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THE SUBMILLIMETER RADIO CONTINUUM OF COMET P/BRORSEN-METCALF

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ABSTRACT

We present observations of comet P/Brorsen-Metcalf in the submillimeter radio continuum. The observations were taken using the James Clerk Maxwell Telescope on Mauna Kea, and include the first truly submillimeter detection ($\lambda < 1$ mm) of a comet, and the first submillimeter continuum spectrum. We attribute the submillimeter radiation to thermal emission from a transient population of large grains with total mass $M \sim 10^9$–10^{10} kg. The large grains may be produced by catastrophic failure of part of the refractory mantle on the surface of the cometary nucleus. Models of the submillimeter continuum are discussed.

Subject headings: comets — radiation mechanisms — radio sources: general

I. INTRODUCTION

The cometary nucleus is a kilometer-sized solid mixture of frozen volatiles and refractory substances thought to date from the earliest epochs in our solar system. When near the Sun, the volatile components sublimate and escape from the nucleus, dragging refractory particles (collectively known as "dust" or "grains") into the coma (Whipple 1950). The grains are visible to the Earth-bound observer at optical and near-infrared wavelengths via scattered solar radiation, and they are prominent in the thermal infrared via thermal emission. Scientific interest in the cometary grains centers on their possible relation to grains in the interstellar medium (see Greenberg 1982), and to circumstellar grains found in disks about young stars (Weintraub *et al.* 1989). Present evidence is insufficient to either confirm or refute hypothesized connections between cometary and other grains, but many observations suggest physical and chemical similarities between cometary and interstellar grains.

Natural distributions of particles are imperfectly sampled by radiation of any one wavelength, λ. Particles with sizes $a \ll \lambda$ are inefficient scatterers and emitters of radiation, and thus are not well observed. Conversely, particles with sizes $a \gg \lambda$ scatter and emit efficiently, but they are typically so rare that they contribute a negligible fraction of the total radiation. It is for these reasons that the mean grain size in comets estimated from optical observations ($\lambda \sim 0.5$ μm) is $a \sim 1$ μm (e.g., Jewitt and Meech 1986), while the mean grain size estimated from thermal infrared observations ($\lambda \sim 10$ μm) is $a \sim 5$–10 μm (Ney 1982).

It has long been recognized that very small and very large grains exist in comets. Evidence for large grains is inferred from the meteor streams, produced when millimeter-sized debris from comets impact the upper atmosphere (e.g., Williams 1990). Thermal infrared "trails" were discovered in the orbits of short-period comets by *IRAS* (Sykes, Hunter, and Low 1986). The trails are best interpreted as emission from 100 μm-sized grains ejected from the parent comets at low velocities. On a scale larger than both the meteor streams and the *IRAS* dust trails, a swarm of grains envelopes the inner solar system. This "Zodiacal Cloud" is thought to consist of particles ejected from comets (Perrin and Lamy 1989). Radar observations of two comets reveal backscattering from populations of decimeter-sized grains outside the nucleus (Goldstein, Jurgens, and Sekanina 1984; Campbell, Harmon, and Shapiro 1989; Harmon *et al.* 1989). More directly, impact counters on spacecraft detected large grains in the coma of comet Halley with abundances high enough to dominate the total mass of the grains. For instance, the largest particle intercepted by Giotto had a mass 5.7×10^{-6} kg, corresponding to radius ~ 1 mm (McDonnell *et al.* 1987). Measurements of 1.3 mm continuum radiation in P/Halley by Altenhoff *et al.* (1986, 1989) were also interpreted as emission from large grains. Physically, it is easy to understand why large particles are found in the comae of active comets, since gas drag exceeds nuclear gravity even for centimeter and decimeter sized particles on active near-Sun comets (Whipple 1950).

The evidence from comet Halley suggests that a substantial fraction of the total grain mass in comets is contained within the few largest particles, while these same particles present only a small fraction of the total grain cross section. If applicable to all comets, the significance of this result would be two-fold. First, the more common measurements of comets at optical and infrared wavelengths are most sensitive to the smaller particles (sizes ~ 1–10 μm) which carry only a small part of the total grain mass. Thus, mass and mass-loss rate estimates based on optical and infrared observations may considerably underestimate these quantities in comets. This would have important implications for the supply of material to the meteor streams, the *IRAS* trails and the Zodiacal Cloud. Second, the comets appear to preserve large agglomerated grains, presumably formed during the accretion of the nucleus. The physical and chemical properties of these grains may reveal much about the process of agglomeration in the early solar nebula.

