Proceedings of The National Conference
On Undergraduate Research (NCUR) 2014
University of Kentucky, Lexington
April 3-5, 2014

Tracking the Polyrhythm: Broadband Photometry and Lightcurve of the Binary Potentially Hazardous Asteroid (285263) 1998 QE2 with Photometric Analysis Methods

Adrian Lawson Carcione
Department of Astronomy
Moorpark College
Moorpark CA 93021 USA

Faculty Advisor: James Somers

Faculty Advisors: Michael D. Hicks
Jet Propulsion Laboratory - NASA
Pasadena CA 91109

Abstract

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. Asteroid 1998 QE2 was observed from Table Mountain Observatory's (TMO) 0.6-m telescope, and broadband photometric data was obtained over a total of three nights from July 16-19, 2013. 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. This paper aims to correlate the photometric lightcurve of asteroid 1998 QE2 with the known presence of the secondary body, and reports the synodic period of 1998 QE2. The R(1,1,□) measurements for asteroid 1998 QE2 clearly follow the trend of a low albedo object. The lightcurve amplitude increased as the solar phase angle increased. This paper describes research photometry for the lightcurve production and analysis of asteroids, and discusses the process involved with reducing photometric image data.

Key Words: asteroids; photometry; lightcurve

1. 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, fine measurements of celestial positions, are used to determine an orbit, and are applied to newly discovered targets or asteroids whose orbital parameters need constraining. Photometric studies are a systematic process that involve data reduction 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. 1989) from the conference at the University of Arizona. This book remains a reliable and accurate source on the classification and description of the asteroids, although it has been followed by *Asteroids III* (Binzel et al. 2002) and hundreds of journal papers. Tholen (1984) 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 (such as Ch) were made in this organizational system. The system eventually developed into the predominating Bus taxonomic system, allowing for subdivisions within the three simplistic classes. At the time of the authorship of *Asteroids II,* this taxonomic system had grown to include many designations, which are summarized within the book.

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

There are approximately seven thousand near-Earth asteroids known. These objects are specified based upon known (observed) limits, and are defined to have a maximum 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 1998 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 (MPC) as a PHA. The MPC acts as 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

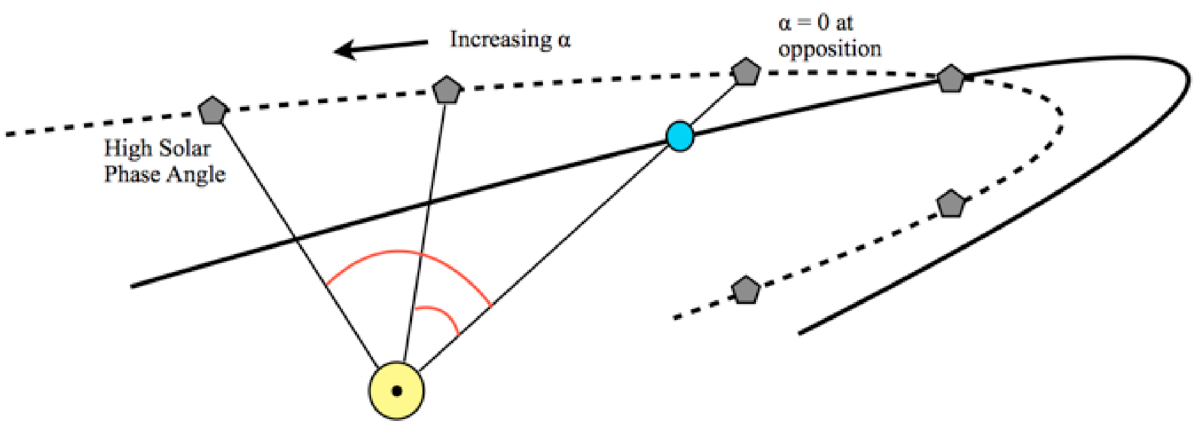

Fig. 1 Changing phase angle/viewing geometry

H) of PHAs must also be brighter than 22 magnitude, and hence these objects are larger than a diameter of 200 meters. This size is significant in the definition of PHA because of the impact energy that would result from such a mass striking the earth, based on the Torino impact scale (Binzel 1997).

