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# CCD Photometry of 2060 Chiron in 1985 and 1991

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We report CCD photometry of 2060 Chiron from two apparitions. A partial light curve was obtained in 1985 January, when the object was intrinsically fainter ($H_V = 6.84$) than it has ever been seen before or since. Nonetheless, there was some evidence for cometary activity even then; the bare nucleus may be fainter still. A complete light curve was obtained over 10 hr on 1991 January 08. Similar in character to the 1990 lightcurve of J. X. Luu and D. C. Jewitt (1990, *Astron. J.* 100, 913–932), it differed in three important respects. The amplitude was lower (0.04 mag), the mean brightness level was higher than recent trends would predict (mean $H_R = 5.65$), and the mean remained constant over 1½ rotations to within better than 0.005 mag.

The light curve shows reproducible structure of relatively high-frequency (~15-min time scale), formerly attributed to noise. These features repeat within the night and also may be discerned in light curves dating back to 1986 (S. J. Bus, E. Bowell, A. W. Harris, and A. V. Hewitt, 1989, *Icarus* 77, 223–238). We believe this structure to be evidence that Chiron is more aspherical (faceted?) than the small-amplitude lightcurve otherwise implies. The rotational lightcurve now is sufficiently well-characterized that it is no longer necessary to obtain data over a complete rotation to monitor the so-called "outburst" behavior of the object. We hope that this will encourage observers to study the cometary behavior of Chiron on time scales of days to weeks.

An updated mean synodic period of 5.917813 ± 0.000007 hr has been derived, and a revised nucleus + coma photometric model is constructed using the new data. The results of this model, along with the observed rapid "dropouts" in the rotational lightcurve, are together taken as evidence for a relatively low-obliquity viewing geometry over the past decade.

## INTRODUCTION

2060 Chiron was discovered in 1977 between the orbits of Saturn and Uranus (Kowal *et al.* 1979). Originally given the asteroid designation 1977 UB, its large orbit has until recently been unique among the asteroid population (Steel *et al.* 1991, Scotti and Rabinowitz 1992). Chiron exhibits a rotational lightcurve of ~5.9 hr, which varies in amplitude from a few hundredths to nearly one-tenth of a magnitude (Bus *et al.* 1989, Buratti and Dunbar 1991, Luu and Jewitt 1990).

Between mid-1987 and the end of 1988, Chiron began to exhibit unequivocal cometary behavior, brightening by 1.3 magnitudes by 1990 (Tholen *et al.* 1988; Hartmann *et al.* 1990). A coma was detected in 1989 (Meech and Belton 1990). In early 1989 Chiron began a secular decrease in brightness which by early 1990 amounted to ~0.5 magnitude. Observational evidence exists for earlier nonasteroidal behavior in 1978, and as far back as 1970 (Bus *et al.* 1991b). We report here seeing evidence of low-level activity in 1985 as well.

In addition to secular changes in brightness occurring on a time scale of years, Chiron also exhibits short-term, impulsive photometric variations. Buratti and Dunbar (1991) reported a 0.1-mag decrease which occurred in a 7-hr period on 1990 January 20, while Luu and Jewitt (1990) observed a comparable brightening just 9 days later. Our 1991 data show no similar outbursts, so they are ephemeral in nature. Disentangling the separate causes and contributions of long-term vs short-term effects may increase our understanding of the mechanisms by which comets release volatiles. A preliminary model of the long-term outbursts was presented by Meech and Belton (1990). In 1990 Bus *et al.* (1991a) detected the CN (0–0) emission line at 3875 Å during one of the short-term outbursts. Similar attempts to detect CN, as well as the $C_2$ and $C_3$ bands at other, less active epochs, have proven unsuccessful (Cochran *et al.* 1988, Cochran and Cochran 1990, Lagerkvist *et al.* 1991).

A 2.1-$\sigma$ detection of Chiron in the thermal infrared was reported by Lebofsky *et al.* (1984) which, when combined with $V$ measurements from the same apparition, yield a diameter estimate of $173^{+40}_{-50}$ km, with an albedo of ~0.13. Sykes and Walker (1991) used nondetections by IRAS to

[1] Observations were made with the 60-inch telescope at Palomar Mountain, which is jointly owned by the California Institute of Technology and the Carnegie Institute of Washington.

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TABLE I
Mean Nightly Observing Geometry for 2060 Chiron

| U.T. Date | $r$ [AU][1] | $\Delta$ [AU][2] | $\alpha$ [deg.][3] |
|---|---|---|---|
| 1985 January 17 | 14.623 | 14.017 | +3.10 |
| 1985 January 19 | 14.619 | 14.042 | +3.19 |
| 1991 January 08 | 10.612 | 9.643 | −0.97 |

[1,2] Heliocentric, geocentric distances.
[3] Solar phase angle: (−) before opposition, (+) after opposition.

place similar constraints on these parameters. Recently, Campins *et al.* (1992) reported a 3.1-$\sigma$ detection at 19.2 $\mu$m, which yields 1-$\sigma$ STM values of $d = 165^{+13}_{-27}$ km and $p_V = 0.22^{-0.04}_{+0.10}$. An important result of the Sykes and Walker work was to show that inclusion of rotation rate, assumed pole position, etc., in their thermophysical model results in much larger estimated diameter. On the other hand, the presence of a coma is not taken into account by these models and tends to lead to a (partially offsetting) overestimate for the diameter. Regardless, if Chiron is a comet, it is by far the largest comet.

Spectrally, Chiron appears similar to 2 Pallas and five other C-type asteroids; Tholen (1984) classifies it as type B. This type is not typical of comets, which in color more closely resemble D-type objects (French *et al.* 1989). The exact history and evolution of Chiron's orbit is unclear, although the current orbit is not stable over the lifetime of the Solar System (Oikawa and Everhart 1979, Scholl 1979, Kowal 1979).

