NEAR INFRARED OBSERVATIONS OF COMET HYAKUTAKE (C/1996 B2) FROM GURUSHIKHAR OBSERVATORY

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Abstract. Near infrared photometric observations were carried out in the preperihelion phase in J, H and K filter bands during the recent apparition of Comet Hyakutake (C/1996 B2) at the 1.2 m telescope at Gurushikhar, India. The effective temperature of the comet is found to be ~20% higher than that of an equilibrium fast rotating blackbody at the same heliocentric distance. A dust albedo of 0.12 ± 0.2 is derived which is similar to values for Comet Kohoutek but distinctly higher than the values for comet Halley. The brightness in the K band varies with the heliocentric distance r as $r^{-4.3\pm0.3}$ law which is again consistent with a long period or aperiodic comet. Passage of two bright infrared sources in the inner coma were monitored but no significant diminution in the star signal was observed.

Key words: Comets, Hyakutake, infrared, albedo, grains.

1. Introduction

Near infrared (1–3 μm) continuum observations of comets are an important means of studying the scattering and thermal emission properties of dust grains in the coma. The infrared (IR) spectral distribution in comets is governed by both intrinsic and extrinsic factors. Extrinsic factors which include heliocentric distance of the comet (r), phase angle (β), geocentric distance of the comet (Δ) depend on the position of the comet in its orbit and can be well predicted. Intrinsic factors, which affect infrared continuum like the amount and extent of dust present, its production rate and distribution, also depend on extrinsic factors but are much less predictable and vary from one comet to another. The composition of comets range from very dusty comets like Bennett (1970 II), through medium dusty comets like Tago-Sato-Isako (1969 IX) to almost dust free comets like Ikeya (1963 I) that displayed only an ion tail.

There has been considerable progress in infrared detection techniques; since the first infrared detection of the bright comet Ikeya-Seki (1965 VIII) by Becklin and Westphal (1966). These authors showed that the infrared radiation was from thermal emission of grains and the cooler temperature was about 30% higher than the grey body temperature for the same heliocentric distance.

Comet Halley was the first comet to be subjected to a thorough scrutiny by a wide range of infrared instrumentation – ground based, airborne and spacecraft based (Hanner and Tokunaga, 1989). However compared to visual region, observations

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of comets in the infrared have been in general limited. The recent apparition of Comet Hyakutake (C 1996 B2) provided a good opportunity, though at relatively short notice of studying a bright comet in the near infrared region.

2. Instrumentation

The infrared observations reported in this paper were carried out at the $f/13$ Cassegrain focus of the 1.2 m Gurushikhar telescope at Mt. Abu, India (24°39′ N, 72°47′ E, 1680 m) with a liquid nitrogen cooled InSb detector. Details of the instrument, which is currently being used extensively for recording lunar occultation light curves and for infrared photometry of close binary systems and galactic novae can be found elsewhere (Ashok et al., 1994). Basically the $f/13$ telescope beam is switched between the source and the sky by a tertiary vibrating mirror before reaching the detector. The preamplifier signal is synchronously detected at the frequency of 'chopping' (typically 15 Hz) with a lock in amplifier and recorded on a PC based data acquisition system. A new feature of the instrument, pertinent to comet observations, is the use of the tertiary mirror in the angular chopping mode. Instead of the conventional linear movement of the tertiary plane mirror, in this case, through a hinged support an angular movement is provided. This arrangement results in larger separation between the signal and reference beams (upto several arc minutes) than conventionally possible with a vibrating tertiary mirror in the sky.

The beam profile when the system is well aligned is distortion free, stable and provides a high degree of photometric accuracy even for large throws upto several arc minutes.

3. Observations

The discovery of Comet Hyakutake (C/1996 B2) on 30th January 1996 was first reported in IAU Circular 6299. Comet was then visually a 10th magnitude object beyond the orbit of Mars. The interest in the comet increased manyfold when it became clear that it would make a close passage to the earth at a distance of 0.1 AU, on its way to perihelion. The expectations of Hyakutake being the brightest comet at least in the last 20 years since Comet West (1976) made it an interesting object for infrared studies with modest sized telescopes. The rapid movement of the comet in relation to the star fields during its close passage to the earth also raised the interesting possibility of a bright infrared stellar source being occulted by the nucleus or undergoing extinction due to cometary material in the near nuclear region. In fact two bright IR sources crossed the inner coma of the comet and these events were monitored by us, as described later.

