COMETARY ACTIVITY AT 25.7 AU: HALE-BOPP 11 YEARS AFTER PERIHELION

Gy. M. Szabó,1,2,3,4 L. L. Kiss,2 and K. Sárncezky2,5,6

Received 2008 February 7; accepted 2008 March 10; published 2008 March 27

ABSTRACT

Eleven years after its perihelion, comet C/1995 O1 (Hale-Bopp) is still active. Between 2007 October 20 and 22, we detected a diffuse coma of $180 \times 10^3$ km in diameter with a slight elongation toward the north-south direction. The integrated brightness was 20.04 mag in $R_C$, implying $A_{dp} = 300$ m and albedo $\times$ dust surface $a(C) = 4300$ km$^2$. The coma was relatively red at $V - R = 0.66$ mag, which is consistent with that of the dust in other comets. The observed properties and the overall fading in brightness between 10 and 26 AU follow the predicted behavior of CO-driven activity. This is the most distant cometary activity ever observed.

Subject headings: comets: general — comets: individual (Hale-Bopp)

Online material: color figures

1 INTRODUCTION

Long-period comets experience little solar exposure and heating, which means they can be used to reveal conditions that existed during the formation and early evolution of the solar system (Delsemme 1977; Lowry & Fitzsimmons 2005). The main evidence supporting this argument is that the post-perihelion activity decreases fast after the cutoff of water sublimation at 3 AU (Fernández 2005), and then the activity usually stops until the next apparition. A few exceptional comets, however, displayed activity far beyond 3 AU, which can be explained by the sublimation of CO, but the processes involved are not well understood (Mazzotta Epifani et al. 2007). Because of this, cometary activity at large heliocentric distances has raised considerable interest recently, addressing the question of how intact the matter in comets is (Lowry et al. 1999). For example, dust activity throughout the entire orbit could result in a continuous resurfacing of the nucleus, while the surface composition could also be altered. The observed diversity of nucleus colors (Luu 1993; Jewitt 2002) may indicate that this is indeed the case. On the other hand, comets with disguised distant activity will have larger mass loss rate per orbit than we estimate, leading to overestimated comet lifetimes (Lowry et al. 1999; Mazzotta Epifani et al. 2007) and underestimated replenishment rate of the zodiacal dust (Liou et al. 1995).

In recent years, a number of studies reported on short-period comets active between 3 and 7 AU (e.g., Lowry et al. 1999; Lowry & Fitzsimmons 2001, 2005; Lowry & Weissman 2003; Snodgrass et al. 2006, 2008; Mazzotta Epifani et al. 2006, 2007). These surveys aimed at the investigation of the bare nucleus, but a surprisingly high number of comets showed comae and even dust tails at large ($R > 3$) heliocentric distances, where volatile sublimation is expected to be low. The activity of some long-period comets is similar, with occasionally long dust tails (Szabó et al. 2001, 2002), while 11 Centaur objects are also known with cometary activity (see, e.g., Rousselot 2008 and references therein). Chiron is known to be active at solar distances between 8 and 14 AU (Meech et al. 1997), and was seen to display considerable outgassing near aphelion (at 17.8–18.8 AU) between 1969 and 1977 (Bus et al. 2001). Meech et al. (2004) found that the Oort Cloud comet C/1987 H1 (Shoemaker) displayed an extensive tail at all distances between 5 and 18 AU, which is, as of this writing, the most distant example of cometary activity ever observed.

Discovered at 7.2 AU from the Sun, C/1995 O1 (Hale-Bopp) has been a prime target for cometary studies. In prediscovery images it had a faint coma 0.4′ in diameter and a total magnitude of ~18 (McNaught & Cass 1995), while the dust production rate was $500$ kg s$^{-1}$ (Fulle et al. 1998) at a solar distance of 13.1 AU. At 7.0 AU, NIR absorption of water ice was detected (Davies et al. 1997). At that time the activity was driven by CO production (Biver et al. 1996; Jewitt et al. 1996), which switched to a water-driven activity at around 3 AU (Biver et al. 1997; Weaver et al. 1997). Approaching the 0.9 AU perihelion distance, the dust production rate was $2 \times 10^6$ kg s$^{-1}$ (Jewitt & Matthews 1999). The size distribution of the dust, especially in the jets, showed a dominance of $\leq 0.5 \mu$m grains, smaller than in any other comet. This was indicated by the unprecedentedly large superheat ($T_f/T_{ib} = 1.5–2$ [Hayward et al. 2000] or 1.5–1.8 [Grün et al. 2001]), and the scattering albedo and polarization (Hayward et al. 2000). The water production was $10^{11}$ molecules s$^{-1}$, the largest value ever observed.

