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A PHOTOMETRIC GEODESY PROGRAM FOR MAIN BELT ASTEROIDS

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This article describes a long-term program to measure the lightcurves of several main belt asteroids, to test whether they have shapes similar to fluid bodies in equilibrium. To use our telescope time most efficiently, our group has developed a series of observing procedures and aids whose use could extend beyond our present project.

Introduction

Are most large asteroids huge chunks of competent material assuming any random shape that their collisional history has molded them into as they spin about their rotation axes? Or are they more like battered heaps of rubble, held together by their own gravity but so weak that they assume shapes dictated by the laws of fluid mechanics?

To answer this question, we have undertaken a multi-year program to test whether or not large, rapidly rotating main belt asteroids have shapes similar to those of fluid bodies in equilibrium. On a gross scale, large bodies such as planets and major satellites behave as fluid bodies since the pressures throughout their interiors, caused by gravitational compression, cause the matter to flow like a viscous fluid. To a large extent, the shape of such fluid bodies depends only on their rotation rate and density: nonrotating bodies would be spheres. Slow and moderate rotations deform into Maclaurin Spheroids, which are flattened at the poles and bulging at the equator (like Jupiter and Saturn), while rapid rotators assume the shape of Jacobi ellipsoids, with three unequal-length axes. Asteroids are so much smaller than big moons or planets, yet some of them also may have shapes like fluid bodies.

The answer lies in the collisional environment of the asteroid belt. Asteroid orbits were stirred up by some process in the past that produced a tangled pattern of intersecting orbits which led to collisions between asteroids. Collisional outcomes depend principally on the sizes of the bodies, since the impact speed is always about 5 km/sec. Small projectiles hitting large targets simply crater them, but as the projectile becomes larger relative to the target, the size of the crater increases until the target is shattered into many fragments. The fate of these fragments depends on the target's size; if it is small, the ejecta depart onto their own heliocentric orbits, but if the target is large enough to have an appreciable gravity field, then the fragments may not have enough energy to escape and instead they collapse back into a single body. In such a fashion, an initially coherent body can be converted into what we call a "gravitationally bound rubble pile." Repeated collisions would further pulverize the fragments and jostle them into assuming a shape like that of a fluid body, just like shaking a box containing sand causes it to relax toward a flat surface.

We have selected 16 large, rapidly rotating (periods less than about 6 hours) asteroids as the best candidates for testing the hypothesis that "gravitationally bound rubble piles" assume quasi-equilibrium shapes (Table I). We also observe other objects covering a range of sizes and compositional classes as controls. To determine the bulk shape of our asteroids requires obtaining lightcurves at different aspects, or angles between the Earth and the asteroid's rotational axis, relative to the rotational poles. Thus the amplitude and mean magnitude of the lightcurve will vary depending on the viewing direction. Our goal is to obtain lightcurves spaced in intervals about 10 degrees apart in ecliptic longitude spanning 60-100 percent of the non-ambiguous 180 degree range for the ecliptic longitude of each asteroid's pole position. Thus the basic data set will consist of well over 200 lightcurves on our highest priority objects.

This data set will allow us to determine pole positions for most of our target asteroids, and in some cases, the sense of rotation as well. We will derive their shapes by comparing the ensemble of lightcurves with synthetic ones computed for ellipsoidal model shapes, or use complex mathematical inversion methods recently developed by S. Ostro and R. Connelly of Cornell University. If the relative dimensions of the three axes are consistent with those of equilibrium Jacobi ellipsoids, then we can conclude that these asteroids are indeed "gravitationally bound rubble piles." In that case, the theory describing such objects will allow us to compute their bulk densities, and hence to infer something about their compositions.

Observing Procedures

At the telescope, each object is sampled at least 6 times per hour in one color (V filter) with a target precision of 1 percent photometry (0.01 magnitude). Since we need a point every ten minutes, it is possible by working rapidly to interleave data points on two or even three asteroids, and thus obtain several lightcurves simultaneously.

