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CCD Photometry of Comet C/1995 O1 (Hale-Bopp): 1995 - 2000*

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Abstract. Some 360 nights of CCD V-band photometry of the inner region (34″) of comet C/1995 O1 (Hale-Bopp) were carried out over an interval of 4.47 years, beginning when the comet was at heliocentric distance r = 7.1 AU, continuing in to r = 1.02 AU, and ending finally at r = 10.3 AU. Before perihelion, the magnitude brightened fairly steadily, with power-law exponent n = 2.55, and — as has been shown elsewhere (Liller 1997) — a well-established 20-day (± 5 days) periodicity persisted for a few months in late 1995. Following perihelion, the character of the light curve changed dramatically. The rate of fading was characterized at first by n = 4.46, but after passing r = 2.5 AU, the comet's brightness decreased irregularly at a rate of $n \approx 2.5$, with the fading interrupted by at least five spectacular outbursts. The projected velocities of the outward flow of material ranged from 62 to 217 m/sec. After perihelion, the brightness of the quiescent comet averaged ≈ 0.18 magnitude fainter than before perihelion.

Introduction.

Shortly after the discovery of comet C/1995 O1 (Hale-Bopp), the author, having at his full-time disposal a fast Schmidt camera equipped with a CCD, embarked on a systematic program of broadband V photometry. The camera, a Celestron 0.2-m $f/1.5$ system designed for photography, had been provided to the author by NASA as a part of NASA's International Halley Watch (see Niedner and Liller 1987 for a description of the program and sample photographs). It has since been on indefinite loan to the author with the proviso that it be used in part for comet research, and is now installed in the author's private observatory in Viña del Mar, Chile. The CCD is an SBIG ST-5 camera having a TC-225 chip with 10-micron pixels; it is mounted at the "Newtonian focus" of the Schmidt camera. At the focus, a pixel measures 6″.8 × 6″.8; the field dimensions are 36′ east-west by 27′ north-south. In the light path is a minus-IR filter (Corion NR-400), chosen after much experimentation to produce a high-throughput passband with an effective wavelength close to that of the standard V system. Its long wavelength cut-off is at ≈ 7200 Å. Measurements of standard stars showed that, at a typical air mass of around 1.3 in the relatively humid atmosphere of the coastal location, the deviations from true V magnitudes over a wide range of $B-V$ colors were never more than a few hundredths of a magnitude (see Liller 1997 for a sample calibration curve).

Observing Program.

Observations were made on most reasonably clear nights when the author was at home, beginning 1995 August 3. This translates into occasional absences of a few weeks at a time, and otherwise an average of three times a week in the southern summer months, and once or twice a week in the winter, with somewhat poorer coverage when the comet was

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in the pre-dawn sky owing to frequent morning fog. Before the availability of magnitudes from the Hipparcos and Tycho projects, magnitudes were determined by observing standard stars and well-photometered cluster stars located nearby, but since then, there have nearly always been several stars in the CCD frame with accurately known V magnitudes. So that the signal from stars as bright as 8th magnitude would not be saturated, individual exposure times were never longer than about 10 seconds, and from 8 to 25 frames were co-added so that the total number of photons recorded from the comet would be great enough to insure accuracies of a few hundredths of a magnitude.

Using the SBIG software, one can select analyzing squares measuring 20″, 34″, 48″, 61″, and 75″ on a side. Because of the relatively strong light pollution from the nearby population centers, and because the comet spent much of its time in and near crowded Milky Way fields (and the Large Magellanic Cloud), it was decided that the observations would, at least for this report, be reduced using the 34″ aperture rather than one of the larger apertures. The individual unpublished magnitudes are being published in this issue of the *International Comet Quarterly*[1]; a description and analysis of these observations follows.

Pre-perihelion behavior.

Following the procedure outlined by Morris and Hanner (1993), the broadband V magnitudes, V_{bb}, were converted to V_o magnitudes by removing the effect of the changing earth-comet distance with the expression $V_o = V_{bb} - 2.5 \log \Delta$. The comet's pre-perihelion light curve appears in Figure 1, together with a selection of visual-magnitude estimates taken from the *IAU Circulars*. A similar curve, but using $V_{bb} - 5 \log \Delta$ for the ordinate, has been published and discussed elsewhere (Liller 1997), but for the sake of convenience — and since a different reduction procedure is followed here — it is felt desirable to include the revised light curve in this report. Notably, it was found that during the first four months after discovery, when $\log r > 0.75$, a discrete Fourier-transform analysis showed that the comet brightness varied periodically with $P = 20 \pm 5$ days with a full amplitude of ≈ 0.20 magnitude. A similar periodicity had been reported by others (Sekanina 1995; Jorda *et al.* 1997). However, during later months, no periodicity could be detected in the photometric data.

