The Magdalena Ridge Observatory's 2.4-meter Telescope: A New Facility for Follow-up and Characterization of Near-Earth Objects

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Abstract

The Magdalena Ridge Observatory's (MRO) state-of-the-art 2.4-meter telescope is contributing to the Near-Earth Object (NEO) effort by working in partnership with existing NASA telescopic survey programs to provide the astrometric and physical characterization follow-up required to meet the congressional directive to identify bodies 140 meters in diameter or larger that have the potential to impact the Earth. The 2.4-meter's large primary mirror size allows the observatory researchers to acquire accurate astrometry and important characterization data (colors, lightcurves, and spectra) on the faintest objects detected. The system is capable of doing 2% photometry on bodies having a V (visual) magnitude of ~20.5 with 60 second exposures. The working limit for astrometric follow-up is V~24-25 under ideal observing conditions. The objective of the program is to characterize the small end of the NEO size distribution to ensure that newly discovered objects are not lost (maximizing the chance that their orbits are accurately catalogued). A significant advantage of a large-aperture telescope is the ability to work effectively in less than photometric conditions, resulting in an overall high productivity rate.

1. INTRODUCTION

The Magdalena Ridge Observatory's (MRO) fast-tracking 2.4-meter telescope, which is now operational, has as its primary science drivers the physical characterization of small solar system bodies [1] and supporting the nation's Space Situational Awareness (SSA) efforts by monitoring and characterizing resident space objects in close proximity to the Earth [2, 3, 4]. The 2.4-meter can track at rates fast enough (slew speeds are up to 15 °/sec) to also support missile tracking studies which is of benefit to national security concerns. The 2.4-meter telescope facility (Fig. 1) is located at 10,612 feet and is operated by the New Mexico Institute of Mining and Technology (NMT), a small research and engineering university in Socorro, NM. First light for the observatory occurred on October 31, 2006, followed by months of additional telescope engineering, commissioning, and software development. 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 new and innovative techniques in non-resolved characterization studies.

Fig.1. Aerial view of the Magdalena Ridge Observatory's 2.4-meter fast-tracking telescope facility.

To address the study of Near-Earth Objects (NEOs), the MRO 2.4-meter facility has initially utilized photometry and color data to characterize the population of interest. The first phase of observatory instrumentation consists of a

4Kx4K CCD imager which offers an 11 arc minute square field of view. Near term plans also include a low-resolution spectrograph.

2. Characterization of NEOs

The characterization of potentially hazardous NEOs (i.e., those that may be on a collision course with the Earth) via photometery, spectrophotometry, and spectroscopic studies can lead to the determination of the spin rate, shape, composition, material strength, internal structure, and size of such bodies. The material strength in particular would have a direct bearing on any mitigation plan that requires knowing the energy needed to completely fragment an NEO into fine dust before it hits the Earth. Both experimental and numerical analyses suggest that an asteroid that has a fractured or rubble pile structure would require considerably more energy to thoroughly disrupt than a competent body of the same size and mass [5]. The acquisition of spin rates of NEOs can be used to deduce strength boundary limits [6]. In particular, the discovery of objects with sub-hour rotation periods is highly indicative of a non-negligible tensile strength. Further, identifying the relative sizes and orbital characteristics of a binary system among the NEO population permits a direct estimation of mean bulk density and a measure of the degree of internal fragmentation or macroscopic porosity. Although a community effort is underway to study binary systems in the NEA population [7], more information of this nature is required, especially at the smaller sizes (i.e., fainter objects). Even derived shapes can be used to infer the degree of internal fracture, as rubble pile objects would tend to exhibit different axial ratios than a solid, intact spall plate created via a collisional event.

