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ASTEROID OBSERVATIONS WITH CCDs

Stephen J. Ratcliff
Department of Physics
Middlebury College
Middlebury, VT 05753-6151

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Abstract

CCD imaging cameras are ideally suited to the study of asteroids, especially with small telescopes which provide relatively large fields of view. Both photometric and astrometric observations are valuable. Photometric studies of asteroids include determination of rotational light curves and of phase curves. The techniques involved are very similar to those required for observations of variable stars, with the additional necessity of following the asteroid as it moves among the background stars. These observations yield information about the compositions, shapes, and rotation-axis orientations of the asteroids. The two-dimensional nature of CCD detectors also makes them valuable for astrometric observations. Positional determinations of asteroids can easily be made with CCDs on small telescopes.

1. Introduction

Worth noting is that the observational techniques used in variable star photometry are of value outside the stellar realm. In particular, the great sensitivity of CCD cameras opens up new possibilities for observers with small telescopes. In this paper, I will describe a number of observational projects concerning minor planets, or asteroids, which are ideally suited to CCD imaging systems. First I will discuss how the familiar techniques of differential photometry can be applied to minor planet light curve studies, and then point out the utility of CCDs in astrometric work.

2. Minor Planet Photometry

Minor planet photometry is important for the same reason that variable star photometry is important: from light variations we learn about the objects. In this case, light variations on short time scales (hours) relate to the rotation and shape of the asteroid. Variations on long time scales (weeks) are related more to the changing distances between the earth and the asteroid, and between the sun and the asteroid, but details of the surface properties of the asteroids are reflected - so to speak - in the exact shape of the phase curve (the dependence of the magnitude, averaged over a full rotation, on the viewing geometry).

2.1 Rotational Light Curves

Rotational periods for asteroids are typically in the range of 4 to 12 hours. Most asteroids show two maxima and minima per rotation period, so that significant variations can actually be observed in an hour or two. The amplitudes and shapes of the light curves for a given asteroid depend on the shape of the asteroid and on where along its orbit the asteroid is observed. Amplitudes of variation are typically 0.1-0.3 magnitude (sometimes higher). Unlike many eclipsing binaries, the light variations are happening continuously, so that the epoch of observation need not be carefully chosen beforehand.

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In most cases, simple differential photometry with comparison stars in the same field of view as the asteroid ("on-chip") is sufficient. It is best to have many comparison stars available, so that intercomparison of the stars with each other can show whether some might themselves be varying on short time scales. Additionally, the signal-to-noise ratio in the differential magnitudes can be increased by combining the light from many stars into one single comparison "star." (Typically, the asteroid's nightly motion is not so great that it crosses the field of view of a CCD chip in less than a few hours' time; one advantage of a short-focal length telescope is its increased field of view!) The appropriate techniques are exactly those as described elsewhere for careful differential stellar photometry (e.g., French and Binzel 1989). It is rare for an asteroid to show color changes during a rotation, so in general it is sufficient to observe in a single filter. This filter may be one which gives the highest overall system quantum efficiency, or it may be chosen so that the data can easily be combined with those from other observatories. (For CCD photometry, it is generally unwise to make unfiltered observations, because the flat-field corrections - vitally important for photometry - are more difficult in that case.) For the analysis of light curves, it is not even always necessary to convert to a standard color or absolute magnitude scale, because the period and amplitude may be derived from the differential light curve.

One important application of light curve observations is using large numbers of them, spread out over several orbits, to determine the shape and/or rotation axis orientation of the asteroid. Most of the readers of this paper are unlikely to want to get involved in the complex mathematical analysis required to complete this exercise, but research on light curves can be coordinated with experts in the field. A simpler, self-contained project is to determine light curve parameters for asteroids (amplitude and period). Of the approximately 5000 asteroids with well-determined orbits, only a small fraction (approximately 15%) have had light curve parameters determined (even crudely), and far fewer (about 1%) have been observed well enough that further light curves would not be likely to improve our knowledge significantly. Table 1 summarizes the situation as of 1991 as reported in Batrakov (1992, hereafter EMP). Among the first 1000 numbered asteroids, which in general are the brightest (and therefore easiest to observe), just over half have tabulated results. Among the next 4000 or so, only about 5% have been studied. Clearly much more remains to be done, and for the majority of the known asteroids, any light curve at all would be helpful.