Observations at submillimeter wavelengths are potentially most sensitive to the large, rare particles in the cometary grain size distribution. Thus, submillimeter continuum photometry

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represents an intriguing and unexplored window on the mass-dominant large grains. Motivated by these considerations, we sought evidence for large grains in periodic comet Brorsen-Metcalf via continuum emission in the submillimeter wavelength range.

II. OBSERVATIONS

The present observations were obtained using the 15 m diameter James Clerk Maxwell Telescope (JCMT) on Mauna Kea. The observations were taken on UT 1989 September 8, 9, and 10. These dates were intended to coincide with the time of minimum geocentric distance, $\Delta = 0.5$ AU, as estimated from the prerecovery ephemeris. A large error in this ephemeris was found by optical observers only two months before the scheduled observing dates (Helin 1989), forcing us to observe the comet in the submillimeter at the somewhat less favorable distance $\Delta = 1.1$ AU. Perihelion of P/Brorsen-Metcalf occurred at heliocentric distance $R = 0.48$ AU on UT 1989 September 11, one day after our last observations.

The JCMT is ideally suited to the present observations of comets, since it has accurate pointing and tracking capabilities, and has a dish surface of high accuracy, thus permitting diffraction-limited observations at submillimeter wavelengths. A sensitive bolometer ("UKT14"; Duncan *et al.* 1990) was used at wavelengths 0.45, 0.8, and 1.1 mm. The submillimeter filters have fractional widths $\Delta\lambda/\lambda < 0.25$. The effective wavelength of each filter is a very weak function of the atmospheric water vapor content and source spectrum (Duncan *et al.* 1990), and we adopt the nominal central wavelengths in this study. The bolometer samples a circular region of sky 20″ in diameter at 0.8 and 1.1 mm, and 15″ in diameter at 0.45 mm. The absolute pointing of the telescope is accurate to about $\pm 2''$, as estimated from pointing tests based on submillimeter sources with well-known coordinates. Tracking of the telescope at cometary rates was accomplished by using a program to linearly interpolate the right ascension and declination of the comet between hourly start and end positions. The accuracy of this program was checked using observations of submillimeter-bright main-belt asteroids. The accuracy of the ephemeris of P/Brorsen-Metcalf was confirmed using positional data from the NASA-IRTF, courtesy D. Griep.

Sky subtraction was performed by chopping the telescope beam 40″ in azimuth at a rate of 7.8 Hz. Every 10 seconds, the telescope was "nodded" so as to place the object in the opposite reference beam, thus cancelling any possible imbalance between the sensitivities of the beams. The success of the sky subtraction was confirmed empirically by observations of blank sky, which always gave net signals consistent with zero. The pointing and flux calibration of the JCMT/UKT14 were periodically checked by observing IRC +10° 216, which is both a position standard and a flux standard for submillimeter astronomy (Sandell and Walker 1989). Its 0.8 mm flux density was taken to be 5.0 Jy. This bright submillimeter source was projected fortuitously close to P/Brorsen-Metcalf in the sky. Typical airmass differences between the comet and IRC +10° 216 were <0.1, minimizing potential uncertainties due to variable atmospheric extinction. Integrations on the comet consisted of 40 cycles of 10 s each, giving 400 s integration per observation. Pointing and flux calibration measurements on IRC +10° 216 were obtained approximately every 40 minutes. The flux of IRC +10° 216 was itself checked for consistency by independent observations of the additional standards CRL 618, CRL 2688 and of the submillimeter primary standard, Mars. Also, the main-belt asteroids 1 Ceres and 11 Parthenope were observed as a check of the standards more commonly used at the JCMT. After a careful intercomparison of various unrelated submillimeter sources in different parts of the sky, we are confident that the errors in the absolute calibration of the P/Brorsen-Metcalf data are substantially less than the statistical errors due to sky subtraction.

TABLE 1

GEOMETRICAL CIRCUMSTANCES

UT Date	R (AU)	Δ (AU)	α (°)
1989 Sep 08.........	0.49	1.05	71.5
1989 Sep 09.........	0.48	1.07	69.1
1989 Sep 10.........	0.48	1.10	66.7

Since the bulk of the comet observations were obtained after sunrise, we also used IRC +10° 216 to monitor the change in focus of the JCMT caused by solar heating (no change was detected). A more serious consequence of solar heating was the appearance of "anomalous refraction," the millimeter wavelength counterpart of bad seeing familiar to optical observers. Observations at the shorter wavelengths (0.45 and 0.8 mm) were sometimes precluded in the late morning by large position excursions due to anomalous refraction. Effective observations of P/Brorsen-Metcalf were confined to a 4 hr interval on each day, bounded at the beginning by the time when the comet rose over the cinder cones to the east of the JCMT, and at the end by the deterioration of the atmosphere due to anomalous refraction. Accuracy of the ephemeris used for the Brorsen-Metcalf observations was confirmed using near-simultaneous position measurements from the IRTF. The maximum error in the pointing direction was $\pm 2''$, small compared to the 20″ beam diameter.

