COMET HALE–BOPP (1995 O1)

Possible Photometric Evolution

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Abstract. Considerable interest has been raised by the discovery of Comet Hale–Bopp (1995 O1) and the possibility that it might become a very bright object in Spring 1997. The evidence to support either of the conflicting hypothesis (an intrinsically bright comet or a faint comet in a very large outburst) is too limited to reach solid conclusions and may remain so for some months yet. The pre-discovery observations encountered to date provide some limits to photometric models and suggest that the comet may be intrinsically bright, but do not yet permit a firm discrimination, even between extreme scenarios, due to the enormous extrapolation that must be made from the heliocentric distance at discovery, to that of perihelion.

Key words: Comets, named objects, Comet Hale–Bopp (199501), photometry

1. Introduction

The discovery, by Alex Hale and Thomas Bopp, of Comet 1995 O1, as a 10th magnitude object, on July 23rd 1995 (Hale and Bopp, 1995) caused a great deal of interest in the astronomical community, particularly when it became evident (Marsden, 1995) that the comet, at discovery, was at an exceptionally high heliocentric distance. In fact, the heliocentric distance of 7.1 AU is, by some distance, the highest ever for a visual discovery and is extremely high for discoveries of any kind. This has led to speculation that the.comet is either an exceptionally large object and intrinsically very brilliant (Marsden, 1995a) or, alternatively, may be suffering a very large outburst (Offutt and Sekalina, 1995).

The recognition of a number of pre-discovery images and, most critically, an image at a heliocentric distance of 13.1 AU (McNaught, 1995), has lent credance to the hypothesis that Comet Hale–Bopp is a particularly large and intrinsically brilliant object and was not in a major outburst at discovery. In view of the possible importance of the object it is of considerable interest, a very least, to attempt to delimit the range of possibilities for the future evolution of the light curve. This study aims to give an idea of the possible future photometric evolution of Comet Hale–Bopp, based on different initial conditions.

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2. The Data

A quite large number of total visual magnitude estimates of Comet Hale–Bopp (1995 O1) have been made in the short time since discovery. These have been published in various IAUCs (e.g. 6194, 6202). Pre-discovery (photographic) observations have also been reported (McNaught, 1995; Riepe *et al.*, 1995), George and Dickinson, 1995) which extend the light curve somewhat back in time.

It is evident, even from a superficial study of the observations, that the total visual magnitudes show a great deal of dispersion. Part of this dispersion is due to the so-called aperture correction; observations with larger apertures consistently give fainter magnitudes than those made with smaller apertures. Part may be due to true variation in the magnitude of the comet, particularly if it is in outburst.

To estimate the aperture correction, all the available total visual magnitude estimates listed above were were examined, assuming that they showed no time variation over the approximately one week which was covered. Observations were then reduced to a standard aperture of 6.78 cm. A relation of the type

$$m_{\text{obs}} = m + 0.017A \quad (1)$$

was found, where A is the aperture used, measured in centimeters. This relation should though be treated with some reserve, as the majority of observations were made with apertures in the range of 35–41 cm. The value of the aperture correction estimated here is approximately double that of 0.08 mag/cm derived for Comet Halley (Fischer and Huttemeister, 1987), but is by no means outlandish for a comet described visually, as being rather diffuse.

3. Absolute Magnitude and Possible Photometric History

Applying the estimated aperture correction, a corrected mean total magnitude estimate for late July 1995 may be found.

$$m_1 = 10.06 \quad (2)$$

at distances of r = 7.105 AU, Δ = 6.194 AU.