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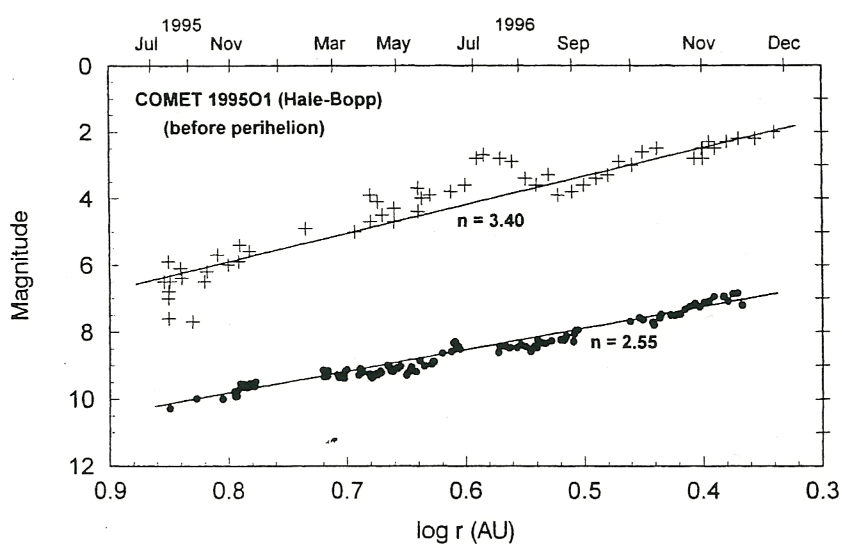

Figure 1. Heliocentric magnitudes, V_o, of the inner region of comet C/1995 O1 before perihelion passage (filled circles). The magnitudes were measured with a CCD using a 34″ square aperture with a broadband V filter. Representative heliocentric visual magnitudes taken from the IAU Circulars are plotted on the same scale (plus signs). A least-squares straight-line fit through the CCD observations is also shown; the location of the straight line through the visual observations was estimated by eye.

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[1] Editor's note: Those magnitudes made by Liller during 1995 Aug. 2-1996 Nov. 19 and published in his 1997 paper (pp. 1507-1508), which were given there to hundredths of a magnitude, have all been added directly into the *ICQ* archive without republication, though with magnitudes rounded to tenths (in the *ICQ*'s usual fashion of "rounding even"), because the estimated errors were stated in the paper to be generally ± 0.03 to 0.12 mag, and sometimes as much as ± 0.2 mag). The previously unpublished magnitudes by Liller (spanning 1997 Apr. 25-2000 Jan. 21), which appear in the tabulation of observations later in this same issue of the *ICQ*, were thus also rounded to tenths of a magnitude.

A least-squares fit to the CCD data points of Figure 1 shows that V_o brightened at the rate $n = 2.55$, and that the data points are never more than 0.5 magnitude from this straight line. However, it should be remembered that "numerous observers ... reported steady, strong jetting activity from both visual and CCD observations" in mid-1996 (cf. *IAUC* 6463), and outbursts were reported optically in September of that year (see, *e.g.*, Schulz *et al.* 2000). For reference, a straight line with $n = 3.40$ has been put through the visual estimates.

Post-perihelion behavior.

Following perihelion passage, the variation in the CCD brightness took on an entirely different nature, as the light curve in Figure 2 shows. Again, selected visual observations have been included. At least five outbursts are evident, and they will be discussed in the next section.

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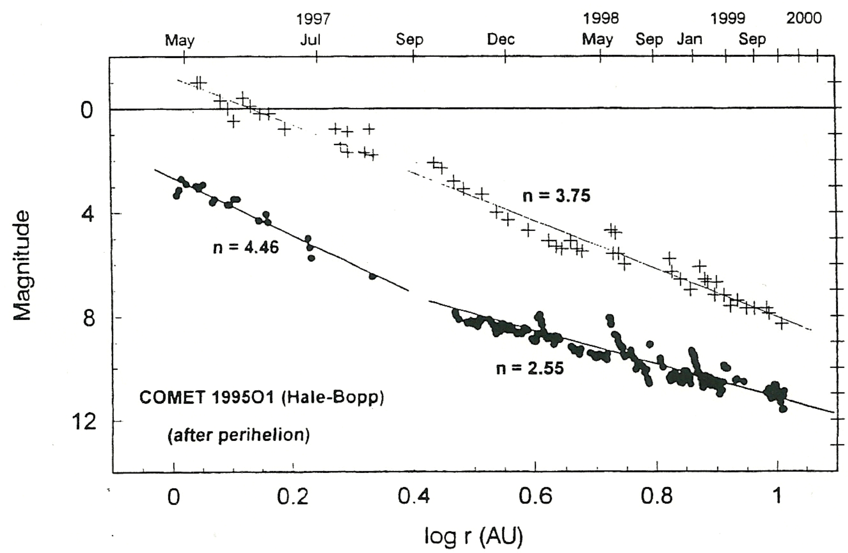

