INFRARED OBSERVATIONS OF COMET HALE–BOPP (C/1995 O1) FROM GURUSHIKHAR OBSERVATORY

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Abstract. During the recent apparition of comet Hale–Bopp (1995 O1) near infrared photometric observations were carried out in the J, H, K filter bands and also in the 3.0–3.4 μm region at the 1.2 m telescope at Gurushikkar, India. The effective temperature of the comet was substantially higher than the equilibrium blackbody temperature. A mean superheat value of 1.83 was derived in the post-perihelion phase which implies that a large fraction of the grain population are made up of small and hot grains with radii $<$0.5 μm. High albedo values of $\sim$0.4 were also derived in the scattering angle range 135° to 160° which could explain the unusual brightness of comet Hale–Bopp.

Keywords: Albedo, comets, grains, Hale–Bopp, infrared

1. Introduction

The importance of infrared observations of comets arises from their ability to provide valuable information about composition and structure of astrophysical dust grains. Cometary nuclei are conventionally believed to contain samples of primordial material of the solar nebula; when these nuclei enter the inner solar system, the frozen material is ablated to form the cometary coma and tail which can be studied by modern techniques. In the context of astrophysical grains, cometary studies are particularly important as the light scattering phase functions of cometary grains are well determined because the cometary position is usually accurately known. The first infrared observations of a comet were made on comet Ikeya-Seki by Becklin and Westphal (1966) who showed that comets could be sources of strong infrared radiation due to thermal emission of ablating grains. Since then many bright comets have been studied for their infrared behaviour (Ney, 1982; Gehrz and Ney, 1992; Chandrasekhar et al., 1996).

From their infrared spectrophotometric study of seven bright comets including comet Halley, Gehrz and Ney (1992) have classified comets into two types. IR type I comets have weak or undetectable 10 μm silicate features and low temperature excess over the blackbody values. IR type II comets have superheated thermal infrared continuua and strong silicate features, indicating smaller grains in the size range 0.5 to 1 μm.

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In this paper we present our near infrared observations made during both the pre-perihelion and post-perihelion phases of comet Hale–Bopp (C/1995 O1) at Gurushikhar Observatory, India and discuss and compare its IR behaviour with other comets.

2. Instrumentation and Observations

Comet Hale–Bopp (C/1995 O1) was discovered in July 1995 as an unusually bright comet at a heliocentric distance (r) of over 7 AU. The large brightness at this distance suggested a nuclear size in the range of $\sim$40 km which along with its perihelion at 0.914 AU would make it one of the most easily observable giant comets in recent times. The comet was well observed in its inbound and outbound passages. Perihelion was reached on 1997 April 1.13811 UT.

The first positive infrared detection of comet Hale–Bopp (C/1995 O1) from Gurushikhar ($24°39'$ N $72°47'$ E, 1680 m altitude) was made on 1997 March 2.044 UT at heliocentric distance of 1.059 AU and a geocentric distance of 1.474 AU. The site is above the atmospheric inversion layer. It is also a dry site, suitable for IR observations particularly in the 3 μm region. The instrument used was a single channel infrared InSb photometer using the standard J, H and K filters. In addition a circular variable filter (CVF) was also available in the photometer which permits continuous variation of transmitted wavelength from 1.7 μm to 3.4 μm. The resolving power of the CVF ($\lambda/\delta\lambda$) over this range is $\sim$60. As the Gurushikhar telescope does not have provision for secondary mirror chopping, a tertiary mirror chopping has been incorporated in the system which is shown in Figure 1. The chopped {(star + sky)-sky} signal is synchronously detected using a lock-in-amplifier. The data is recorded with 16 bit resolution in a PC based data acquisition system. Details of the photometer are discussed in Ashok et al. (1994).

A new feature of the instrument pertinent for comet observations is the use of the tertiary mirror in the angular chopping mode. Instead of conventional linear movement of the tertiary plane mirror, a hinged support is provided through which angular movement of the mirror is possible. This arrangement permits chopper throws in the sky in excess of 2 arcminutes in the frequency range, 10–15 Hz.

