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A jet-related colour change in the inner coma of comet Hale-Bopp (1995 O1)?*

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Abstract. Comet Hale-Bopp (1995 O1) has been intensely monitored with the 82cm IAC-80 Telescope at Teide Observatory, Tenerife, Spain. Multicolour photometry taken on various nights in mid-August 1995 shows that the inner coma was redder than solar colours, with a power law spectrum of index ~ -3.5, consistent with dust scattering. A large change in the colour indices to a rather bluer colour and much flatter spectrum was observed simultaneous with an increase in the brightness of the inner coma. This occurred shortly before the August jet event was detected. Extrapolation of the jet expansion back to the origin suggests that the brightening and colour change may have been the initial stages of the formation of the jet. We suggest that it was due to a change in the scattering properties of the circumnuclear region, caused by the ejection event of small, icy grains and/or an increment in the gas to dust ratio.

Key words: comets: Hale-Bopp (1995 O1)

1. Introduction

Comet Hale-Bopp (1995 O1) has been intensely observed with many telescopes around the world since its discovery on July 23rd 1995. The reason for the high degree of interest shown in the comet is its very large heliocentric distance at discovery, combined with an extremely bright absolute magnitude. This has led to comparisons being made (Marsden, 1995) with Comet Flaugergues (1811 F1), a comet with a similar orbit and absolute magnitude to Comet Hale-Bopp, which was a spectacular naked-eye object (Kronk, 1984) despite its perihelion being slightly outside the Earth's orbit.

Comet Hale-Bopp has shown a high degree of activity, virtually unprecedented in a comet at such a large heliocentric distance. The most spectacular aspect of its behaviour has been the series of spiral jets observed in the inner coma (eg: Offutt, 1995; Jewitt and Luu, 1995) which show an average interval between them of 19.5 days. These jets are potentially able to supply information on the nuclear rotation, orientation and position of the vents that cause them. Although it was originally suggested that only one emitting vent might be involved (Sekanina, 1995a, b, c), detailed modelling has shown that it is also possible that three distinct orifices, situated at different latitudes, are involved (Kidger et al., 1995).

Initial estimates of the diameter of the nucleus of Comet Hale-Bopp from the photometric profile of the inner coma suggest that this comet does belong to the class of giant comets with a diameter of ∼40km (Weaver, 1996).

The possible future photometric evolution of Comet Hale-Bopp is still highly uncertain, although the estimated nuclear diameter would correspond to an absolute magnitude $m_\circ \sim 1.5$ (Delsemme, 1987) and hence to a maximum observed magnitude at perihelion around +1, although the photometric behaviour is more compatible with $m_\circ \sim -1$. Such a magnitude is bright enough to make this comet the brightest since Comet West in 1976 and the first really bright object to be observable with the current state of the art detectors, hence its importance to cometary studies. CCD observations of the photometric behaviour of the comet at high heliocentric distance potentially offer a method of distinguishing between conflicting scenarios. These range from predictions that Comet Hale-Bopp could become an extremely bright object with $m_1 \sim -2$, to the possibility of a more discrete apparition, with $m_1 > +6$.

2. Observations and reduction

Comet Hale-Bopp has been observed with the CCD camera on the 82cm IAC-80 Telescope (IAC-80) on 50 nights starting on August 10th 1995. The IAC-80 has a 1024×1024 Thompson

* Observations taken with the IAC-80 Telescope at Teide Observatory, Tenerife, Spain