The first positive infrared detection of Comet Hyakutake from Gurushikhar observatory was made on 1996 April 6 at $r = 0.77$ AU and $\Delta = 0.414$ AU in the

Table I

S. No	Date	Time	Filter	Focal plane aperture (arcsec)	Chopper throw (arcsec)	r (AU)	Δ (AU)	Phase angle β	Solar elongation Θ	Air mass
1.	1996 April	6.604	J,K	26	60	0.773	0.414	111.4	45.9	2.46
2.	1996 April	7.604	J,H,K	26	60	0.750	0.446	111.2	44.2	2.61
3.	1996 April	8.601	J,K	26	60	0.726	0.478	110.8	42.5	2.63
4.	1996 April	9.595	K	26	60	0.702	0.510	110.3	41	1.93
5.	1996 April	10.599	K	26	60	0.678	0.542	109.8	39.5	2.75
6.	1996 April	23.578	K	26	35	0.355	0.969	85.5	20.6	5.21

Table II

Date 1996 April UT	Focal plane aperture (arcsec)	Chopper throw (arcsec)	K	ΔK (1σ)	H	ΔH (1σ)	J	ΔJ (1σ)
6.604	26	60	4.91	0.05	–	–	5.70	0.07
7.604	26	60	4.52	0.04	4.73	0.04	5.06	0.05
8.601	26	60	4.27	0.03	–	–	5.04	0.03
9.595	26	60	4.50	0.07				
9.595	39	60	4.46	0.04				
10.599	26	60	4.36	0.04				
23.378	26	60	2.61	0.10				

K band. The comet was subsequently detected on successive days in the K band till 10th April and then after a gap, due to telescope time constraints, again on 23 April. The comet was observed generally under difficult observing conditions – twilight, large hour angles (low elevations) and limited observing time. On a few days following April 6, 1996, J and H filter observations could also be taken. The journal of observations is given in Table I.

After each comet observation, the telescope was moved 2 arcmin in RA, first East and then West and sky measurements were taken with the same aperture and throw. Standard star used was α Persei (K = 0.56). As many observations were made at large air masses a careful evaluation of the extinction corrections in J, H and K bands were carried out for the site using α Persei at large air masses. The values derived are K_K = 0.14 mag/air mass, K_H = 0.2 mag/air mass, K_J = 0.3 mag/air mass.

The derived photometric values after extinction corrections and the corresponding errors in measurement (1σ) are given in Table II.