## OBSERVATIONS

### *1991 January*

CCD observations of Chiron were obtained on the night of UT 1991 January 08 with the Palomar Mountain Observatory 1.52-m reflector. A TI-365 800 × 800 CCD and filter combination closely approximating the Gunn-$R$ system was used ($R_G$). This chip (Palomar Chip No. 4; cf. Oke *et al.* 1988) has a readout noise of $\sim$8 $e^{-1}$ and an approximate gain of 2.0 $e^{-}$/ADU. Focal-plane reducing optics were used, and the chip was clocked out in unbinned mode to yield an effective image scale of 0.477 arcsec per 15-$\mu$m pixel. An autoguider was used to track the telescope at the sidereal rate. Any image smear due to the (small) motion of Chiron during an integration is much smaller than the chosen object aperture (a square, 11 pixels on a side) and is of no practical consequence to our analysis. Mean geometric circumstances for 2060 Chiron appear in Table I for each night that the object was observed; in the actual reductions instantaneous values were calculated using the ubiquitous ephemeris program written by D. Tholen.

The January 08 data were obtained through occasional thin cirrus, although at times the raw count rates were quite stable. On-chip field stars (up to six) were used as local comparison objects. Data were gathered for approximately 10 hr or 1½ rotations, and observations were terminated when an air-mass factor of 3 was reached.

Wiśniewski and McMillan (1987) demonstrate that accurate *differential* photometry is indeed possible under such conditions. The small angular separation and simultaneous arrival of photons from program object, comparison objects(s), and background sky regions ensure that all suffer essentially the same atmospheric effects. When reduced differentially, temporal and spatial variabilities cancel to high order, given that the exposure time is long compared to the time it takes a parcel of air to move through the field of view. Since our integration times were typically ~5 min (adjusted slightly to account for changes in seeing and air-mass factor), this criterion has been met.

In recent years, Chiron has been passing near the Galactic Plane, usually resulting in fairly crowded fields. Our data reduction technique employed square "sky" apertures placed at the vertices of a larger, square "object" window. The method is employed so that should an appulse to a nearby field star occur, one of the four sky apertures can be "turned off" until the program object has moved past. Had we used the traditional circular aperture and sky annulus, the effective cross section of our object + sky ensemble would have been so large that either observations would have had to be suspended for the duration of the appulse or the field star flux would have had to be subtracted out. The latter option forces one to assume that the field star is not variable over the interval of observation. It also requires the investment of additional observing time and reduction effort to determine precisely both the absolute brightness and the colors of the offending star, which, more often than not, is substantially fainter than the already dim Chiron. Subdivision of what we designate as "sky" into smaller regions permits statistical comparison of the subregions to ensure that they have not been compromised by some faint background object at the limit of detection. Relative fluctuation in the subregions provides an independent estimate of the total "noise" in the sky measure. Other square patches, much further removed from the vertices of the object window, were used as a control to test for the existence of contamination by any coma which might have been present at the time.

The results of the Palomar photometry are displayed as Fig. 1 and tabulated in Table II. On 1991 March 15 E. S. Howell and M. C. Nolan kindly performed absolute flux calibration of the field from the University of Arizona 1.55-m Catalina Station telescope on Mt. Bigelow. The

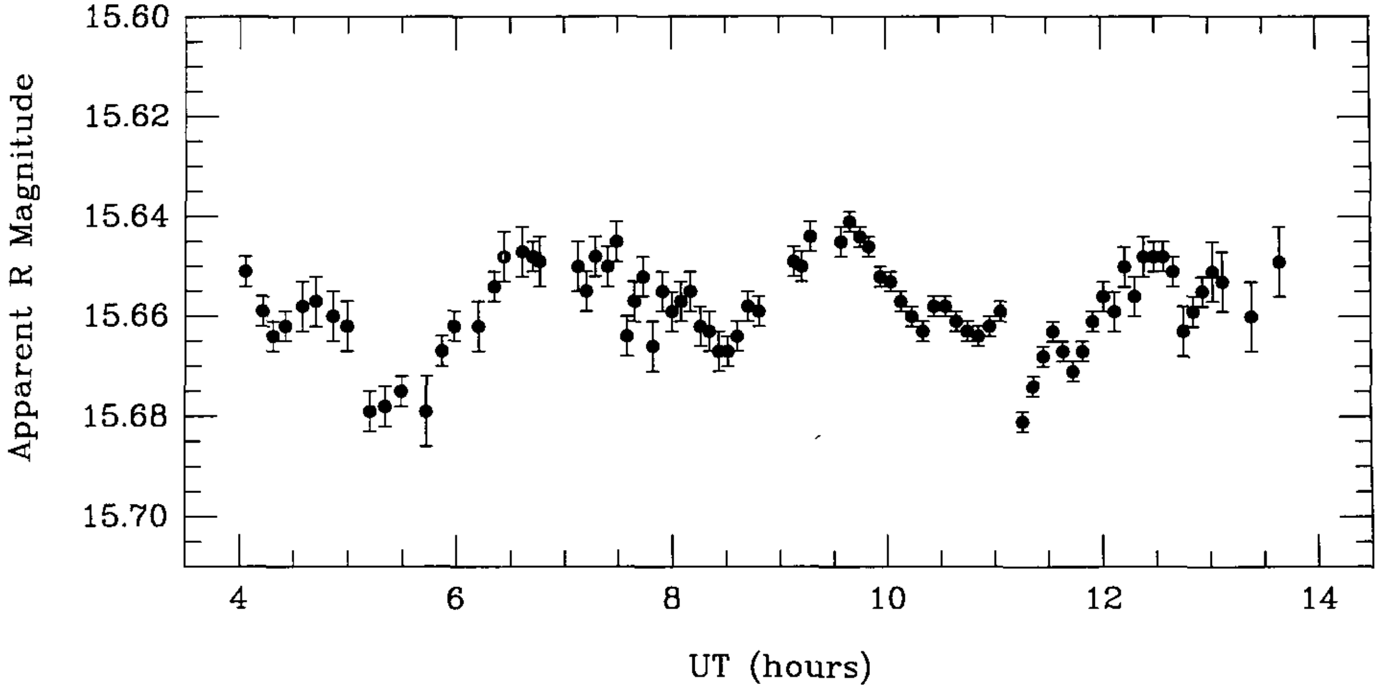

FIG. 1. CCD lightcurve obtained 1991 January 08 at the Palomar 1.52-m reflector. The 5.9-hr period is clearly visible, but nonasteroidal change (secular drift) was absent to within 0.5% over the course of the night. The photometry spans ~1½ rotations.

