On August 19, 1998, LINEAR at Lincoln Laboratory ETS in New Mexico discovered near-Earth asteroid (285263) 1998 QE2 (MPEC 1998-Q19). The asteroid made its closest approach of the 21st century on May 31, 2013 at a distance of 0.039 AU, and was identified by the Minor Planet Center as being a Potentially Hazardous Asteroid. We observed asteroid 1998 QE2 from Table Mountain Observatory’s (TMO) 0.6-m telescope. We obtained broadband photometric data over a total of four nights from July 16-19, 2013. Long-slit CCD spectrograms of 1998 QE2 were obtained using the Palomar 5-m Hale Telescope on June 05, 2013 (ATel #5132). Both the spectral and photometric data analyses show that that 1998 QE2 is a Ch-type asteroid (Bus taxonomy). The asteroid was also a radar target observed at Goldstone throughout June 2013 by the JPL Radar Team, where it was determined to have a moon. We shall try to correlate our photometric lightcurve of asteroid 1998 QE2 with the known presence of the secondary body, and shall determine the synodic period of 1998 QE2. Our R(1,1,α) measurements for asteroid 1998 QE2 clearly follow the trend of a low albedo object. The lightcurve amplitude increased as the solar phase angle increased. I will describe research photometry for the lightcurve production and analysis of asteroids, and discuss the process involved with reducing photometric image data.

Key Words: asteroids; photometry; lightcurve.

I. Asteroid Research Background

The study of the near-Earth asteroids (NEAs) is achieved by two main types of astronomical observations: photometry and astrometry. Most often, astrometric observations of asteroids, taking fine measurements of celestial positions used to determine a minor planet circular, are applied to newly discovered targets or asteroids whose orbital parameters need constraining. Photometric studies involve a systematic data reduction process for a great number of images of an asteroid taken during its apparition. This photometric analysis determines the physical constants describing the object, and can be used to produce a rotational lightcurve and shape model for the asteroid. The predominant scientific consensus in the 20th century regarding asteroid research methods was collected in the publication of Asteroids II (Binzel et. al) in 1989 from the conference in Arizona, a book which remains a reliable and accurate source on the classification and description of the
asteroids. Tholen et al. made the pioneering studies of asteroid taxonomy, and worked towards developing a definitive classification system. The three simplistic classes are: S type, C type, and M type. As the number of asteroids with a growing record of data increased, sub-classes became evident, and new partitions were made in this organizational system. The system eventually developed into the predominating BUS system. At the time of the authorship of Asteroids II, this taxonomic system had grown to include many designations, which are summarized within the book.

II. Overview of the Near-Earth Asteroids and Potentially Hazardous Asteroids

There are approximately seven thousand near-Earth asteroids known. These objects are specified within the most practical known limits, and are defined to have a minimum perihelion distance of 1.3 astronomical units (AU). Within the population of discovered NEAs, three orbital types have been identified: the Aten, Apollo, and Amor asteroid groups. In general, the Aten asteroids orbit more or less within the orbit of Earth, while the Amor asteroids follow paths near to the superior boundary of Earth’s orbit. Apollo asteroids are those NEAs whose orbital paths cross the orbital path of Earth. 1998 QE2 is an Amor type asteroid that made a close approach on May 31, 2013, which will not occur again within this century. There are approximately one thousand Potentially Hazardous Asteroids (PHAs) which have been identified by the Minor Planet Center based on three criteria: minimum orbit intersection distance (MOID), magnitude, and diameter. Though QE2 has an Amor type orbit, this asteroid’s minimum geocentric distance during the most recent approach came closer than 0.05 AU, which is the farthest acceptable MOID in order to be classified by the Minor Planet Center as a PHA. The Minor Planet Center (MPC) facilitates a clearinghouse for astrometric reporting and publishes reliable orbit circular records for many of the NEAs. The MPC also offers detailed and categorical instructions for members of the amateur astronomical community who are motivated to contribute to the improvement of the known orbital parameters for particular NEAs. By definition, the absolute magnitude (denoted H) of PHAs must also be brighter than 22 mag., and hence these objects are larger than a diameter of 200 meters.

III. Phase Angle and the HG Magnitude System

Asteroids have phases. During the approach of a NEA, the target can pass through a large range of viewing geometry and phase angles as it makes its pass by Earth. This is an ideal opportunity for
astronomers to collect phase curve data for the target. An asteroid’s phase curve is a plot of solar phase angle $\alpha$ along with the changing reduced magnitude of the asteroid, $R(1,1,\alpha)$. Main belt asteroids are observable in a narrower range of phase angles because of their increased heliocentric distance. As a rule and trend, solar system bodies are observable at a wider range of phase angles when they are inferior to the orbit of the observing site. Conversely, objects increasing in distance from the Sun beyond the orbit of a given observing site will exhibit a narrower range of phase angles, as the main belt asteroids do.