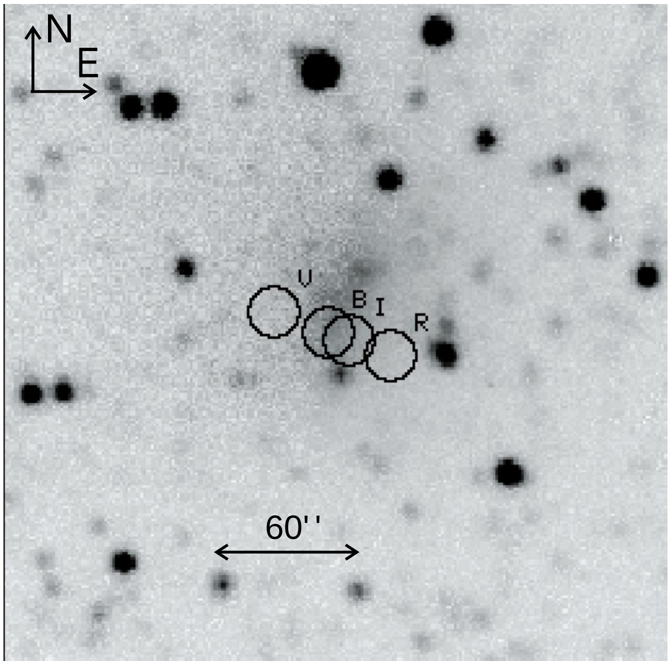

Fig. 1. The aperture positions for the four integrations of Comet Hale-Bopp (1995 O1) reported in the text. The comet has been subtracted from the image to show the stellar background. Note that no bright stars are visible in the aperture positions; some residual emission from the comet can be seen above and below the apertures.

Table 1. The observing log for the data reported in the text.

Date	Filter	No. Images	Exposure (sec)	UT start
1995 Aug 14	B	1	1000	21:15
	V	1	500	21:36
	R	6	2060	21:03
	I	1	500	21:47
1995 Aug 15	B	5	2000	21:26
	V	3	1200	22:08
	R	6	2400	22:32
	I	4	960	21:03
1995 Aug 16	B	3	1200	22:07
	V	1	400	22:33
	R	3	460	21:38
	I	1	400	21:56

Table 2. Photometry of the inner coma of Comet Hale-Bopp. We estimate that the errors on these magnitudes are $\sim$5%. The large increase in brightness at shorter wavelengths is very clearly seen.

Date	B	V	R	I
1995 Aug 14	14.76	13.72	13.06	12.06
1995 Aug 15	14.86	13.75	12.99	11.94
1995 Aug 16	13.78	13.04	12.75	12.04

CCD, with a pixel size of 0.41 arcseconds on the sky and a field of view of approximately 7.5 arcminutes. Standard broad band filters have been used for the observations, corresponding fairly closely to the Landolt system (Landolt, 1983).

Integrations were initially taken in various filters on each night of observation to extract colour information. After the detection of the jet on August 25th, attention switched to long series of exposures in a single band, in an effort to study the morphology of the jet(s). We are thus only able to derive colours for the comet on a limited number of nights before this jet was first detected.

The Landolt standards 111-773 and 111-775 were observed before and after the comet on each night of observation, to provide the photometric calibration. We note though that the airmass of the comet was never significantly less than 2 and, on occasion, higher than 2.5 at some stages of the observations, hence some caution must be used when interpreting the data. In an attempt to overcome this problem, the two standards were observed at least three times in each filter, both before and after the comet and the widest possible airmass range for the standards was observed (typically $\sim$1.3 - 2.5).

The data were reduced using the routines in the IRAF package[1]. The overscan was subtracted from the images, which were then flat fielded using very high signal to noise master flats, each taken from the mean of ten dome flat exposures made shortly before the start of observing.

Given that the comet moved appreciably in 600s, where deep exposures were required we summed multiple exposures of shorter duration, recentering on the nucleus of the comet. Total exposures from 400-2400s were made, according to the night and the conditions. The longest exposures were made in B (our least sensitive band, to obtain adequate counts) and in R (our most sensitive band, to get as deep as possible). Where multiple exposures were taken, the exposures in a single filter were usually, but not always, made consecutively. As the seeing in the IAC-80 is typically $\sim$1.5 arcseconds, a comparatively large, fixed aperture of radius 6.2 arcseconds was used around both the nucleus and the standard stars.

Two significant, related problems are encountered in the data reduction. The first and most critical is that our exposures have a very high degree of confusion in the background, to the extent that it is almost impossible to calculate a sky background. To check for the effects of contamination by background stars, we have calculated the position of the photometric aperture in the field of view (Fig. 1). We find that no star of a brightness sufficient to affect the photometry to any significant degree enters the aperture. Note that a background of faint stars affects the sky subtraction seriously, but is less critical for point source photometry. This is because there are a large number of counts within the photometric aperture, whereas the level of variation caused by the integrated total of faint stars entering and leaving the aperture is very low.