Figure 2. Heliocentric magnitudes of the inner region of comet C/1995 O1 after perihelion passage. The plotted quantities are the same as in Figure 1. However, the line extending from 0.4 < log r < 1.012 is the same least-squares straight line that appears in Figure 1 — indicating that the comet, when quiescent, was running approximately 0.18 magnitude fainter than before perihelion.

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During the first several months after perhelion, the magnitudes showed a clear change in rate of fading. A least-squares fit to the data in the range $0 < \log r < 0.4$ yields $n = 4.46$ — substantially steeper than the brightness behavior before perihelion. It should be noted, however, that the several pre-perihelion points at $\log r > 0.4$ do seem to show an upturn (see Figure 1), and with r now < 2.5 AU, the increasingly prominent appearance of emission bands would be expected to cause the comet to brighten more rapidly. But by $\log r > 0.45$, the brightness of the comet underlying the outbursts decreased at a slower rate; an eye-estimate of the slope yields $n \simeq 2.5$, effectively in agreement with the pre-perihelion slope.

To compare the pre- and post-perihelion behaviors at $r > 0.45$ AU, the least-squares fit to the pre-perihelion data is reproduced in Figure 2 as the straight line labelled $n = 2.55$. As can be seen, after perihelion, the quiescent comet was running ≈ 0.18 mag fainter than before perihelion.

The post-perihelion outbursts.

The characteristics of the five major post-perihelion outbursts are summarized in Table 1. Here r and D are the heliocentric and geocentric distances to the comet in AU, dm is the amplitude of the outburst in magnitudes (as measured through the $34'' \times 34''$ aperture), dt is the number of days since previous outburst, and t1 is the number of days for the outburst to fade 1.0 magnitude. Owing to interruptions in the observing, the rate of decline of the third and fifth outbursts could not be determined precisely.

The fourth outburst was also noted by Garradd (1998), who reported "a remarkable 3-mag brightening of the nuclear region of this comet between his CCD observations on Dec. 11 and 21"; and by Pearce (1998), observing visually, who found on Dec. 18.78 that "at low power the nuclear condensation contributed 90-95 percent of the light" and "by Dec. 25.75 the condensation had enlarged and dispersed though the coma". Later, Pearce (1999), and Griffin and Bos (1999), reported an apparent outburst in mid-October 1999 when $\log r = 0.98$. No clear outburst was observed then in Viña del

TABLE 1. Major Post-Perihelion Outbursts.

#	Date (yyyy mm dd)	r (AU)	D (AU)	dm (mag)	dt (days)	t1 (days)
1	1998 01 11	4.03	3.88	0.8	-	19
2	1998 05 13	5.26	5.44	1.6	122	21
3	1998 08 17	6.15	6.30	1.4	96	< 39
4	1998 12 20	7.23	7.28	1.1	125	25
5	1999 04 14	8.16	8.21	0.7	115	< 76

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Mar; however, the coverage was sporadic during that time.

The largest and best observed outburst, number 2 (Table 1), occurred 97 hours after the previous observation, and Figure 3 shows its light curve in detail. Here the rapid increase in brightness is well emphasized, as is the slow exponential decay. It is possible that a small outburst occurred around log $r = 0.75$. In Figure 4 we see an enlargement of CCD frames, with the outburst image subtracted from the comet image taken 18.9 days later; the two images were centered on the pixel of highest counts. The inital outburst is the small sharp-edged black circle (diameter $\approx 42''$), with the much expanded outburst appearing as an irregular white cloud situated primarily to the north-northeast of the nucleus. (The direction to the sun is in the direction 33° west of north.) The images show that the brightness of the central $6''.8$ (26800 km) pixel increased by 2.6 magnitudes. The disturbance propagated outwards at a projected velocity of $\approx$ 62 m/sec. The noticeable asymmetry of the outburst, relative to the center of the coma, became apparent about a week after the outburst.

Analyses of outbursts numbers 1 and 4 yield projected propagation velocities of $\approx$ 171 and $\approx$ 217 m/sec, respectively. Because of the spotty coverage, no attempt was made to derive expansion velocities of the other two outbursts. Moreover, it may well be that there was an additional outburst several weeks after the occurrence of outburst number 3.