IHW CCD system of S. Larson was used to obtain images of the field and the Landolt (1983a) equatorial stars SA 101-389, SA 101-311, and SA 99-408. We believe the absolute (zeropoint) flux calibration of the Chiron observations to be accurate to ~2–3%.

### *1985 January*

CCD observations were also obtained by one of us (R.L.M.) on the nights of 1985 January 17 and 19 with the 1.55-m Catalina Station telescope of the University of Arizona. 300-second integrations of the Chiron field were made in Johnson-*V*, with the LPL CCD and reducing optics, at an effective image scale of 0.95 arcsec per pixel. A preliminary reduction of these data was presented by Marcialis (1989).

As originally reported, the individual exposures were too short to conclude much about Chiron's rotational lightcurve behavior. However, binning the data (median window, three images per bin; see Table III) sufficiently improves the signal-to-noise ratio so that a partial lightcurve can be discerned on the night of January 19 (triangles, Fig. 2). Because the lightcurve is only partial, we can only place a *lower* limit of 5–6% on the amplitude. Also plotted in Fig. 2 are data obtained two nights earlier, on 17 January. They have been rotated forward in time to the equivalent rotational phase, *but with ordinate shifted downward by* $0^m.07$. Chiron's nonasteroidal variations had not been recognized until later (Tholen *et al.* 1988) and at the time this shift was attributed to some unexplained night-to-night error.

At our request, W. Grundy (LPL) reimaged the Chiron fields using the same telescope and instrument configuration on the nights of 1989 October 09 and 10. The original zeropoint determination was confirmed and refined by interleaved exposures of the standard star (SA 44-113; Landolt 1983b). The overall absolute flux calibration of the 1985 data is believed to be better than 2%. We conclude that Chiron indeed had dimmed some 7% during the course of the two nights back in 1985.

Radial image profiles for Chiron and comparably exposed field stars were constructed by azimuthally integrating counts in annuli about each image centroid. A typical pair of profiles are plotted in Fig. 3. Chiron and stellar radial point spread functions are indistinguishable; we see no evidence for coma at any time during the observing run. (At the time, 1 arcsec projected to ≈10,200 km at Chiron's distance. For comparison, the coma seen by Meech and Belton had a projected distance of at least 70,000 km. West (1991) reported a coma during the 1990 apparition extending as much as 230,000 km from the nucleus.)

At $H_V = 6.84$, the January 19 observations represent the faintest intrinsic magnitude ever reported for Chiron, either before or since. Since the observed time scales for both growth and decay of the coma are long compared to the rotation period (Meech and Belton 1990), to conclude that the bare "nucleus" was seen at that time is