We *believe* that these effects influence the accuracy of our data at a comparatively low level. The night to night variations in our calculated magnitudes, particularly the stability of the

[1] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

light curve in quiescence, suggests that our total error, from all sources, is 5%, or less. This stability also puts comparatively strong limits on the rotational modulation of the brightness of the inner coma.

3. Results

High quality photometry in BVRI was obtained on three nights in mid-August 1995, with the comet at heliocentric and geocentric distances of r = 7.2AU and Δ = 7.0AU respectively. An observing log for the data is given in Table 1.

Our photometric data (Table 2) shows that the magnitude in the I band remained constant to 5% over the three nights of observation. In R, V and B though, although the magnitudes were constant to within our errors on the first two nights of observation, a systematic brightening is seen on August 16th, the amplitude of this brightening increasing steadily from R to B. Amplitudes of ΔR = 0.28 mags, ΔV = 0.70 mags and ΔB = 0.93 mags are registered. These amplitudes imply that the inner coma became very much bluer in the 24 hours between observations.

We have checked the data very carefully, in an attempt to confirm that the change of the continuum colour is genuine. The *nominal* errors on the data from August 16th are very small, although this does not prove that the *true* errors are also small. We have examined the star trails in the summed images for evidence of variations that might be caused by cirrus, or by thicker clouds and find that they are even, as would be expected if the observations were taken in photometric conditions. The small nominal error in the photometry does imply though that the individual measures of the Landolt standards are internally highly consistent, indicating that they were taken in photometric conditions. We also note that the amplitude of the increase in brightness in each filter is almost exactly linear against log frequency, typical of a systematic effect (eg: an outburst with a strongly blue colour), rather than a random one (eg: large errors in magnitude, caused by measuring in non-photometric conditions).

Fig. 2 shows the continuum photometry for the three nights of observation which are treated here. The magnitudes are converted to fluxes using the calibration of Mead et al. (1990). We see that the data from August 14th and 15th show very similar power-laws, with a spectral index $\alpha \sim -3.5$. The photometry is clearly different from pure reflected solar colours (broken line). However, on August 16th, we see a very much flatter power law, of $\alpha \sim -1.8$; the data show more dispersion from the power law, but we believe that this is due to the non-simultaneity of the data, with R being taken almost an hour before V, at a time when the brightness of the inner coma was increasing rapidly.

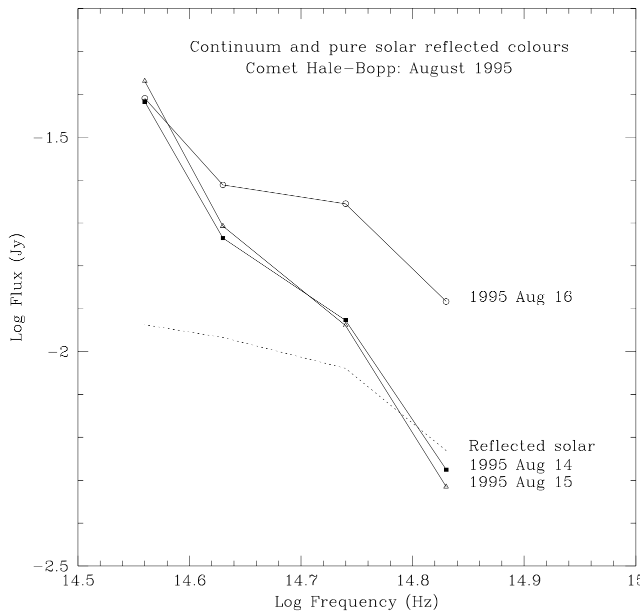

Fig. 2. Continuum spectra for Comet Hale-Bopp (1995 O1) for the data presented in the text. The broken line represents the spectrum that would be seen if the comet had pure solar colours (normalised to V=14.0).