Details of the photometric observations made and the relevant cometary parameters are given in Table I. The first three rows refer to the pre-perihelion phase and the rest to post-perihelion phase. After each observation the telescope was moved over 2 arcmin sometimes, 4 arcmin in RA in East and then West and sky measurements were taken with the same focal plane aperture and chopper throw. Beam switching was also carried out. At all wavelengths of comet observations, sky subtraction was limited by sky noise. Typical photometric accuracies for stellar work with the photometer are 0.03 magnitudes in the JHK filters and 0.05 magnitudes in the 3.0–3.4 μm region. For comet observations at large airmasses due to larger chopper throws ($2'$) the achieved accuracies are poorer as shown in Table II. Stand-

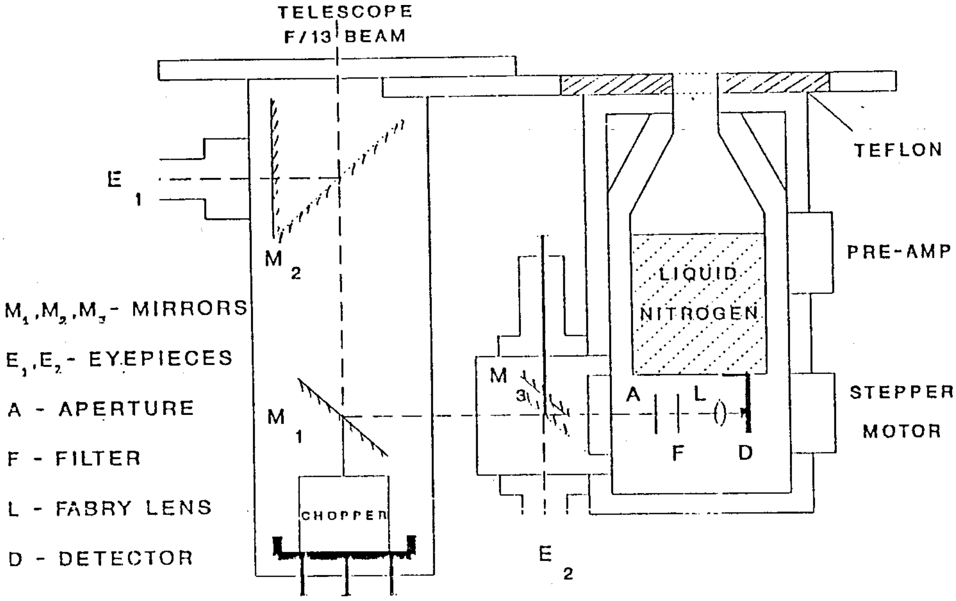

Figure 1. Schematic diagram of the Infrared photometer; M3 is the tertiary mirror chopper.

ard stars used were α Cyg, β Tau, and α Vir. As many observations had to be made at large airmasses, a careful evaluation of extinction corrections in J, H and K bands were carried out using α Persei at different airmasses. The airmass range covered is from 1.0 to nearly 4.0. The values derived are K_K = 0.14 Mag/airmass, K_H = 0.2 Mag/airmass and K_J = 0.3 mag/airmass. Further since cometary coma are extended sources of IR emission some coma emission is present in the reference beam used for background cancellation. The total emission in a beam is proportional to the volume of coma material interrupted. Correction for effects of beam diameter (ϕ) and reference beam throw (ψ) need to be incorporated in the data analysis. Gehrz and Ney (1992) have discussed a standard model of a comet in which coma grains are produced by ablation of the nuclear material at a constant rate and are moving outward with constant velocity. They derive a correction term for reference beam contamination of the form $\frac{4\psi}{4\psi-\phi}$ where ψ is the angular separation between signal and reference beams and ψ is the beam size. We have incorporated this correction in our analysis. The derived photometric values after extinction corrections and corresponding errors (1σ) are listed in Table II. The circular variable filter observations were taken on two days during post-perihelion period. The spectral range, 1.7–3.4 μm is covered in two parts: 1.7–2.4 μm and 3.0–3.4 μm. For each range sky observations were taken separately. The atmospheric spectral feature in the observed data were removed by ratioing the CVF spectrum with that of an early type star and multiplying the result by the blackbody equivalent of the early type star. Finally the entire spectrum was normalised using the comet photometric value in the K band.