TABLE II
New Photometric Observations of 2060 Chiron, 1991 January 08

| UT (mid) | exp. | $R_{Gunn}$ | $\sigma$ | $H_{R_G}$ | JD (ltc) | UT (mid) | exp. | $R_{Gunn}$ | $\sigma$ | $H_{R_G}$ | JD (ltc) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [hr] | [sec] | | [mag] | | 2,448,264+ | [hr] | [sec] | | [mag] | | 2,448,264+ |
| 4.0228 | 200 | 15.651 | 0.003 | 5.539 | 0.6119 | 9.1836 | 150 | 15.650 | 0.003 | 5.539 | 0.8270 |
| 4.1747 | 250 | 15.659 | 0.003 | 5.547 | 0.6183 | 9.2628 | 200 | 15.644 | 0.003 | 5.533 | 0.8303 |
| 4.2697 | 250 | 15.664 | 0.003 | 5.552 | 0.6222 | 9.5431 | 200 | 15.645 | 0.003 | 5.534 | 0.8419 |
| 4.3811 | 300 | 15.662 | 0.003 | 5.550 | 0.6269 | 9.6294 | 200 | 15.641 | 0.002 | 5.530 | 0.8455 |
| 4.5314 | 350 | 15.658 | 0.005 | 5.546 | 0.6331 | 9.7225 | 200 | 15.644 | 0.002 | 5.533 | 0.8494 |
| 4.6589 | 350 | 15.657 | 0.005 | 5.545 | 0.6384 | 9.8072 | 200 | 15.646 | 0.002 | 5.535 | 0.8529 |
| 4.8128 | 350 | 15.660 | 0.005 | 5.548 | 0.6448 | 9.9050 | 250 | 15.652 | 0.002 | 5.541 | 0.8570 |
| 4.9389 | 350 | 15.662 | 0.005 | 5.550 | 0.6501 | 10.0011 | 250 | 15.653 | 0.002 | 5.542 | 0.8610 |
| 5.1497 | 400 | 15.679 | 0.004 | 5.567 | 0.6589 | 10.0994 | 250 | 15.657 | 0.002 | 5.546 | 0.8651 |
| 5.2892 | 400 | 15.678 | 0.004 | 5.566 | 0.6647 | 10.1983 | 250 | 15.660 | 0.002 | 5.549 | 0.8692 |
| 5.4328 | 400 | 15.675 | 0.003 | 5.563 | 0.6707 | 10.2989 | 250 | 15.663 | 0.002 | 5.552 | 0.8734 |
| 5.6678 | 400 | 15.679 | 0.007 | 5.567 | 0.6805 | 10.4044 | 250 | 15.658 | 0.002 | 5.547 | 0.8778 |
| 5.8083 | 400 | 15.667 | 0.003 | 5.555 | 0.6863 | 10.5089 | 250 | 15.658 | 0.002 | 5.547 | 0.8822 |
| 5.9389 | 300 | 15.662 | 0.003 | 5.550 | 0.6918 | 10.6100 | 250 | 15.661 | 0.002 | 5.550 | 0.8864 |
| 6.1603 | 300 | 15.662 | 0.005 | 5.550 | 0.7010 | 10.7108 | 250 | 15.663 | 0.002 | 5.552 | 0.8906 |
| 6.3019 | 350 | 15.654 | 0.003 | 5.542 | 0.7069 | 10.8128 | 250 | 15.664 | 0.002 | 5.553 | 0.8948 |
| 6.4142 | 220 | 15.648 | 0.005 | 5.536 | 0.7116 | 10.9183 | 250 | 15.662 | 0.002 | 5.551 | 0.8992 |
| 6.5856 | 200 | 15.647 | 0.005 | 5.535 | 0.7187 | 11.0211 | 250 | 15.659 | 0.002 | 5.548 | 0.9035 |
| 6.6861 | 150 | 15.648 | 0.003 | 5.536 | 0.7229 | 11.2308 | 250 | 15.681 | 0.002 | 5.570 | 0.9123 |
| 6.7511 | 150 | 15.649 | 0.005 | 5.537 | 0.7256 | 11.3247 | 250 | 15.674 | 0.002 | 5.563 | 0.9162 |
| 7.1119 | 120 | 15.650 | 0.005 | 5.538 | 0.7406 | 11.4228 | 220 | 15.668 | 0.002 | 5.557 | 0.9203 |
| 7.1931 | 120 | 15.655 | 0.004 | 5.543 | 0.7440 | 11.5136 | 220 | 15.663 | 0.002 | 5.552 | 0.9240 |
| 7.2792 | 120 | 15.648 | 0.004 | 5.536 | 0.7476 | 11.6028 | 220 | 15.667 | 0.002 | 5.556 | 0.9278 |
| 7.3944 | 120 | 15.650 | 0.004 | 5.538 | 0.7524 | 11.6950 | 220 | 15.671 | 0.002 | 5.561 | 0.9316 |
| 7.4700 | 150 | 15.645 | 0.004 | 5.533 | 0.7556 | 11.7886 | 220 | 15.667 | 0.002 | 5.557 | 0.9355 |
| 7.5622 | 150 | 15.664 | 0.004 | 5.552 | 0.7594 | 11.8867 | 220 | 15.661 | 0.002 | 5.551 | 0.9396 |
| 7.6328 | 150 | 15.657 | 0.004 | 5.545 | 0.7623 | 11.9819 | 250 | 15.656 | 0.003 | 5.546 | 0.9436 |
| 7.7131 | 150 | 15.652 | 0.004 | 5.540 | 0.7657 | 12.0842 | 250 | 15.659 | 0.004 | 5.549 | 0.9478 |
| 7.7928 | 200 | 15.666 | 0.005 | 5.554 | 0.7690 | 12.1792 | 250 | 15.650 | 0.004 | 5.540 | 0.9518 |
| 7.8875 | 200 | 15.655 | 0.004 | 5.543 | 0.7730 | 12.2744 | 220 | 15.656 | 0.004 | 5.546 | 0.9557 |
| 7.9733 | 200 | 15.659 | 0.004 | 5.547 | 0.7765 | 12.3633 | 220 | 15.648 | 0.004 | 5.538 | 0.9595 |
| 8.0564 | 200 | 15.657 | 0.004 | 5.545 | 0.7800 | 12.4569 | 220 | 15.648 | 0.003 | 5.538 | 0.9634 |
| 8.1431 | 200 | 15.655 | 0.004 | 5.543 | 0.7836 | 12.5458 | 220 | 15.648 | 0.003 | 5.538 | 0.9671 |
| 8.2328 | 200 | 15.662 | 0.004 | 5.551 | 0.7873 | 12.6372 | 220 | 15.651 | 0.003 | 5.541 | 0.9709 |
| 8.3186 | 200 | 15.663 | 0.004 | 5.552 | 0.7909 | 12.7256 | 220 | 15.663 | 0.005 | 5.553 | 0.9745 |
| 8.4028 | 200 | 15.667 | 0.004 | 5.556 | 0.7944 | 12.8194 | 220 | 15.659 | 0.003 | 5.549 | 0.9785 |
| 8.4919 | 200 | 15.667 | 0.003 | 5.556 | 0.7981 | 12.9081 | 220 | 15.655 | 0.003 | 5.545 | 0.9821 |
| 8.5803 | 200 | 15.664 | 0.003 | 5.553 | 0.8018 | 13.0022 | 220 | 15.651 | 0.006 | 5.541 | 0.9861 |
| 8.6767 | 200 | 15.658 | 0.003 | 5.547 | 0.8058 | 13.0931 | 220 | 15.653 | 0.006 | 5.543 | 0.9899 |
| 8.7797 | 200 | 15.659 | 0.003 | 5.548 | 0.8101 | 13.3611 | 220 | 15.660 | 0.007 | 5.550 | 1.0010 |
| 9.1044 | 200 | 15.649 | 0.003 | 5.538 | 0.8237 | 13.6194 | 250 | 15.649 | 0.007 | 5.539 | 1.0118 |

not at all certain: there was definite activity only 2 days earlier. Our observations do, however, tighten constraints on the visual magnitude of Chiron's nucleus. The details of how this affects Chiron modeling are discussed in the next section.

## RESULTS

### *Lightcurve Structure*

The 1991 lightcurve spans about 1$\frac{1}{2}$ rotations of Chiron. Its peak-to-peak amplitude is $\sim 0^{m}.04$. Several features in the lightcurve reproduce from rotation to rotation (see Fig. 4). For example, the W-shaped feature at UT 4–5 hr again shows up at UT 10–11 hr (rotational phases ~0.4–0.5 in Fig. 4). This feature immediately precedes a rather abrupt "dropout," fully half of the peak-to-peak lightcurve excursion. This dropout takes less than 10 min to occur. One of the lightcurve maxima contains a V-shaped "notch" in it as well. All of these features may be discerned in the photometry obtained by Luu and Jewitt in 1990 and to a lesser degree in the lightcurve obtained in 1986 by Bus *et al.* (1989). We believe such high-frequency