3. Phase Angle and the HG Magnitude System

Asteroids exhibit phases during their orbits (Fig. 1). 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. Knowing the phase data for an asteroid is important because it enables astronomers to determine the albedo and the type of asteroid.

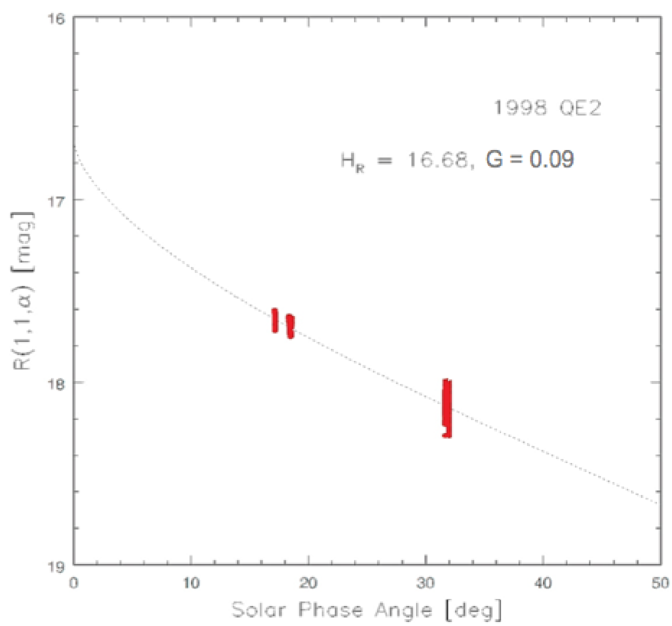

Fig. 2 Phase curve of 1998 QE2

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. 1989). Observed magnitude is uncompensated for both heliocentric and geocentric distances, as well as phase angle at the time of observation.

An asteroid's phase curve (Fig. 2) is a plot of solar phase angle α along with the changing reduced magnitude of the asteroid, R(1,1,α). The brightness decreases at higher phase angles, and increases at lower phase angles. 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. To illustrate the dynamic and changing nature of a near-Earth asteroid passing through its close approach, Fig. 3 displays the changing celestial coordinates of 1998 QE2 from 2013 through 2033, based upon JPL Horizons Database ephemerides. The

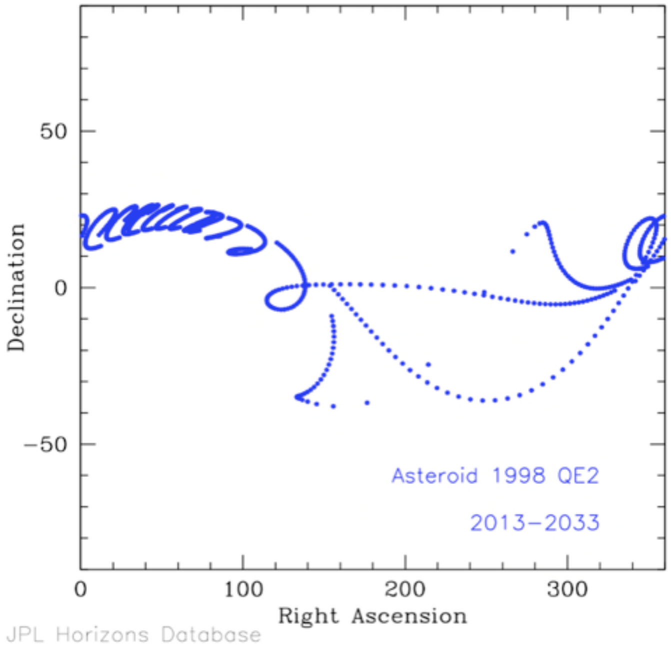

Fig. 3 1998 QE2 Celestial Coordinates 2013-2033

rapidly changing region of this curve is a representation of the most recent approach of 1998 QE2 in May 2013. Each of the smaller loops represent the effect of one of Earth's orbits around the sun upon the celestial coordinates of 1998 QE2 while this asteroid is at a greater distance.

