THE VISUAL LIGHT CURVE OF C/1995 O1 (HALE–BOPP) FROM DISCOVERY TO LATE 1997

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Abstract. We present a light curve of C/1995 O1 (Hale–Bopp) compiled from more than 3000 visual observations of the comet made by members of the *The Astronomer Group* world-wide. These observations cover the period from discovery through to the end of 1997. The light curve shows that the rate of brightening of the comet varied widely at different times, with rapid rates of brightening at high heliocentric distance pre-perihelion and a comparably rapid post-perihelion fade. There is no evidence that the comet was suffering a large photometric outburst when first discovered, although a small outburst can be identified at perihelion. At least five difficult brightening regimes can be identified in the light curve between discovery and perihelion. From 2.5 AU to perihelion the rate of brightening with decreasing heliocentric distance was typical for "fairly" new comets ($n \sim 3.5$, where "n" is the power law exponent of the heliocentric distance), although this was preceded by a period of very slow brightening with $n \sim 1$ from $r \sim 4.0$ AU to $r \sim 2.8$ AU and followed by an initially more rapid brightening which appears to be related to the on-set of rapid water sublimation activity. We derive the light curve parameters at different stages of the comet's apparition.

Keywords: Comets, named objects, C/1997 O1 (Hale–Bopp), photometry

1. Introduction

Amateur visual observers have had a proud tradition for many years of supplying valuable information on the evolution and activity of comets. Despite the increasing professional use of narrow-band photometry to isolate species, a great deal of information can be obtained from estimates of the total visual magnitude of comets, especially in terms of the "switch-on" of different components as the comet's heliocentric distance decreases.

Comet Hale–Bopp offers a chance of a particularly detailed study given that it was bright and also far from perihelion at the moment of discovery. This fact differentiates it from other bright comets of recent decades, such as 1P/Halley which was only bright for a few months around perihelion at relatively small helio-

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centric distance, or C/1996 B2 (Hyakutake) which was discovered only shortly before perihelion and which faded rapidly post-perihelion. This extended light curve coverage allows, for example, the transition from CO-based to water-based activity to be studied. It also permits hypotheses, such as the suggestion that there was a large pre-discovery outburst, to be examined critically. Comet Hale–Bopp has been subject to a particularly intense monitoring effort from different amateur groups, allowing what is possibly the best-covered light curve ever of a comet to be compiled.

2. The Database

The light curve of C/1995 O1 (Hale–Bopp) has been compiled from the archive of the “The Astronomer Group” and the “British Astronomical Association Comet Section”. Whilst the latter is mainly composed of British amateur astronomers, the former has a world-wide network of active observers covering all five continents, with a significant number of southern hemisphere observers. This ensures that the comet has been regularly observed over a wide range of dates covering its entire apparition.

A total of 2917 total visual magnitude estimates have been used, covering the range of dates from July 24th 1995 to November 30th 1997. A further 337 observations give estimates of the tail length, degree of condensation, etc. without an estimate of total visual magnitude. The estimates were made using a range of instruments from the naked-eye up to telescopes of 41-cm aperture. The largest number of individual estimates was made with the naked-eye, reflecting the long interval during which the comet was naked-eye visible; the duration of naked-eye visibility, from May 17th 1996 to December 9th 1997, appears to be the longest on record for a comet, far exceeding the 9 months of naked-eye visibility of C/1811 F1 (Flaugergues). The next largest number of estimates used a 50-mm aperture, typical of the most popular binoculars used for cometary observation.

2.1. THE APERTURE CORRECTION

No aperture correction has been applied to the data as a negligible correlation was found between aperture and estimated total visual magnitude. As $\sim$93% of all estimates were made with apertures of 80-mm or less, close to the 67-mm standard aperture for comet total visual magnitude estimates, we would argue that the effect on the light curve of neglecting the aperture correction is generally very small.