**TABLE III**
**Photometric Observations of 2060 Chiron, 1985 January 17, 19**

| UT (mid) [hr] | $V$ [mag] | $\sigma$ [mag] | $H_V$ [mag] | JD (ltc) 2,446,000+ |
|---|---|---|---|---|
| 3.4975 | 18.447 | 0.010 | 6.774 | 82.5648 |
| 3.6525 | 18.447 | 0.007 | 6.774 | 82.5713 |
| 3.8097 | 18.433 | 0.007 | 6.760 | 82.5778 |
| 4.7603 | 18.433 | 0.007 | 6.760 | 82.6175 |
| 5.0289 | 18.467 | 0.007 | 6.794 | 82.6286 |
| 6.4669 | 18.467 | 0.010 | 6.794 | 82.6886 |
| 3.2000 | 18.502 | 0.010 | 6.824 | 84.5523 |
| 3.3231 | 18.502 | 0.006 | 6.824 | 84.5574 |
| 3.5764 | 18.519 | 0.006 | 6.840 | 84.5680 |
| 3.6794 | 18.519 | 0.006 | 6.840 | 84.5723 |
| 3.7867 | 18.527 | 0.006 | 6.849 | 84.5767 |
| 4.0083 | 18.527 | 0.006 | 6.849 | 84.5860 |
| 4.1175 | 18.529 | 0.006 | 6.851 | 84.5905 |
| 4.2219 | 18.543 | 0.006 | 6.864 | 84.5949 |
| 4.9028 | 18.543 | 0.006 | 6.864 | 84.6233 |
| 5.1844 | 18.518 | 0.006 | 6.839 | 84.6350 |
| 5.7631 | 18.518 | 0.006 | 6.839 | 84.6591 |
| 5.8622 | 18.538 | 0.010 | 6.859 | 84.6632 |

structure in the lightcurve supports the following conjectures: (1) Chiron may be more aspherical, or "faceted," in its figure than the small lightcurve amplitude alone might indicate; and (2) the inclination of Chiron's rotational axis to the line of sight is probably, at least during the past few years, rather substantial in magnitude.

We note that only an extremely unlikely albedo distribution can cause the sudden variabilities we observed (e.g., an anomalously bright or dark albedo sector, with long axis aligned from pole to pole). Therefore, the dropout more probably is attributed to shape, rather than albedo.

### *Improved Synodic Period*

West (1991) determined Chiron's synodic rotation period as $P = 5^h.91783 \pm 0^h.00005$. Our datasets extend the baseline of Chiron photometry by 1 year at either end, or some ~3000 additional body rotations. We derive an improved value for the synodic period of $5^h.917813 \pm 0^h.000007$. The main source of error in this determination derives from the absence of a clear-cut extremum in the 1985 data. However, the descending branch of that lightcurve can be used in any case to pin down the total number of revolutions which transpired during the 7-year interval to better than about 1/20 of a revolution.

### *Nonasteroidal Brightness Variations*

Figure 5 shows a plot of Chiron's absolute magnitude, $H_V$, vs year. Bowell *et al.* (1989) discuss how these absolute magnitudes are calculated. We have used the rigorous equations that they detail on page 550, rather than the simpler, more symmetric equations on page 551, noting that *the simpler equations should be used only for prediction of ephemerides, and not the reduction of actual data.* The mean of our 1985 photometry, $H_V = +6.84$, is intrinsically fainter than at any other epoch, either before or since, and sets a new lower limit on the brightness of Chiron's nucleus. It is also substantially fainter than all previous workers have used to estimate Chiron's size and albedo (Lebofsky *et al.* 1984, Sykes and Walker 1991) or to model the coma and nucleus (Meech and Belton 1990, Luu and Jewitt 1990, West 1991, Boice *et al.* 1991). Yet, as mentioned earlier, there was evidence for coma activity even when this faintest measurement was obtained.

Under the assumption that Chiron is a low-albedo object, our new lower limit for the nuclear magnitude tends

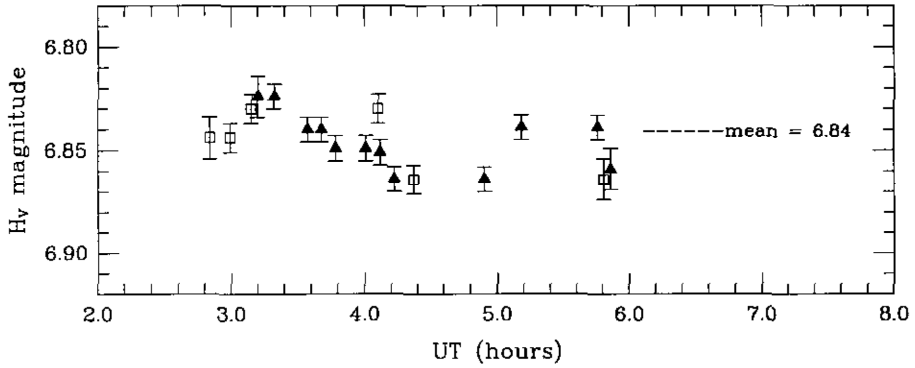

FIG. 2. CCD photometry obtained 1985 January 17 (squares) and 19 (triangles) at the University of Arizona 1.55-m Catalina telescope. The mean absolute magnitude on January 19, $H_V = 6.84$, is intrinsically the faintest that Chiron has ever been observed. Data from the first night have been shifted *downward* by 0.07 mag to align the two nights' photometry. Subsequent recalibration of the two star fields shows that this dimming was real and indicates that some cometary activity was present even at this epoch. An improved synodic period of $5^h.917813 \pm 0^h.000007$ is derived.