TABLE I

S. no.	UT date	Filter	Heliocentric distance r (AU)	Geocentric distance Δ (AU)	Phase angle β (deg)	Solar elongation (deg)	Airmass
1.	1997 March 2.044	J,H,K	1.059	1.474	42.2	45.9	2.22
2.	1997 March 3.035	J,H,K	1.050	1.460	42.7	46.0	2.47
3.	1997 March 4.035	J,H,K	1.042	1.447	43.3	46.0	2.60
4.	1997 April 17.60	J,H,K	0.960	1.549	39.0	37	2.53
5.	1997 April 18.63	J,H,K +CVF	0.966	1.565	38.4	36.6	4.5
6.	1997 April 20.60	J,H,K	0.978	1.596	37.0	35.9	2.68
7.	1997 April 27.6	J,H,K	1.028	1.712	32.4	33.1	2.65
8.	1997 May 16.59	J,H,K +CVF	1.210	2.033	21.6	26.1	3.32

3. Discussions and Results

3.1. SUPERHEAT

The color temperatures of comets are generally greater than the equilibrium blackbody temperatures at the same heliocentric distance. For the recent case of comet Hyakutake (C/1996 B2) we derived an average excess of 20% (Chandrasekhar et al.). In comparison the temperature excess was 8% for comet Kobayashi-Bergar-Milon (1975 IX), 26% for comet Kohoutek (1973), 45% for comet Bennett, 40% for comet Ikeya-Seki (1965) (Ney 1982). For wavelengths $\lambda \gg 2\pi a$ where a is the grain size, the absorptivity or emissivity decreases very quickly, the grain cannot radiate efficiently and is heated up. Thus, small absorbing grains which radiate inefficiently in the infrared are responsible for this temperature excess. Gehrz and Ney (1992) have quantified this excess by introducing a quantity called Superheat (S). The superheat S is defined as the ratio of the near infrared carbon grain continuum color temperature (T_{color}) to the temperature of black conducting spheres at the same heliocentric distance r.

$$S = \frac{T_{\text{color}}}{T_{BB}} = \frac{T_{\text{color}}\sqrt{r}}{278}$$

In a recent paper Williams et al. (1997) find, from near-IR and mid-IR spectrophotometric observations of comet Hale–Bopp about 40 days before perihelion,

TABLE II

S. no.	UT date 1997	Beam size (ϕ) arcsec	Chop-per throw (ψ) arcsec	Corr. factor	J	ΔJ	H	ΔH	K	ΔK
1.	March 2.044	26	58	1.126	2.79	0.22	2.70	0.12	2.31	0.06
2.	March 3.035	26	58	1.126	2.68	0.03	2.57	0.06	2.30	0.04
3.	March 4.035	26	58	1.126	2.35	0.08	2.18	0.09	2.02	0.04
4.	April 17.60	26	60	1.1215	2.40	0.05	2.10	0.05	1.74	0.05
5.	April 18.63	26	60	1.1215	2.60	0.07	2.30	0.05	1.99	0.08
6.	April 20.60	26	60	1.1215	2.87	0.10	2.42	0.10	2.07	0.10
7.	April 27.6	26	60	1.1215	3.25	0.10	2.80	0.10	2.49	0.10
8.	May 16.59	26	60	1.1215	4.89	0.05	4.57	0.05	4.60	0.05

that submicron grain with an average radius of 0.4 μm dominate visual scattering and near-IR emission. The surprising brightness of comet Hale–Bopp may have been largely due to properties of these small grains rather than a large nucleus. They derive a superheat value of 1.84 and an albedo of 0.41 which are the highest values for these parameters ever observed.