The dust-to-gas ratio was very high, between 5 and 10, regardless of the solar distance (Colom et al. 1997; Lisse et al. 1997; Weaver et al. 1999). The production rates observed post-perihelion were similar to those observed preperihelion (Capria et al. 2002), foreshadowing long-lasting distant activity. We have indeed detected evidence for cometary activity at 25.7 AU from the Sun; this Letter presents our major findings based on broadband imaging in late 2007.

2 OBSERVATIONS

New observations were taken with the 2.3 m ANU telescope at the Siding Spring Observatory on 2007 October 20, 21, and 22. The solar distance of the comet was 25.7 AU. We took $9 \times 240$ s exposures in Johnson-Cousins $VR_C$ filters with a $2 \times 2$ binned image scale of 0.67′ pixel$^{-1}$. The seeing was 2.0′′–2.5′′ on the three nights (see Table 1 for exposure data and ephemerides).

The images were corrected in a standard fashion, including bias and flat-field correction and fringing correction of the $R_C$ images. Every night we aligned and co-added the images by...
TABLE 1

| Date (UT) | R.A. | Decl. | λ (deg) | β (deg) | R (AU) | Δ (AU) | E (deg) | α | V Exp. (s) | S (arcsec) | R Exp. (s) | S (arcsec) |
|-----------|------|-------|---------|---------|--------|--------|---------|---|-----------|-----------|-----------|-----------|
| 2007 Oct 20 | 04 11 58.98 | −86 27 28.7 | 280.76 | −70.31 | 25.75 | 25.86 | 82.69 | 2.20 | ... | ... | 9 × 240 | 2.5 |
| 2007 Oct 21 | 04 09 56.22 | −86 28 46.5 | 280.76 | −70.31 | 25.76 | 25.87 | 82.37 | 2.20 | 9 × 240 | 2.0 | 9 × 240 | 2.1 |
| 2007 Oct 22 | 04 07 53.57 | −86 30 04.2 | 280.76 | −70.31 | 25.77 | 25.88 | 81.98 | 2.20 | ... | ... | 9 × 240 | 2.2 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

fitting a coordinate grid to the stars, yielding a “star field” image for photometric calibrations. The images were then re-aligned with respect to the proper motion of the comet, to get untrailed “comet” images. In this step, the MPC ephemerides at the time of each observation were used to match the individual frames. Figure 1 shows the “comet” image on 2007 October 21. The estimated size of the coma is 180 × 103 km, slightly elongated north/southward (Fig. 2).

2.1. Photometry

A good proxy to the dust content inside the coma is its brightness, which we have measured by aperture photometry in a single aperture of 14” across. On October 21, the comet and field stars were calibrated with all-sky photometry using the SA 98 field of Landolt (1992), observed between air masses 1.17 and 1.65 (Hale-Bopp was at X = 1.72). Due to the slow apparent motion, we could use the same field stars as local standards on the other two nights as well. The measured brightnesses on October 21 were V = 20.70 ± 0.1 mag, R_c = 20.04 ± 0.1 mag. This corresponds to \( A_f \rho = 30,000 \) cm, according to the definition by A'Hearn et al. (1984). For comparison, this value is twice as large as that for 29P/Schwassmann-Wachmann 1 in outburst (Szabó et al. 2002), and 3 times larger than for 174P/Echeclus in outburst (Rousselot 2008).

