NSG7500

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2060 CHIRON: CCD PHOTOMETRY

'87 SEP 16 A7:45

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IN-35 CR

213040

26P.

Received________________1987

(NASA-CR-185068) THE 2060 CHIRON: CCD PHOTOMETRY (Lowell Observatory) 26 p CSCL 14E

N89-25435

Unclas

G3/35 0213090

Submitted to *Icarus* 29 July 1987

Manuscript totals 26 pages, including 2 figures and 4 tables.

RUNNING HEAD: 2060 CHIRON: CCD PHOTOMETRY

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ABSTRACT

R-band CCD photometry of 2060 was carried out on nine nights in November and December 1986. The rotation period is 5.9181 $\pm$ 0.0003 hr and the peak-to-peak lightcurve amplitude is 0.088 $\pm$ 0.003 mag. Photometric parameters are $H_R = 6.24 \pm 0.02$ mag and $G_R = 0.70 \pm 0.15$, though formal errors may not be realistic. The lightcurve has two pairs of extrema, but its asymmetry, as evidenced by the presence of significant odd Fourier harmonics, suggests macroscopic surface irregularities and/or the presence of some large-scale albedo variegation. The observational rms residual is $\pm$ 0.015 mag. On time scales from minutes to days there is no evidence for nonperiodic (cometary?) brightness changes at the level of a few millimagnitudes.

INTRODUCTION

2060 Chiron is the most distant object classified as an asteroid (Kowal *et al.* 1979). Its unique Saturn- and Uranus-crossing orbit is subject to strong perturbation by Saturn on a time scale of thousands of years; as a consequence, Chiron cannot be regarded as a member of a putative stable cloud of asteroidal objects between Saturn and Uranus (Scholl 1979). Indeed, Chiron's orbit is chaotic and appears to be evolving inward, perhaps like the orbits of the short-period comets (Oikawa and Everhart 1979). Hence, there is strong expectation that Chiron originated either in the outer solar system or in the Oort Cloud.

Physical observations have so far supported the asteroidal nature of Chiron. From *JHK* photometry, Hartmann *et al.* (1981) excluded the presence of clean ice on Chiron's surface. Its spectral characteristics match those of *C* asteroids, but the presence of large amounts of exposed ices is not ruled out because even a minor admixture of dark material suffices to quench the spectral signature of ice (e.g., Hanner 1981). Lebofsky *et al.* (1984) presented evidence from thermal infrared photometry that Chiron's albedo is about 10%, although a much higher value is possible. They estimate Chiron's diameter to be 180^{+40}_{-50} km. Tholen (1984), in a detailed discussion of asteroid taxonomy, placed Chiron in a new *B* class, a subclass of *C* asteroids containing only six known members, one of which is Pallas. Lebofsky *et al.* also discussed a few broadband photometric observations of Chiron, most taken during the Eight-Color Asteroid Survey (ECAS, Zellner *et al.* 1985). However, they were unable to say much about Chiron's rotational brightness variation, in part because of a discrepancy with unpublished observations made in 1978 by Bowell and A. V. Hewitt. Using just their own observations, Lebofsky *et al.* found a best-fit period of 7 hr and an amplitude of 0.3 mag. Finally, IDS spectroscopy by Cochran *et al.* (1986) was aimed at detecting comet-like spectral features in a sample of nonmain-belt asteroids, including Chiron. No cometary activity was observed.

Our aim in establishing Chiron's photometric properties has been to add to the inferences already drawn regarding its nature and origin. For example, are Chiron's rotational properties intrinsically unusual: Does it rotate more rapidly or slowly than most asteroids and (nonsynchronous) satellites? Does the form of the lightcurve indicate unusual shape or large-scale albedo variegation? And, particularly, is there any photometric evidence for nonperiodic (cometary?) brightness variation?

Photometry using a CCD camera offers high quantum efficiency and stability, and it is well suited to the study of rotational brightness variation of faint asteroids and satellites, where differential brightness measurements with respect to field stars can be carried out even in conditions of imperfect atmospheric transparency. We describe here CCD observations of Chiron obtained during its 1986 apparition. The CCD observational technique and some aspects of data reduction, being innovative, are treated in more detail than usual.

OBSERVATIONS

Images of Chiron were obtained on 27 and 28 November and again on seven nights between 23 and 31 December 1986 (Table I). The November observations, being interspersed with images taken for faint asteroid astrometry, were limited;

but they were sufficient to hint at the period and amplitude of Chiron's lightcurve and were valuable in determining a strategy for the December observing run. A more ambitious observing effort was made in December, during which some nights yielded almost eight hours of quasi-continuous observation of Chiron. In all, 286 usable frames of Chiron were acquired.

The observations were obtained using the Lowell Observatory CCD camera, mounted at the Cassegrain focus of the 1.8-m Perkins reflector. The camera consists of a Photometrics Ltd. dewar and control system, and uses an RCA SID501EX 320×512 CCD. A 4:1 reduction box was used in the optical path to provide an image scale of 0.81 arcsec per pixel. A wide R-band filter, centered at 7000 Å and having a FWHM bandpass of 2100 Å, was used for all observations. The filter was selected to optimize photon throughput while limiting the sky background in moderate moonlight. An integration time of 5 minutes was used for each exposure, providing an average signal of 15,100 ADUs (Analog/Digital Units) above sky, at a gain of 20 electrons per ADU, integrated over the image of Chiron.