The geometrical circumstances of comet P/Brorsen-Metcalf on the dates of observation are given in Table 1. The measured submillimeter flux densities are listed in Table 2, together with their uncertainties. As may be seen in Table 2, Brorsen-Metcalf was not detected in the radio continuum on UT 1989 September 8 or 9. However, firm detections were achieved on UT 1989 September 10 at both 0.8 and 1.1 mm. Surprised by the emergence of substantial flux on UT 1989 September 10, we undertook a number of experimental tests to confirm the reality of the detected signals. In order to demonstrate that sky subtraction was correctly achieved, we moved the telescope to an adjacent area of blank sky, and confirmed that no net signal was recorded at this location. The Brorsen-Metcalf signal persisted upon return to the comet. The signal was again present after slewing to and from the flux standard IRC +10° 216. Repeated measurements of the flux standard, and inspection of the real-time trace output from UKT14 confirmed the high quality of the submillimeter atmosphere above Mauna Kea. Furthermore, the comet was independently detected at 0.8 and

TABLE 2

SUBMILLIMETER FLUX DENSITIES[a]

UT Date	$F_{0.45}$	$F_{0.8}$	$F_{1.1}$
1989 Sep 08.........	...	≤24 mJy	...
1989 Sep 09.........	...	≤40 mJy	...
1989 Sep 10.........	≤515 mJy	90 ± 18 mJy	45 ± 13 mJy

[a] Quoted flux density limits are at 3 σ confidence.

at 1.1 mm. We checked for the possibility of confusion with background sources. The signals cannot be attributed to confusion with background sources since (1) the comet was moving at 400″ per hr with respect to sidereal rate, so that background sources would spend a maximum of 3 minutes inside the projected diaphragm (whereas the signal was consistently detected for a period of hours) and (2) background sources in a beam-switched measurement should give rise to temporary negative as well as positive excursions in the signal, but none were seen. As a result of these observational precautions, we are compelled to interpret the measured flux densities as real emission from comet Brorsen-Metcalf. Subsequently, we learned of a probable detection of Brorsen-Metcalf at 1.3 mm by W. Altenhoff (1989, private communication) using the IRAM millimeter telescope.

The submillimeter spectrum of P/Brorsen-Metcalf on UT 1989 September 10 is plotted in Figure 1. The point at 0.45 mm is a 3 σ upper limit to the flux density, while the points at 0.8 and 1.1 mm are firm detections, and are plotted with their estimated uncertainties. Lines drawn in Figure 1 represent power-law spectra, both normalized to the measurement at 0.8 mm. The lines represent the Rayleigh-Jeans (blackbody) spectrum, for which the spectral index

$$\alpha = -\frac{d \ln F_\nu}{d \ln \lambda} \tag{1}$$

is given by $\alpha = 2$, and, for comparison, a spectrum in which $\alpha = 3$. The figure shows that the available submillimeter data are consistent with power-law spectra with indices

$$1 \leq \alpha \leq 3 \; . \tag{2}$$

Substantially steeper spectra would violate the upper limit to the flux density at 0.45 mm, and are thus inconsistent with the data. Likewise, a very flat spectrum, $\alpha < 1$, would violate the 2:1 ratio of the flux densities at 0.8 and 1.1 mm.

There is an uncertainty in the 0.45 mm measurement introduced by the need to correct the measurements to a single beam diameter. The magnitude of this correction is dependent on the geometry of the submillimeter source. If the comet is a submillimeter point source (or is at least compact relative to the 15″ beam size) then the aperture correction would be zero. If the submillimeter surface brightness mirrors the optical surface brightness distributions of dust comae (see Jewitt 1990) then the correction factor would equal the ratio of the beam diameters, namely 20/15 = 1.33 (i.e., the 0.45 mm measurement would need to be increased by 33%). The geometry of the emitters in Brorsen-Metcalf is not known. We argue in § IV*a* that an unresolved source interpretation is likely. On this basis, we have not made the 33% augmentation to the 0.45 mm flux density.

