

SUBMILLIMETER CONTINUUM OBSERVATIONS OF COMET HYAKUTAKE (1996 B2)

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ABSTRACT

We report submillimeter continuum observations of comet Hyakutake (1996 B2) in the wavelength range $350 \leq \lambda \leq 2000 \mu\text{m}$. Submillimeter continuum emanates primarily from large (millimeter sized), solid particles in the coma. C/Hyakutake was the strongest source of cometary submillimeter radiation observed to date, allowing new measurements of unprecedented quality. The equivalent blackbody cross section at $800 \mu\text{m}$ is $(1.16 \pm 0.12) \times 10^2 \text{ km}^2$, corresponding to a dust mass $M \approx 1.8 \times 10^9 \text{ kg}$ and a dust mass production rate $dM/dt \approx 2.8 \times 10^4 \text{ kg s}^{-1}$. The gradient of the emission spectrum is relatively flat, with an opacity index $\beta = 0.89 \pm 0.10$. The cometary β is comparable to values measured in the circumstellar disks of young stars. A small map at $800 \mu\text{m}$ shows a coma radial surface brightness variation that is compatible with steady emission of solids from the nucleus on timescales $\approx 0.7 \text{ day}$. © 1997 American Astronomical Society. [S0004-6256(97)00103-9]

1. INTRODUCTION

Comets are aggregates of ices and refractory dust particles thought to have been formed in the outer regions of the pre-planetary accretion disk of the sun (Whipple 1951). Our understanding of their nature and significance is undergoing a renaissance, as new techniques are brought to bear on the study of these primitive objects. One of the most surprising findings of the last decade is that much of the particulate mass ejected from the nucleus may be carried by large (radius $a > 1 \text{ mm}$) particles which, nevertheless, are sufficiently rare that they contribute negligibly to the optical cross section. Historically, the production rate of cometary solids has been routinely assessed from optical and near-infrared photometry (e.g., Ney 1982). However, observations at wavelength λ are most sensitive to particles of size $a \approx \lambda$. Therefore, optical ($\lambda \approx 0.5 \mu\text{m}$) and near-infrared ($\lambda \approx 10 \mu\text{m}$) observations refer to particles at the small end of the cometary grain size distribution, and yield only weak constraints on potentially mass-dominant millimeter sized and larger particles.

The importance of the larger particles has been recognized from several different kinds of observations. Doppler-broadened centimeter wavelength radar echoes from near-Earth comets (e.g., Goldstein *et al.* 1984; Harmon *et al.* 1989) provide strong evidence for centimeter-sized particles

in the near-nucleus coma. Narrow infrared (12, 25, and $60 \mu\text{m}$) dust trails in the orbits of several short-period comets provide evidence for the low-velocity ejection of millimeter-sized particles (Sykes *et al.* 1986). Most directly, spacecraft in the comae of comets P/Halley (McDonnell *et al.* 1991) and P/Giacobini-Zinner (McDonnell *et al.* 1993) determined relatively flat particle size distributions, and were struck by particles up to 1 mm in size.

Submillimeter continuum observations provide another route to the study of large dust grains in comets. Careful measurements using ground-based bolometers show that considerable dust mass may be carried by comparatively rare millimeter sized and larger debris (see Jewitt & Luu 1992). However, experience shows that comets are typically weak sources of submillimeter continuum, requiring integrations of many hours for even quite modest signal-to-noise ratios. The fortuitous appearance of C/Hyakutake in late March 1996 prompted us to attempt observations of its submillimeter continuum, in the hope that these might be used to assess the abundance and nature of large solid particles in its coma. Our efforts were amply rewarded with the first submillimeter continuum spectrum (Sec. 3) and a limited map of the coma at $800 \mu\text{m}$ (Sec. 4).

2. OBSERVATIONS

The JCMT is a 15 m diameter telescope located at 4 km altitude near the summit of Mauna Kea, Hawaii. Its dry location permits observations at wavelengths down to $350 \mu\text{m}$. Mechanical stability of the JCMT allows pointing to about $\pm 1.5 \text{ arcsec rms}$ over much of the sky. The accuracy of the

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TABLE 1. Observational circumstances.