Size is also an important parameter when assessing the threat from potential Earth impactors. Albedos are known for only a small fraction of the NEO population, leading to size estimates that can be uncertain by up to a factor of ~2 [8]. However, the albedo scatter within a particular taxonomic class is significantly smaller. Therefore, placing constraints on the taxonomic classifications of NEOs will lead to more accurate estimates of the NEA size distribution [9, 10]. Spectrophotometric and spectroscopic data can be acquired very readily to constrain albedo, resulting in lower uncertainties in the inferred diameters of discovered objects. Thermal measurements can also be used to better constrain size.

Although the MRO's 2.4-meter telescope is a new facility, significant accomplishments have been made during the first phase of shared-risk operational commissioning. The facility's astronomers have contributed to Near-Earth Object (NEO) efforts working in partnership with existing survey programs to provide the astrometric and physical characterization follow-up required for the faintest potentially hazardous asteroids discovered. Figure 2 shows the detection of an ~50-meter diameter asteroid (2007 WD5) which had the potential to impact Mars on January 30, 2008. Orbital data acquired by the 2.4-meter telescope in December 2007 and January 2008 was used to improve the accuracy of the asteroid's orbit and constrain the impact probability. Further, the facility astronomers have worked both separately and within an international collaborative to provide lightcurve data on recently discovered NEOs as well as mainbelt asteroids.

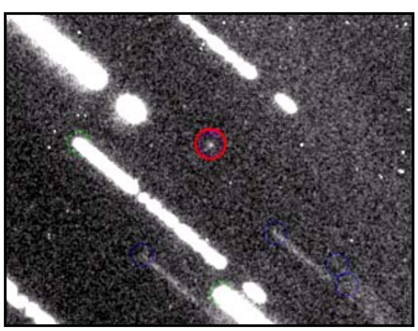

Fig. 2. Detection (see red circle) of potential Mars impacting asteroid 2007 WD5 (visual magnitude ~24). The image is composed of 42 stacked 2 minute exposures taken over a 1.5 hour period. The object was moving at 0.25 arcseconds/minute.

3. Technical Approach

MRO's approach to studying NEOs is to complement the efforts of discovery surveys through faint object astrometric follow-up and physical characterization of both newly discovered NEO targets of opportunity and detailed study of known NEOs. In particular, we have established collaborations with existing NASA-funded survey telescopes in order to facilitate the rapid communication of critical targets of opportunity. The primary issues that need to be addressed include:

1. The need to confirm and catalog the orbits of faint NEOs.
2. The uncertainty in the NEO population size distribution.
3. The unknown material strengths of NEOs.

The NASA-funded MRO 2.4-meter NEO characterization program currently consists of the acquisition of time-series photometric data (i.e., lightcurves), spectrophotometry, and astrometric follow-up of the faintest objects being discovered. Under dark sky conditions with the sub-arc-second seeing that it typical of the site, the system is capable of doing 2% photometry on objects having a visual magnitude of V~20 with 60 second exposures and have a 5-sigma detection limit of V~22. Under the better seeing conditions of 0.6-0.7” experienced to date, these limits extend 1 - 2 magnitudes fainter (V~23 - 24). In Fig.’s 3 and 4, we plot the predicted visual magnitudes of a 140-meter low and medium albedo asteroid, respectively, as a function of position in the near-Earth region. As can be seen, even in the low albedo asteroid case, sufficient time exists during a near-Earth flyby to perform photometric and astrometric follow-up, assuming rapid response to any recent discoveries. Therefore, the MRO 2.4-meter is capable of detecting, tracking, cataloging, and characterizing near-Earth objects having diameters of 1 km and larger, as well as addressing the need for study of objects as small as 140 m. Further, as larger aperture survey telescopes come on line, our 2-meter class telescope will become an invaluable asset in follow up to detections of small objects in the near-Earth zone.