TABLE I

Aperture sizes used for total visual magnitude estimates of comet Hale–Bopp in the database referred to in the text. Almost 40% of all estimates were made with the naked-eye and a further 27% with binoculars of 50-mm aperture

Aperture	Number of estimates
Naked-eye	1145
23–32 mm	31
35–42 mm	135
50 mm	781
60–63 mm	73
70–78 mm	40
80 mm	495
10–12.5 cm	117
15–20.3 cm	42
25–30 cm	27
35–41 cm	30

3. The Light Curve

Figures 1–3 present the light curve compiled from the visual database. In the first two plots the vertical, dotted line marks the date of perihelion. There was an initial, rapid rate of brightening after discovery, particularly after the Winter 1995–96 solar conjunction but, significantly, no sharp change in slope around discovery, indicating that there was no pre-discovery outburst. A prominent knee is then seen, initiating some 270 days before perihelion ($r \approx 4.0$ AU) when, over a period of $\approx$3 months there was almost no brightening. From 200 days before perihelion ($r \approx 2.6$ AU) there is fairly constant rate of brightening through to perihelion. The light curve is slightly asymmetric around perihelion, with both the apparent and the intrinsic maximum brightness occurring at $T \approx -2$ days, the former slightly later than had been expected.

4. The Light Curve Fit

The slope of the $m_1 - 5 \log \Delta$ against $\log r$ curve shows evident variations at different moments; although water is, by composition, the dominant volatile overall in the nucleus, water sublimation is not expected to start until approximately

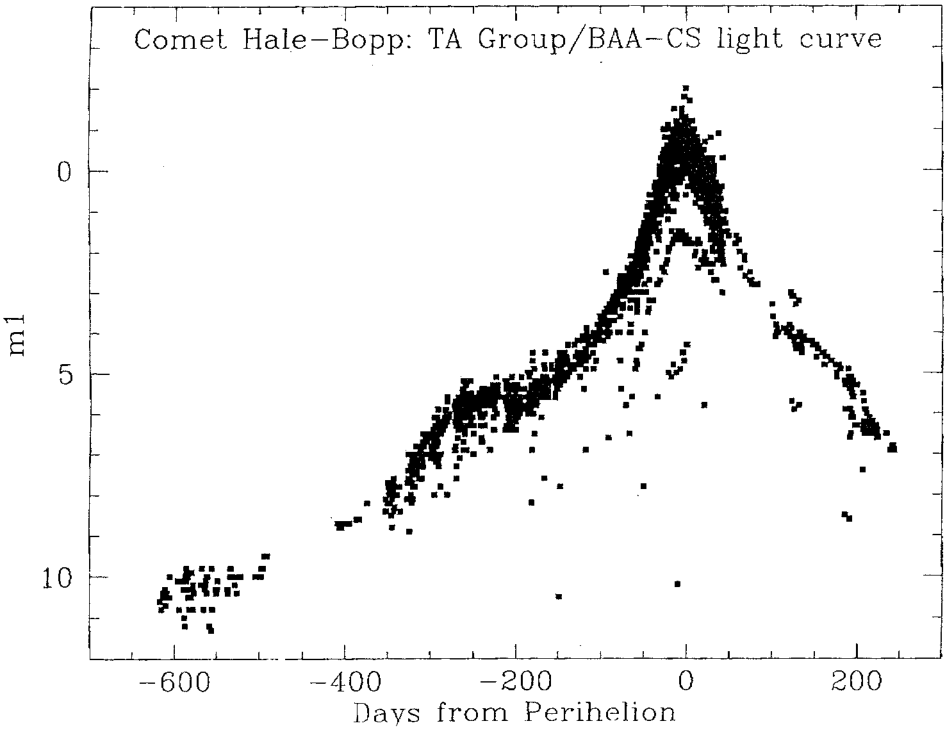

Figure 1. The raw light curve from the observations described in the text.

3 AU. Beyond 3 AU, at least out to 7 AU, the dominant volatile is found to be CO (Prialnik, 1997), although there is some water vapour activity present too, this is rapidly quenched.

At least five different brightening regimes, marked by changes of slope, can be identified in Figure 3, even without including the very rapid brightening at greater than 7 AU inferred from pre-discovery observations (Kidger, 1996).

The light curve compiled from the visible database was fitted by means of a series of least squares fits. A number of faint data points in the light curve have the effect of making the fitted absolute magnitude slightly fainter than would be found from a best eye fit to the data.

The general light curve solution is:

$$m_1 = m_0 + 5 \log \Delta + n \log r. \qquad (1)$$

Although an alternative presentation is sometimes preferred, replacing "n" with "2.5n", such that "n" becomes the index of the power law fit to the light curve. Here we adopt the former of the two conventions.