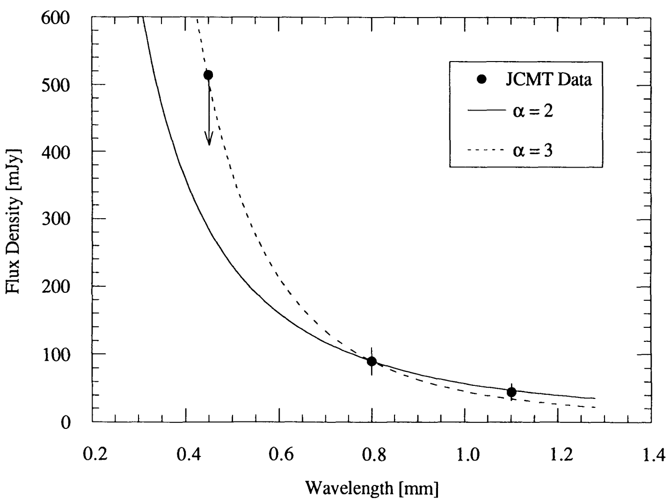

FIG. 1.—The flux densities measured UT 1989 September 10 are plotted vs. the wavelength of observation. The point plotted at $\lambda = 0.45$ mm is a 3 σ upper limit. Also plotted are lines representing the Rayleigh-Jeans spectrum ($F \propto \lambda^{-2}$) and inverse cube emission ($F \propto \lambda^{-3}$).

III. INTERPRETATION

We interpret the submillimeter continuum in terms of thermal emission from cometary solids. Free-free emission from cometary plasma is too weak to be detected, since the likely electron column densities through the inner coma are very small. We anticipate the existence of two thermal sources: a point-like source due to emission from the central nucleus plus emission from solid grains in an optically thin coma. The total flux density due to these sources may be written

$$F_\nu = \frac{2k}{\lambda^2 \Delta^2} \left[T_n C_n + \int_{a-}^{a+} T(a) Q_a(a, \lambda, m) \pi a^2 n(a) da \right] . \tag{3}$$

In equation (3), $F_\nu[W \text{ m}^{-2} \text{ Hz}^{-1}]$ is the measured flux density, $k = 1.38 \times 10^{-23}$ J K^{-1} is Boltzmann's constant, $\Delta[m]$ is the geocentric distance (see Table 1) and $\lambda[m]$ is the wavelength of observation. The first term accounts for Rayleigh-Jeans emission from a monolithic nucleus at uniform temperature T_n and with cross section C_n. The second term accounts for emission from solid grains in the coma of radius $a[m]$, at temperature $T(a)$. The grains are assumed to occupy a size distribution such that the number of grains having radii in the range a to $a + da$ is given by $n(a)da$, and the minimum and maximum grain sizes in the distribution are $a-$ and $a+$, respectively. $Q_a(a, \lambda, m)$ is the grain absorption efficiency factor, a function of grain size, wavelength and complex refractive index, m.

Our objective is to fit equation (3) to the observations presented in Table 2 and Figure 1. Clearly, we cannot expect to obtain a unique fit, since the number of parameters in equation (3) considerably exceeds the number of independent data points listed in Table 2. Nevertheless, we are able to use equation (3) to identify ranges of plausible solutions, and so to constrain certain aspects of the physical nature of the solid components of comet Brorsen-Metcalf.

a) The Nucleus

We use the nondetection of the comet on UT 1989 September 8 and 9 to place an upper limit to the flux density from the bare nucleus. The more stringent of the two flux density limits (that from September 8) gives $F_{0.8} \leq 24$ mJy. We represent the nucleus as a spherical object in instantaneous thermal equilibrium with the solar radiation field. Neglecting the coma contribution to the emitted flux density, we obtain the nucleus flux density

$$F_\nu = \frac{2kT_n C_n}{\lambda^2 \Delta^2} \; . \tag{4}$$

The approximate surface temperature of the nucleus is determined by radiation balance and can be estimated from

$$T_n = \left[\frac{F_\odot(1-A)}{2R^2\epsilon\sigma}\right]^{0.25}, \quad (5)$$

where $F_\odot = 1360$ W m^{-2} is the solar constant, R [AU] is the heliocentric distance, $A \sim 0.05$ is the nucleus Bond Albedo (A'Hearn 1988), $\epsilon \sim 1$ is the thermal infrared emissivity and $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is Stefan's constant. Equation (5) assumes that the bulk of the solar energy is absorbed and radiated from one hemisphere of the nucleus, and refers to the temperature of a nonvolatile mantle (i.e., sublimation is neglected). Substitution into equation (5) gives $T_n \sim 327R^{-0.5}$. We ignore the fact that submillimeter radiation penetrates beneath the surface, and so may emanate from regions at temperatures lower than given by equation (5). This is a reasonable approximation since the radiation penetration depth (a few millimeters) is small compared to the thermal skin depth (roughly given by $[P\kappa]^{0.5} \sim 10$ cm, where $P \sim 10$ hr is the assumed nucleus rotation period and $\kappa \sim 10^{-7}$ m^2 s^{-1} is the thermal diffusivity). When combined and suitably normalized, equations (4) and (5) yield