Most of our data have been acquired at the Number 2 0.9-m telescope at Kitt Peak National Observatory, an ideal telescope for our program. It's large aperture allows us to observe in reasonable time to V magnitudes as faint as 15. More important, it has a high pointing accuracy and is computer controlled, allowing us to find targets quickly and efficiently.

Positional information for each asteroid and comparison star is entered into the telescope's computer during the day and these data are called up as the telescope slews toward the position of the first asteroid's comparison star. The photometer begins a series of three 5-second integrations of the comparison star, after which the telescope automatically offsets a minute of arc (usually to the north) so that it can measure the sky background which is subsequently subtracted. This procedure is then followed for the asteroid, which is usually within a degree of the comparison star, so that the telescope is capable of slewing to the object by itself. Enough integrations are obtained so that we obtain at least 20,000 net photon counts. That number provides the required 1 percent precision if the sky is dark and moonless. However, we have found that on moonlit nights we need more counts than this and have derived a formula that takes excess sky brightness into account. We repeat this entire procedure for up to three asteroids at once, and since our program requires us to observe each asteroid 6 times per hour, our nights are busy!

As the night advances, both observer and assistant continue to gather data at a pace that ranges from moderately challenging to furious. We move from comparison star to background to asteroid to background to new object, trying to return to the first object within 10 minutes, all the while keeping watch on the sky for possible cirrus clouds. Because there is no easy access to the outside from the 0.9-m dome, the sky watch is a cumbersome but necessary adjunct to our observing program. As the data continue to come in, they are checked in two ways: first, the three or more integrations that make up a single observation should be within one percent of each other, and second, the comparison stars should remain consistent with earlier readings. At high airmasses the comparison stars appear to change more radically. Although each asteroid has but one comparison star, at any hour we are observing two or possibly three comparison stars as well as a series of well known standard stars.

Real-Time System

To give us a better immediate idea of the behavior of the asteroids we are watching, one of us (CRC) devised a real-time monitoring system. Using an inexpensive Color Computer with cassette recorder and television monitor that are connected to the Kitt Peak computer, we obtain almost instantaneous displays of the lightcurve data which we have collected.

The advantages of the real-time system are threefold. First, we can quickly verify that we have located the correct object by its changing brightness, which is helpful if the asteroid is moving slowly; second, we can favor the observation of a particular object if we know that it is near an extremum in its lightcurve; third, we can discover instantly if the period of any of our objects is incorrect as published. This happened recently with 683 Lanzia, formerly a priority 1 object with a reported 4.3 hour period. When we discovered during one frustrating night that Lanzia satisfies a much longer period, the object was dropped from our program which thus saved us several months of observing before the new period would have shown up in our normal reductions.

Asteroids in Twilight

Thanks to a special reduction program prepared to correct for sky brightness, observations of our asteroids can proceed well into a brightening sky. Since it is often necessary to observe asteroids at extreme phase angles, we find this an extremely useful feature. We consider that the program works so long as the sky can be treated as decreasing or increasing in brightness linearly between the observations of the asteroid and its comparison star. This means that we begin observing in the evening as soon as we can see an asteroid in the telescope and then we continue until we have problems seeing predawn objects. It also means that a December or January observing run can last as long as 13 frigid, windy, uninterrupted hours. With the telescope moving some 700 degrees across the sky to make 60 measurements in a typical hour of observing, this is definitely not an activity for the faint of spirit!

Standard Stars

Standard stars are observed at six opportunities each night in order to serve as controls on the atmospheric and other conditions of our program. We choose three stars, whose characteristic B-V values are well known, from the list of Selected Areas. The evening set is chosen so that it is at a low airmass (between 1 and 1.5) within 2 hours after the evening begins. The three stars and the background sky are observed in two colors, but since the three objects are within a degree of each other, finding them with the telescope is not as time-consuming as it appears.