If one assumes an inverse 4th power magnitude law, i.e. in the standard equation for describing the total magnitude of a comet as a function of its geocentric distance (Δ) and heliocentric distance (r)

$$m_1 = m_0 + 5\log\Delta + n\log r \quad (3)$$

a value of $n = 10$ is supposed, we can estimate the absolute magnitude m_0 of the comet at discovery of:

$$m_0 = -2.4 \quad (4)$$

Table I
The ten brightest known comets, in terms of absolute magnitude (m_0). Adapted from Hughes (1987)

Year	Name	m_0
1729	Sarabat	−3.0
1577	(Tycho)	−1.8
1747	De Chéseaux	−0.5
1811 I	Flaugergues	0.0
1744	De Chéseaux	+0.5
1882 II	Cruls	+0.8
1914 V	Delavan	+1.1
1433		+1.2
1962 VIII	Humason	+1.35
1500		+1.6
1807	Great Comet	+1.6

This absolute magnitude is quite exceptional, as may be seen by comparing it with the ten intrinsically brightest comets observed during the last six centuries:

Superficially then, Comet Hale–Bopp would appear to have the second brightest absolute magnitude known to date. Adopting the formula of Delsemme (1987) for the radius of the nucleus:

$$r_{\rm nuc} = 10^{1.59-0.199 m_0} \tag{5}$$

we find a possible diameter of ~240 Km. This diameter is comparable with the largest Kuiper Belt objects reported to date (Jewitt and Luu, 1995).

For comets in outburst though, such magnitudes are not unprecedented. A sample (by no means exhaustive) of typical comets in outburst is given in Table II, below:

Table II shows that, if Comet Hale–Bopp is assumed to be in outburst, its absolute magnitude at maximum outburst is comparable to the outbursts of intrinsically bright objects (eg: P/Halley, P/Schwassmann–Wachmann 1) rather than intrinsically faint, or very faint objects (e.g. P/Holmes, P/Biela, P/Metcalf–Brewington). This table *suggests* that, even if the comet is in outburst, it is likely to have $m_0 < 4$ in quiescence.

3.1. THE PRE-DISCOVERY OBSERVATIONS

The majority of pre-discovery observations were made during Summer 1995; these are amateur photographic plates which have later been examined and found to include images of the comet. These recent pre-discovery images give magnitudes which are slightly fainter than the discovery magnitude. When one takes into

Table II

Some well known cometary outbursts showing the change in absolute magnitude between outburst and the normal, quiescent state of the comet

Comet	m_0 (outburst)	m_0 (normal)	Notes
Schwassmann–Wachmann I	−5.5	3.1	(1, 2)
Halley	−2.8	3.9	(3, 4)
Metcalf–Brewington	9.5	>15.9	(5, 6)
Holmes	6.0	10.9	(1, 2)
Biela	7.1	?	(2, 7)

(1) Absolute magnitude in quiescence according to Hughes.
(2) Absolute magnitude in the brightest observed outburst calculated from the brightest total magnitude listed by Kresák and Kresákova (1987).
(3) Absolute magnitude derived by Fischer and Hüittemeister (1987).
(4) 1992 outburst to $m_1 = 19$.
(5) Absolute magnitude from Kresák and Kresákova (1987) for the 1906 apparition.
(6) Estimated nuclear magnitude from Kidger (1992).
(7) Never observed in quiescence, assumed to be very faint, or defunct.

account a possible 1.5 magnitude increase in brightness of the comet with decreasing heliocentric distance between March 1995 and discovery and the tendency of photographic observations to underestimate the total magnitude, the 1995 pre-discovery images are consistent with constant absolute magnitude. This implies that any outburst has been of comparatively long duration and stable maximum. The image reported by George and Dickinson (1995), on 1995 May 29.40, at m_1 = 11.7 is unexpected bright, when taking into account the greater heliocentric and geocentric distances, compared to Riepe *et al.* (1995); this suggests that there may have been a small outburst during Summer 1995, but is not, in itself, compelling evidence.

The two pre-discovery observations by McNaught (1995), a presumed positive sighting at r = 13.07, Δ = 12.68 AU (1993 April 27th) and a negative observation at r = 16.7, Δ = 16.2 AU (1991 September 1st) theoretically allow the light curve's photometric history to be extrapolated backwards in time by several years and a considerable range in heliocentric distance.