There are several contexts for the use of the word magnitude when one refers to the asteroids. Reduced magnitude is a value which describes the brightness of the target asteroid at any given solar phase angle if the asteroid were positioned one astronomical unit from the Sun and one astronomical unit from the Earth simultaneously. This differs from the absolute magnitude of an asteroid, $R(1,1,0)$, which describes the brightness of the target asteroid at opposition (solar phase angle = 0) and also at the heliocentric and geocentric distances of one astronomical unit simultaneously. Both of these values are concluded from the two main equations of the HG Magnitude System (Bowell et al. 1985). Observed magnitude is uncompensated for both heliocentric and geocentric distances, as well as phase angle at the time of observation.

$$R(1,1,\alpha) = V_{\text{obs}}(r,\Delta,\alpha) - 5 \log(r\Delta) \quad \text{Eq. 1}$$

where

- $r$ heliocentric distance to asteroid
- $\Delta$ geocentric distance to asteroid
- $\alpha$ solar phase angle

$$R(1,1,\alpha) = H(1,1,0) - 2.5 \log[(1-G)\phi_1(\alpha) + G \phi_2(\alpha)]$$

Eq. 2

where

$$\phi_i(\alpha) = e^{-A_i(\tan \alpha/2)B_i}$$

and

- $i = 1$ or 2
- $A_1 = 3.33$, $B_1 = 0.63$
- $A_2 = 1.87$, $B_2 = 1.22$

The phase curve of an asteroid comes out of Eq. 2, and Eq. 1 converts observed magnitude to reduced magnitude.

When comparing and contrasting lightcurves, there are certain benefits to the reduced magnitude
form, which compensates for the incidental observed distances. It allows astronomers to compare the brightness of objects observed in different viewing geometries without the effects of distance on brightness. Therefore, lightcurves of the asteroids are almost always plotted in reduced magnitude.

When an asteroid reaches opposition, it displays a sharp increase in brightness called the opposition effect (Belskaya and Shevchenko, 1999). Though the surface of the asteroid is not, of course, perfectly mirror-like, this steepening of the solar phase curve at phase angles close to zero is due to the fact that the light which reflects from the surface of the asteroid bounces off in a “forward gloss vector” as well as a “backwards gloss vector,” both of which have the same direction when the object reaches opposition. These directed rays of light are reflected back towards the light source, and are well-measurable from Earth’s ground based observatories (R. K. Buchheim). The constant G within Eq. 2 of the HG Magnitude System describes the overall shape of the phase curve’s for a given asteroid, and particularly indicates the steepness of the opposition effect. G is referred to as the phase parameter. If the phase parameter for a particular asteroid is not yet known, then a value of 0.15 is assumed.

IV. Phase Coefficients and Albedo

In their paper describing the Opposition Effect of Asteroids (1999), Belskaya and Shevchenko demonstrated a linear connection between the albedo of the asteroids and their phase coefficients β (always expressed in magnitudes per degree). The phase coefficient, β, is the slope of the linear portion of an asteroid’s phase curve. By calculating the phase coefficient, β, using values at angles of 10 and 20 from the solar phase curve of 1998 QE2, I plotted a data point along the best fit linear relationship of albedo and β and was able to estimate the albedo of QE2 at 0.091. This confirms the target to be a dark object fitting in well with the C type classes of objects.

I calculated the coefficient from g = 0.09 as follows:

\[R(10) = H - 2.5 \log \left[ (1-0.09)(0.4879) + (0.09)(0.90871) \right] = H + 0.698\]

\[R(20) = H - 2.5 \log \left[ (1-0.09)(0.3276) + (0.09)(0.7984) \right] = H + 1.080\]

Then since phase coefficient is in mags/degree,

1.080 - 0.698 = 0.382

And, 0.382/(20-10) = 0.038 = phase coefficient
The best fit for the data from Belskaya and Shevchenko is:

$$\beta = -0.023 \log(p) + 0.0130$$

Based on this phase coefficient, the x value from the best fit line was calculated as -1.042.

So 1998 QE2's data falls at (-1.042, 0.038).

So the albedo of 1998 QE2 would be $10^{-1.042} = 0.091$

V. Observing Nights and Data Collection

Our NEO-PHOT team of interns at JPL spent the summer of 2013 taking images of near-Earth asteroids with the 0.6-m cassegrain telescope and Spectral Instruments 2K CCD with plate scale 0.29 arcseconds/pixel at Table Mountain Observatory near Wrightwood, CA.