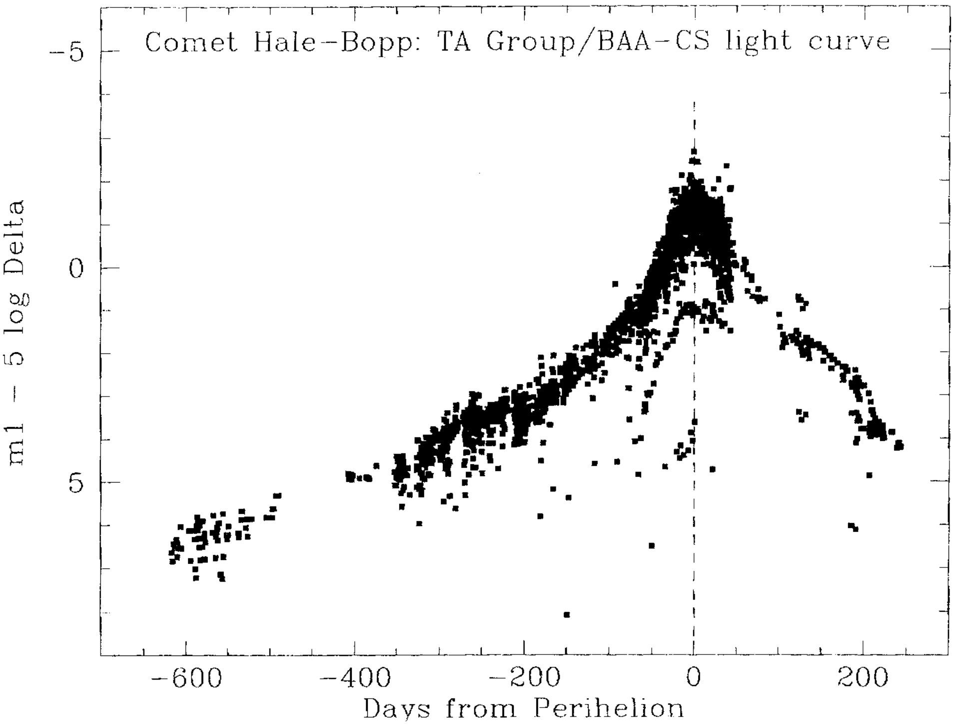

Figure 2. The light curve of C/1995 O1 (Hale–Bopp) corrected for changing geocentric distance.

TABLE II

Light curve evolution close to perihelion. A small outburst appears to have occurred shortly before perihelion, leading to a slight light curve assymmetry

Time relative to perihelion	Number of estimates	Median m_1	Median $m_1 - 5 \log \Delta$
−12 to −9 days	44	−0.6	−1.19
−9 to −6 days	37	−0.5	−1.10
−6 to −3 days	72	−0.7	−1.31
−3 to 0 days	72	−0.8	−1.44
0 to +3 days	64	−0.6	−1.29
+3 to +6 days	45	−0.6	−1.32
−2 to +2 days	91	−0.7	−1.38