Uncertainties in these velocities arise primarily from the difficulty in determining precisely the location of the outermost edge of the expanding cloud. The estimated uncertainties in the values given above range from $\pm$ 20 m/sec for the first outburst to $\pm$ 40 m/sec for the fourth.

The expansion velocities derived here, 62 to 217 m/sec, are very similar to those reported for the pre-perihelion outbursts of September 1996, namely from 112 to 225 m/sec (see Larson *et al.* 2000; Schultz *et al.* 2000; Tao *et al.* 2000).

Conclusions.

More than 360 nights of broadband-V CCD observations were made of comet C/1995 O1 during the more-than four years that the comet was followed with a dedicated telescope from Viña del Mar. Comparison of the pre- and post-perihelion light curves (Figures 1 and 2) shows striking differences: before perihelion the rise in brightness was relatively steady, but after perihelion five major outbursts were observed.

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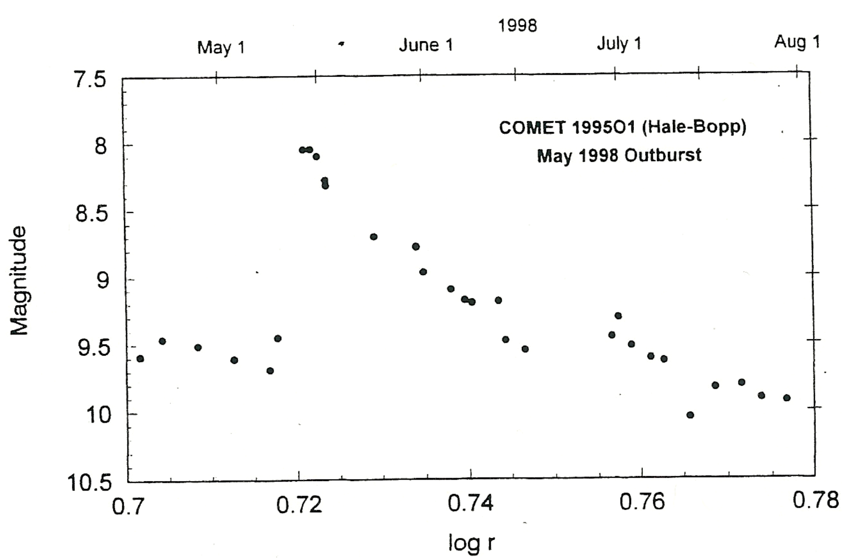

Figure 3. The light curve of the outburst of May 1998. The plotted quantities are the same as in Figure 1.

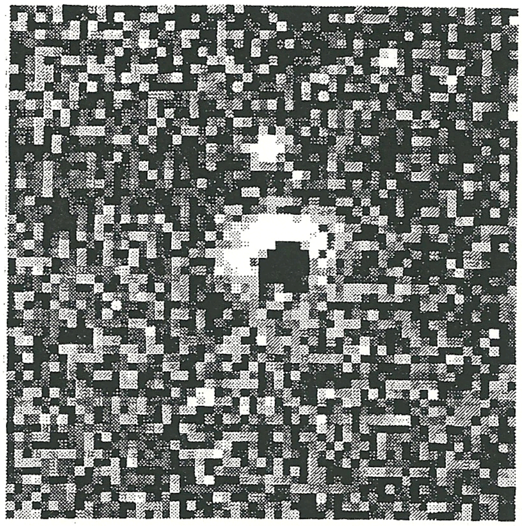

Figure 4. The CCD V-band image of comet C/1995 O1 taken during the outburst of 1998 May 13, subtracted from an image of the comet taken 18.9 days later. The outburst appears as the irregular black area near the center, with the white cloud of expanding material appearing mainly to the north and northeast. The frame measures 6'.5 square; pixels are 6''.8 square. North is up; east to the left.

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The approximately equal spacing of the outbursts, the roughly equally strong flare-ups, and the similar expansion velocities strongly suggest that the outbursts were caused by recurrent activity in the nuclear region of the comet rather than the result of collisions with asteroidal objects. In many ways the behavior of comet C/1995 O1 resembles that of comet 29P/Schwassmann-Wachmann, where outbursts can be as large as five magnitudes with expansion speeds of 100 to 500 m/sec (see Hughes 1975). However, there is one important difference: for comet C/1995 O1, the outbursts occurred over a wide range of heliocentric distance, while the solar distance of comet 29P varies only from 5.76 to 6.48 AU. Although it is generally accepted that these outbursts result from the sudden release of dust, it would be interesting to have spectral information on or shortly after the above-listed dates of outburst.

Acknowledgements.

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