The telescope tracked at sidereal rate, allowing Chiron to drift slowly across a portion of the detector. The motion of the object was so slow that images obtained during the 5-minute exposures were elongated by less than 1 pixel. Images of Chiron were positioned on regions of the CCD chip that were relatively free from steep gradients in sensitivity and from major cosmetic flaws, as identified from flat-field frames. Because of Chiron's proximity to the galactic plane, field stars were abundant. We thought that crowding by stars would be a potential problem, but it turned out to be only a minor inconvenience, Chiron being too close to surrounding stars for only about one hour per night. When that occurred, observations were suspended until Chiron had moved clear.

Some of the observations were made in less than photometric conditions. However, as has been shown elsewhere (Howell and Jacoby 1986; Wisniewski and McMillan 1987), differential photometry using CCDs is quite feasible through thin cirrus and haze. Due to the faintness of Chiron, a limit of about 0.5 mag of extinction was set, past which observations were not attempted. Data from consecutive nights were successfully linked together photometrically by reobserving the comparison stars from previous nights under photometric conditions. Transformation to the R band was made by observing eight standard stars in the KPNO CCD fields in NGC 2264 and NGC 2419 (Christian *et al.* 1985).

REDUCTION OF CCD FRAMES

All the reductions were carried out using routines, some modified, from the Tololo–Vienna Interactive Image Processing System (see, for example, Albrecht 1979). For the most part, standard procedures of bias subtraction and flat fielding were followed. In the Lowell CCD system, the readout bias level is known not to be uniform across the detector. To compensate for nonuniformity, a special bias frame was prepared by first averaging 10 separate bias frames and then smoothing the result, using a 3×3-pixel boxcar filter. This frame was then subtracted from each of the data frames. The bias level, monitored several times each night, was found to be extremely stable.

We regularly obtained both dome and twilight sky flat fields. Despite efforts to correct the color-temperature of the flat-fielding light source, use of the dome flats resulted in excessive fringing across the images of Chiron. As the asteroid image moved across the detector, these fringe patterns made accurate photometry nearly impossible. Better results were obtained by using flats taken of the twilight sky, though slight fringing (1%–2% of adjacent sky) was still present. This problem is common (Gunn and Westphal 1981) and is most prevalent in broadband observations made at wavelengths longer than 7000 Å, where strong emission lines are present in the night sky. A superior reduction technique, wherein fringe patterns can be subtracted from CCD images (Tyson 1987), will be implemented by us in future efforts at CCD photometry.

Instrumental magnitudes of Chiron and several comparison stars were measured using an aperture photometry algorithm that sums all signal within a square or circular aperture of given size. We chose a circular aperture of radius eight pixels. The sky level was determined from a four-pixel-wide annulus just outside the aperture. On each frame, bad pixels were replaced with the average value of the surrounding pixels. In the same way, faint star images close to Chiron were removed, thus providing accurate determination of the sky background around the asteroid.

For each night, an average of four comparison stars was chosen on the basis of their brightness (usually $16 < R < 17$ mag) and lack of contamination by surrounding stars. All comparison stars were measured on each of the frames and were intercompared to check for variability. On the nine nights of observations, only one of 35 comparison stars showed signs of variability and was dropped from the analysis. Chiron was then compared differentially to each of the comparison stars. The resulting lightcurves were scaled to the same magnitude and averaged. This process greatly reduced the measurement uncertainty associated with just a single comparison star. Standard photometric procedures were then followed to intercompare data from different nights and to place the entire data set on an absolute scale. Since no regular attempt was made to measure extinction stars, a standard extinction model was used with consistently good results. Again, because of the nonstandard bandpass of the wide R-band filter, a large rms scatter of $\pm$ 0.07 mag occurred betweeen our measurements of the KPNO standard fields and the published R magnitudes given by Christian *et al.* (1985).

RESULTS

Aspect data for each night of observation are listed in Table II. Tabular values are given for 8^h U.T., a time generally near the center of the range of observation. The phase-angle bisector, a quantity that can be used to estimate the possible difference between the measured synodic and true sidereal periods, has been discussed by Harris *et al.* (1984). Values of the reduced mean R-band magnitude of Chiron are described below.

Each night's observations were reduced to absolute magnitudes at a constant reference phase angle α, for convenience that at 8^h U.T. In addition to the usual distance correction ($-5 \log r\Delta$, where r is the asteroid's heliocentric distance and Δ its geocentric distance, both in AU), the magnitudes were adjusted by a small amount to account for changing phase angle during the course of the night. In Table III, a header for each night's observations gives the Julian Day Number – 2400000, along with the reference phase angle. Following these, Julian Day fractions, corrected for light time, and the adjusted reduced magnitudes $R(1,\alpha)$ are listed.