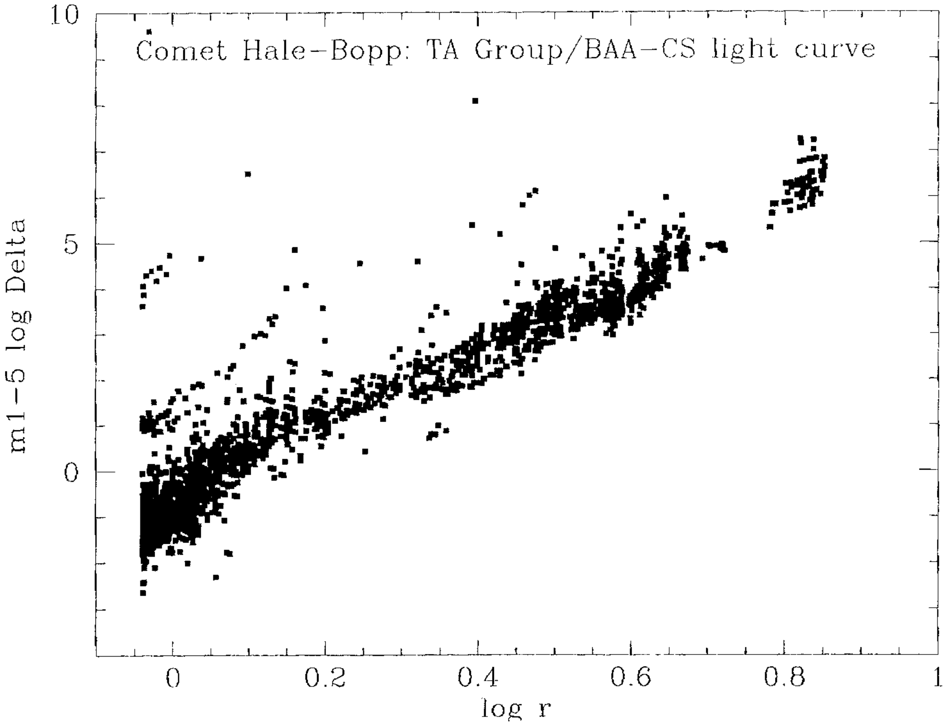

Figure 3. $m_1 - 5 \log \Delta$ against $\log r$ for the observations described in the text.

4.1. FITS TO INDIVIDUAL RANGES OF HELIOCENTRIC DISTANCE

4.1.1. $r > 4.0$ AU

There are 307 observations at $r > 4.0$ AU, from 1995 July 24 to 1996 June 25. These show a very bright absolute magnitude ($m_0 = -2.10$), surpassed only by comet Sarabat of 1737. The comparison between the two comets is valid as comet Sarabat reached perihelion at $q = 4.05$ AU, thus it was observed at the same heliocentric distance as comet Hale–Bopp. Both objects were faint naked-eye objects at this heliocentric distance. The light curve solution obtained is:

$$m_1 = -2.10 \pm 0.34 + 5 \log \Delta + 10.12 \pm 0.39 \log r. \tag{2}$$

The 1σ dispersion of the observations around this fit is −0.25, +0.29 magnitudes. At this distance from the Sun, whilst in the CO sublimation dominated regime, the comet followed the exact r^{-4} brightening law expected of a *well-behaved* comet.

4.1.2. $2.6 < r < 4.0$ AU

There are 572 observations over this range of heliocentric distance, made between 1996 June 25 and 1996 October 21. Over this period the light curve shows a “stand-still” with only a slow rate of brightening and, in consequence, a much fainter absolute magnitude from the fit, although this is still one of the ten brightest absolute magnitudes ever recorded and significantly brighter than even for acknowledged giant objects such as C/1927 E1 (Stearns). The light curve fit obtained is:

$$m_1 = +1.28 \pm 0.37 + 5 \log \Delta + 4.15 \pm 0.61 \log r. \tag{3}$$

The 1σ dispersion of the observations around the fit is -0.28, +0.29 magnitudes. Over this period the brightening law flattened to $r^{-1.5}$, although there is an interval when the comet actually faded slightly with decreasing heliocentric distance. At this point water sublimation had not started, although CO sublimation appears to have choked-off.

4.1.3. *2.1 < r < 2.6 AU*

There are 97 observations over this range of heliocentric distance, made between 1996 October 21 and 1996 November 30th. The light curve shows a renewed more rapid rate of brightening and, consequently, once again, a much brighter absolute magnitude. The light curve solution is:

$$m_1 = -1.04 \pm 0.67 + 5 \log \Delta + 9.46 \pm 1.70 \log r. \tag{4}$$

The 1σ dispersion around the fit is -0.36, +0.19 magnitudes. The light curve parameters have larger errors due to the relatively small range of heliocentric distance fitted. The brightening law is $r^{-3.8}$, close to the mean rate of brightening found in historical studies for “fairly new comets” (Oort, 1951). This section of the light curve corresponds to the range of heliocentric distance where water vapour sublimation began to dominate the comet’s activity. The switch-on distance for water vapour activity obtained from the light curve (r = 2.8 AU) is very close to that estimated by (Prialnik, 1997), of r = 3 AU.

4.1.4. *1.07 < r < 2.1 AU*

There are 517 observations over this range of heliocentric distance, made between 1996 November 30 and 1997 February 28. A renewed slow-down is seen, although the absolute magnitude ($m_0 = -0.09$) is still one of the brightest ever recorded. The light curve fit is:

$$m_1 = -0.09 \pm 0.67 + 5 \log \Delta + 7.33 \pm 2.03 \log r \tag{5}$$

The 1σ dispersion of the observations around the fit is -0.40, +0.25 magnitudes. The brightening law at this distance, where water sublimation is completely dominant, r^{-3}, is close to the mean value for new comets found by (Oort, 1951).