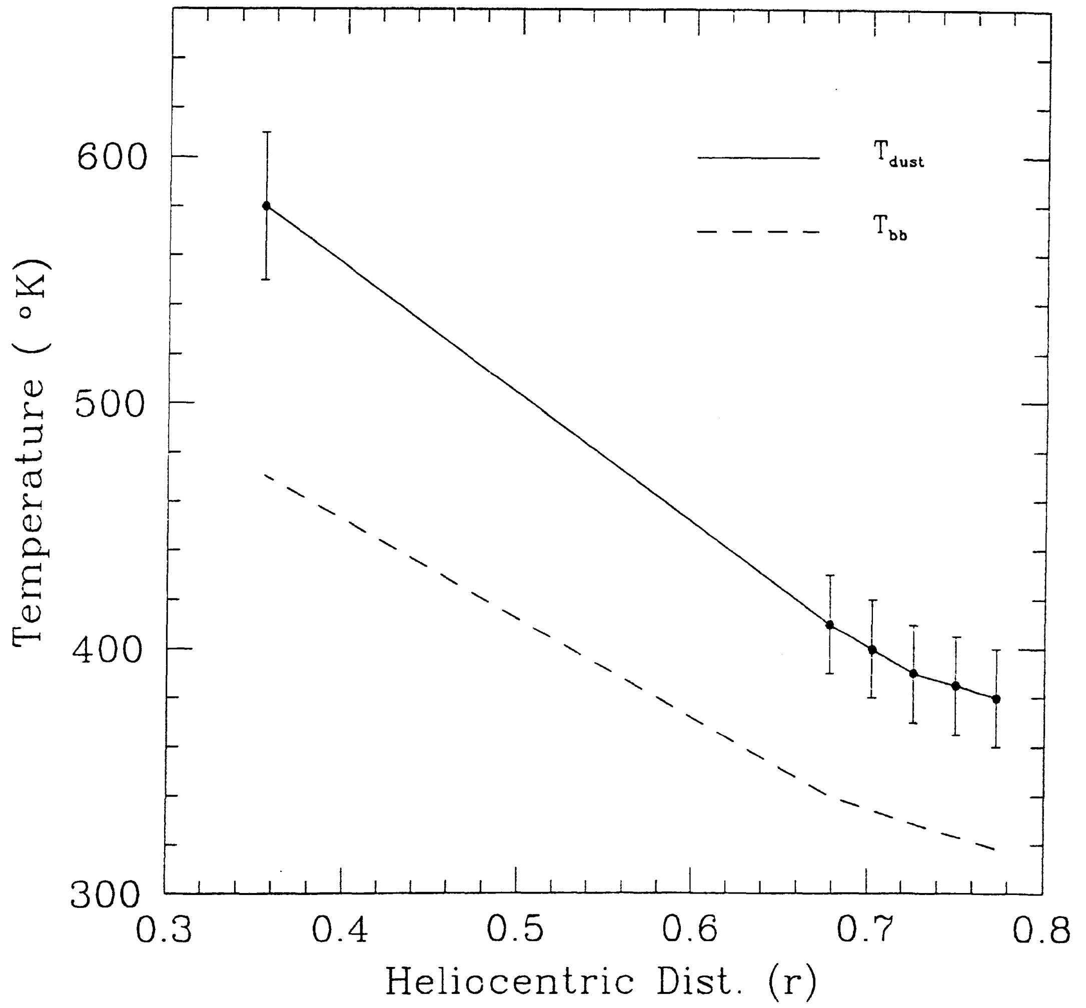

Figure 1. Dust temperatures derived at the epoch of observations against the heliocentric distance. Also plotted is the equilibrium temperature of a perfectly conducting blackbody at the same heliocentric distance.

4. Discussion and Results

Contemporaneously, infrared observations of Comet Hyakutake have also been reported by Mason et al. (IAU Circulars, 6365, 6378, 6396). Their observations have been carried out on 1996 March 21.4, March 23.3, April 10.1 and April 23.1 UT and cover a wider spectral range from 1.2 to 18 microns. They report dust temperatures which are generally 20–40% higher than equilibrium blackbody (small black spheres) temperature at the same heliocentric distance. In Figure 1 we have plotted the dust temperatures derived at our epoch of observations against the heliocentric distance of the comet. Also plotted is the equilibrium temperature of a perfectly conducting blackbody at the same heliocentric distance. The actual values are given in Table III.

The temperature excess over the equilibrium blackbody temperature is ~20% for the period of our observations. In comparison, the temperature excess was 8% for Comet Kobayashi-Bergar-Milon (1975 IX), 26% for Comet Kohoutek (1973

Table III

Date 1996 April (UT)	r (AU)	T_{bb} (K)	$T_{\rm dust}$ (K)	% Excess in temperature
6.604	0.773	317	380	19.8
7.604	0.750	322	385	19.3
8.601	0.726	327	390	19.3
9.595	0.702	333	400	20.1
10.599	0.678	338	410	21.3
23.378	0.355	468	580	23.9

XII), 45% for Comet Bennett, 40% for Comet Ikeya Seki (1965). For wavelength $\lambda \gg 2\pi a$ where a is the grain size, the absorptivity or emissivity decreases very quickly so that the grain cannot radiate efficiently and gets heated up. Thus small absorbing grains which radiate inefficiently in the infrared are responsible for the temperature excess. Since the silicate emission feature at 9.7 μm has been seen in the observations of Mason et al., on comet Hyakutake, the dominant grain size must be $\ll$ 10 μm. Further in the absence of observable Rayleigh scattering (blue colour; isotropic scattering) the contribution of grains smaller than optical wavelengths is small. In the infrared beyond 3.5 μm thermal emission of the dust dominates the cometary spectrum. With reference to grain model presented by Campins and Hanner (1982) it appears that the temperature excess of ~20% can be accounted for by the cometary grains being predominantly silicate of radius ~1 μm with an imaginary index of refraction $n'' \approx 0.04$ representing the absorbing component.