UT 1996 March	R (AU) ¹	Δ (AU) ²	α (deg) ³
1996 Mar 23.4438–23.5013	1.080	0.118	−43.1
1996 Mar 24.4125–24.4813	1.060	0.105	−51.4

¹Heliocentric distance.²Geocentric distance.³Phase angle.

telescope pointing was measured using repeated observations of known galactic and extragalactic continuum sources near C/Hyakutake. Photometric calibration was also obtained from observations of standard sources Uranus, NGC 2071IR, AFGL 490, NGC 6334I, and IRAS 16293-2422 (Sandell 1994). Observations of C/Hyakutake were obtained shortly before closest approach to the Earth, on UT 1996 March 23.4438–23.5013 and 24.4125–24.4813. One arcsecond corresponded to 80 km at the (0.11 AU) distance of the comet. Cometary ephemerides were provided by Brian Marsden (Center for Astrophysics) and adapted for use at the JCMT by David Tholen (Institute for Astronomy). On UT March 24, the proper motion of the comet reached $0.7 \text{ arcsec s}^{-1}$. The pointing of the telescope was updated in real time using a linear interpolation algorithm. The geometric circumstances of the observations are listed in Table 1.

All observations were taken using the facility bolometer UKT14. This is a single element Ge:In:Sb detector sensitive to radiation at wavelengths from the atmospheric cut off at $350 \mu\text{m}$ to a functional limit at $2000 \mu\text{m}$ (Duncan *et al.* 1990). Radiation was admitted to UKT14 through a 65 mm diameter aperture and a series of filters at the $f/35$ Nasmyth focal plane. The angular diameter of the photometry beam is 16 arcsec at $\lambda=800 \mu\text{m}$. The filters match regions of high transmission through the terrestrial atmosphere. We do not distinguish between the effective wavelengths and the central wavelengths (Table 2) since these differ by, at most, a few percent (Duncan *et al.* 1990). Sky cancellation was achieved by chopping the photometry aperture 120 arcsec in azimuth at a frequency of 7.8 Hz. In addition, the telescope was nodded with a period of 20 s in order to eliminate possible asymmetries between the object and sky beams. Mapping observations (Sec. 4) show that the photometric error incurred by chopping onto the outer coma at 120 arcsec is negligible.

3. THE SUBMILLIMETER SPECTRUM

Strong continuum detections were obtained at 350, 450, 800, and $1100 \mu\text{m}$ on both UT 1996 March 23 and 24 (Matthews *et al.* 1996). Observations at 350 and $450 \mu\text{m}$ were repeated twice on UT March 23. In addition, a $2000 \mu\text{m}$ observation was attempted on UT March 24 and resulted in an upper limit to the flux density. The results are summarized in Table 2. Uncertainties listed in columns 4 and 5 of Table 2 are 1σ standard deviations on the weighted means of each sample. The agreement among measurements at 800 and $1100 \mu\text{m}$ on different days is remarkably good, and suggests that photometry at these wavelengths is repeatable at the $\pm 1\%$ ($800 \mu\text{m}$) to $\pm 15\%$ ($1100 \mu\text{m}$) level. Significantly, the hydroxyl radical production rates of the comet on these dates were also constant at $Q_{\text{OH}}=10^{29.17}$ and $10^{29.18} \text{ s}^{-1}$, respectively (Schleicher 1996), corresponding to a water outgassing rate of 4500 kg s^{-1} .

The scatter of the measurements at $350 \mu\text{m}$ (and, to a lesser extent, at $450 \mu\text{m}$) is greater than would be expected from the standard deviations of the individual samples. Presumably, non-uniformities in the atmospheric opacity are responsible. Such photometric variations are common at submillimeter wavelengths, even from the high altitude Mauna Kea site. To take account of this extra variability, we use the unweighted mean and standard deviation of the three samples at 350 and $450 \mu\text{m}$ as our best estimate of the true values (column 6 of Table 2). Atmospheric variations at $\lambda \geq 800 \mu\text{m}$ appear small, and column 6 lists for these longer wavelengths the weighted mean of the measurements on March 23 and 24. We further list in column 7 of Table 2 the flux densities corrected to a common (16 arcsec) angular beam size. For this correction, we simply assumed that the flux density in a beam of diameter ϕ is proportional to ϕ , as would be expected of a coma in steady state. Our mapping data (Sec. 4) validate this assumption. The resulting spectrum is plotted in Fig. 1.