Eq.1 converts observed magnitude to reduced magnitude, while the phase curve of an asteroid comes out of Eq. 2. These are the equations of the HG Magnitude System (Bowell 1989):

$$R(1,1,\alpha) = V_{obs}(r,\Delta,\alpha) - 5\log(r\,\Delta) \qquad (1)$$

where

r heliocentric distance to asteroid

Δ geocentric distance to asteroid

α solar phase angle

$$R(1,1,\alpha) = H(1,1,0) - 2.5\log[(1-G)\varphi_1(\alpha) + G\,\varphi_2(\alpha)] \qquad (2)$$

where $\varphi_i(\alpha) = e^{[-A_i(\tan\alpha/2)B_i]}$ and

i = 1 or 2

$A_1 = 3.33$ $B_1 = 0.63$

$A_2 = 1.87$ $B_2 = 1.22$

When comparing and contrasting lightcurves, there are certain benefits to the reduced magnitude system, 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 the reduced magnitude system.

When an asteroid reaches opposition, it displays a sharp increase in brightness called the opposition effect (Belskaya and Shevchenko 2000). Since the surface of the asteroid is not 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," (Buchheim 2010) 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. The constant G determined from Eq. 2 of the HG Magnitude System describes the overall shape of the phase curve 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.

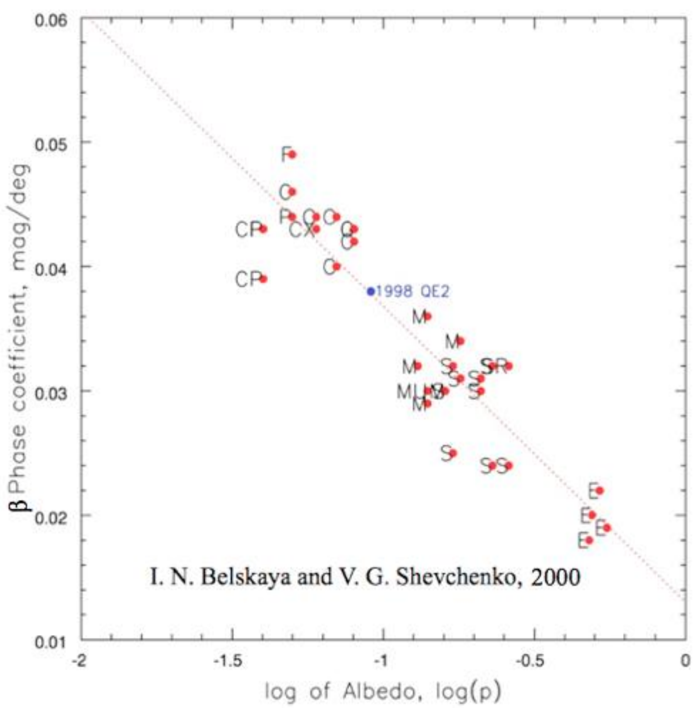

Fig. 4 Relationship between the phase coefficient and the albedo

4. Phase Coefficients and Albedo

In the paper describing the *Opposition Effect of Asteroids*, Belskaya and Shevchenko (2000) 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, a data point was plotted along the best fit linear relationship of albedo and β (Fig. 4) in order to estimate the albedo of 1998 QE2 at 0.091. This confirms the target to be a dark object fitting near the *general* C type classes of objects.

To demonstrate, the phase coefficient is calculated from $G = 0.09$ as follows:

$$R(10) = H - 2.5 \log [(1-0.09)(0.4879) + (0.09)(0.90871)] \quad (3)$$

$$= H + 0.698$$

$$R(20) = H - 2.5 \log [(1-0.09)(0.3276) + (0.09)(0.7984)] \quad (4)$$

$$= H + 1.080$$

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 (2000) is:

$$\beta =-0.023\log(p)+0.0130 \quad (5)$$

Based on this phase coefficient, the x value from the best fit line was calculated as -1.042. So 1998 QE2's datum falls at (-1.042, 0.038).