We have used our J, H, K photometric and CVF observations in the 3.0–3.4 μm region to determine the superheat value for comet Hale–Bopp on two occasions during the post perihelion period. Figures 2a and b show J, H, K and 3.0–3.4 μm fluxes for April 18, 1997 and May 16, 1997 when the heliocentric distance increased from 0.966 AU to 1.210 AU.

It can be seen that the JHK values fall on the solar continuum blackbody curve at 5700 K. The CVF values in the region beyond 2.2 μm show the turn off from scattered solar continuum to the comet's thermal spectrum. The CVF values in the 3.0–3.4 μm region clearly show the presence of thermal emission from the cometary grains on both days. It has not been possible to give an extinction cor-

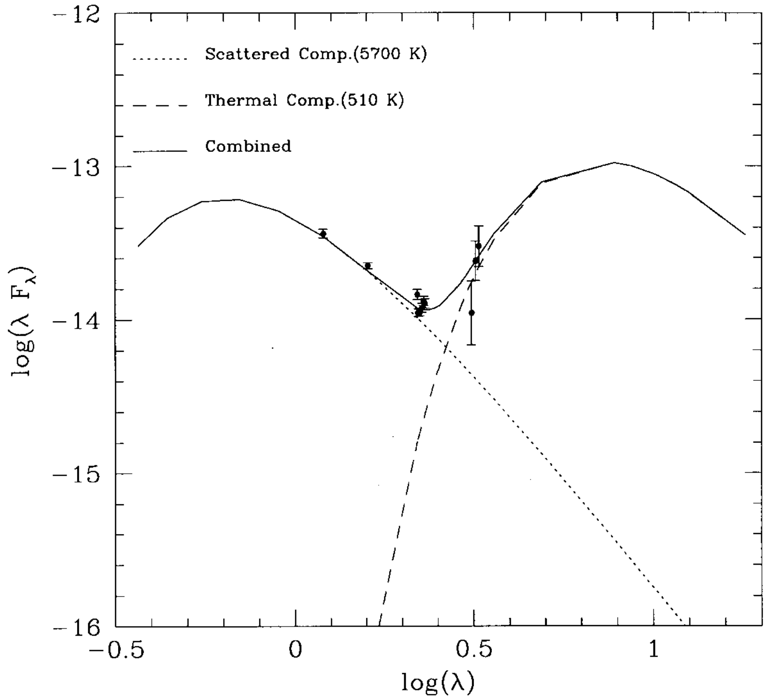

Figure 2a. The spectral energy distribution of comet Hale–Bopp on 18 April 1997. The closed circles are the observed J, H, K and CVF values longward of K including 3.0–3.4 μm region. The units of λF_λ are in W/cm^2. The wavelength λ is in microns. The heliocentric distance to the comet at the time of the observation was 0.966 AU.

rection to the data in 3.0 μm region. However, the estimated errors are expected to fully account for any variation due to extinction effects. The CVF wavelengths are well determined by laboratory calibration with errors of less than 0.03 μm. The measured fluxes and estimated errors in this region for both days are shown in Table III. The effect of the errors on the derived superheat temperature is not large. For instance, for the observations of 16 May 1997, an error of ±0.3 magnitudes at $m_{3.28} = 2.53$ leads to a superheat temperature in the range 450–490 K. The derived physical parameters for comet Hale–Bopp on these days is given in Table IV. For comparison we have also listed the preperihelion value of comet Hale–Bopp of Williams et al. (1997) in Table IV. In Table IV $A(\theta)$ is the scattering angle dependent albedo defined as

$$A(\theta) = \frac{f(\theta)}{1 + f(\theta)}$$

where

$$f(\theta) = \frac{[\lambda F_\lambda(\theta)]_{\mathrm{max,scatt}}}{[\lambda F_\lambda(\theta)]_{\mathrm{max,IR}}}$$