Even from the limited multiwavelength observations that we have, following the method of Ney (1982) we can arrive at an estimate of the albedo of the dust in the coma.

Assuming flux at 1.65 μm to be totally due to scattering we can calculate the total scattered energy from the comet as due to a blackbody at 5750 K normalised to the measured value at 1.65 μm. We obtain a value for the total scattered flux (integrated overall wavelengths) on the day we have complete J, H, K photometry (April 7, 96) as

$$F_{\rm Scatt} = 1.033 \times 10^{-14}\ {\rm W\ cm^{-2}}. \quad (1)$$

The total thermal radiation (integrated over all wavelengths) from the comet ($F_{\rm rad}$) on the same day is obtained knowing the effective temperature of the comet (385 K) and attributing the measured excess in the K band over the scattered component to the thermal component in K band. The (H–K) colour of the comet on this day of +0.21 ± 0.04 is considerably redder than the solar H–K value of 0.06

(Hanner and Tokunaga, 1989) and indicates the contribution of thermal component in K band. We obtain

$$F_{\mathrm{rad}} = 7.26 \times 10^{-14}\ \mathrm{W/cm^2}. \tag{2}$$

Hence the grain albedo,

$$\gamma = \left(\frac{F_{\mathrm{scatt}}}{F_{\mathrm{scatt}} + F_{\mathrm{rad}}}\right) \simeq 0.12 \pm 0.02. \tag{3}$$

In comparison the albedo for comet Kohoutek is in the range 0.14–0.20 in the scattering angle range 89–135°. As pointed out by Ney (1982) this value is fairly independent of scattering angle for angles in the range 60° to 150°. Our K band observations are confined to scattering angles in the range 65° to 95°. The derived albedo value for Comet Hykutake appears fairly typical of long period and aperiodic comets. For Comet Halley the measured albedo values were lower 0.032 in J and 0.045 in H. (Tokunaga et al., 1986).

It was first pointed out by O'Dell (1971) that from simultaneous infrared and optical observations of the comet bolometric Bond albedo could be computed.

Following the arguments of O'Dell, the effective temperature T is given by

$$T = \langle R_A \rangle^{1/4} T_{bb}, \tag{4}$$

where T_{bb} is the blackbody temperature for the heliocentric distance r given by

$$T_{bb} = 280/r^{1/2}\ \mathrm{Kelvin}. \tag{5}$$

Hence

$$\langle R_A \rangle = \frac{\text{Optical Absorptivity}}{\text{Infrared Emissivity}} = \frac{Q_A(\text{optical})}{Q_A(IR)} = \left(\frac{T}{T_{bb}}\right)^4 \tag{6}$$

for a 20% increase observed over T_{bb}

$$\langle R_A \rangle = (1.2)^4 \approx 2, \tag{7}$$

i.e., the IR emissivity or absorptivity is less than visual value by a factor of 2.

4.1. Brightness Variations with Heliocentric Distance (r)

As we have a consistent set of photometric values of the comet in the K band (2.2 microns) we attempt to derive the intrinsic brightness variations of the comet using these values. In this process it is necessary to correct the observed flux for

(a) thermal component in the K band
(b) the varying geocentric distance to the comet (Δ)