2.2. Morphology

The observed brightness can be converted to albedo \( \times \) dust surface, \( a_b C \) (Eddington 1910), which is the cross section of reflecting particles (C, in m^2) in the aperture, multiplied by the geometric albedo \( a_b \) in the \( R_c \) photometric band. It is calculated as

\[
a_b C = \frac{2.22 \times 10^{22} \pi R_c^2 \Delta^2 10^{0.4(m_{\odot} - m_{\text{comet}})}}{10^{-0.4ab}},
\]

where \( m_{\odot} = -27.11 \) mag, the apparent \( R_c \) brightness of the Sun, and the \( \beta \) phase coefficient is usually assumed to be 0.04. Substituting the measured total brightness yields \( a_b C \approx 4300 \) km^2. For comparison, this cross section is 450 times larger than that of the dust cloud ejected in the Deep Impact experiment (e.g., Milani et al. 2007). After calibrating the image flux, the azimuthally averaged comet profile was determined from surface photometry. From this the local filling factor of the dust, \( f \), can directly be expressed by replacing \( m_{\text{comet}} \) with the \( \mu \) surface brightness:

\[
a_b f = \frac{1.34 \times 10^{17} R_c^2 10^{0.4(m_{\odot} - \mu)}}{10^{-0.4ab}},
\]

that is, the measured surface brightness relative to that of a reflecting surface with 1.0 albedo. We found that the surface brightness was 20.3 mag in the inner coma, corresponding to \( a_b f \approx 9 \times 10^{-6} \), which remained above \( 10^{-6} \) in the inner 70,000 km (Fig. 3).
where $f$ is the fraction of the active area, $\zeta(T)$ is the gas production rate in molecules $m^{-2} s^{-1}$, and $l$ is the latent heat loss per one molecule. CO molecules deposited on CO ice (e.g., inclusions) and CO molecules deposited on H$_2$O can sublime at large solar distances, due to their high volatility. By neglecting the CO ice inclusions, CO is condensed on water ice, for which $l = 10^{-20}$ J molecule$^{-1}$ (Delsemme 1982), and log $\zeta(T) \approx 755.7/T - 35.02$ (Mukai et al. 2001). The heat loss of such a nucleus is plotted in Figure 4 for different values of $f$ and as a function of temperature.

The equivalent temperature of a freely sublimating ice globe ($f = 1$) at 25.7 AU is 48.0 K, which is slightly less than 54.8 K for a blackbody ($f = 0$), due to the sublimation of $2 \times 10^{19}$ molecules $m^{-2} s^{-1}$. This corresponds to $Q(\text{CO}) = 4\pi r^2 \zeta(T) = 2.1 \times 10^{20} r^2$ molecules $s^{-1}$. If the active area covers 1% of the surface, the equilibrium temperature is 53.1 K, $\zeta(T) = 6.2 \times 10^{20}$ molecules $s^{-1} m^{-2}$, $Q(\text{CO}) = 8 \times 10^{14} r^2$ molecule $s^{-1}$. The $Q(\text{CO})$ production rate and the temperature just slightly depend on $f$; thus we can get a reasonable estimate assuming $f = 0.01$. The thermal velocity of the gas is $u_e = (3kT/m_{\text{CO}})^{1/2} = 210$ m s$^{-1}$, which is enough to carry off small dust grains ($m_{\text{CO}}$ is the mass of one CO molecule). The acting drag force $F_d = \pi a^2 u_e \zeta(T)m_{\text{CO}}$, where $a$ is the size of the dust particle. Particles are carried off if the drag force exceeds the gravitation, $F_p > F_d = (4\pi/3) \rho_s a^3 r$; $\rho_s$ and $\rho_p$ are the density of the nucleus and the dust particle, respectively. Thus, the maximum radius of the escaping dust particles is

$$a_{\text{max}} = \frac{9}{16\pi} \frac{u_e \zeta(T)m_{\text{CO}}}{\rho_s \rho_p G r}.$$  

For an order-of-magnitude estimate we assumed $\rho_s = 1000$ kg m$^{-3}$ (Capria et al. 2002), $\rho_p = 2500$ kg m$^{-3}$, and $r = 15$ km (Meech et al. 2004) or $r = 30$ km (Fernández 2000), leading to $a_{\text{max}} \approx 100$ µm and $Q(\text{CO}) \approx 1.7 \times 10^{28}$ s$^{-1} = 790$ kg s$^{-1}$ in the case of the $r = 15$ km nucleus, and $Q(\text{CO}) \approx 6.8 \times 10^{28}$ s$^{-1} = 3160$ kg s$^{-1}$ if $r = 30$ km.