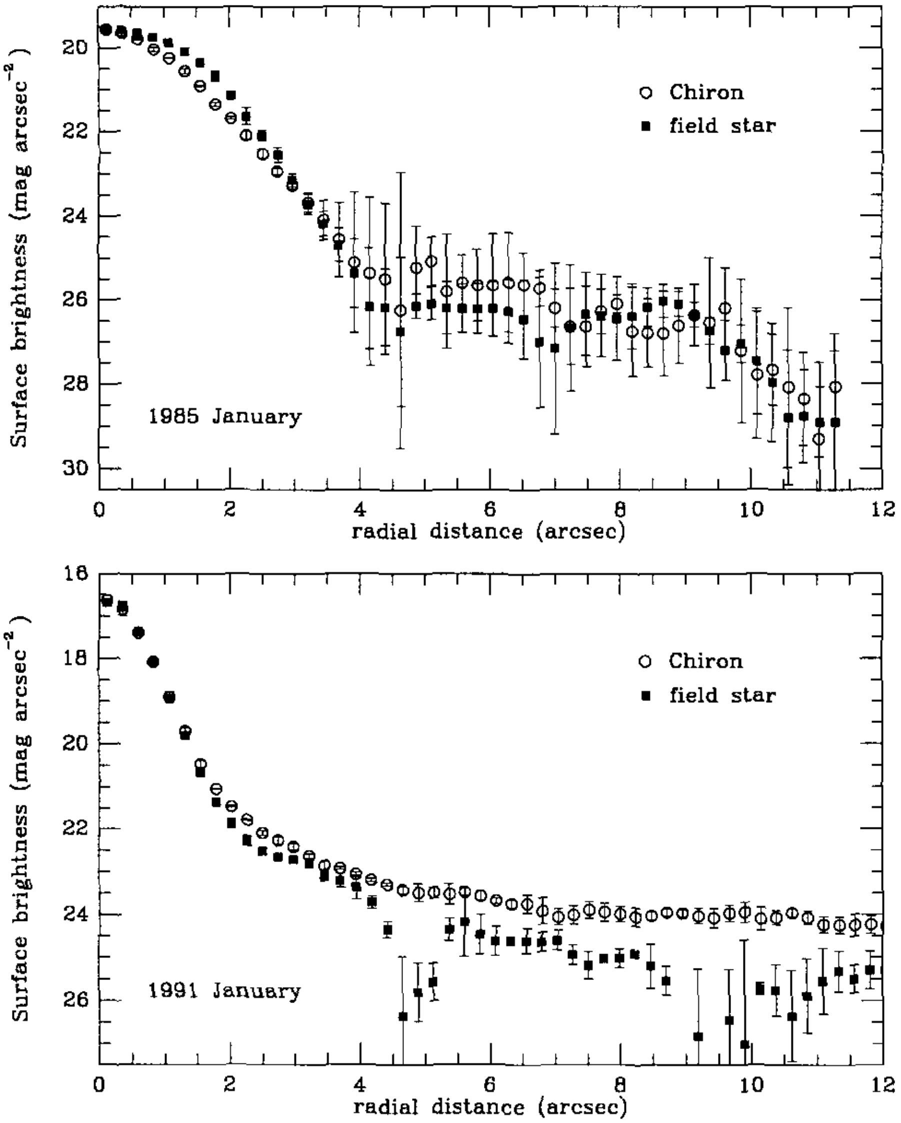

FIG. 3. Radial image profiles (azimuthally integrated) for Chiron and comparably bright field stars from the same image sets. The profiles have been normalized such that the total (integrated) number of counts for each object are identical. (Top) The wings of both point spread functions are identical, implying the absence of any *extended* coma during the 1985 January observations. Each of these profiles represents the sum of four 300-sec integration images. (Bottom) Same as above, but for three images from the 1991 run. The wings of the Chiron's point spread function clearly are elevated compared to those of the field star's, demonstrating that an extended coma existed at this time. Total integration times for lower profiles were 600 sec.

to lower the estimated albedo by 10–15%, but has very little effect on the derived size (Sykes, personal communication; Lebofsky, personal communication). One must keep in mind, however, that thermal detections of Chiron to date (Lebofsky *et al.* 1984, Hartmann *et al.* 1991, personal communication, Campins *et al.* 1992, Marcialis *et al.* 1993, in preparation) have all been at relatively low signal-to-noise ratio, ranging from 2 to 3. Thermal emission from the coma is included in these measurements, but has not been accounted for in the modelling. We suggest that the diameter estimates found in the literature are perhaps not as definitive as previously thought. Furthermore, given Chiron's penchant for rapid nonasteroidal variations (Buratti and Dunbar 1991, Luu and Jewitt 1990), it is strongly recommended that future attempts at detection in the thermal IR be accompanied by visual flux estimates to be of value. Simultaneous visual and thermal detections should be attempted over a *range* of coma activity levels, so that a proper model can be constructed.

The implication of Chiron's low $H_V$ in 1985 is perhaps much more important than its exact numerical value. Independent of the nonasteroidal variations that we noticed

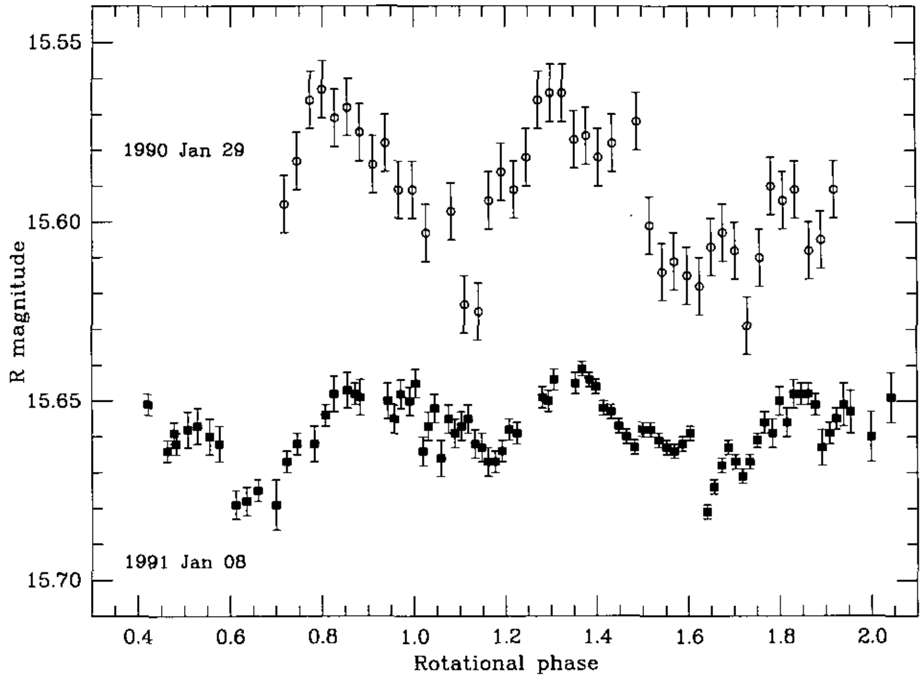

FIG. 4. Comparison of photometry to data obtained by Luu and Jewitt from the previous apparition. The 1990 data were obtained during an outburst, the slope of which has been removed. The amplitude of the 1991 lightcurve is only ⅗ that of 1990. Nevertheless, reproducible structure of relatively high-frequency (~15-min time scale), is clearly visible. These features repeat within the night and are seen in both lightcurves, as well as in photometry dating back to 1986 (Bus *et al.* 1989a).

between 17 and 19 January, it shows that the comet most certainly *was not* in a quiescent phase from 1983 to 1987. Thus, a new, and fainter baseline must be assumed in coma models such as that proposed by Meech and Belton (1990). Recent discussion with M. Belton (1992, personal communication) reveals that his model also may need revision.