Therefore the albedo of 1998 QE2 would be $A = 10^{\beta} = 10^{-1.042} = 0.091$.

5. Observing Nights and Data Collection

The Near-Earth Object Photometry 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 (SI2K) with plate scale 0.29 arcseconds/pixel at Table Mountain Observatory near Wrightwood, CA.

The binary PHA 1998 QE2 was observed on the nights from July 16-18 UT, and the data reductions were performed for these nights using relative photometry. Three lightcurves were generated, as well as extinction curves that were used to assess the atmospheric conditions on each of the three nights. On the first, second, and third observing nights, 136, 147, and 276 images were collected respectively. The standard electronic file format in astronomy is the .fits file, and these files were processed with a routine data reduction technique through the usage of the standard Image Reduction and Analysis Facility (IRAF) software, written and supported by the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. A standard complement of images from one full night typically incorporates several types of images: bias frames, skyflats, the target science images, and standard star field images. Bias frames are taken while the telescope cover and dome are closed, allowing the CCD chip to collect its electronic signal without stimulation from external light. An odd number of bias frames are taken because a median image is created through a procedure using IRAF software (by selecting median pixel values). This median bias frame is subtracted from the pixel values in each of the target science images of the asteroid or standard stars (which are to be used in the photometric reduction later). Skyflats are images of the civil twilight sky taken before nightfall while the sun is setting, or in the morning while the sun is rising. Skyflat images are used in the flat-fielding of the target science images, which is a procedure using IRAF where a median image is first created out of an odd numbered group of skyflats (by selecting median pixel values). Then, pixel values of each target image are divided by pixel values from this median flat field image. For the telescope operators, it is important that the skyflat images are taken at the proper time during sunset or sunrise and in the appropriate region of sky, in order to ensure an overall pixel value count between 20-25K for each skyflat image. As the sky becomes darker at sunset or lighter during sunrise, the telescope operator taking skyflats lengthens or shortens the exposure time, respectively, in order to maintain these overall pixel value counts between 20-25K. These procedures eliminate or reduce the effect of imperfections from the CCD chip and random cosmic rays appearing in the target science images.

5.1 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 photometry, when the magnitudes of the target asteroid and standard stars are measured. These two types of images, bias frames and skyflats, are critical before the photometric reduction process. For each night of data, the median bias frame was created using an odd number of biases taken, and then subtracted from all science images. Aberrations or distortions can be compensated

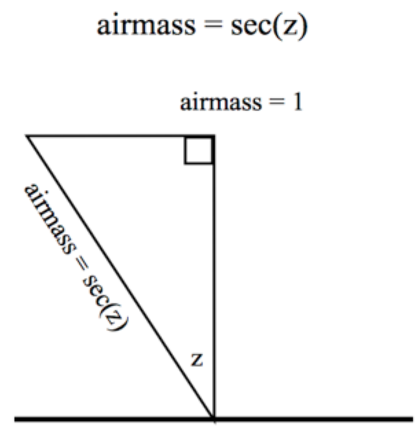

Fig. 5 Fluctuating airmass throughout observations

by cleaning the data first through flat fielding. The CCD chip is not immune to showing the effects of cosmic rays or dust halos, which pass through the images every night. Cosmic rays can seriously alter the photometric measurement of the target asteroid or standard star in any given frame. This type of image degradation is cleaned through the process called flat-fielding. This is the reason it is important that the telescope operator adjusts the exposure times of the skyflats to maintain the overall pixel counts at 20-25K as the sky either darkens or lightens. The quality of photometric measurements was greatly increased by following this process.