The flux density due to a blackbody emitter of cross-section $C_{\text{BB}}(\text{m}^2)$ is given by

$$S_\nu = B_\nu(T) \frac{C_{\text{BB}}}{\Delta^2}, \quad (1)$$

where $B_\nu(T)$ is the Planck function at temperature T (K), and Δ (m) is the geocentric distance. Adopting $T=300 \pm 30$

TABLE 2. Continuum spectrum of C/Hyakutake (1996 B2).

λ^1 (μm)	$\Delta\lambda^1$ (μm)	ϕ^1 (arcsec)	S_ν (Jy) 1996/03/23	S_ν (Jy) 1996/03/24	S_ν (Jy) ² mean	S_ν (Jy) ³ Scaled
350	46	19.0	6.35 ± 0.32 7.36 ± 0.36	5.02 ± 0.31	6.24 ± 0.67	5.25 ± 0.56
450	55	17.5	3.90 ± 0.31 3.22 ± 0.28	3.17 ± 0.27	3.43 ± 0.24	3.14 ± 0.22
800	210	16.0	0.548 ± 0.013	0.549 ± 0.020	0.55 ± 0.01	0.55 ± 0.03
1100	306	18.7	0.229 ± 0.015	0.194 ± 0.024	0.22 ± 0.01	0.19 ± 0.03
2000	536	27.0	...	0.097 ± 0.072	0.10 ± 0.07	0.06 ± 0.04

¹Central wavelength, full width at half maximum, and angular diameter of the beam, all from Duncan *et al.* (1990).²Weighted mean and error on the mean of measurements taken UT March 23 and 24.³The weighted mean of the measurements taken on UT March 23 and 24, scaled by the factor $16/\phi$ to correct for the effects of differing beam FWHM.

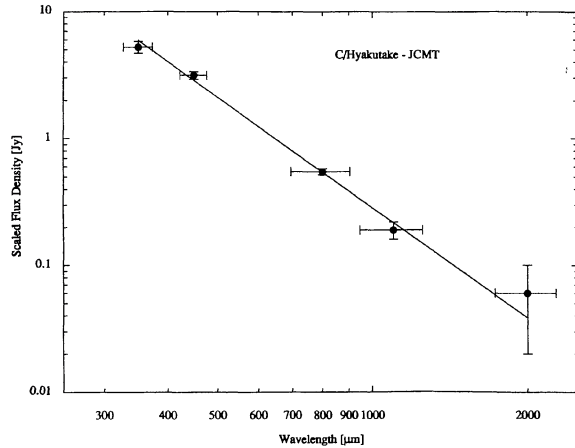


FIG. 1. Submillimeter spectrum of C/Hyakutake. The flux densities have been scaled to a 16 arcsec (1280 km) diameter aperture. The straight line shows a weighted, least-squares power law fit to the data. Vertical error bars mark 1σ photometric uncertainties while horizontal bars denote the filter FWHM (Table 2). The derived opacity index is $\beta = 0.89 \pm 0.10$.

K, and scaling to the 800 μm measurement on March 23 (Table 2), we find $C_{\text{BB}} = (1.16 \pm 0.12) \times 10^8 \text{ m}^2$. The effective blackbody diameter is $D_{\text{BB}} = (4C_{\text{BB}}/\pi)^{1/2} \approx 12.1 \pm 0.6 \text{ km}$. Ostro (1996) used 3.6 cm radar to estimate the nucleus diameter as $D \leq 3 \text{ km}$, which immediately implies that the 800 μm emission is too strong to be attributed to the nucleus alone. A 300 K blackbody of 3 km diameter situated 0.11 AU from Earth would give $S_\nu(800) = 34 \text{ mJy}$, which is 16 times smaller than the measured 550 mJy. Therefore, the nucleus contributes no more than 1/16th of the submillimeter cross section. Independently, our submillimeter map (Sec. 4) clearly shows extended emission incompatible with a point-like nucleus. We proceed on the assumption that the submillimeter emission is due to solids in the coma of C/Hyakutake.