From the plots of the individual lightcurves, it was clear that a period of about 6 hours would fit the data, assuming two pairs of extrema per rotation cycle. A Fourier analysis of the data in Table III was performed using the method described by Harris *et al.* (1987). The best fit, giving an rms dispersion of $\pm$ 0.015 mag, resulted from the inclusion of Fourier coefficients through order 5. Moreover, all amplitudes through order 5 are significant, whereas higher order ones are not. The Fourier coefficients and amplitudes are listed in Table IV, their formal uncertainties being ± 0.0009 and ± 0.0013, respectively. The sine and cosine terms pertain to the function

$$R(\alpha) = \overline{R}(\alpha) + \sum_{n=1}^{5}[A_n \sin n\frac{2\pi}{P}(t - t_0) + B_n \cos n\frac{2\pi}{P}(t - t_0)],$$

where $\overline{R}(\alpha)$ is the mean reduced magnitude at phase angle α, t is the Julian Date of observation, t_0 = JD 2446789.0, and P is the rotation period.

The rotation period and its 1-σ uncertainty are 5.9181 $\pm$ 0.0003 hr, and the peak-to-peak brightness variation is 0.088 $\pm$ 0.003 mag. It is noteworthy that, since the odd harmonics are significant at the 3-σ level, the half-period solution can almost certainly be rejected. Figure 1 is a plot of the composite lightcurve, in which the magnitude zero-point is identified with $\overline{R}(\alpha)$. The observed magnitudes were in the range $17.35 \lesssim R \lesssim 17.45$ mag.

We fitted the mean magnitudes $\overline{R}(\alpha)$ on each night (cf. Table III) by means of the H, G magnitude system (Bowell *et al.* 1987), with the following results: $H_R = 6.24 \pm 0.02$ mag and $G_R = 0.70 \pm 0.15$; error quantities are $e_1 = 0.51$, $e_2 = 0.19$, and $\rho_{12} = -1.00$. Calculated values of the period and slope parameter are not significantly correlated. The constants in the linear phase coefficient system are inferred to be $\overline{R}(1,0) = 6.36$ mag and $\beta_R = 0.017$ mag/deg. Figure 2 is a plot of the $\overline{R}(\alpha)$, the fitted phase curve, and its formal error envelope. Because of problems in transforming to the R band, the real uncertainty in H_R is perhaps $\pm$ 0.1 mag; and, in view of the very limited span of phase angles, we attach little significance to the formal value of G_R.

DISCUSSION

The rotational brightness variation of Chiron reveals no particularly unusual properties. Its period is shorter than the geometric mean period of asteroids (9.9 hr), but the dispersion of rotation periods of the general population is sufficiently broad that about 20% of asteroids of comparable diameter rotate faster (Harris 1986). Whether Chiron's period can usefully be compared to those observed or inferred for comets is moot, given the current paucity of suitable observations and the uncertainty in modelling the rotational evolution of those bodies (D. G. Schleicher, personal communication).

Chiron's observed peak-to-peak brightness variation is likewise quite ordinary and comparable to the average for main-belt asteroids of similar large diameter. One can say little about Chiron's shape because its aspect is unknown. As usual, there are two pairs of extrema per rotation, suggesting that the lightcurve is produced mainly by the rotation of an elongated body. The odd Fourier harmonics alone account for about 20% of the total brightness variation, and it is tempting, following Lupishko *et al.* (1983), to ascribe them to the presence of large-scale albedo variegation. Lupishko *et al.* argued that, at zero phase angle, a photometrically homogeneous asteroid exhibits the same brightness when viewed from opposite sides, regardless of its shape. They compared departures from zero of the magnitude differences ω and $\omega + \pi$ for eleven suitably observed asteroids, and went on to conclude that the "albedo component" of asteroid lightcurves can reach 0.15 mag. Although they correctly reasoned that such an approach is valid for regular axisymmetric bodies such as ellipsoids and cylinders, they failed to realize that it does not necessarily hold for irregular bodies unless viewed equatorially or from diametrically opposite directions in the sky. Thus, inasmuch as Chiron's aspect is unknown and our observations were not made exactly at zero phase, we can conclude only that the form of its lightcurve indicates macroscopic surface irregularities and/or the presence of some large-scale albedo variegation.

Because our CCD photometry of Chiron could not be accurately transformed to the R band, it is not possible to make precise comparisons with other observations. However, some remarks are useful. The three 1982/1983-apparition ECAS observations (Zellner *et al.* 1985) were made at phase angles between $1^{\circ}\!.81$ and $2^{\circ}\!.88$. Using the period determined in this paper, it is evident that the first (1982 Dec 16.25) and last (1983 Jan 7.20) observations were made at almost exactly the same rotational phase. The reduced V magnitudes suggest a phase curve that is much steeper than that ever observed for an asteroid, even allowing for observational error, and are quite incompatible with our phase-curve data. Assuming $V - R = + 0.52$ mag and $G_R = 0.70$, the three ECAS observations give $H_R = 6.17 \pm 0.12$ mag, which, since the rotational phases are unknown, agrees with our result.

Unpublished observations by Bowell and A. V. Hewitt, made in the V band using a Kron camera at the 1.55-m astrographic reflector of the U. S. Naval Observatory Flagstaff Station, have been commented on by Lebofsky *et al.* (1984). Twenty-four acceptable images of Chiron were obtained on five nights in September and November 1978. The nightly rms magnitudes are about $\pm$ 0.15 mag, only $\pm$ 0.04 mag of which can be ascribed to rotational variation (assuming the lightcurve had the same shape as in 1986). Indeed, phasing the observations in accordance with our lightcurve and phase curve does nothing to remove the incoherence, nor is any clear-cut phase-angle effect apparent. Fixing $G = 0.70$ leads to $H = 6.05 \pm 0.10$ mag or $H_R = 5.53 \pm 0.10$ mag, about 0.7 mag brighter than expected. We have carefully checked the observations and their reductions with respect to brighter comparison stars that were subsequently observed photoelectrically, and can find no errors. While noting the result, the observations must, reluctantly, be viewed with suspicion.