We next observe the standards when they are at about 1.8 to 1.9 airmasses and then again between 2.3 and 2.5. This final reading occurs generally just before midnight, and shortly after midnight we begin the same procedure with a new set of standards that is rising in the east. We try to adjust our asteroid reading procedure at this point to reduce the time lost because of the need to read standard stars, by reversing the order and reading, for one cycle after the standard set, the asteroid first and then the comparison star. Moreover, by reading the standards when the telescope is already near a target asteroid, we reduce the time lost between asteroid readings. The standards are important because they provide a constant check on the consistency of our data at various airmasses.

History and Plans

During the past year, our nights at the telescope were generally productive with the number of photometric hours somewhat higher than 1982. During one particularly "cost effective" two night run in December 1982, we obtained 8 full light curves and in 4 nights in April 1983 we managed to obtain 10 full and 3 partial lightcurves.

The project has another 18-24 months to proceed, depending to a large extent on the weather. Following that, we will likely need more time to fill in gaps in our data. As our reductions and analysis proceed, we are discovering ways to refine our observing process. We expect that when this project is concluded, we will know much more about both these asteroids and how scientists can best observe them photometrically.

Asteroid	Period (hours)	Diameter (km)	Type	Amplitude (mag)
16 Psyche	4.196	249	M	0.34
22 Kalliope	4.15	175	M	0.30
29 Amphitrite	5.39	199	S	0.13
39 Laetitia	5.14	158	S	0.54
45 Eugenia	5.70	250	UC	0.33
87 Sylvia	5.19	251	P	0.42
107 Camilla	4.85	252	C	0.53
125 Liberatrix	3.969	103	M	0.32
129 Antigone	4.96	113	M	0.32
130 Elektra	5.25	143	U	0.30
201 Penelope	3.75	144	M	0.56
216 Kleopatra	5.39	219	M	1.2
337 Devosa	4.61	100	CSM	0.2
349 Dembowska	4.70	145	R	0.40
354 Eleonora	4.28	156	UR	0.30
511 Davida	5.17	335	C	0.25

Table I
Priority 1 Target Asteroids

PHOTOELECTRIC PHOTOMETRY OF ASTEROID 60 ECHO

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Photoelectric observations of asteroid 60 Echo were made from Gila Observatory on 13 nights between January 29 and February 20, 1984. A synodic rotational period for Echo of 25.208 ± 0.048 hours was determined. The observed amplitude of the lightcurve was 0.22 ± 0.02 magnitudes.

During 1984 the asteroid 60 Echo had a very favorable opposition with a predicted B magnitude at opposition of 11.4. Photometric observations of Echo were undertaken by the authors as part of a program to determine the rotational periods for asteroids with no published lightcurve or whose rotational period is not accurately known, as was the case for Echo.

The observations reported here were made with the 28 cm (11 inch) Schmidt-Cassegrain telescope at Gila Observatory. All photometric observations were made using an uncooled Optec SSP-3 solid state photometer interfaced to a TRS-80 model 3 micro-computer with 16 K of RAM memory. The photometric observations were made using no filters and no transformation of the data to B or V was attempted. However, the unfiltered response of the SSP-3 photometer is most similar to R with a peak response near 8000 angstroms. During the course of the observations described here, the stars SAO 117836, 2 Leo, and SAO 98495 with spectral types G5, F9, and K0, respectively, were used as comparison stars. These comparison stars were never further than 1.5 degrees away from the target asteroid. Differential atmospheric extinction corrections were applied to all data. The choice of near solar-type comparison stars minimized color-dependent variations in atmospheric extinction between the asteroid and comparison star.

Photometric integration times of 90 seconds were used for both the comparison star and the asteroid. Each 90 second integration was composed of three separate 30 second integrations of comparison star or asteroid and four 15 second integrations of the sky background. The sequence of these integrations was sky, asteroid, sky, asteroid, sky, asteroid, sky and sky, comp, sky, comp, sky, comp, sky. Each differential magnitude was derived from a set of three 90 second integrations in the sequence: comparison, asteroid, comparison. An average of six photometric readings of the asteroid were recorded every hour during an observing run. The computer recorded the photometric readings as well as the time of each reading and stored this data in RAM memory for later data reduction. At the completion of a photometric data run, the computer calculated