It is interesting to note that although nonasteroidal variations were present in 1985, when the comet was intrinsically faintest, there were no brightening or dimming trends

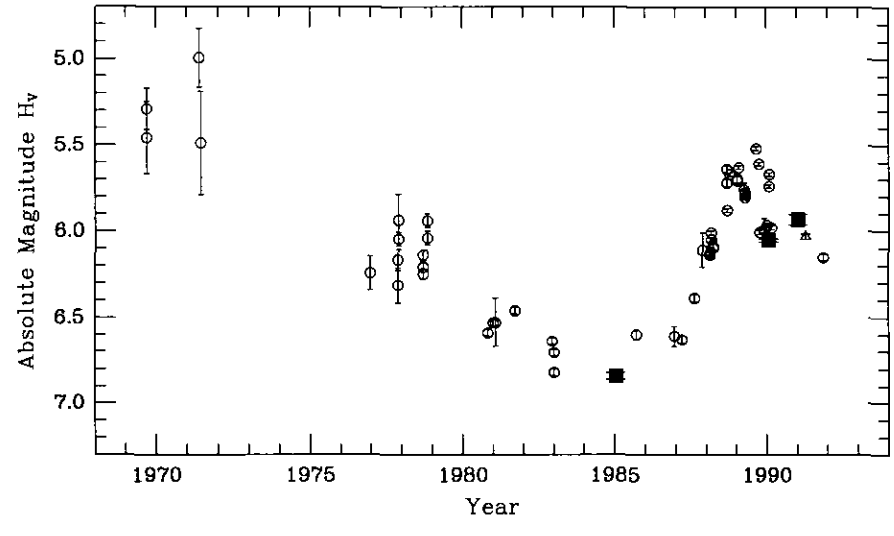

FIG. 5. Intrinsic variability of Chiron's brightness versus year. Circles are values previously reported in the literature; filled squares represent our contributions. The penultimate datum (triangle) was supplied by B. E. A. Mueller (personal communication): 1991 April 19, at rotational phases 0.57–0.72. This corresponds to UT 07.5–08.3 in Fig. 1. After correcting for different viewing geometry between January and April, it is seen that Chiron's mean magnitude has faded by several percent during that interval, back to the intensity level of the 1990 apparition. However the exact amount of dimming depends upon the assumed value of the slope parameter.

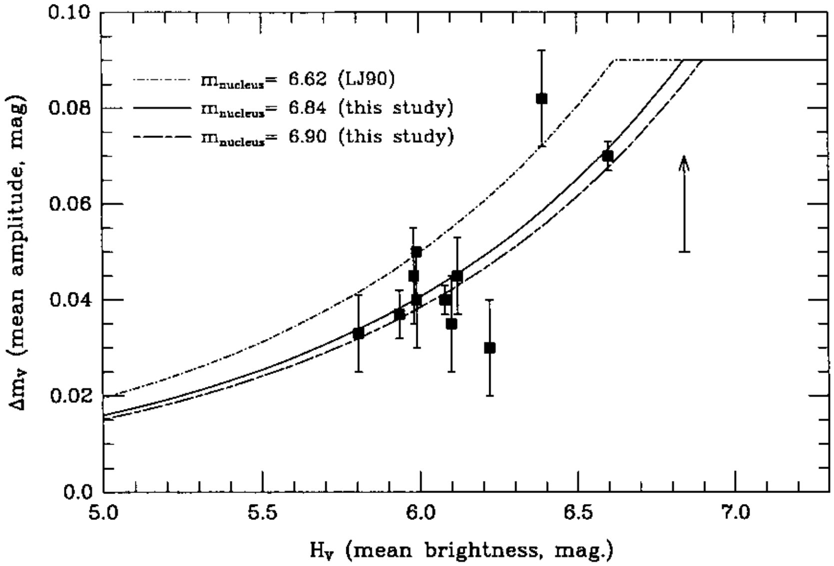

FIG. 6. Improved photometric model for Chiron. A rotating nucleus is assumed to be imbedded in an optically thin coma, as per Luu and Jewitt (1990) and Meech and Belton (1990). It is clear that the amplitude-absolute magnitude relation is approximated better by a fainter nuclear contribution than previously has been assumed. The lower limit estimate at $H$ = 6.84 (arrow) is due to the lack of clear-cut extrema in the 1985 observations.

superposed on the 1991 January 08 photometry to within $\leq 0^{\mathrm{m}}.005$ (0.5%). This may be seen readily by replotting Fig. 1 with rotational phase as its abscissa. Thus, the *absence of background modulation does not necessarily imply the absence of coma.* This is consistent with the dissipation time ($\sim 3 \times 10^7$ sec) of micrometer-sized dust particles in the coma by radiation pressure, as derived by Luu and Jewitt (1990).

The mean $H_V$ for the 1991 January 08 data, 5.934, is somewhat brighter than would be predicted by smooth extrapolation of Chiron's recent rate of dimming. If the exponential dust growth and decay model presented in Meech and Belton (1990) is correct, this implies that a third outburst episode occurred sometime early in the apparition and that there is substantial overlap with the tail of the previous episode, which, according to the model, began in 1987 August. Indeed, by 1991 April 15, the mean $H_V$ had relaxed to 5.984 (B. E. A. Mueller, personal communication), assuming $G$ = 0.7 (Bus *et al.* 1989).