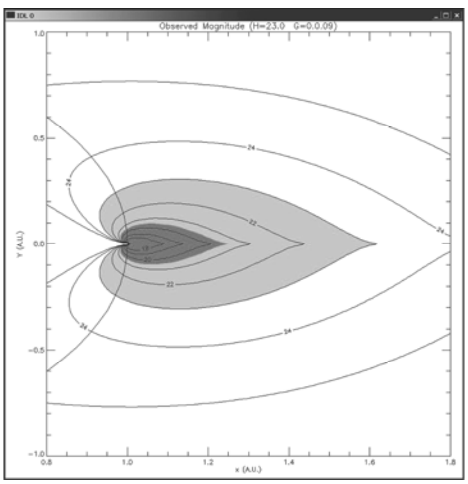

Fig. 3. Contour plot showing the apparent visual magnitude of a dark albedo (e.g., C-type) 140m NEO as a function of position in the near Earth vicinity. The Earth’s location is at (1,0) and the partial circle represents the Earth’s orbit. The shadings represent the photometric (darker inner most shade) and astrometric limits (lighter middle shade) based on 60 second exposures as described in the text.

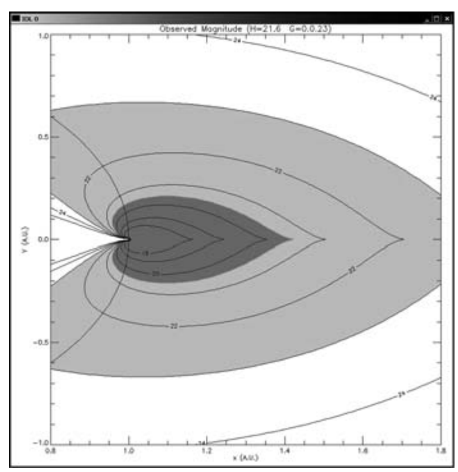

Fig. 4. Contour plot showing the apparent visual magnitude of a medium albedo (e.g., S-type) 140m NEO as a function of position in the near Earth vicinity. The Earth’s location is at (1,0) and the partial circle represents the Earth’s orbit. The shadings represent the photometric (darker inner most shade) and astrometric limits (lighter middle shade) based on 60 second exposures as described in the text.

The 2.4-meter's control system is designed to provide convenient and accurate non-sidereal tracking, allowing for longer exposure times to be utilized, even for fast moving NEOs. Fig. 5 illustrates the telescope’s ability to track on a 17th magnitude near-Earth object (2007 FK1) for a 300 second duration. Since in most cases for fast moving objects separate exposures will be required for the target NEO and the comparison stars, this technique is most useful in photometric conditions. During non-photometric conditions, differential photometry with longer effective exposures is accomplished through strategic stacking of shorter exposures (“stack and shift” methods). In this technique, multiple exposures are stacked and averaged once centered on the moving object and then again centered on the field stars. This results in an increase in the signal to noise while still preserving the simultaneity of the photometric measurements, crucial when working in non-photometric conditions. The increased photometric precision gained by this technique of shifting and stacking pairs of images is demonstrated in the lightcurve fragment shown in Figure 6a and 6b using data obtained during an engineering test in thin cloud conditions. Depending on the temporal precision required and the number of images stacked, the photometric precision can be extended somewhat indefinitely. This ability to utilize longer exposures allows us to extend our typical detection and photometric limits, as well as increase the amount of usable observing time in marginal conditions.

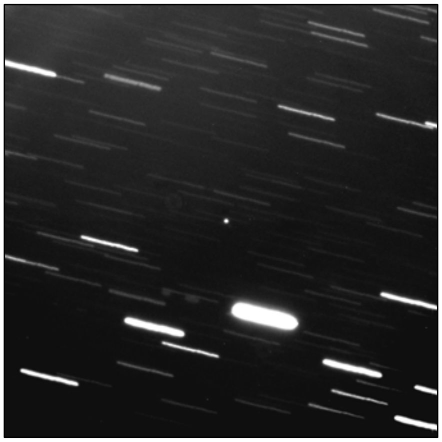

Figure 5. Near-Earth object 2007 FK1 (center) as tracked by the 2.4-meter telescope over a 300 second duration on May 27, 2007. The object's visual magnitude is ~17.1, and it is moving at a rate of 7 arcseconds per minute. Sub-arc-second point source profiles of the target asteroid were regularly obtained in this experiment. The camera used during this engineering test is an off-the-shelf 2Kx2K Apogee U-42 thermo-electrically cooled device.