With a more sophisticated model (the surface is dominated by water ice instead of CO on water, the majority of CO is present in inclusions, crystalization heats the nucleus, the nucleus rotates), Capria et al. (2002) predicted $Q(\text{CO}) = 5 \times 10^{27}$ molecules $s^{-1}$ (equivalent to 230 kg s$^{-1}$) at 25 AU (see Figure 4 in their paper). Assuming that the dust loading remained high ($m_{\text{dust}}/m_{\text{nuc}} = 101$), the total dust production ranges from 230 to 2300 kg s$^{-1}$. For example, if 500 kg s$^{-1}$ dust is produced in the form of 1 µm–sized particles, the projected area is 0.25 km$^2$. Assuming a 0.05 albedo results in a 12,000 m$^2$ excess of $a_{\text{e}}C$ every second. With these assumptions, the nucleus can produce the observed amount of matter in the coma within ~5 days. The measured radius of the coma and the timescale of dust production needed gives a measure of dust ejection velocity as 90,000 km/5 days $\approx 210$ m s$^{-1}$, which is consistent with the thermal gas velocity derived at 25.7 AU.

This self-consistent picture is also supported by the brightness variation of Hale-Bopp of between 10 and 26 AU. In Figure 5 we plot the observed brightness of Hale-Bopp (collected from ICQ and MPC bulletins) against the solar distance. For comparison, data for six dynamically young Oort Cloud comets are also plotted (Meech et al. 2004). Hale-Bopp was consistently 3–5 mag brighter than these Oort comets at all distances $\leq$15 AU. Beyond that, other comets quickly disappeared as opposed to Hale-Bopp, which kept its slow rate of fading. We also show a theoretical light curve predicted from
the CO production curve by Capria et al. (2002), after scaling with $R^{-2.2}/A^{-2}$ and a constant dust loading. The overall agreement indicates that the distant brightness change is consistent with CO-driven activity.

An alternative explanation of the present activity of Hale-Bopp could be that the light halo is not a real coma but a preserved debris tail (e.g., Jenniskens et al. 1997; Sekanina et al. 2001). Comets with periods over a few thousand years are unlikely to preserve dense debris tail, but, as Lyytinen & Jenniskens (2003) remarks, giant comets such as Hale-Bopp can be exception. At the current position, the orbital path of Hale-Bopp seems to suggest genuine differences beyond the difference in nucleus size.

4. CONCLUSION

Comet Hale-Bopp has been the single most significant comet encountered by modern astronomy, and 11 years after perihelion it still displays fascinating phenomena. The detected activity can be well explained by theoretical models invoking CO sublimation at large heliocentric distances. Compared to other young Oort Cloud comets, the long-term behavior of Hale-Bopp seems to suggest genuine differences beyond the difference in nucleus size.

The main results of this paper can be summarized as follows:

1. We detected cometary activity of Hale-Bopp at 25.7 AU, which is the most distant activity detection so far.
2. Our analysis indicates that the extrapolation of the Capria et al. (2002) model works very well for the distant Hale-Bopp, which confirms the physical assumptions of this model.
3. Further observations with 8 m-class telescopes can help constrain the presence of gas in the coma, effects of superheat due to small dust particles, and, ultimately, the cessation of mass-loss processes in Hale-Bopp.

This research was supported by the “Bolyai János” Research Fellowship of the Hungarian Academy of Sciences and a Group of Eight European Fellowship (Gy. M. Sz.), a University of Sydney Research Fellowship (L. L. K.), and a Hungarian State “Eötvös” Fellowship (K. S.).