Table 1. Statistics on our knowledge of asteroid rotation parameters (from the 1992 EMP)

	First 1000 numbered asteroids	*remainder (≈ 4000)*
Period, shape, and orientation of axis known	46	6
Some (not all) rotational parameters known	413	170
"tentative results; may be completely wrong"	55	31

Figure 1 shows the results obtained with the CCD system at Middlebury College (Photometrics PM512 CCD camera, DFM 0.41-meter reflecting telescope, broad red filter) for MP (694) Ekard. The data reduction was performed by Anastasia Alexov, an undergraduate at Wesleyan University. The results are consistent with the published value for the rotation period of 5.922 hours (recall that there are two maxima and minima per rotation).

2.2. Phase Curves

Over a several-week period, the mean magnitude of an asteroid will change, as it moves closer to or farther from the sun and the earth. Although one might imagine a fairly simple relationship between the distance from the sun, the distance from the earth, the (mean) fraction of illumination, and the resultant apparent magnitude, the actual relationships vary based on surface properties of the asteroids. See Bowell *et al.* (1989) for some illustrations of the various possibilities. These differences are especially notable at low phase angle (when the opposition passage carries the asteroid through a point in the sky almost diametrically opposite the Sun). For asteroids with large orbital inclinations, low phase angles will not be reached during every opposition passage. The observations required to construct these phase curves are, however, more difficult to make. They require either a homogeneous set of observations (from one observatory) over a wide range of phase angle, with all magnitudes referenced to a single standard star (which of course could not possibly be on every CCD frame!), or else the combination of data from many observatories, which therefore must all be transformed to a common magnitude system. The techniques for doing this are, in both cases, the same as normally used in stellar photometry. In the first case, it means, in effect, all-sky photometry; in the second it requires the observing system's transformation coefficients to be known, and requires the observation of standard stars. Therefore, the relative advantage of the CCD is not so great, since one probably cannot rely solely on on-chip comparison stars.

3. Astrometry

Compared to variable star photometry, one apparent drawback of observing asteroids is that they move, and therefore you must have predictions of positions for each night of observation. For any asteroid whose light curve may be readily measured with a CCD on a modest-sized telescope, the orbit is known well enough that the predicted position will be in error by only a small fraction of the field of view of your CCD chip. On the other hand, actually seeing the asteroid move adds greatly to the excitement of the observations.

Additionally, the two-dimensional (imaging) nature of the CCD detector allows for something that aperture photometers don't: CCD frames provide astrometric (positional) information. As an example, Figure 2 presents some results from astrometric reduction of CCD images of MP (694) Ekard. For the images upon which the light curve of Figure 1 is based, we determined the celestial coordinates of the asteroid by using the known catalog positions of comparison stars from the Hubble Space Telescope *Guide Star Catalog* (GSC). Of course, had we not known the asteroid's position in advance, we would not have been able to find it in the first place. However, when we compared our observed positions to the predicted positions - from orbital elements determined from observations 10 or more years old - we got the results shown in Figure 2. The histograms of residuals show that the observed positions differed from the predicted positions by several seconds of arc in each coordinate, whereas the root-mean-square residual was only a few tenths of an arc second. Astrometric observations such as these are valuable in refining the elliptical orbital elements of asteroids, which, due to planetary perturbations, are not constant.

In fact, every year the EMP contains a "critical list" of asteroids which either have orbits based on a small number of observations, or (less likely) simply have not been observed astrometrically in 10 or more years (as was the case in 1991 for 694 Ekard).

In addition, newly discovered asteroids are likely to be "lost" if they are not followed up astrometrically over a period of weeks or months following discovery. The CCD camera on a small telescope can contribute significantly to astrometric observations of these asteroids. While the data reduction requires a computer program in addition to whatever photometry package one might already have, and access to a copy of the GSC is essentially required, one has the advantage that flatfielding is probably unnecessary, and therefore one can observe with no filter in order to reach very faint objects.

Finally, a fun exercise is the observation of parallaxes of asteroids. Many asteroids pass close enough to earth that they will show parallax when observed simultaneously from two widely separated sites. Though the scientific content is low and more planning is required - one must collaborate with some other, distant observatory - the rewards are high. For more details, see the paper by Ratcliff *et al.* (1993).

4. Resources

The *Minor Planet Bulletin* is an excellent source of information on asteroid observations, including suggestions for projects and also for ephemerides (tables of positions). For information on a subscription contact: Derald D. Nye, 10385 East Observatory Drive, Tucson, AZ 85747, USA. Additionally, *Sky & Telescope* occasionally reports on asteroids of note.

A good professional reference is the book *Asteroids II* (Eds. Binzel *et al.* 1989) and the sources referred to therein. It contains several asteroid databases.

Some source of ephemerides is also required. One possibility is to use published orbital elements (such as those in *Astronomical Almanac*), along with microcomputer programs. Another possibility, though difficult to find perhaps, is the EMP, which contains just about everything you need (although the ephemerides it contains are on ten-day intervals and therefore require interpolation).