The optical depth averaged over the beam is $\tau \approx (D_{\text{BB}}/2L)^2$, where $2L \approx 1280 \text{ km}$ is the diameter of the projected UKT14 beam. We obtain $\tau \approx 10^{-4}$, justifying our neglect of optical depth effects in the inner coma. We write the effective cross section as $C(\lambda) = \kappa(\lambda)\mathcal{M}$, where $\kappa(\lambda)$ is the opacity and $\mathcal{M}$ (kg) is the total grain mass. We further write the opacity as $\kappa(\lambda) = \kappa(\lambda_0)(\lambda/\lambda_0)^{-\beta}$, where $\lambda_0 = 1 \text{ mm}$ is a reference wavelength. The detected flux density may then be written

$$S_\nu = B_\nu(T) \frac{\kappa(\lambda_0)\mathcal{M}}{\Delta^2(\lambda/\lambda_0)^\beta} \quad (2)$$

We performed a weighted least squares fit of Eq. (2) to the data in Table 2 to determine the opacity index β . The temperature of the emitting grains is not constrained by the submillimeter data, because these wavelengths fall on the Rayleigh–Jeans side of the Planck function in which the emission is only weakly temperature dependent. Near infrared measurements by Mason *et al.* 1996 on March 21 suggest $T \approx 340 \text{ K}$, but the smaller grains sampled by their 10 μm observations are likely to be hotter than the large grains sampled in the submillimeter as a result of geometric depression of the emissivity when $a \ll \lambda$ (the so-called “superheat”:

Ney 1982). Fortunately, neither β nor $\mathcal{M}$ depends critically upon the adopted temperature. For example, with $T = 300 \text{ K}$ we obtain

$$\beta = 0.89 \pm 0.10 \quad (3a)$$

and

$$\kappa(\lambda_0)\mathcal{M} = (9.2 \pm 1.4) \times 10^7 \text{ m}^2. \quad (3b)$$

The error bar on β is essentially independent of the adopted T (temperatures in the range $270 \leq T \leq 330 \text{ K}$ change β by less than ± 0.01). The error bar on $\kappa(\lambda_0)\mathcal{M}$ reflects the $\pm 15\%$ error introduced by varying the temperature over the same range. Likewise, omission of the 2000 μm datum from the spectral fit changes β by only 0.01. The opacity index in C/Hyakutake is consistent with upper limits determined earlier in comets P/Brorsen-Metcalf ($\beta < 1$; Jewitt & Luu 1990) and P/Swift-Tuttle ($\beta < 3.6$; Jewitt 1996). It remains to be seen whether different comets show different β , or whether β changes with time in a given comet.

The opacity is a function of the particle size distribution, composition, shape, and porosity. Pollack *et al.* (1994) found $\kappa(1 \text{ mm}) = 0.05 \text{ m}^2 \text{ kg}^{-1}$ from extensive numerical calculations, and concluded that the opacity is known to within a factor of 4 (we have converted from Pollack *et al.*’s tabulated opacities per unit total mass to opacity per unit dust mass by assuming a cosmical dust to gas mass ratio of 1/100). This assertion is consistent with Hildebrand’s (1983) estimate $\kappa(1 \text{ mm}) = 0.06 \text{ m}^2 \text{ kg}^{-1}$ for interstellar dust but smaller than Beckwith *et al.*’s (1990) adopted $\kappa(1 \text{ mm}) = 0.26 \text{ m}^2 \text{ kg}^{-1}$ for circumstellar dust around premain-sequence stars. High values of κ were calculated for conducting fractal aggregates by Wright (1989), but it is not clear that such particles are abundant in comets.

Using $\kappa(1 \text{ mm}) = 0.05 \text{ m}^2 \text{ kg}^{-1}$ in Eq. (3) we obtain an estimate of the dust mass in the 16 arcsec (1280 km diameter) JCMT beam on UT March 23 and 24 as

$$\mathcal{M} = (1.8 \pm 0.3) \times 10^9 \text{ kg}, \quad (4)$$

where the error bar is the $\pm 15\%$ uncertainty carried from Eq. (3b). The mass is uncertain by a systematic factor of 4 due to the poorly known $\kappa(\lambda_0)$.