5.2 Standard Stars, Extinction Curves, And Data Reduction

Images of standard stars, which have known photometric magnitudes, are used to determine atmospheric extinction curves on each of the nights. The catalog of standard stars used throughout the observations of 1998 QE2 was the Main Index of Equatorial UBVRI Photometric Standard Stars maintained by the WIYN Consortium/NOAO (Landolt 1992). Selected standard star fields were imaged at different times of the night: at transit, and at hour angles of approximately three to four hours (on either side of transit). The purpose of this is to achieve photometric measurements of each standard star field while observing through different airmass (Fig. 5). In this way, the atmospheric extinction was determined on each night of observation: For each standard star field, the measured photometric values were compared with the cataloged magnitudes in the WIYN Consortium/NOAO database. Relative photometry was performed on all three nights of data, 2013 July 16-18 UT.

An atmospheric extinction curve (Figs. 6a, 7a, 8a) is a plot of the instrumental magnitudes minus the cataloged magnitudes as a function of airmass for each standard star in each image, and is an indicator of observing quality based upon the atmospheric extinction. These cataloged magnitude values are obtained from the standard star database, and the airmass is recorded immediately upon exposure of each image. A best fit line y=f(x) was calculated for the instrumental magnitudes minus the cataloged magnitudes as a function of airmass for each standard star in each image. Then instrumental magnitudes were converted into observed magnitudes by subtracting the value of f(x) from the instrumental magnitudes. The standard deviation of the difference between observed magnitudes and cataloged magnitudes was computed and displayed upon each extinction curve.

Subsequently, each night's atmospheric extinction best fit curve was applied to the instrumental photometric measurements of the asteroid 1998 QE2 in each image to attain observed magnitudes from each target science image. Then these observed magnitudes were converted into reduced magnitudes using Eq. 1 from the HG Magnitude System (Bowell 1989):

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

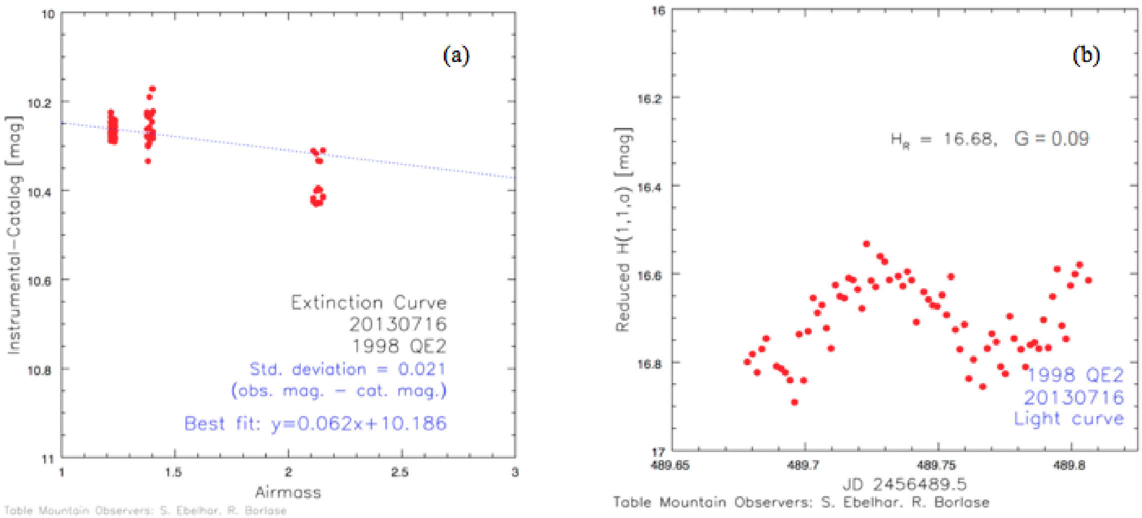

Fig. 6a, 6b Extinction curve and lightcurve from the first night observing 1998 QE2, 2013 July 16 UT