The positive detection, at an estimated $m_1{\sim}18$, $m_2{\sim}19$, whilst the comet was at $r > 13$ AU also suggests that Comet Hale–Bopp is an intrinsically bright object, although it does not rule out the presence of a significant outburst component to the total magnitude at discovery.

Table III

Photometric solutions for the light curve of Comet Hale–Bopp, based on the recent post-discovery total visual magnitude estimates, published on IAUCs, combined with the remote pre-discovery observations by McNaught. c is the correction to the McNaught photographic magnitude to make it compatible with total visual magnitude estimates

c	n	m_0
1	20.3	−11.2
2	16.6	−8.0
3	12.8	−4.8
3.7	10	−2.4

Unfortunately, these magnitudes are very approximate estimates which are not photometrically calibrated. As the total magnitude was estimated photographically and with a large (1.2 m) aperture, the possibility arises that the true m_1 might be rather brighter. The aperture correction estimated in Equation eaote would, for a 1.2 m aperture, give an estimated correction of 2.0 magnitudes. Photographic, or even CCD magnitudes, may underestimate the total brightness of a comet by one magnitude, or more (compare the visual total magnitude estimates of Comet Hale–Bopp with the values on, for example, IAUC 6188) because of failure to register the true extent of the coma. In other words, for these photographic data:

$$m_1 = m_{\text{obs}} - c_{\text{ap}} - c_{\text{phot}} \tag{6}$$

In the case of a photographic observation with a large aperture, it is not clear if the two terms are additive, or even if $c_{\text{ap}} > 0$. Hence we group the two terms and define:

$$m_1 = m_{\text{obs}} - c \tag{7}$$

To investigate the photometric evolution, we must calculate m_0 and n for a range of values of c. If we define:

$$c = [0, 1, 2, 3] \tag{8}$$

we may calculate a range of possible photometric solutions. We assume that the comet has obeyed Equation (3) exactly and that the outburst amplitude:

$$A_{\text{outburst}} = 0 \tag{9}$$

The photometric solutions which are obtained, are shown in Table III:

Any of the above relations *for an active nucleus*, would put the comet close to, or below the plate limit for the 1991 UK Schmidt plate. The comet would be from

1.6–2.7 magnitudes fainter at the greater heliocentric distance. The estimate of 1 magnitude difference at the larger heliocentric distance (IAUC 6198) corresponds to the relation for a bare nucleus:

$$m_2 = m_0 + 5\log\Delta + 5\log r \tag{10}$$

Thus, if the comet were active at high heliocentric distance, there is no prima facie evidence of outburst from the fact that the comet was not detected 19 months before the first positive pre-discovery observation. Activity at such high heliocentric distances is unusual, but not unprecedented (e.g. 2060 Chiron at aphelion of 18.5 AU (Bus *et al.*, 1993); Comet P/Halley at 14.3A U (Hainault *et al.*, 1992); Comet Bowell (1982 I) at ~10-12 AU and Comet Torres (1987 V) at ~13 AU (see: Meech (1993) for a summary of observations of these two comets). Whilst the $1/a$ values are +0.000027 and +0.000059 for Comets Bowell and Torres respectively (Marsden and Williams, 1992), implying that they are "new" comets, both P/Halley and 2060 Chiron are considered very old objects, which have completed many revolutions around the sun.

If the correction term defined in Equation (7) is very small ($c \leq 2.5$) we find extremely high discovery absolute magnitude and an improbably large value for n. These values would imply that a substantial outburst had occurred. Values of c~3 magnitudes, give credible photometric solutions without implying a major outburst and may still be consistent with the negative, September 1991 observation.

Even consistent solutions with n~10 do not demonstrate that an outburst has not occurred, they simply imply that one is not needed to account for the two early prediscovery observations. If an outburst has occurred, it is probable that it took place at $r > 13$ AU and has given a quite stable absolute magnitude for more than 2 years. Such long lasting outbursts are not unknown, as it is supposed, due to its sudden disappearance, that Comet P/Biela may have remained in outburst for its entire observational history (1772–1852).