Dust grains travelling from the nucleus at the center of the photometry aperture will reach the edge in a time

$$t_c \approx 3.7 \times 10^5 \phi \Delta / V (\text{s}), \quad (5)$$

where $\phi = 16 \text{ arcsec}$ is the beam diameter, $\Delta \approx 0.11 \text{ AU}$, and V is the dust ejection velocity. The dust velocity is not constrained by the present observations. The minimum velocity is the escape velocity which, for the 1.5 km radius of C/Hyakutake, is about 1 m s^{-1} . Large grains are accelerated by gas drag to terminal velocities much smaller than the gas outflow speed (of order 1 km s^{-1}). For millimeter and centimeter sized particles, hydrodynamic calculations (e.g., Crifo 1991) suggest terminal speeds of order 10 m s^{-1} at 1 AU heliocentric distance (although because of the potentially nonuniform gas flow near the nucleus there is not an exact correlation between particle size and speed). Doppler broadening of the radar echo from C/Hyakutake independently gives particle velocities relative to the nucleus of order 10

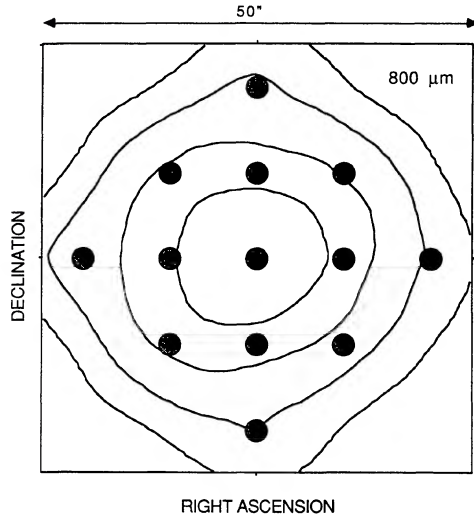


FIG. 2. Map of C/Hyakutake taken at $800\ \mu\text{m}$ on UT 1996/03/24. The grid marks the set of positions at which map data were obtained. Grid spacing is 10 arcsec. The faintest contour and the contour step size are both 100 mJy per beam. North is to the top, east to the left.

m s^{-1} (Ostro 1996). With $V \approx 10\ \text{m s}^{-1}$, we find $t_c \approx 6.4 \times 10^4\ \text{s}$ (0.7 day). The entire dust mass [Eq. (4)] must be replaced on time scale t_c , leading to the dust mass production rate $dM/dt \approx M/t_c \approx 2.8 \times 10^4\ \text{kg s}^{-1}$. This is six times the instantaneous gas production rate determined from OH (Schleicher 1996). It is likely that the high value of the dust to gas production rate ratio reflects, in part, an impulsive ejection of debris from the nucleus on UT March 21 (cf. Sec. 5.1)

4. THE $800\ \mu\text{m}$ MAP

The continuum emission was mapped at $800\ \mu\text{m}$ on three occasions on UT 1996 March 23 and 24. Small R.A.-DEC grids of either 9 or 13 positions were observed, centered on the ephemeris location, and with a separation between adjacent points of 10 arcsec. The grid pattern is shown in Fig. 2. As a result of small ephemeris errors and pointing drift in the JCMT, we found that the center of light moved significantly between the three maps. Accordingly, we shifted the three maps to a common center of light, and numerically resampled the flux density at the position of each new pixel assuming a Gaussian response function for the beam. The resulting surface brightness contours (Fig. 2) show that the coma is approximately circularly symmetric on angular scales of 50 arcsec (4000 km). The resampled map data are summarized in Table 3.

We define the effective radial position of a pixel on the cometary coma as the geometric radius weighted by the coma surface brightness, $\Sigma(x, y)$, and the JCMT beam response, $G(x, y)$:

$$r_e = \frac{\iint (x^2 + y^2)^{1/2} \Sigma(x, y) G(x, y) dx dy}{\iint \Sigma(x, y) G(x, y) dx dy}, \quad (6)$$

where x, y are the coordinates of a point on the coma measured relative to the nucleus and the integrations are carried

TABLE 3. Map data.

Δx^1 (arcsec)	Δy^1 (arcsec)	S_v (mean) (mJy)
-20	0	194 ± 44
-10	-10	273 ± 30
-10	0	348 ± 22
-10	10	269 ± 30
0	-20	146 ± 36
0	-10	301 ± 59
0	0	503 ± 41
0	10	313 ± 29
0	20	162 ± 29
10	-10	192 ± 30
10	0	319 ± 36
10	10	236 ± 30
20	0	122 ± 44

¹Offsets from the $800\ \mu\text{m}$ photocenter, measured East and North in arcseconds. The listed $800\ \mu\text{m}$ flux densities are the weighted means of up to three independent determinations made on UT March 23 and 24.

out over the beam. We find that the difference between the effective radius and the geometric radius is small except for the central pixel, where the spatial variation in the coma surface brightness is largest. For the central pixel, and with $\Sigma(x, y) = \text{constant}/(x^2 + y^2)^{1/2}$, we estimate $r_e = 3.6$ arcsec and have used this value in computing the surface brightness profile.