Finally, we ask whether there is any evidence of nonperiodic brightness changes in Chiron that could be ascribed to "cometary" emission. It is not our purpose here to examine the mechanism of possible cometary outbursts on Chiron, nor to ask whether such outbursts would even be expected at Chiron's distance from the Sun. We do note, however, that P/Schwassman-Wachmann 1, in an almost circular orbit at Jupiter's heliocentric distance, exhibits major thermally induced outbursts (their incidence is unknown); and C/Bowell has an ever-expanding dust cloud still detectable at 13.6 AU (Meech and Jewitt 1987). Obviously, the latter phenomenon, should it pertain to Chiron, would probably not give rise to short-term changes in brightness, so even a negative photometric result should not be interpreted as an *absence* of cometary activity.

We suppose that imperfections in the observed magnitudes arise from three sources: (1) the variance due to photon statistics and other random noise; (2) erroneous correction for color terms; and (3) night-to-night linkage errors because of differing comparison stars. We recall that the rms dispersion of observations with respect to the best-fit lightcurve of Chiron is 0.015 mag.

Howell *et al.* (1987) have given a rigorous method for evaluating the effect of photon statistics in CCD observations. Our observations were not suited to their treatment, however, so we took an empirical approach. Over the course of each night, at least four comparison stars were observed repeatedly. Rejecting one star that showed signs of variability, we derived an error quantity e_{ij} related to the brightness difference between pairs of stars:

$$e_{ij} = \sqrt{\frac{1}{n_i} + \frac{1}{n_j}} \quad ; \quad i, j = 1, 2, 3, \ldots; \; i \neq j,$$

where n_i and n_j are the sky-subtracted ADUs for pairs of stars (sky ADUs did not vary greatly throughout the observations). If ϵ, taken to be positive, is the rms error of the observed magnitude difference between two stars, then about two-thirds of the 23 values of e_{ij} were enclosed by

$$\epsilon = -0.008 + (2.44 \pm 0.49)e_{ij} \quad ; \qquad 0.004 \lesssim e_{ij} \lesssim 0.012.$$

On average, n_i for Chiron was 15100 ADU, and n_j for a comparison star was effectively 80000, so $e_{ij} = 0.009$ and $\epsilon = 0.014 \pm 0.004$ mag (note that e_{ij} and ϵ are insensitive to n_j in this case and that the uncertainty in ϵ should be comparable to its standard deviation).

ϵ contains the effects of color terms, which may be estimated separately by grouping the observations according to airmass. For airmasses greater than 1.3, the rms residual with respect to the best-fit lightcurve was $\pm$ 0.016 mag, whereas for airmasses less than 1.3 it was $\pm$ 0.014 mag, giving a small overall effect of about $\pm$ 0.001 mag.

Night-to-night errors of comparison star linkage may be evaluated as follows: The expected uncertainity ϵ in the magnitude difference between two stars can be calculated for one star observed on two nights (the expected magnitude difference is, of course, zero, and $n_i \approx n_j$). Comparing the observed magnitude difference ΔR with that expected, we found an average of $\Delta R/\epsilon = 0.8$. This implies that night-to-night errors of linkage are, on average, very small, though it does not exclude systematic errors due to poor photometric conditions. Indeed, the night-to-night magnitude errors for bright stars are close to the photometric limit proposed by Walker (1984).

The total accountable error budget is therefore $\pm$ 0.014 ($\pm$ 0.004) mag, which is to be compared to the rms residual in the fitted lightcurve of Chiron of $\pm$ 0.015 mag. We conclude that, on time scales ranging from minutes to days, there is no evidence for brightness changes that could be ascribed to "cometary" emission at the level of a few millimag. (It is begging the question, but a similar conclusion can be reached by examining the residuals to the fitted phase curve, the rms of which is $\pm$ 0.005 mag.)

ACKNOWLEDGMENTS

We thank Brian A. Skiff for observing assistance and Tobias J. Kreidl for his programming expertise. Most of the research reported here was funded by NASA grant NSG-7500. The work at JPL was carried out under contract from NASA.

REFERENCES

Albrecht, R. (1979). Interactive analysis of optical astronomical images. In *Image Processing in Astronomy* (G. Sedmak, M. Capaccioli, and R. J. Allen, Eds.), pp. 155–172. Osservatorio Astronomico di Trieste, Italy.

Bowell, E., K. Lumme, and A. W. Harris (1987). A two-parameter magnitude system for asteroids. In preparation.

Christian C. A., M. Adams, J. V. Barnes, H. Butcher, D. S. Hayes, J. R. Mould, and M. Siegel (1985). Video camera/CCD standard stars (KPNO video camera/CCD standards consortium). *Publ. Astron. Soc. Pac.* **97**, 363–372.

Cochran, W. D., A. L. Cochran, and E. S. Barker (1986). Spectroscopy of asteroids in unusual orbits. In *Asteroids, Comets, Meteorites II* (C.-I. Lagerkvist,

B. A. Lindblad, H. Lundstedt, and H. Rickman, Eds.), pp. 181–185. Uppsala University, Sweden.

Gunn, J. E., and J. A. Westphal (1981). Care, feeding, and use of charge-coupled device (CCD) imagers at Palomar Observatory. *Proc. S.P.I.E.* **290**, 16–23.