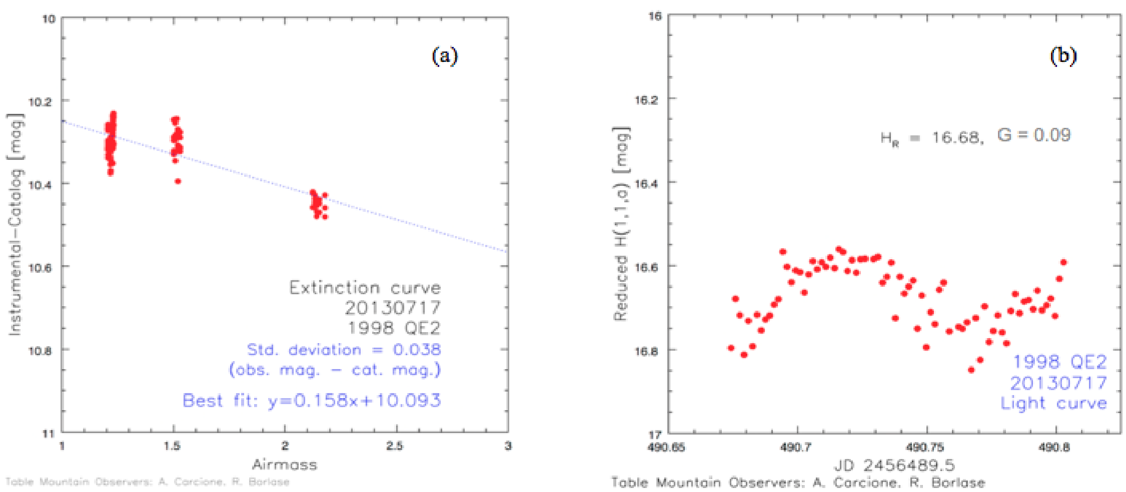

Fig. 7a, 7b Extinction curve and lightcurve from the second night observing 1998 QE2, 2013 July 17 UT

which is calculated based upon the phase angle α, heliocentric distance r, and geocentric distance Δ of the asteroid during the time of observation. Lightcurves of 1998 QE2 were generated for each night of observation by plotting the reduced magnitudes H(1,1, α) as a function of the Julian Date, taken at the instantaneous midpoint of each image exposure.

6. Results and Analysis

Knowing that 1998 QE2 was determined as a binary asteroid with a moon by the JPL Radar Observing Team (L. Benner and M. Brozovic 2014), the lightcurves were inspected for any sign of the presence of this moon (refer to Figs. 6b, 7b, and 8b).

In the week that 1998 QE2 was observed (2013 July 16-18 UT), the atmospheric extinction curves on each of the three nights 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 the standard star measurements, July 16 UT was a photometric night, and July 17 UT was a 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 by applying the correction from the extinction curve. A photometric night will show some decrease in