The resulting radial surface brightness profile is shown in Fig. 3. Error bars in Fig. 3 were computed from the weighted mean of all the data at each radius. For comparison, we show a model in which dust is assumed to flow from the nucleus at a steady rate. In this model, the number density of dust par-

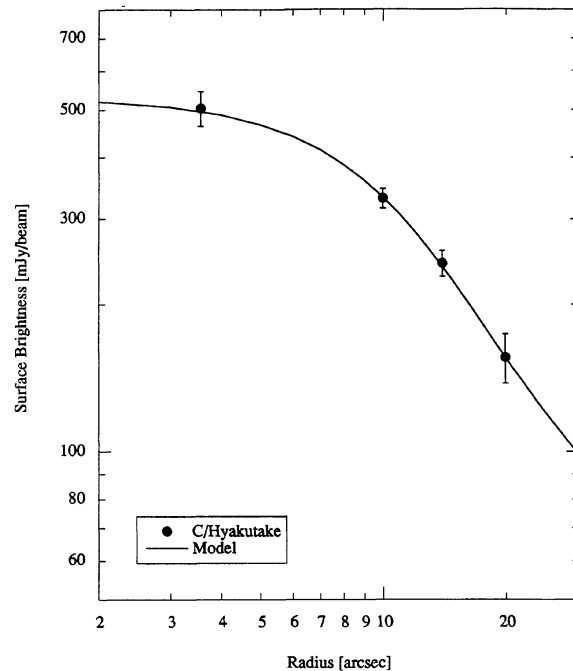


FIG. 3. Radial surface brightness profile of C/Hyakutake at $800\ \mu\text{m}$, computed from the data in Fig. 2. The solid line shows the surface brightness profile expected for isotropic outflow at constant velocity. Depression of the central profile is due to the finite angular resolution of the JCMT data.

TABLE 4. Comparison with comets Halley and Swift-Tuttle.

Property	Symbol	P/Swift-Tuttle	P/Halley	C/Hyakutake
Nucleus radius	r_n (km)	10.8 ^a	5 ^b	1.5 ^c
Nucleus mass ¹	$\mathcal{M}$ (10^{12} kg)	2,600	260	7
Cross section ²	C_{BB} (10^2 km ²)	60 ± 13^a	8 ± 1^d	1.2 ± 0.1^e
Gas production at 1 AU	Q_{OH} (10^{29} s ⁻¹)	6 ^f	2.5 ^g	1.5 ^c
Active fraction	f (%)	5 ^e	10 ^h	67 ^e
Dust/gas	$\mathfrak{R}$	2.8 ^a	2–3 ^h	6 ^e

Notes

^aJewitt (1996).^bKeller *et al.* (1987).^cOstro (1996).^dJewitt & Luu (1992).^eThis work.^fBockelee-Morvan *et al.* (1994).^gSchloerb *et al.* (1987).^hMcDonnell *et al.* (1991).¹ $\mathcal{M} = (4/3)\pi\rho r_n^3$, with density $\rho \approx 500$ kg m⁻³.²Equivalent blackbody cross section determined from submillimeter observations.

ticles varies with the inverse square of the distance from the nucleus, while the column density (and surface brightness) varies with the inverse of the projected radius. We accounted for the effects of finite resolution in the JCMT data by convolving the dust model with a Gaussian of FWHM $\phi = 16$ arcsec. Within the uncertainties of the data, the agreement with the convolved steady-state model is good, and we find no evidence in the 800 μ m map that the dust outflow is different from steady state. The timescale over which this statement applies is just the diaphragm crossing time, $t_c \approx 0.7$ days [Eq. (5)]. This result is further compatible with the observation that the 800 μ m flux density did not substantially change between March 23 and 24 (Table 2).