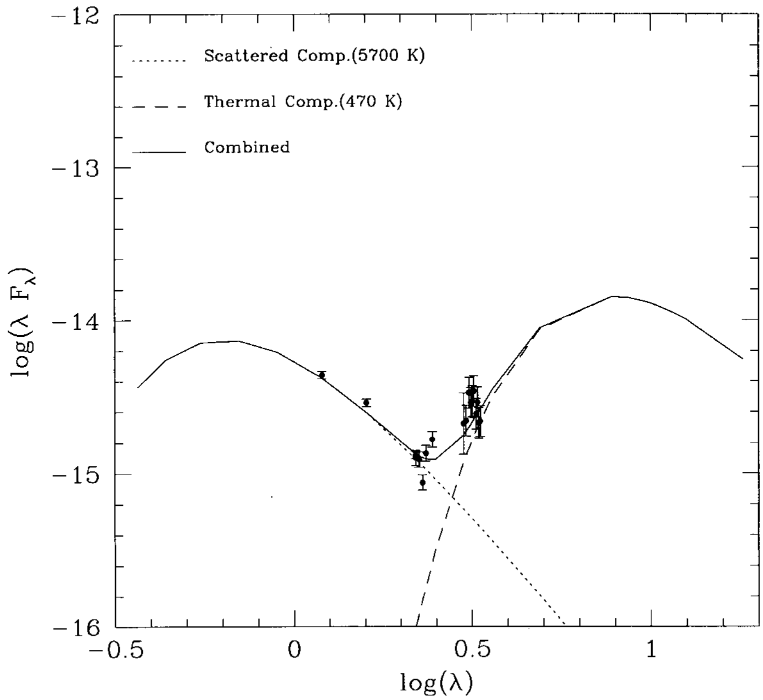

Figure 2b. The spectral energy distribution of comet Hale–Bopp on 16 May 1997. The closed circles are the observed J, H, K and CVF values longward of K including 3.0–3.4 μm region. The units of λF_λ are in W/cm^2. The wavelength λ is in microns. The heliocentric distance to the comet at the time of the observation was 1.1210 AU.

TABLE III

Wavelength μm	18 April, 97 $\times 10^{-15}$ W/cm^2/μm	16 May, 97 $\times 10^{-16}$ W/cm^2/μm
3.0		7.0 ± 1.4
3.05		7.2 ± 0.7
3.10		11.0 ± 1.0
3.12	3.5 ± 0.7	
3.14		9.2 ± 0.9
3.17		9.3 ± 0.9
3.20	7.5 ± 1.0	11.0 ± 1.0
3.25		7.5 ± 0.8
3.28	9.2 ± 1.2	8.8 ± 0.9
3.31		6.4 ± 0.6
3.34		6.5 ± 0.7

TABLE IV

Parameter	18 April, 97	16 May, 97	20 Feb., 97 (Williams et al. 1997)
r(AU)	0.966	1.210	1.15
Δ(AU)	1.565	2.033	1.64
Scattering angle (deg)	142	158	144
T_{color}(K)	510	470	475
T_{BB}(K)	283	253	260
Superheat S	1.80	1.86	1.84
$[\lambda F_\lambda(\theta)]_{\mathrm{max,scat}}$W/cm^2	6.1×10^{-14}	7.4×10^{-15}	1.5×10^{-14}
$[\lambda F_\lambda(\theta)]_{\mathrm{max,IR}}$W/cm^2	8.4×10^{-14}	1.4×10^{-14}	2.2×10^{-14}
$f(\theta)$	0.73	0.53	0.69
$A(\theta)$	0.42	0.35	0.41