Finally, for astrometric work, the only reasonable star catalog is the GSC. It is commercially available on CD-ROM through the Astronomical Society of the Pacific. Its use requires a CD-ROM reader on a computer.

5. Acknowledgements

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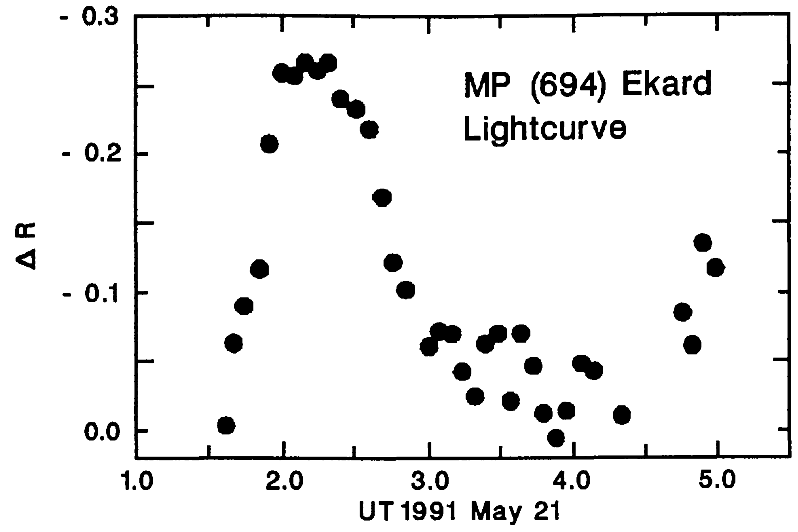

Figure 1. The light curve of asteroid (694) Ekard on May 21, 1991, observed with a CCD camera through a broad (2000 Angstrom) red filter. The differential magnitude is with respect to an artificial comparison star, whose intensity was the sum of the intensities of several stars visible in the same CCD frames.

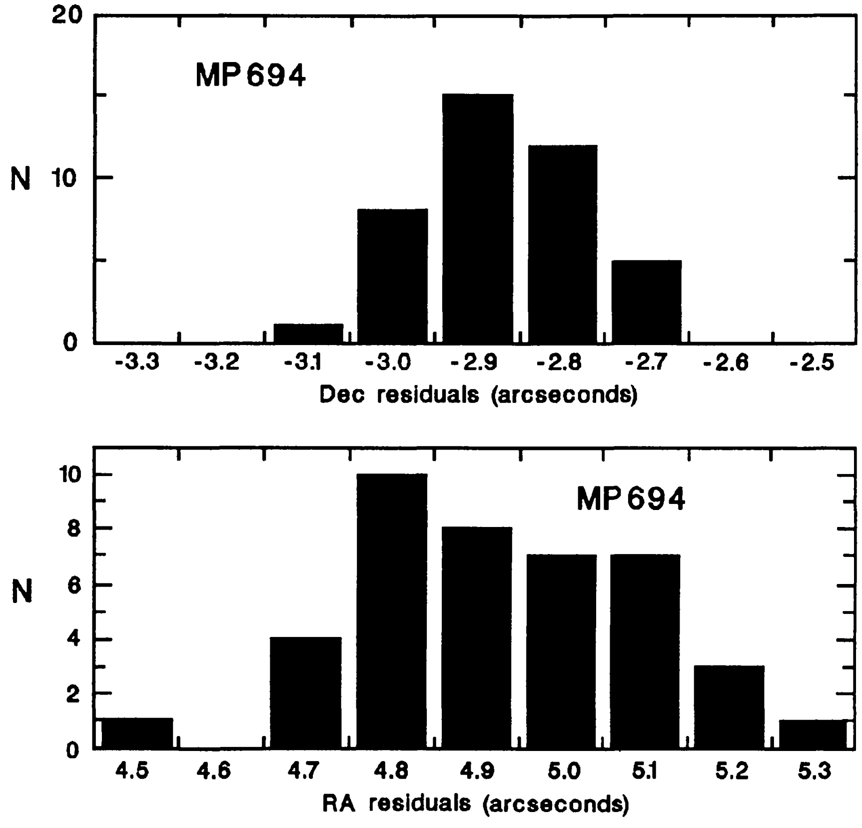

Figure 2. Histograms of the residuals (in seconds of arc) for Dec and RA in the positions of (694) Ekard, as compared with the positions predicted by the orbital elements as known and tabulated in 1991. The rms deviation is only a few tenths of an arcsecond, in both cases much smaller than the mean residual, indicating that the 1991 orbital elements were in error.