We also note that the surface brightness profile in Fig. 3 provides no hint of point-like emission from the unresolved central nucleus, confirming our previous conclusion that the bulk of the 800 μ m signal emanates from dust in the near-nucleus coma rather than from the nucleus itself. Specifically, the profile sets an empirical 3σ upper limit to the flux density from an embedded point-like nucleus of $S_\nu(800) < 120$ mJy. This corresponds to a 3σ upper limit to the nucleus diameter [from Eq. (1)] $D < 5.7$ km, which is fully compatible with the $D \approx 3$ km estimate based on radar data (Ostro 1996).

5. DISCUSSION

5.1 Temporal Variations

Optical observations (Lecacheux *et al.* 1996) show that C/Hyakutake ejected several small fragments on or about UT March 21.0 $\pm$ 0.3 (Sekanina 1996), 60 hours before the JCMT observations were obtained. Particles leaving the nucleus at $V \leq 3$ m s⁻¹ on March 21.0 (i.e., particle sizes ≥ 1 mm) would still be in the JCMT aperture during our observations. Indeed, we expect that the JCMT photometry is influenced, in part, by the earlier fragmentation episode. The elevated dust mass, dust mass production rate, and dust/gas ratio (Sec. 3) may result from macroscopic debris ejected on March 21. Schleicher (1996) reported that the OH outgassing rate was systematically high (by a factor of 2) on March 23 and 24, compared to the preceding and following days. On the other

hand, the OH was steady between these two days. As already remarked, both the absolute photometry (Table 2) and the 800 μ m surface brightness profile (Fig. 3) show that the continuum was also steady in the March 23–24 interval. It thus appears that our observations may have sampled debris from the March 21 event, but nevertheless show no sign of temporal variations caused by it.

5.2 Comparison with Other Comets

In Table 4 we compare the gross characteristics of C/Hyakutake as deduced here with the corresponding parameters in comets P/Halley and P/Swift-Tuttle. The nucleus of C/Hyakutake is small (1.5 km effective radius) compared to those of P/Halley (5 km) and P/Swift-Tuttle (10.8 km). Scaled to its diminutive nucleus, the submillimeter cross section and the OH outgassing rates at 1 AU are seen to be extraordinarily high. The nucleus of P/Halley was found to have surface area 400 km², but outgassed from an “active fraction” of only $f = 10\%$ of the surface (Keller *et al.* 1987). We scale the active fractions of P/Swift-Tuttle and C/Hyakutake from

$$f = 0.1 \frac{(Q_{OH}/Q_{OH}(H))}{(r_n/r_n(H))^2}, \quad (7)$$

where H denotes Halley, and the other quantities are listed in Table 4. These active fractions are individually uncertain by factors of order 2, in part because we have neglected well-documented short term variability (in P/Halley) of about this magnitude. Nevertheless, it appears that the nucleus of C/Hyakutake is less mantled than is P/Halley.

Simple models suggest that noncohesive mantles of comets travelling on elliptical orbits could be highly unstable due to rising internal gas pressures on the approach to perihelion (Rickman *et al.* 1990). Could the March 21 fragmentation event (Sec. 5.1) mark the ejection of part of an unstable debris mantle from the nucleus? The mantle mass is $\mathcal{M}_m \approx 4\pi r_n^2 d\rho$, where $r_n = 1.5$ km is the nucleus radius (Table 4), $d \approx 0.05$ m (Rickman *et al.* 1990) is the mantle

thickness and $\rho \approx 10^3 \text{ kg m}^{-3}$ is the mantle density. We find $M_m \approx 1.4 \times 10^9 \text{ kg}$, which is of the same order as the dust mass in Eq. (4). Impulsive ejection of (say) 50% of the mantle might simultaneously account for (1) the transient optical phenomena, including subnuclei, observed in late March (Lecacheux *et al.* 1996), (2) the large active fraction (cf. Table 4), (3) the presence of large debris capable of scattering 3 cm radar (cf. Ostro 1996), and (4) the elevated dust/gas production rate ratio ≈ 6 (Sec. 3). Unfortunately, observational circumstances prevented us from taking submillimeter continuum observations before or after those described here and, as a result, we possess insufficient information to test this idea further.