We observed the binary PHA 1998 QE2 on the nights from July 16-18 UT, and I performed the data reductions for these nights. I generated three lightcurves, as well as extinction curves that I used to assess the atmospheric conditions on each of the three nights. On the first, second and third observing runs, we collected 136, 147, and 276 images, respectively. The standard photographic file format in astronomy is the .fits file, and these files were processed with a specific data reduction technique through the usage of the Image Reduction and Analysis Facility (IRAF) software. A standard complement of images from one full night typically incorporates several types of images: skyflats, bias frames, the target science images, and standard star field images.

Standard Stars and Extinction Curves
The standard star images are used to determine atmospheric extinction curves on each of the nights. The standard star database which was used throughout our observations was the Main Index of Equatorial UBVRI Photometric Standard Stars through WIYN and NOAO. Standard star fields were imaged at different times of the night-- at transit, as well as at hour angles of approximately three to four hours. The purpose of this variation in hour angle is to achieve measurements of each field at different airmasses. The atmospheric extinction curve is a plot of the instrumental mag. minus catalog mag. as a function of airmass. These catalog magnitude values are obtained from the standard star database, and an airmass is recorded for each image taken.

$$\text{airmass} = \sec(z)$$

Cleaning the Data
The SI2K CCD chip carries dust particles which inevitably affect the images produced. Flat-fielding and bias-subtraction are the two methods of cleaning the photometric data before the magnitudes of the target asteroid and standard
stars are measured. At the beginning of our observing runs, we collected an odd number of both skyflat images during sunset or sunrise as well as bias frames taken with the dome closed. These two types of images are critical in the photometric reduction process. Aberrations or disturbances can be compensated by cleaning the data first through bias subtracting. For each night of data, I created a median bias frame using the odd number of biases taken, and then subtracted this median bias from all science images. In addition, the CCD chip is not immune to showing the effects of cosmic rays or dust halos, which pass through our images every night. Cosmic rays can seriously alter the photometric measurement of the target or standard star in any given frame. This type of degradation is cleaned through the process called flat-fielding. Skyflats are images used to divide all science images by, and are taken in a civil twilight sky at 20-25K overall counts. The exposure times are slowly adjusted to maintain the overall pixel counts at 20-25K as the sky either darkens or lightens. For each night, I combined the odd number of skyflats into a median skyflat frame for each night, and used this to divide. The quality of my photometric measurements was greatly increased by following this process.

VI. Results

With the knowledge that QE2 was determined as a binary asteroid with a moon by the JPL Radar Observing Team (L. Benner and M. Brozovic), I scrutinized my lightcurve reductions for any sign of the presence of this moon.

In the week that we observed (2013 July 16-18 UT), the atmospheric extinction curves on each of the three night showed an explicit trend of decreasing quality due to the effects of a relatively nearby fire whose smoke and particulate matter may have caused a degraded air quality. From my standard star measurements, July 16 UT was a photometric night, and July 17 UT was an acceptably photometric night. However, the atmospheric extinction curve for July 18 UT displayed a scatter of measurements, indicating
that perhaps the entire night may not have been photometric. When a night is photometric, the astronomer is able to make reliable measurements of light for the target. A perfectly photometric night would not show any decrease in standard star magnitude at high airmasses, and the extinction curve would then be horizontal. Some of the standard stars with a designation RED from the NOAO catalog were omitted from the calculation of the best fit line.

The lightcurve for July 16 and 17 portray a half-night of data collection for QE2, whereas the lightcurve for July 18 reflects a full night of imaging the object. We determined the rotational period of QE2 as 5.39±0.02 hrs. Since this rotational period is close to a factor of 24 hrs, the lightcurves for July 16 and 17 may portray the same part of QE2’s rotation.
Usually, if an asteroid is observed at the same times each night, and the rotation period is near to a factor of 24 hrs, then the lightcurve will likely portray the same part of the rotation on both nights.

The lightcurve from July 18 UT deserves extra attention due to the fact that it suggests a large decrease in QE2’s brightness towards the latter half of the night and sunrise. Knowing the nature of 1998 QE2 as a binary system, this sharp decrease in brightness may in fact be evidence of the presence of this asteroid’s moon. However, since the extinction curve for July 18 indicates that the night may not have been completely photometric, the reason for this drop in brightness remains undetermined.

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Bibliography

Buchheim nd. Methods and Lessons Learned Determining the H-G Parameters Of Asteroid Phase Curves.