Hanner, M. S. (1981). On the detectability of icy grains in the comae of comets. *Icarus* **47**, 342–350.

Harris, A. W. (1986). Asteroid lightcurve studies. In *Asteroids, Comets, Meteorites II* (C.-I. Lagerkvist, B. A. Lindblad, H. Lundstedt, and H. Rickman, Eds.), pp. 35–44. Uppsala University, Sweden.

Harris, A. W., J. W. Young, E. Bowell, L. J. Martin, R. L. Millis, M. Poutanen, F. Scaltriti, V. Zappalà, H.-J. Schober, H. Debehogne, and K. W. Zeigler (1987). Photoelectric observations of asteroids 3 Juno, 24 Themis, 60 Echo, 261 Prymno, and 863 Benkoela. Submitted to *Icarus* .

Harris, A. W., J. W. Young, F. Scaltriti, and V. Zappalà (1984). Lightcurves and phase relations of the asteroids 82 Alkmene and 444 Gyptis. *Icarus* **57**, 251–258.

Hartmann, W. K., D. P. Cruikshank, J. Degewij, and R. W. Capps (1981). Surface materials on unusual planetary object Chiron. *Icarus* **47**, 333–341.

Howell, S. B., and G. H. Jacoby (1986). Time-resolved photometry using a CCD. *Publ. Astron. Soc. Pac.* **98**, 802–808.

Howell, S. B., K. J. Mitchell, and A. Warnock III (1987). Statistical error analysis in CCD time-resolved photometry with applications to variable stars and quasars. Submitted to *Astron J.*

Kowal, C. T., W. Liller, and B. G. Marsden (1979). The discovery and orbit of (2060) Chiron. In *Dynamics of the Solar System* (R. L. Duncombe, Ed.), pp. 245–250. D. Reidel, Dordrecht.

Lebofsky, L. A., D. J. Tholen, G. H. Rieke, and M. J. Lebofsky (1984). 2060 Chiron: Visual and thermal infrared observations. *Icarus* **60**, 532–537.

Lupishko, D. F., L. A. Akimov, and I. N. Belskaya (1983). On photometric heterogeneity of asteroid surfaces. In *Asteroids, Comets, Meteors* (C.-I. Lagerkvist and H. Rickman, Eds.), pp. 63–70. Uppsala University, Sweden.

Meech, K. J., and D. Jewitt (1987). Comet Bowell at record heliocentric distance. Submitted to *Nature*.

Oikawa, S., and E. Everhart (1979). Past and future orbit of 1977UB, object Chiron. *Astron. J.* **84**, 134–139.

Scholl, H. (1979). History and evolution of Chiron's orbit. *Icarus* **40**, 345–349.

Tholen, D. J. (1984). Asteroid taxonomy from cluster analysis of photometry. Ph.D. Thesis, pp. 150. University of Arizona, Tucson.

Tyson, J. A. (1987). Low light level CCD imaging in astronomy. *J. Opt. Soc. Am.*, in press.

Walker, A. R. (1984). CCD observations of photoelectric standard stars. *Mon. Not. Roy. Astron. Soc.* **209**, 83–91.

Wisniewski, W. Z., and R. S. McMillan (1987). Differential CCD photometry of faint asteroids in crowded star fields and non-photometric sky conditions. *Astron. J.* **93**, 1264–1267.

Zellner, B., D. J. Tholen, and E. F. Tedesco (1985). The eight-color asteroid survey: Results for 589 minor planets. *Icarus* **61**, 355–416.

TABLE I

JOURNAL OF CHIRON OBSERVATIONS

JD 2400000+	Date (UT)	UT of first and last observation	Number of observations	Sky conditions
46761	1986 11 27	07:32 – 11:55	22	Photometric
46762	1986 11 28	06:37 – 10:52	16	Thin cirrus
46787	1986 12 23	05:48 – 07:00	9	Clouds
46790	1986 12 26	03:14 – 06:37	30	Photometric
46791	1986 12 27	02:40 – 09:34	45	Photometric
46792	1986 12 28	02:09 – 10:16	56	Photometric
46793	1986 12 29	02:45 – 09:27	56	Photometric
46794	1986 12 30	07:30 – 08:42	10	Clouds
46795	1986 12 31	02:39 – 07:27	42	Cirrus after 04:30 UT

TABLE II

ASPECT DATA FOR CHIRON

Date (U.T.)	R.A. (1950)	Dec. (1950)	Phase angle bisector Long.	Phase angle bisector Lat.	r (AU)	Δ (AU)	α	$\overline{R}(\alpha)$ (mag)	σ (mag)
1986 11 27.3	$5^h\,13^m.7$	$+17°\,20'$	78°.4	−5°.5	13.438	12.485	1°.14	6.317	±0.004
1986 11 28.3	5 13.5	+17 20	78.3	−5.5	13.436	12.479	1.07	6.311	0.005
1986 12 23.3	5 07.3	+17 10	77.8	−5.5	13.391	12.436	1.05	6.300	0.006
1986 12 26.3	5 06.5	+17 09	77.8	−5.5	13.386	12.444	1.27	6.309	0.003
1986 12 27.3	5 06.3	+17 09	77.8	−5.5	13.384	12.448	1.34	6.325	0.003
1986 12 28.3	5 06.1	+17 08	77.7	−5.5	13.382	12.451	1.41	6.327	0.002
1986 12 29.3	5 05.8	+17 08	77.7	−5.5	13.380	12.455	1.48	6.332	0.002
1986 12 30.3	5 05.6	+17 08	77.7	−5.5	13.378	12.459	1.55	6.338	0.005
1986 12 31.3	5 05.4	+17 08	77.7	−5.5	13.377	12.464	1.62	6.329	0.003