5.3 Comparison with Circumstellar Dust

It is generally supposed that comets accreted in the distant solar nebula, probably in the region now occupied by the outer gas giants Uranus and Neptune. Dust sedimenting to the nebula mid-plane would grow by colliding and sticking with other grains. The detailed evolution of these growing dust aggregates is the subject of much speculation (e.g. Weidenschilling & Cuzzi 1993). Here, we note that the processes leading to the growth of dust aggregates and comets are the same as those thought to operate in the circumstellar disks of pre-main-sequence stars. The dust in comets may provide a snap-shot of collisionally evolving dust from the early solar system. Accordingly, it is interesting to compare the properties of the C/Hyakutake emission with that measured from the circumstellar disks, also observed at submillimeter wavelengths.

The interpretation of submillimeter emission from circumstellar disks is less direct than in the cometary case. Disks are spatially structured, are typically viewed from an unknown angle, support radial temperature gradients, and may be optically thick in their inner regions at some wavelengths (Beckwith *et al.* 1990). In comets, by contrast, the observing geometry is fully known, the temperature is well determined, and the coma is demonstrably optically thin. Observations of 29 disks show opacity indices $0 \leq \beta \leq 1$ (Beckwith & Sargent 1991). High quality observations of T Tauri disks around DG Tau, Haro 6-13 and DO Tau, yield $\beta = 0.55^{+0.13}_{-0.11}$, $0.66^{+0.18}_{-0.10}$, and $0.67^{+0.25}_{-0.09}$, respectively (Mannings & Emerson 1994). The mean opacity index, $\beta = 0.6 \pm 0.1$, is consistent with Hyakutake's $\beta = 0.89 \pm 0.11$ within the errors, emphasizing the similarity between cometary and circumstellar grains. Grains in the Rayleigh limit ($a \ll \lambda$), such as those in the interstellar medium, have $\beta \approx 2$ and so are clearly distinguished from the particles in C/Hyakutake. Macroscopic (blackbody) particles have $\beta \approx 0$.

A plausible and self-consistent explanation for the intermediate β in C/Hyakutake is simply that the grains are larger than in the interstellar medium, having grown by collisions in the Sun's own circumstellar disk (Miyake & Nakagawa 1993).

Simple physical considerations confirm that the emitters in C/Hyakutake must be optically large (radius $a > \lambda \approx 1 \text{ mm}$). The best argument for this is that small grains would be well coupled to the outflowing gas, and would depart the JCMT aperture so quickly that the implied rate of replenishment would violate the bounds of plausibility. For example, at $V = 1 \text{ km s}^{-1}$, we find $t_c \approx 6.4 \times 10^2 \text{ s}$ and $dM/dt \approx 2.8 \times 10^6 \text{ kg s}^{-1}$, which is unphysical because the sublimated gas carries too little momentum to drive such a large dust outflow.

6. SUMMARY

(1) C/Hyakutake was a strong source of submillimeter continuum radiation when near the Earth in 1996 March, permitting spectral and mapping observations not possible on fainter, previously observed comets.

(2) The equivalent blackbody cross section of C/Hyakutake is $(116 \pm 12) \text{ km}^2$, much larger than can be attributed to the nucleus. It corresponds to a dust mass $(1.8 \pm 0.3) \times 10^9 \text{ kg}$, within 640 km of the nucleus on UT March 23 and 24.

(3) The opacity index is $\beta = 0.89 \pm 0.10$ in the wavelength range ($350 \leq \lambda \leq 2000 \mu\text{m}$). This is intermediate between the geometric optics ($\beta = 0$) and Rayleigh ($\beta = 2$) limits, but is consistent with the best determined values in the circumstellar dust disks of T Tauri stars. The intermediate β is naturally explained if the submillimeter cross section is dominated by large particles (radii $a > 1 \text{ mm}$).

(4) The radial surface brightness profile at $800 \mu\text{m}$ is consistent with the profile expected of a steady-state dust coma, once the effects of finite angular resolution of the data are taken into proper account. The absence of a central excess above the coma profile sets a limit on the diameter of the nucleus of $D < 5.7 \text{ km}$ (3σ). This is independent of, but consistent with, the $D \approx 3 \text{ km}$ estimate based on radar data.

(5) We find that the active fraction of the nucleus of C/Hyakutake is $f \approx 0.67$, significantly larger than in P/Halley ($f \approx 0.1$; Keller *et al.* 1987) or other short-period comets.

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