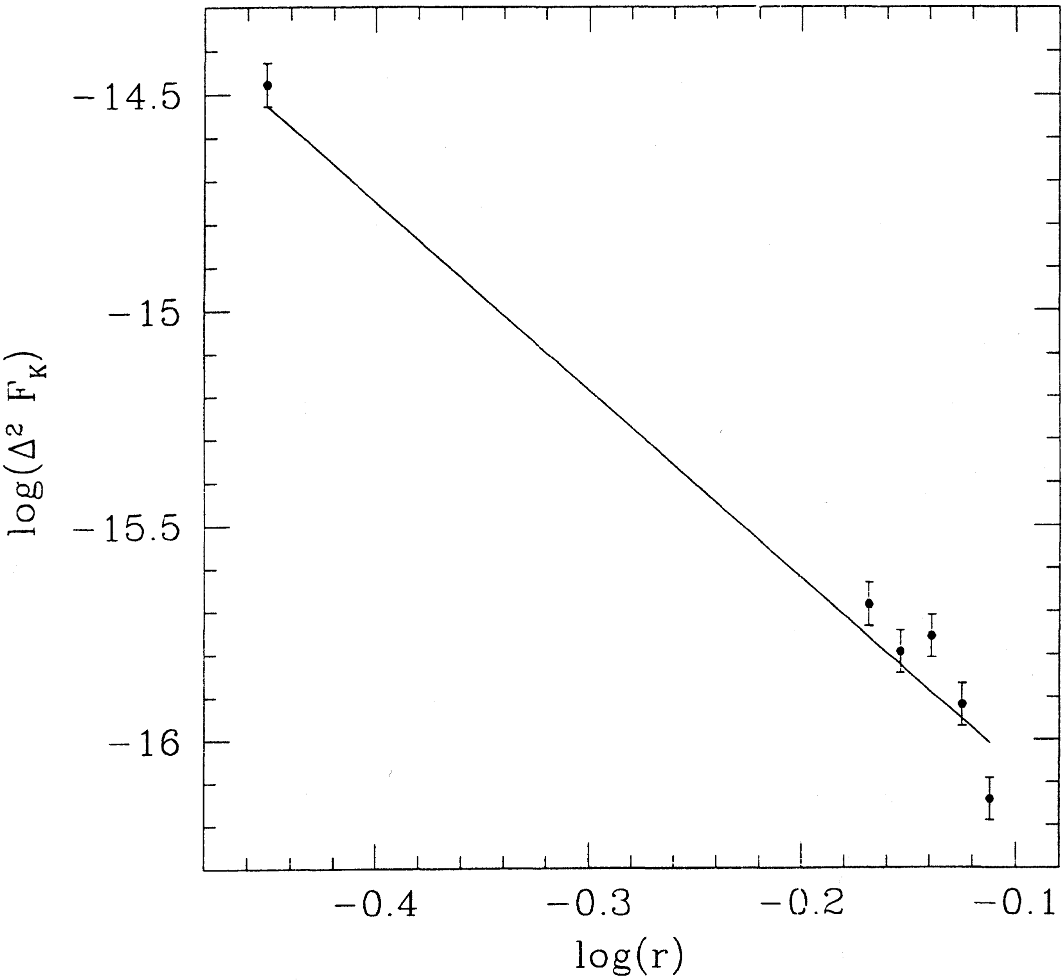

Figure 2. K band flux (F_K) corrected to the varying geocentric distance (Δ) against the heliocentric distance (r). The solid line shows the least-square fit to the data.

(c) the scattering phase function
(d) the diaphragm used in the photometry (d).

Following Ney (1987) the phase function can be considered to be a constant and does not affect the brightness variation.

The scattered flux in the K band can be written as

$$F_K \quad \alpha \, \frac{d^{\alpha}}{r^n \, \Delta^2} . \tag{8}$$

For a simple model of the coma where the dust is ejected isotropically with a uniform velocity the dust space density varies with cometocentric distance (R) as $1/R^2$ and will give rise to a value of $\alpha \approx 1$.

In Figure 2 we depict the heliocentric variation of cometary brightness of comet Hyakutake by plotting log ($\Delta^2 F_K$) against log r. We obtain a value of $n = -4.3 \pm 0.3$. The result is generally more typical of a nonperiodic comet than a periodic one (Mendis, Houpis and Marconi, 1985).