TABLE V

S. no.	UT date 1997	T_{BB} (K)	T_{color} (K)	$F_{3.28}$ $\times 10^{-15}$ W/cm^2/μm	$(\lambda F_\lambda)_{\mathrm{max,IR}}$ $\times 10^{-14}$ W/cm^2	$(\lambda F_\lambda)_{\mathrm{max,SC}}$ $\times 10^{-14}$ W/cm^2	Scatt. angle θ	Albedo	
								$f(\theta)$	$A(\theta)$
1.	Mar. 2	271	502	6.1	7.5	5.0	137.8	0.67	0.40
2.	Mar. 3	272	505	6.7	8.0	5.6	137.3	0.69	0.41
3.	Mar. 4	273	507	9.1	11.0	7.5	13.67	0.68	0.41
4.	Apr. 17	285	528	8.7	8.7	7.2	141.0	0.83	0.45
5.	Apr. 18	283	526	9.2	9.3	6.1	141.7	0.66	0.40
6.	Apr. 20	282	523	5.7	5.9	4.7	143.0	0.79	0.44
7.	Apr. 27	275	510	4.0	4.6	3.3	147.6	0.72	0.42
8.	May 16	253	472	0.88	1.4	0.74	158.5	0.52	0.35

where $[\lambda F_\lambda(\theta)]_{\mathrm{max,scatt}}$ and $[\lambda F_\lambda(\theta)]_{\mathrm{max,IR}}$ refer to the Planckian maxima of the scattered and thermal spectral energy distribution respectively. It can be seen from Table IV that the superheat values have not appreciably changed during the perihelion passage, at least till the period of our observations.

3.2. ALBEDO VS. SCATTERING ANGLE

Our observations span a scattering angle range from 136 to 158 degrees. We have attempted to calculate the albedo $A(\theta)$ as a function of scattering angle θ utilising the J, H, K photometric values and also utilising the concept of superheat discussed earlier. J H K values as seen from Figures 2a and 2b represent the scattered component and are well represented by a solar type blackbody at 5700 K. For each day of our observation we can calculate $(\lambda F_\lambda)_{\text{max,scatt}}$ corresponding to the peak of the scattered component. These values are listed in Table V. Also listed in Table V are the superheat temperatures (superheat ~1.86) and expected blackbody temperatures corresponding to the thermal component of the IR emission from the comets. From JHK photometry with corresponding solar type blackbody fit we obtain the scattered component to be 8% and 10% on the two days of the detected continuum emission in the 3.0–3.4 μm region. Assuming the scattered component to be in this range for the other days of observation we derive the expected thermal component fluxes at 3.28 μm and hence $(\lambda F_\lambda)_{\text{max,IR}}$ values for each day of observation and consequently $f(\theta)$ and albedo $A(\theta)$ can be calculated. These values are listed in Table V.

It can be seen from Table V that the $A(\theta)$ is nearly constant, hovering around 0.4 for the period of observation. While the value agrees with the perihelion results of Williams et al. (1997), it a]so reinforces the view that the albedo of comet Hale–Bopp was higher than those of other comets. Our albedo value for comet Hyakutake (C/1996 B2) at 0.75 AU from. the sun was 0.12 ± 0.02 at a scattering angle of 690. Figure 3 compares the albedo values of comet Hale–Bopp with a few other comets in the range of our scattering angles of observation.

The large albedo values for comet Hale–Bopp suggest that it contains a substantial population of hot absorbing grains with radii $a \leqslant 0.5$ μm, both before and after perihelion passage. As pointed out by Williams et al. (1997), these dust radii are comparable to the radii of star dust in nova outflows. However, our results are constrained by the limited data set essentially in the post-perihelion phase. The possibility that the dust was anomalous giving rise to these large superheat values only around perihelion has to be considered. Wooden et al. (IAU Cir. 6741) report that in 1997 June 25.84, when the comet was at a heliocentric distance of 1.7 AU the measured continuum flux at 8.6 μm was well fit by a black body at 295 K. The inferred superheat value is 1.38, smaller than the value of 1.86 derived by us or 1.84 derived by Williams et al. (1997). Further Harker et al. (1997) from spectrophotometry in the 7–13 μm region, at 1.6 AU in the post-perihelion period, find the reservoir of small grains to be apparently exhausted after perihelion passage. The possibility of some of these small grains being pristine with an interstellar connection cannot be ruled out, though definitive results would have to wait for a sample return mission to a comet.