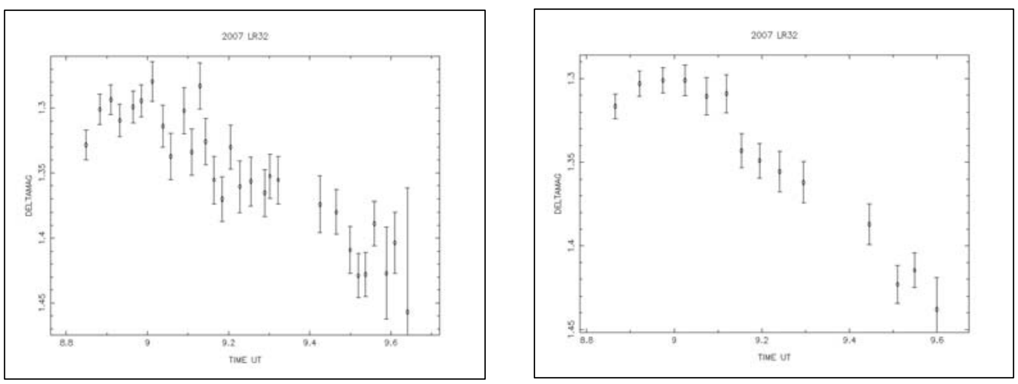

Fig. 6 (a, b) The plot to the left is a lightcurve fragment taken of NEO 2007 L32R on August 6, 2007 over a 45 minute period (during monsoon season and in cloudy weather). The plot on the right has been generated using the stack and shift method displaying the improvement in photometric precision by co-adding images in pairs.

In the paragraphs that follow, we detail the current focus areas for our NEO follow-up and characterization program: follow up astrometry and spectrophotometry.

Astrometry

On any given night, anywhere from a few to tens of newly discovered NEOs are posted on the Minor Planet Center's NEO Confirmation Page (NEOCP). Currently, much of the effort in confirming the existence and providing the astrometry required to determine the initial orbits of these NEOs has relied on the tremendous contributions from the amateur astronomy community. However, as the newer, larger-aperture discovery surveys come online, astrometric follow-up with small aperture telescopes will become increasingly more difficult, leading to the potential loss of many smaller objects. Although some surveys plan to do their own follow-up, this will not always be feasible due to weather, scheduling priorities, and the possibility of smaller objects getting lost between observing cadences. Therefore, our program targets astrometric follow-up (and determination of absolute magnitudes) of recently detected objects, with the priority put on fainter targets that would be missed by facilities with smaller telescopes.

Targets are chosen from the NEOCP as well as from direct communication with discovery surveys. Working synergistically in this manner, we can ensure that the orbits of objects associated with the small end of the NEO size distribution are accurately cataloged. In general, we follow up and report on an average of 50 newly discovered asteroids per month (pending weather).

Time-series Photometry

NEO lightcurves are collected in order to determine spin rates, spin orientations, and shapes. These observations fall into two categories. The first category is comprised of short term (usually over 1 - 2 nights) efforts to determine spin rates and amplitudes of recently discovered objects. The results of these observations provide initial hints regarding object structure, as well as serve to reveal any unusual objects warranting further study. Once again, our focus is on fainter targets that are not feasible for smaller aperture telescopes to discern. The second category involves longer term lightcurve studies of selected NEOs spanning the object's full apparition. Although it takes many oppositions for Main Belt asteroids, it is sometimes possible to obtain lightcurves from enough different viewing geometries to make a reasonable estimate of a near-Earth asteroid shape during a single apparition [11]. In addition, longer term observations increase the chance of identifying binary systems [7] or asteroids experiencing non-principal axis rotation (tumbling). For example, Fig. 7 shows an anomalous attenuation event in the lightcurve of the main belt asteroid, 3782 Celle, a photometric signature that is indicative of a binary companion. A preliminary model of the Celle binary system yielded an estimate of it bulk density of ~2.2 g/cm^3, implying that one or both of its components had a moderate to highly fractured internal structure [12].