TABLE III

WIDE R-BAND REDUCED MAGNITUDES OF CHIRON

JD frac	α mag	JD frac	α mag	JD frac	α mag	JD frac	α mag	JD frac	α mag	JD frac	α mag
46761	**1.14**	.71997	6.342	.62922	6.270	.68373	6.393	.60326	6.323	.76272	6.365
.74180	6.332			.63372	6.277	.68820	6.360	.61326	6.338	.76774	6.369
.74637	6.318	**46790**	**1.27**	.63816	6.325	.69266	6.341	.61816	6.326	.77278	6.360
.75097	6.307	.56263	6.327	.64316	6.327	.69717	6.330	.62298	6.318	.78029	6.344
.75585	6.318	.56884	6.314	.65174	6.357	.70450	6.318	.62746	6.332	.78550	6.356
.76136	6.288	.57420	6.321	.65622	6.364	.70960	6.321	.63191	6.333	.79050	6.331
.76751	6.294	.57873	6.328	.66073	6.373	.71402	6.321	.63672	6.374		
.77209	6.279	.58390	6.326	.66520	6.352	.71846	6.294	.64116	6.349	**46795**	**1.62**
.77776	6.245	.58845	6.305	.66966	6.377	.72293	6.302	.64560	6.351	.53857	6.344
.78233	6.251	.59433	6.292	.67558	6.349	.72981	6.273	.65007	6.368	.54385	6.313
.78696	6.249	.59944	6.305	.68006	6.364	.73424	6.311	.65449	6.365	.54911	6.320
.79292	6.277	.60546	6.316	.68448	6.377	.73865	6.318	.66249	6.364	.55349	6.332
.79746	6.308	.60990	6.284	.68892	6.374	.74311	6.317	.66685	6.385	.55793	6.305
.80198	6.325	.61473	6.284	.69338	6.347	.74751	6.313	.67120	6.362	.56238	6.309
.80653	6.313	.61918	6.290	.70257	6.328	.75405	6.318	.67558	6.355	.56689	6.294
.81107	6.341	.62447	6.298	.70708	6.359	.75847	6.329	.67998	6.329	.57236	6.287
.81839	6.325	.62888	6.269	.71157	6.330	.76285	6.340	.68488	6.353	.57680	6.306
.82290	6.348	.63329	6.281	.71607	6.322	.76724	6.341	.68928	6.336	.58121	6.321
.82741	6.360	.63882	6.280	.72066	6.328	.77166	6.356	.69374	6.314	.58560	6.328
.83246	6.358	.64329	6.278	.72680	6.318	.78062	6.356	.69813	6.289	.58999	6.310
.83742	6.381	.64766	6.291	.73129	6.315	.78504	6.362	.70253	6.285	.59622	6.340
.91960	6.273	.65212	6.308	.73580	6.291	.78943	6.355	.71182	6.282	.60062	6.325
.92418	6.287	.65653	6.296	.74142	6.283	.79383	6.341	.71623	6.276	.60546	6.340
		.66284	6.317	.80241	6.371	.79826	6.343	.72103	6.284	.60990	6.337
46762	**1.07**	.66726	6.338	.80898	6.355	.80452	6.319	.72541	6.278	.61427	6.339
.70369	6.308	.67162	6.320	.81344	6.358	.80896	6.327	.72987	6.301	.61917	6.352
.71250	6.327	.67598	6.331	.81790	6.351	.81340	6.310	.73472	6.315	.62354	6.382
.79481	6.330	.68047	6.339	.82239	6.325	.81785	6.323	.73911	6.317	.62790	6.374
.80061	6.329	.68640	6.338	.82684	6.314	.82228	6.339	.74360	6.345	.63232	6.378
.80701	6.308	.69081	6.357			.82848	6.285	.74818	6.344	.63673	6.345
.81252	6.318	.69514	6.332	**46792**	**1.41**	.83306	6.297	.75258	6.384	.64462	6.321
.82119	6.345	.69962	6.355	.51758	6.337	.83752	6.295	.76650	6.374	.64900	6.326
.82681	6.351	.70403	6.350	.52285	6.344	.84208	6.278	.77088	6.377	.65340	6.331
.83319	6.371			.53092	6.381	.84652	6.296	.77526	6.366	.65789	6.311
.83982	6.365	**46791**	**1.34**	.53615	6.382	.85174	6.268	.77964	6.354	.66234	6.292
.84565	6.356	.53956	6.358	.54153	6.368	.85616	6.264	.78403	6.371	.66733	6.290
.85202	6.357	.54586	6.357	.54594	6.361			.78876	6.365	.67212	6.281
.85949	6.325	.55537	6.333	.55055	6.341	**46793**	**1.48**	.79311	6.347	.67655	6.275
.86644	6.315	.55984	6.323	.55722	6.339	.54241	6.329	.79749	6.373	.68097	6.274
.87247	6.278	.56436	6.321	.56158	6.333	.54882	6.330	.80187	6.358	.68540	6.303
.88080	6.249	.57096	6.337	.56600	6.322	.55860	6.335	.80633	6.318	.69295	6.312
		.57711	6.337	.57039	6.324	.56298	6.348	.81329	6.330	.69732	6.296
46787	**1.05**	.58157	6.314	.57482	6.340	.56741	6.302	.81766	6.318	.70166	6.318
.66984	6.248	.58615	6.314	.58118	6.304	.57178	6.286	.82204	6.334	.70601	6.303
.67559	6.271	.59059	6.291	.58581	6.293	.57620	6.288			.71041	6.310
.68087	6.265	.59719	6.297	.65156	6.344	.58112	6.287	**46794**	**1.55**	.72077	6.347
.68652	6.290	.60235	6.291	.65836	6.349	.58566	6.291	.74030	6.357	.72512	6.376
.69176	6.278	.60680	6.270	.66298	6.367	.59006	6.296	.74556	6.360	.72958	6.359
.69794	6.272	.61129	6.271	.66756	6.373	.59442	6.285	.75237	6.371	.73444	6.391
.70418	6.290	.61577	6.267	.67221	6.345	.59884	6.292	.75736	6.379	.73880	6.392
.71299	6.326	.62424	6.277	.67924	6.366						

