoing NEO follow-up and characterization program collects data monthly throughout the year on the smallest NEAs being discovered. At the current asteroid discovery rate, the number of known mission opportunities will continue to increase as studies for a 2025 manned mission to an asteroid proceed; our program will also continue to target these objects.

7. REFERENCES

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