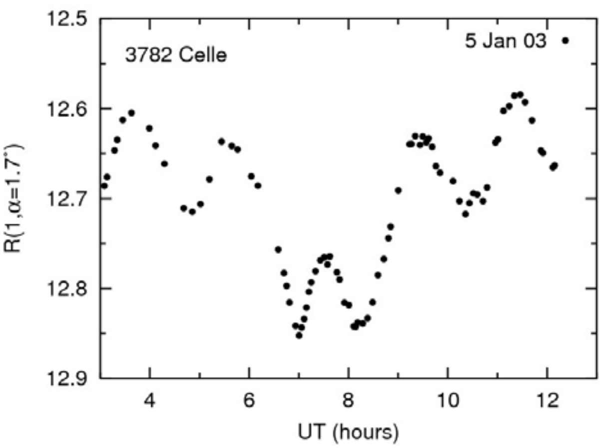

Fig. 7. An anomalous attenuation event in the lightcurve of 3782 Celle (a member of the main belt Vesta asteroid family) indicative of the occultation of a binary companion [12] is shown above.

Spectrophotometry

Although the current capabilities of the MRO 2.4-meter are limited to broad band photometry (using a UBVRI Bessel filter set), this technique has been demonstrated to be useful in providing first indications of taxonomic class [13, 14]. In particular, the ability to distinguish C and S class asteroids, and hence provide a first estimate of their albedos, contributes to lowering the uncertainty in the size distribution of the NEA population. Single-color photometry based on astrometric catalog magnitudes are a natural by-product of our astrometric follow up effort. However, we aslo include interpolated observations in multiple filters as part of our NEO program when feasible, calibrated using photometric standards. This results in both more precise magnitude estimates and color determinations for a large number of newly discovered objects. In addition, accurate mean magnitudes and colors will result from the lightcurve observations described in the previous section. For the case of targets chosen for longer term study, magnitude-phase relationships are studied, which, combined with colors, provide an even better indication of the objects' taxonomy, and hence, constrain albedo and size uncertainties.

Plans for actual spectroscopic work are underway, and a low-resolution spectrograph will be added to the instrumentation available for our NEO program in the near future. Characterization of the NEO population also provides clues to its origin. The typical lifetimes of NEOs are on the order of 10^6 - 10^7 years [15] compared to the typical timescales of 10^9 years associated with the main belt. Therefore, the current population is a relatively recent product that has to be continually re-supplied. Spectroscopic analysis of NEOs helps characterize their taxonomic distribution and as well as shed light on mechanisms such as space weathering [16] that modify their surface properties. Comparison with the taxonomic properties of potential source regions would then enhance understanding of the origin of the current NEO population. Although this is of interest scientifically, it can also help estimate the magnitude of the hazard threat from still undiscovered asteroids as well as provide guidance to optimize search strategies.

4. CONCLUSIONS

The characterization and follow up of faint NEOs is crucial for a successful program of threat detection and mitigation. For the objectives of such a program to be met, data must be acquired to:

- Confirm and catalog orbits from astrometric data.
- Reduce the uncertainty of the NEO size distribution using techniques such as polarimetry and from taxonomic information via colors and phase curves, initially, and later via spectroscopy.
- Infer material strengths and internal structure from lightcurve data, and from identification and modeling of any discovered binaries.

The MRO 2.4-meter telescope has been used effectively to complement the work of survey programs in order to contribute substantially to the dataset required to meet each of these goals.

Acknowledgements

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