TABLE IV

FOURIER COEFFICIENTS OF

CHIRON'S FITTED LIGHTCURVE

n	A_n	B_n	Amplitude
1	−0.0013	+0.0047	0.0049
2	−0.0374	−0.0070	0.0380
3	−0.0044	+0.0021	0.0049
4	+0.0005	+0.0041	0.0041
5	−0.0019	−0.0041	0.0045

FIGURE CAPTIONS

Figure 1. Composite rotational lightcurve of Chiron resulting from 286 CCD frames. Symbols indicate departures of the observed magnitudes $R(\alpha)$ from the mean magnitude $\overline{R}(\alpha)$ at solar phase angle α. The solid curve is a fifth-degree Fourier fit to the data as discussed in the text.

Figure 2. Phase curve of Chiron. Symbols are reduced mean magnitudes $\overline{R}(\alpha)$ and their standard deviations (cf. Table II). The solid curve is the phase curve fitted using the H, G magnitude system (Bowell *et al.* 1987), and dashed curves show the formal error envelope.

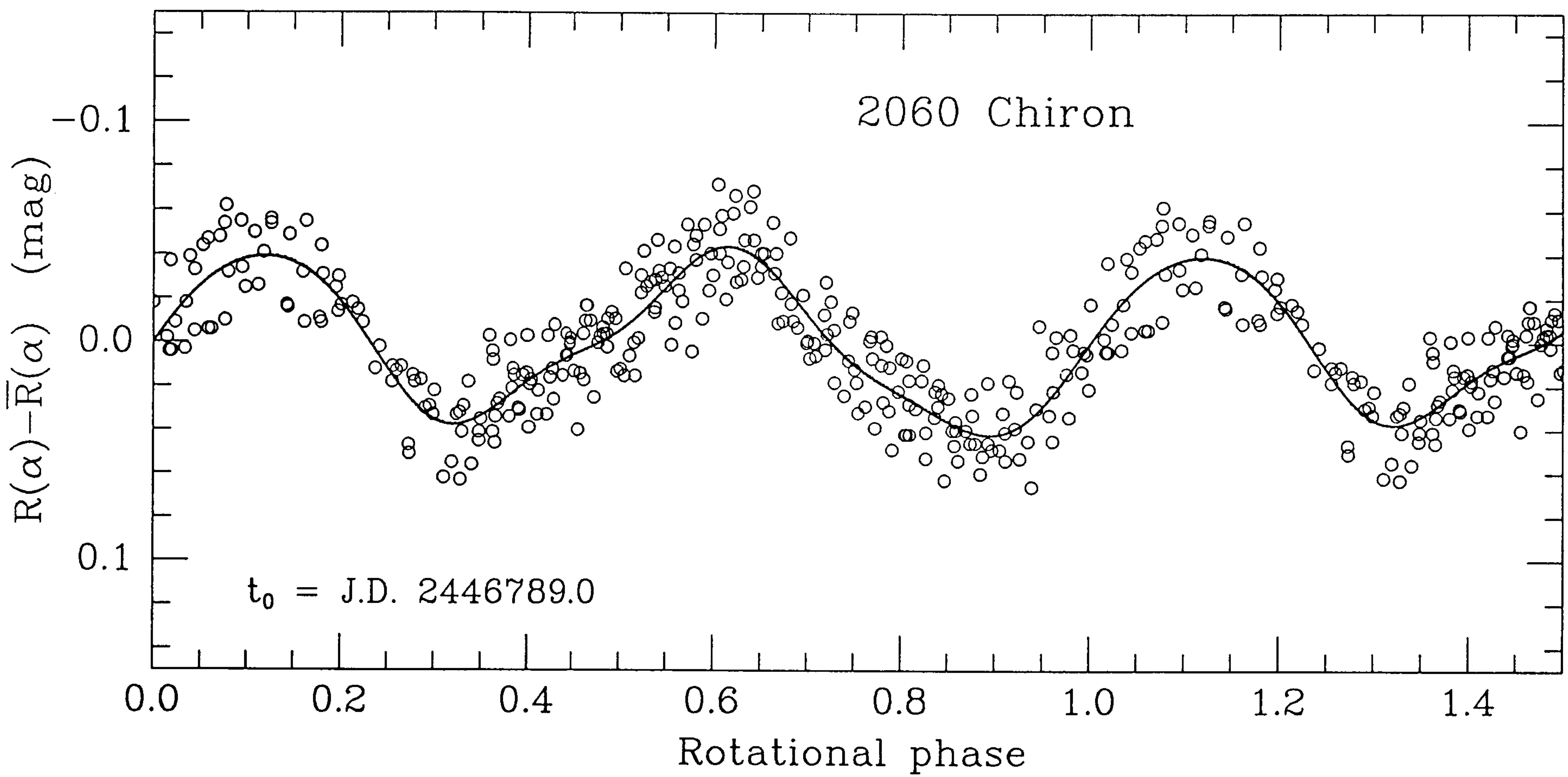
2060 Chiron
−0.1
0.0
0.1
R(α)−R̄(α)   (mag)
t₀ = J.D. 2446789.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Rotational phase