It must be pointed out that there are alternative suggestions to the presence of small submicron grains in comet Hale–Bopp. Li and Greenberg (1998) have

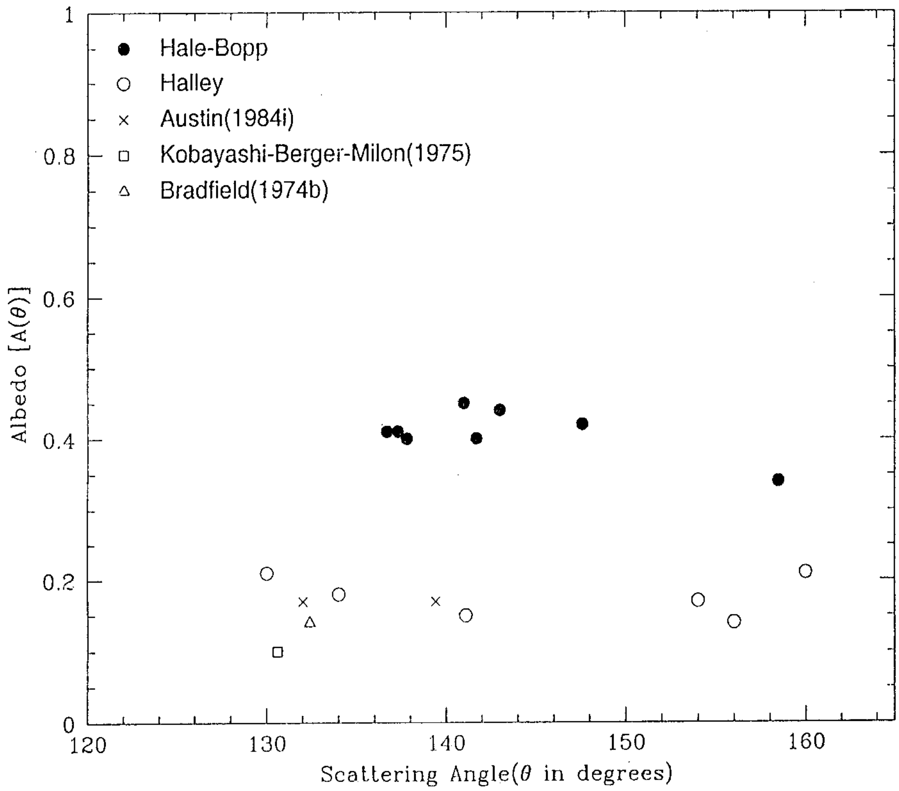

Figure 3. Comparison of our values of albedo $A(\theta)$ for comet Hale–Bopp with those of other comets in the same range of scattering angles. Data for other comets is from Gehrz and Ney (1992).

modelled the 3–20 μm IR thermal spectrum of the comet at a heliocentric distance of 1.15 AU. They derive mean grain masses 2–3 orders of magnitude higher than those estimated from the empirical superheat method or IR emission modeling, both of which use small silicate or carbon grains.

4. Conclusions

Near Infrared observations at J, H, K wavelengths were carried out at the 1.2 m Gurushikhar telescope for 8 nights during both the preperihelion and post perihelion phase of comet Hale–Bopp (1995 O1). CVF observations in the 2.0–2.4 micron and 3.0–3.4 micron regions were obtained for two nights during the post perihelion period.

The effective temperatures derived from photometry are substantially higher than the equilibrium blackbody temperatures at the same heliocentric distance. A mean Superheat value of 1.83 derived in the post perihelion phase are consistent with other pre-perihelion observations on the same comet. These superheat values imply that a substantial fraction of the coma grain population are made up of small hot grains with radii <0.5 microns at least for a short period around perihelion. Later observations point to a depletion of the small hot grains. The derived albedo values of 0.4 are consistently higher than corresponding values of other comets and may be the cause for the unusual brightness of comet Hale–Bopp.

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