REFERENCES

A'Hearn, M. F., et al. 1984, AJ, 89, 579
Biver, N., et al. 1996, Nature, 380, 137
———. 1997, Science, 275, 1915
Bus, S. J., A'Hearn, M. F., Bowell, E., & Stern, S. A. 2001, Icarus, 150, 94
Capria, M. T., Coradini, A., & De Sanctis, M. C. 2002, Earth Moon Planets, 90, 217
Colom, P., Gérard, E., Crovisier, J., Bockelée-Morvan, D., Biver, N., & Rauer, H. 1997, Earth Moon Planets, 78, 37
Davies, J. K., et al. 1997, Icarus, 127, 238
Delsemme, A. H. 1977, in Comets, Asteroids, Meteorites, ed. A. H. Delsemme (Toledo: Univ. Toledo), 3
———. 1982, in Comets, ed. L. L. Wilkening (Tucson: Univ. Arizona Press), 85
Eddington, A. S. 1910, MNRAS, 70, 442
Fernández, J. A. 2005, Comets: Nature, Dynamics, Origin, and Their Cosmological Relevance (Dordrecht: Springer)
Fernández, Y. R. 2000, Earth Moon Planets, 89, 3
Fulle, M., Cremonese, G., & Böhm, C. 1998, AJ, 116, 1470
Grün, E., et al. 2001, A&A, 377, 1098
Hayward, T. L., Hanner, M. S., & Sekanina, Z. 2000, ApJ, 538, 428
Ishiguro, M., et al. 2007, Icarus, 189, 169
Jenniskens, P., Bleyl, H., & de Lignie, L. M. 1997, ApJ, 479, 441
Jewitt, D. 2002, AJ, 123, 1039
Jewitt, D., & Matthews, H. 1999, AJ, 117, 1056
Jewitt, D., et al. 1996, Science, 271, 1110
Landolt, A. U. 1992, AJ, 104, 340
Liou, J. C., Dermott, S. F., & Xu, Y. L. 1995, Planet, Space Sci., 43, 717
Lisse, C. M., et al. 1997, Earth Moon Planets, 78, 251
Lowry, S. C., & Fitzsimmons, A. 2001, A&A, 365, 204
Lowry, S. C., & Fitzsimmons, A. 2005, MNRAS, 358, 641
Lowry, S. C., Fitzsimmons, A., Cartwright, I. M., & Williams, I. P. 1999, A&A, 349, 649
Lowry, S. C., & Weissman, P. R. 2003, Icarus, 164, 492
Luu, J. X. 1993, Icarus, 104, 138
Lyytinen, E., & Jenniskens, P. 2003, Icarus, 162, 443
Mazzotta Epifani, E., Palumbo, P., Capria, M. T., Cremonese, G., Fulle, M., & Colangeli, L. 2006, A&A, 460, 935
———. 2007, MNRAS, 381, 713
McNaught, R. H., & Cass, C. P. 1995, IAU Circ. 6198
Meech, K. J., Buie, M. W., Samarasinha, N. H., Mueller, B. E. A., & Belton, M. J. S. 1997, AJ, 113, 844
Meech, K. J., Hainaut, O. R., & Marsden, B. G. 2004, Icarus, 170, 463
Milani, G. A., et al. 2007, Icarus, 187, 276
Mukai, T., et al. 2001, in Interplanetary Dust, ed. E. Grün et al. (Heidelberg: Springer), 445
Rousselot, P. 2008, A&A, 480, 543
Sarugaku, Y., et al. 2007, PASJ, 59, L25
Sekanina, Z., Hanner, M. S., Jessberger, E. K., & Fomenkova, M. N. 2001, in Interplanetary Dust, ed. E. Grün et al. (Heidelberg: Springer), 90
Snodgrass, C., Lowry, S. C., & Fitzsimmons, A. 2006, MNRAS, 373, 1590
———. 2008, MNRAS, 385, 737
Szabó, G. M., Csisá, B., Sárnezky, K., & Kiss, L. L. 2001, A&A, 374, 712
Szabó, G. M., Kiss, L. L., Sárnezky, K., & Sziládi, K. 2002, A&A, 384, 702
Weaver, H. A., et al. 1997, Science, 275, 1900
———. 1999, Icarus, 141, 1

Fig. 5.—Light curve of Hale-Bopp compared to observations of 6 dynamically young Oort Cloud comets (Meech et al. 2004; the last five point are upper limits). The dashed curve shows the prediction of the activity model (Capria et al. 2002).