Figure 1

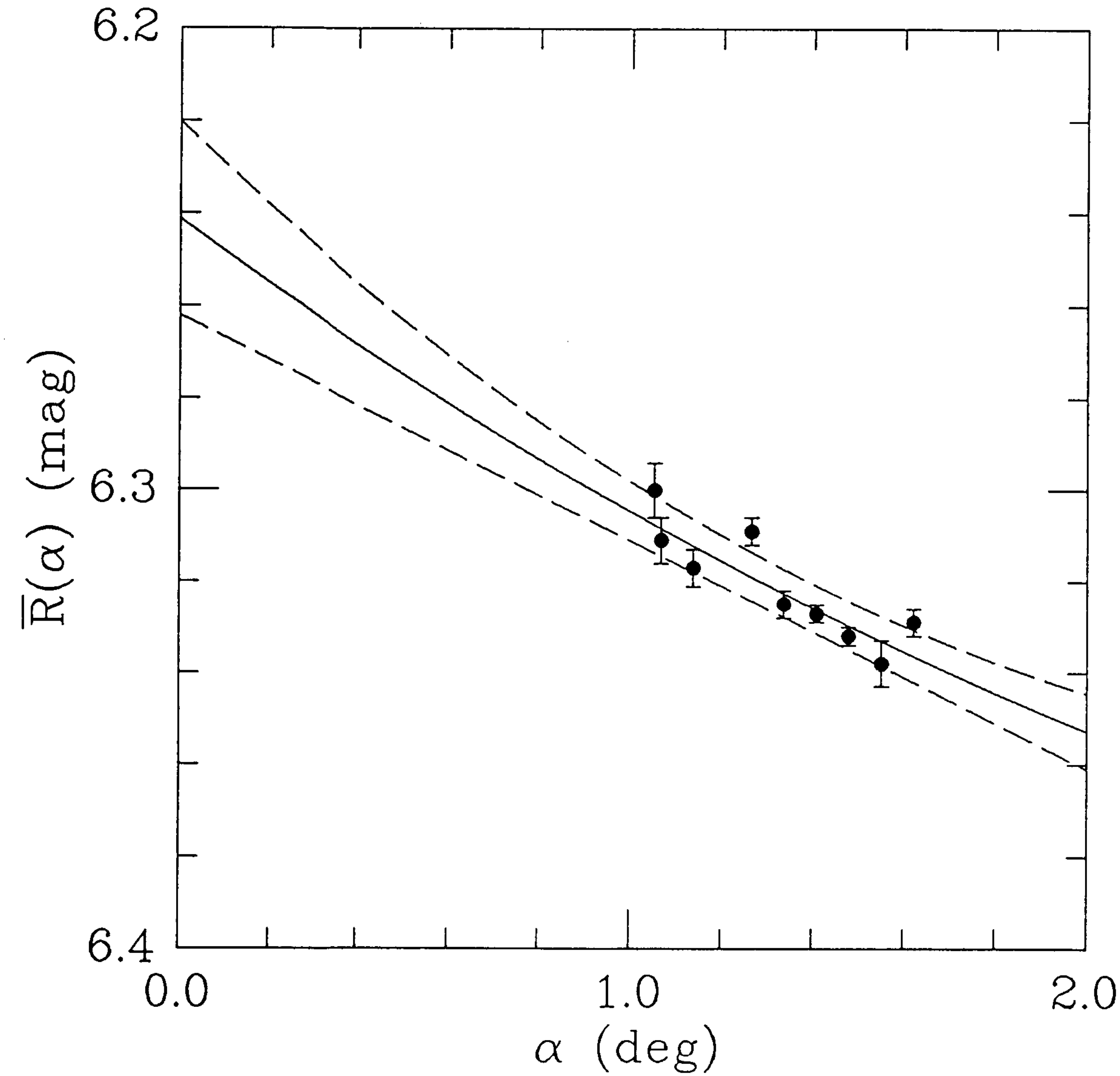

Figure 2