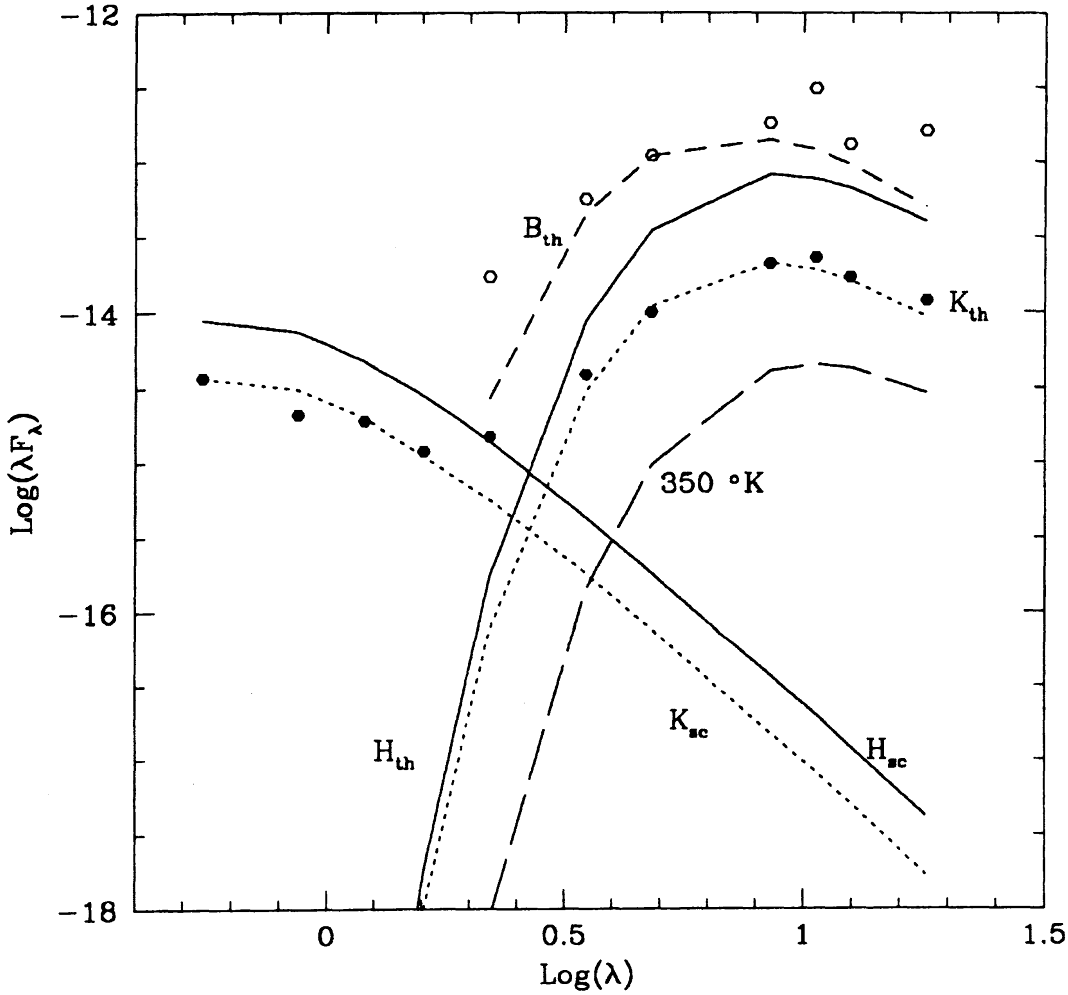

Figure 3. Comparison of Comet Hyakutake (H) with comets Kohoutek (K) and Bennett (B). The thermal and the scatttered components are marked with subscripts 'th' and 'sc'. The open and closed circles correspond to the data points of Bennett and Kohutek. Also shown is the 350° K black body.

In Figure 3 we have compared the energy spectrum of comet Hyakutake with those of other comets, a very dusty comet Bennett (1970 II) (4 April 1970) and Kohoutek (1973 XII) (10 December 1973), all at the same heliocentric distance of 0.65 AU. The effective temperature of Hyakutake at this heliocentric distance as derived from Figure 1 is 420 K which is lower than 518 K for Bennet and 440 K for Kohoutek.