Table 3. A comparison of solar colours with the colour indices of the nuclear condensation of Comet Hale-Bopp (1995 O1) at quiescence and at the start of the outburst described in the text. All three cometary colour indices are considerably redder than the solar colours in quiescence, but get much bluer as the outburst starts. The solar colours are taken from Allen (1973) and transformed using the relations provided by Landolt.

	(B-V)	(V-R)	(V-I)
Hale-Bopp (ave. Aug 14-15th)	+1.08±0.05	+0.71±0.07	1.74±0.11
Hale-Bopp (Aug 16th)	+0.74	+0.29	+1.00
Solar colours	+0.65	+0.36	+0.64

4. Discussion

Both the observation of a large brightening of the inner coma in 24 hours and the change in colour, suggest that we have probably detected the initiation of the jet on August 16th. The change in colour could be interpreted as an outburst of gaseous emissions, or as a very large increment in the number of small solid particles (possibly water ice), in the coma.

The colours observed before August 16th seem to be similar to, or redder than the solar colours, which is consistent with a low gas to dust ratio comet (i.e. Jewitt & Meech 1986, Boehnhardt et al. 1986). High gas to dust ratio comets tend to have a bluer continuum, as was found by A'Hearn et al. (1979), so an increment in the gas production rate could produce the change in colour. Cochran, Cochran & Barker (1982) reported spatially resolved spectra of P/Schwassmann-Wachmann 1 in an outburst, and showed that the continuum in certain parts of the coma was bluish, and that the data could be explained by an excess of small particles, using the Mie scattering theory.

As we used broad band filters, we can not determine whether the change in colour indices was due to an increment in the gas emission lines (in other words, that a large emission of gas caused the temporary appearance of spectral lines), or to a change in the colour of the continuum. We note that there are no reports of emission lines from plasma (eg: CO^+) in the visible or ultraviolet region of the spectrum, either in quiescence, or during jet activity, although both CO and CN have been detected as neutral gas (CO by Matthews et al. 1995 and by Rauer et al. 1995; CN by Fitzsimmons & Cartwright, 1996), which would suggest that a change in the *scattering* characteristics is the most probable explanation. In any event, a large change in the nuclear activity does seem to be detected just before the first jet became visible.

We would thus suggest that the outburst which led to the formation of the jet started around August 16.5, with an ejection of a quantity of very small ice grains. The expulsion of these grains increased the total reflecting area around the nucleus, leading to a large brightening. Due to the low projected expansion velocity ($\sim$300 m/s), it would take several days for the jet to develop to a point where it could detected by ground-based telescopes. Even so, it is somewhat surprising that such a large outburst should remain undetected until it was first registered in exposures with the IAC-80 on August 25.9 and, later, at various observatories around August 29.0; this implies that it had already been active for $\sim$9.5 days and was, presumably, well advanced on its decline phase.

The light curve of the inner coma for the September jet was particularly well observed with the IAC-80 (Kidger et al. 1995), showing an increase in brightness of close to 2 magnitudes in R. A comparison of these data with the partial light curve record for the August jet suggests that the inner coma may have increased in brightness by an order of magnitude, or more, at the peak of the August outburst.

5. Conclusions

The visible colours of the comet at $r = 7.2$AU are very much redder than the solar colours when the comet is in quiescence. Between August 15.9 and August 16.9, the magnitude in the V band brightens by 0.71 mags; this appears to be a genuine event in the light curve and not an artifact. At the same time, the spectral index flattens considerably and the colours of inner coma get much bluer. This we interpret as probably being due to the expulsion of a large quantity of small icy grains. We suggest that this event marks the initiation of the jet event first directly detected at Teide Observatory, with the IAC-80 Telescope, on August 25.9 (Kidger et al. 1996). If so, the August jet was active for approximately 21 days, by far the greatest duration of any of the observed jets. The amplitude of the brightening of the nuclear condensation was also probably considerably in excess for any of the other jets: comparison with the well observed September jet outburst suggests that the inner coma may have brightened by as much as 3 magnitudes at maximum.

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