4.1.5. *0.91 < r < 1.07 AU*

The section of the light curve around perihelion is the best sampled, with 598 observations, mainly made with the naked-eye, or binoculars of small aperture. The observations cover the period front 1997 February 28 to 1997 April 1. Here we see the fastest rate of brightening of any section of the light curve out to r = 7 AU. The absolute magnitude (m_0 = −0.63) confirms the comet as one of the intrinsically brightest objects ever seen at this heliocentric distance. The light curve fit obtained is:

$$m_1 = -0.63 \pm 0.93 + 5 \log \Delta + 10.29 \pm 0.58 \log r. \tag{6}$$

The 1σ dispersion around this fit is −0.50, +0.30 magnitudes, the largest dispersion seen in any section of the light curve, probably due to the large coma diameter and the difficulty of separating the coma and the tail in the magnitude estimate. As at $r > 4.0$ AU, the brightening law is r^{-4}, rather faster than is normal for a comet at this distance from the Sun; this rapid brightening led to comet Hale–Bopp being somewhat brighter than had seemed probable at Christmas 1996.

4.1.6. *Post-perihelion, 0.91 < r < 2.1 AU*

The light curve is still extremely well sampled, with a mostly homogeneous set of observations, despite the increasing difficulties of observing the comet from the northern hemisphere as the declination decreased. There are 659 observations in this interval. The rate of fade at this distance is similar to the rate of brightening observed at the same distance pre-perihelion, although the absolute magnitude (m_0 = −0.78) is somewhat brighter. Due to this relatively slow fade the comet remained a bright object for longer than expected. The duration of its visibility as a negative magnitude object (7 weeks) seems to be the longest ever seen in a comet. The light curve solution obtained is:

$$m_1 = -0.78 \pm 0.65 + 5 \log \Delta + 7.95 \pm 1.97 \log r. \tag{7}$$

The 1σ dispersion around this fit is −0.49, +0.40 magnitudes.

4.1.7. *Post-perihelion, 2.1 < r < 3.6 AU*

The light curve sampling becomes sparse due to the comet's solar conjunction and visibility only from the southern hemisphere, away from the largest concentration of comet observers in the world.

The comet initiated a more rapid rate of fade, with water vapour sublimation apparently switching-off at a much lower heliocentric distance post-perihelion than it had switched-on pre-perihelion, leading to a deceptively bright, nominal value of the absolute magnitude. The rapid fade led to the comet ceasing to have naked-eye visibility relatively early, whereas a symmetrical light curve about perihelion would have permitted it to remain visible well into 1998. Despite this, the period of naked-eye visibility (19 months, 1996 May 17 to 1997 December 9), is more than double the previous longest naked-eye visibility ever recorded for a comet (9 months, for C/1811 F1 (Flaugergues)). The fit to the light curve is:

$$m_1 = -2.61 \pm 0.54 + 5 \log \Delta + 12.15 \pm 0.98 \log r. \tag{8}$$

The 1σ dispersion of the observations around this fit is -0.42, +0.28 magnitudes. The rate of fade increased steadily at this time. A more limited data set of 65 points exists for $3.26 < r < 3.84$ AU which show that "n" increased significantly. The fit over this rather limited range of heliocentric distance (November and December 1997) is:

$$m_1 = -3.40 \pm 0.13 + 5 \log \Delta + 13.82 \pm 0.25 \log r. \tag{9}$$

Thus the brightening (or, to be pedantic, fading) law is $r^{-5.5}$ for the most recent observations, significantly steeper than at any other time covered by this study, although similar to the brightening law seen at $r > 7$ AU pre-perihelion.

4.2. THE ABSOLUTE MAGNITUDE AT A HELIOCENTRIC DISTANCE OF 1.0 AU

The *median* absolute magnitude registered pre- and post-perihelion, from observations made at exactly r = 1.0 AU is:

Pre-perihelion, $m_0 = -0.91$, 28 observations

Post-perihelion, $m_0 = -1.08$, 18 observations.

We thus find that the absolute magnitude is slightly brighter at 1 AU post-perihelion than during the approach to perihelion. Part of this difference is apparently due to a small outburst near perihelion. The absolute magnitudes are brighter than the least squares regressions due to the skewed distribution of the observed total visual magnitude estimates at any epoch, which will give a somewhat fainter mean than median value.

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