4.2. Passage of Two IR Stellar Sources through the Coma of Comet Hyakutake

From the ephemeris of Comet Hyakutake it was noted that at Gurushikhar Observatory the comet would be passing relatively close to the line of sight of two bright infrared sources, namely IRC 30265 (m_k = 2.0) on March 23, 96 and IRC 70123 (m_k = 1.13) on March 25,1996. Neither of the sources was predicted to be occulted by the comet nucleus. However as the star light was passing through the inner

Table IV

Date	Source	Sp type	m_K	Δ (AU)	Time of approach (UT)	Closest separation (arcsec)	Cometocentric distance (km)	Star counts	Noise (1σ)
23/3/96	30265	M1	2.0	0.114	1750	389	32,247	27640	374
25/3/96	70123	M2	1.13	0.103	2000	1549	116,017	16240	306

coma, it was decided to monitor for about an hour the sources in the K band during their passage through the cometary atmosphere to look for possible cometary obscuration. The details of the two events are given in Table IV. During the events, the star was tracked and the comet was allowed to drift across it.

During both the events there was no detectable decrease in signal level from the star which could be attributable to a cometary obscuration. The noise limits in our system for 1st event for 1^S of integration at the 1.2 m telescope corresponds to 1σ value of 6.67 mag in K. For the second event the corresponding value is 5.44 magnitude in K. The comet itself was undetectable in the 26″ diaphragm used on the days of the events.

We derive, from our observations an upper limit to the optical depth at a wavelength of 2.2 microns through the comet at a cometocentric distance of 32000 km as $\tau_K < 0.014$.

For the second event the corresponding value of τ at a cometocentric distance of 101 000 km is $\tau_K < 0.019$.

One can estimate the value of τ_K in the following manner.

Following Ney (1982) one can define the optical depth τ as

$$\tau = (\Theta/d)^2, \tag{9}$$

where Θ is the blackbody angular size corresponding to the observed flux from the comet and d is the diaphragm used in the photometry (26 arcsec in our case).

We have calculated earlier the total thermal emission from the comet (on 1996 April 7) as 7.26×10^{-14} W cm^{-2}. Putting in the values (T = 385 K) we find

$$\Theta^2 \sigma T^4 < 7.26 \times 10^{-14}, \tag{10}$$

$$\Theta \simeq 0.15 \text{ arcsec}. \tag{11}$$

As d is 26 arcsec in our case,

$$\tau_K < \left(\frac{0.15}{26}\right)^2 \simeq 3 \times 10^{-5}. \tag{12}$$

It would seem that only very close passages to the nucleus within arcseconds could lead to measurable optical depths.

5. Conclusions

The relatively sudden appearance of comet Hyakutake (C/1996 B2) in comparison to the well predicted apparitions of comets like Hale-Bopp and Halley permitted only limited observations in the infrared of which those presented in this paper form an important part. The effective temperatures derived from our infrared photometry are about 20% higher (in comet Hyakutake) than the calculated radiative equilibrium blackbody temperatures at the same heliocentric distance. This excess can be explained by a reduced absorptivity/emissivity ratio in infrared by a factor of 2 compared to visible region. The grain albedo derived is 0.12 ± 0.02 which is comparable to the values derived for long period comets like Kohoutek but larger than the values for comet Halley.

The passage of two bright near infrared sources through the coma of comet Hyakutake was monitored but no diminution in their light level in the K band was detected above noise level. We derive an upper limit to the optical depth at 2.2 microns of 0.01. The expected optical depths are in the range of 10^{-5}. The brightness in the K band of comet Hyakutake is found to vary as $r^{-4.3\pm0.3}$ where r is the hehocentric distance. Such a variation is more typical of a nonperiodic comet like comet Kohoutek than a periodic one.

In summary, the limited near infrared observations made during the sudden apparition of comet Hyakutake (1996 B2) suggest that it belongs to the class of comets like Kohoutek and is distinctly different from inner solar system comets including comet Halley.

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