### *Improved Photometric Model*

Our data, when combined with previously published photometry, can be used to derive a refined photometric model for Chiron. Following Luu and Jewitt (1990), we consider a two-component model, consisting of a nucleus imbedded in an optically thin coma. The nucleus scatters light roughly in proportion to the instantaneous illuminated cross section, and the intrinsic nuclear lightcurve is diluted by the additional flux contributed by the coma. This coma flux is due primarily to sunlight reflecting from entrained dust particles. We assume that the sub-Earth latitude has been approximately constant over the past decade, as would be the case for a reasonably low polar obliquity. (The quality of the available data supports this last assumption; their number certainly do not allow anything of additional significance to be extracted were it to be relaxed.)

As the photometric contribution of the coma increases, the overall magnitude brightens, and the peak-to-peak excursions of the lightcurve become smaller. As the coma becomes optically thicker, the overall lightcurve falls to zero in the limit. Removal of the coma leaves just the classical asteroid rotational lightcurve, with its amplitude determined by the shape, albedo distribution, and scattering properties of Chiron's solid figure.

Figure 6 shows the observed photometric excursions, $\Delta m_V$, as a function of absolute intrinsic magnitude, $H_V$. We have transformed separately the several $R$-band (Johnson, Cousins, Mould, and Gunn) measurements to a common system of $H_V$ estimates (cf. Kent 1985, Landolt 1983a, Fernie 1983). Error bars represent uncertainty in the *amplitude* of the lightcurve at each epoch. Since no extrema were observed during our 1985 observing run, the datum at the extreme right of the plot therefore is only a lower limit to the amplitude at that epoch. Also plotted are three curves (following Equation 19 of Luu and Jewitt), for nuclear $H_V$'s of 6.62, 6.84, and 6.90. Clearly, the fainter values of the nuclear magnitude provide better fits to the available data; perhaps a nuclear

$H_V = 6.90$ is closer to the truth. We interpret the improved fit as further evidence for a nucleus substantially fainter than previous workers have assumed.

We believe that the lightcurve shape and period, and photometric model of the coma + nucleus are now sufficiently well known that it is no longer necessary to acquire photometry over an entire rotation in order to monitor Chiron's activity. It is our hope that this will encourage observers to monitor Chiron as a "target of opportunity." In this manner, it is hoped that the nonasteroidal variability of Chiron on time scales of days to weeks can be watched more thoroughly. Programs such as this would serve to alert the community as to the onset of outbursts, rather than leaving the detection of such eruptions to pure chance. It is of particular importance for observers to acquire photometry *throughout* an apparition, rather than merely within a week to either side of opposition, as is by now customary. We are currently engaged in just such an observing program (Larson and Marcialis, 1992) and invite others to participate.

## SUMMARY

Observations of 2060 Chiron obtained since its discovery in 1977 provide a basis to describe—at least at the empirical level—three well-defined (and therefore most probably physically separate) types of photometric variability. First, Chiron has a distinct asteroidal lightcurve, which repeats in its structure, if not in amplitude, since at least 1985. Second, secular changes in brightness of up to ~1.5 mag occur on time scales of several years. Third, "impulsive" brightenings of at least 0.1 mag of ~1-day duration were documented by two groups in 1990 January (Buratti and Dunbar 1991, Luu and Jewitt 1991). Our current results suggest the possibility of similar outbursts occurring as early as 1985. At least one of the outbursts in 1990 was accompanied by the presence of CN emission features (Bus *et al.* 1991a).

Chiron's rotational lightcurve was first reported by Bus *et al.* (1989) based on measurements obtained in 1986 and 1988. Although the period they report is consistent with subsequent observations, the amplitudes reported by Luu and Jewitt (1990), Buratti and Dunbar (1991), and the present work, are one-half to one-fourth that observed by Bus *et al.* (our 1985 observations do not span a sufficient fraction of a rotation to determine an amplitude). This decrease in amplitude is associated with a large increase in Chiron's mean brightness and is most probably due to dilution of the nucleus by an intensified coma. We see no evidence for a change in the amplitude of Chiron's lightcurve with ecliptic longitude, as would be expected of an object having a high-obliquity rotational axis. We find several short term (~10- to 15-min) features in the lightcurve which repeat in 1986, 1990, and 1992 observations. These features probably are due to an irregular or faceted body figure, and they offer evidence that Chiron currently presents an approximately equatorial aspect to the Earth. We report an improved value for Chiron's synodic period of 5.917813 ± 0.000007 hr.

Chiron's most recent long-term secular brightness variation was first reported in mid-1987 and was associated with the appearance of a comet-like coma (Meech and Belton 1990). Analysis of prediscovery plates of Chiron covering the epoch just before discovery show at least one other similar major outburst in the early 1970s (Bus *et al.* 1991b). Our 1991 January observations show a clear (between 0.1 and 0.2 mag) increase in brightness since the previous apparition. Our 1985 January observations were obtained when Chiron was at a minimum in its observed brightness and constrain the onset of the long-term brightening to have been no earlier than the Spring of 1985.

Impulsive short-term variations in Chiron's brightness were discovered in 1990 by Luu and Jewitt (1991), and by Buratti and Dunbar (1991). Our 1985 measurements obtained two nights apart show evidence for similar variations even then. These variations, coupled with an updated coma model, suggest that the absolute brightness of the bare nucleus is ~10% less than what we observed in 1985 and up to 30% fainter than what previous workers have assumed. We observed no outbursts during our 1991 observations larger than one-half of one percent, however, it is clear that a well-behaved lightcurve is in no way an indicator of coma activity (or lack thereof). The very different characteristics of the two types of brightenings seen suggest that they are derived from two distinct physical mechanisms. Secular (yearly) change is due to the gradual dissipation and resupply of material (mainly dust) throughout the coma, while the impulsive (daily) brightenings are probably due to the sudden release of pockets of entrapped volatiles, such as $CO_2$, CN, or possibly $H_2O$ (Stern 1989).

Chiron is a particularly important object because it currently displays properties typical of both asteroids and comets. Our understanding of the mechanisms involved hopefully will shed light on the relationships between these two types of small bodies.

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