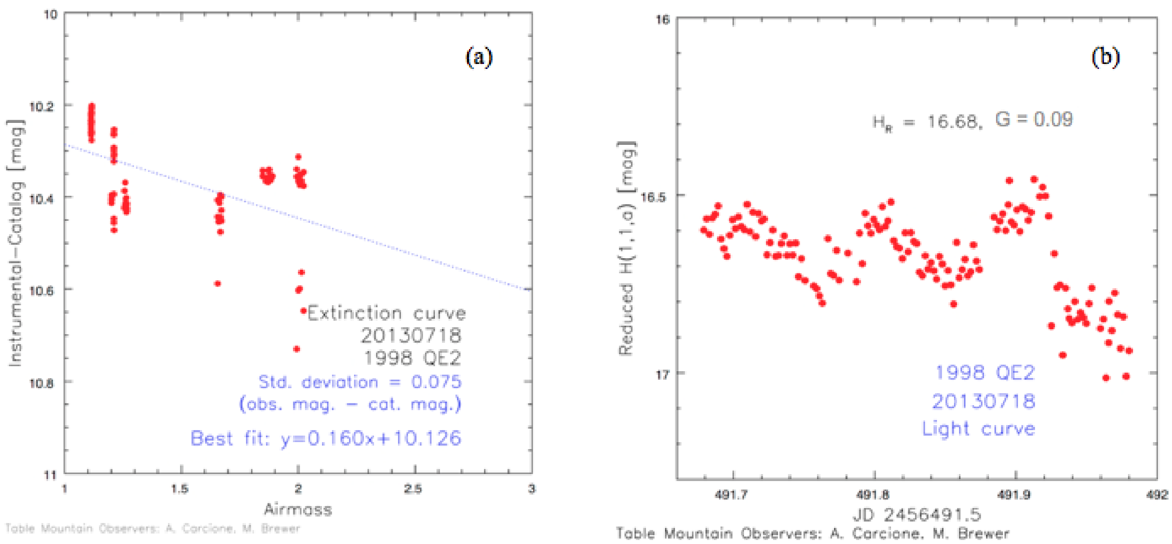

Fig. 8a, 8b Extinction curve and lightcurve from the third night observing 1998 QE2, 2013 July 18 UT

standard star magnitude at high airmass, and this is why the extinction correction is performed. Correcting for atmospheric extinction is crucial to photometry because of the atmosphere's unavoidable influence on photometric measurements. Even when a night is not photometric, an astronomer can still do reliable work with data differently. Some of the standard stars with a designation RED from the NOAO catalog were omitted from the calculation of the best fit line because they were outliers. The effects of atmospheric extinction at high airmass are less influential on redder stars than blue stars, which can cause a significant difference at large airmass.

The lightcurve for July 16 and 17 portray a half- night of data collection for 1998 QE2, whereas the lightcurve for July 18 reflects a full night of imaging the object. The rotational period of 1998 QE2 was determined 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 1998 QE2's rotation.

Fig. 9 0.6-m Telescope and control room at Table Mountain Observatory, Wrightwood, CA

Typically, 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 1998 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.

7. Acknowledgments

I would like to thank my project mentor Dr. Michael Hicks (JPL/Caltech), C.U.R.E. Program Director Professor Paul McCudden, my project advisor Professor James Somers, Richard Alvidrez, and Heath Rhoades for their guidance, teaching, mentorship, and collaboration. I would also like to thank my fellow interns Stephen J. Ebelhar, Mark A. Brewer, and Randal B. Borlase for spending many splendid nights observing in partnership at Table Mountain Observatory near Wrightwood, CA (Fig. 9). This research is supported by NSF REU Grant #AST-1156756 to Los Angeles City College and was performed at Table Mountain Observatory and NASA's Jet Propulsion Laboratory.

8. Bibliography

1. Belskaya, I., and V. Shevchenko. (2000). Opposition Effect of Asteroids. *Icarus.,* 147, 94-105.

2. Benner L.A.M. et al. (2014). Radar derived shape model of binary near-Earth asteroid (285263) 1998 QE2. 45th Lunar and Planetary Science Conference. 1-2.

2. Buchheim, R. (2010). Methods and Lessons Learned Determining the H-G Parameters Of Asteroid Phase Curves. Proceedings for the 29th Annual Conference of the Society for Astronomical Sciences. 101-117.

3. Bowell, E. et al. (1989). Application of Photometric Models to Asteroids, *Asteroids II* (R.P. Binzel, T. Gehrels, M.S. Matthews, eds.) University of Arizona Press, Tucson. 524-555.

4. Binzel, R. P. (1989). An overview of the asteroids, *Asteroids II.* University of Arizona Press, Tucson. 3-17.

5. Binzel, R. P. (1997), A Near-Earth Object Hazard Index. Annals of the New York Academy of Sciences, 822: 545–551. doi: 10.1111/j.1749-6632.1997.tb48366.x

6. French, L., and R. Binzel. (1989). CCD Photometry of Asteroids, *Asteroids II.* University of Arizona Press, Tucson. 54-65.

7. Harris, A. (1989). Photometric Lightcurve Observations and Reduction Techniques, *Asteroids II.* University of Arizona Press, Tucson. 39-53.

8. Landolt, A.U. (1992). UBVRI photometric standard stars in the magnitude range 11.5-16.0 around the celestial equator. Astrophysical Journal, 104(1), p. 340-371, 436-491. doi: 10.1086/116242

9. Tholen, D.J. (1984). Asteroid Taxonomy from Cluster Analysis of Photometry. Ph.D. Thesis, Univ. of Arizona.