Taking the outbursts of Comet Halley and P/Schwassmann–Wachmann 1 as the reference point for outbursts in large and relatively active cometary nuclei, it is probable that the outburst amplitude is, at most, 6–8 magnitudes. The absolute magnitude of Comet Hale–Bopp at discovery is not inconsistent with that obtained by moderately large comets in major outbursts. A 6 magnitude outburst amplitude would make the true absolute magnitude of Comet Hale–Bopp m_0~3.5, still well above the average for new discoveries. In this case the comet would not be a brilliant object close to perihelion, but would reach naked eye visibility.

If Comet Hale–Bopp is not in outburst and the current absolute magnitude is a true reflection of its brightness, a continuation of the [$n = 10$, $m_0 = 2.4$] law through to perihelion would suggest a maximum of $m_1 \sim -2.2$, whilst a [$n = 12.8$, $m_0 = -4.8$] law would give a *theoretical* maximum of $m_1 \sim -4.6$. Even when we consider that, at $r < 1.5$ AU, the value of n usually reduces sharply, as the nucleus switches to water sublimation generated activity, from the sublimation of more volatile ices, maximum magnitudes of $m_1 \sim -1$ and $m_1 \sim -2$ are still possible.

If such a breakpoint in the light curve is though, combined with a significant outburst amplitude at discovery, Comet Hale–Bopp might be a difficult naked-eye object at best. Even moderately optimistic scenarios can thus give disappointing near-perihelic performance. The distribution of probable maximum magnitude, according to scenario, is somewhat skewed to the lower end of the magnitude range. The most pessimistic scenario might even see the comet disappear gradually, before even reaching

4. Conclusions

There are a least three possible hypotheses to explain the bright absolute magnitude of Comet Hale–Bopp at discovery:

(1) That it is an intrinsically faint comet which has suffered an exceptional outburst. The worst-case scenario.

(2) That it is an intrisically bright comet which has suffered and important outburst.

(3) That it is an intrinsically very bright comet, which is showing normal light curve activity. The best-case scenario.

Of the three, the first can probably be ruled out due to the very bright absolute magnitude, which appears inconsistent with the capabilities of a very faint cometary body. The various pre-discovery observations also suggest that there has been no really major outburst. At present though, the available observations are unable to distinguish clearly between hypothesis (2) and (3). The range of magnitude at perihelion between these two, most probable scenarios, can still be extremely large ($\sim$10 magnitudes) though, depending on the extrapolation that is made of the light curve. The best combination of circumstances would give a maximum in late March and early April 1997 of $m_1 \sim -4$, making Comet Hale–Bopp one of the ten brightest objects ever seen (see Table II in Kidger, 1994); a worst combination of circumstances would give a maximum around $m_1 \sim +6$, making this comet a very difficult naked-eye object at best.

If we take a middle value between the two extremes, there is a reasonable probability that Comet Hale–Bopp will reach a total visual magnitude of $m_1 \sim +1$, unless its activity at high heliocentric distance is playing us false. If the worst case scenario is the correct one, we might reasonably expect large deviations of the light curve from its expected brightening to become rapidly obvious, probably before the end of 1995.

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Note Added in Proof

Orbital calculations made from post-discovery observations only cast doubt on both the Dickinson and George and the McNaught pre-discovery observations [Yeomans, 1995, Internet posting, Comet Hale–Bopp Home Page], although both observations seem to be of genuine cometary objects. At present it is not clear what the true situation is with them; if neither is really Comet Hale–Bopp then there has either been a large outburst of the comet, or the nucleus has suddenly "switched on" at around $r = 7.5$ AU. The large diameter of the nucleus estimated from HST observations (Weaver, H., 1995, Internet posting, Comet Hale–Bopp Home Page) supports a bright absolute magnitude $M_0 \sim +1.5$) rather than a bright outburst.