$$F_\nu(mJy) = \frac{0.04C_n[\mathrm{km}^2]}{\lambda[\mathrm{mm}]^2 R[\mathrm{AU}]^{0.5}\Delta[\mathrm{AU}]^2}, \quad (6)$$

for the flux density (in mJy) emitted thermally at wavelength λ[mm] by an object of cross section C_n[km^2] situated Δ[AU] from the Earth and R[AU] from the Sun. We demonstrated the essential validity of equation (6) by taking observations of asteroids 1 Ceres and 11 Parthenope, using the JCMT. The physical parameters (radius, albedo, geocentric, and heliocentric distances) of these asteroids are known with confidence—hence they make useful calibration objects for this project. The measured flux densities agreed with those calculated from equation (6) within 30%. The weak dependence of the emitted flux density on the temperature gives us further confidence in the use of equations (5) and (6). (We note in passing that Redman *et al.* 1990 have reported substantial departures from eq. [6] in some asteroids.)

Substitution of $F_{0.8} \leq 24$ mJy into equation (6) gives a 3σ upper limit on the cross section of the nucleus

$$C_n \leq 325 \text{ km}^2, \quad (7)$$

corresponding to an equal-area circle of radius 10 km. Uncertainties in C_n derive primarily from the uncertain submillimeter phase function of the nucleus. If the submillimeter radiation is strongly beamed in the solar direction, equation (7) may underestimate the cross section of the nucleus. Unfortunately, nothing is known about the submillimeter phase functions of small solar system bodies. Naively, one would expect the submillimeter emission to be a weaker function of phase than shorter wavelength (e.g., thermal infrared) radiation, since the submillimeter radiation emanates from several wavelengths beneath the physical surface, and should thus be less affected by diurnal thermal variations. For comparison, we note that the limit on C_n is about thrice the geometric area of the nucleus of P/Halley ($C_n = 78$ km^2; Keller *et al.* 1987) but comparable to the area of the nucleus of P/Neujmin 1 ($C_n = 310$ km^2; Campins, A'Hearn, and McFadden 1987).

b) The Coma

The 0.8 mm flux density detected on UT 1989 September 10 is substantially larger than the upper limit to the flux density determined at the same wavelength on UT 1989 September 8. We interpret the difference as the result of an increase in the total cross section of the comet, due to particles ejected between September 8 and September 10. The uncertainty of the submillimeter observations obtained September 9 is larger than that obtained on the preceding and following nights (Table 2), due to fluctuations in the atmosphere. Thus, we do not know whether the increase in the cross section apparent on September 10 was underway on the 9th, or whether it began between the 9th and the 10th. From an inspection of Table 2, we assume that the flux densities measured on UT 1989 September 10 are dominated by emission from the coma, and we simply note that the submillimeter coma appeared at an unspecified time between the 8th and the 10th of September. Thus, we assume that the nucleus contribution to the September 10 detection is negligible and that we may ignore the first term on the right-hand side of equation (3).

In order to solve equation (3) we assume that the grain size distribution may be approximated by a power law, such that

$$n(a)da = \Gamma a^{-q}\, da, \quad (8)$$

where Γ and q are constants. Impact-counter measurements of the particles in the coma of comet Halley support the use of equation (8), with the caveat that the index q was found to vary with particle size in the approximate range $3 \leq q \leq 4$ (Lamy, Grün, and Perrin 1987). The size distributions of grains in comets other than Halley are not known with confidence. Neglecting the nucleus contribution, equation (3) becomes

$$F_\nu = \frac{2\pi\Gamma k}{\lambda^2\Delta^2}\int_{a-}^{a+} T(a)Q_a(a, \lambda, m)a^{2-q}\, da. \quad (9)$$

The mass of material responsible for the submillimeter emission from the coma may be found from

$$M = \tfrac{4}{3}\pi\rho\Gamma\int_{a-}^{a+} a^{3-q}\, da, \quad (10)$$

in which ρ[kg m^{-3}] is the density of the material and the other symbols are already defined. The constant Γ is determined by the fit of equation (9) to the submillimeter photometry, and then substituted in equation (10) to obtain the mass, M. Clearly, the mass depends on the shape and extent of the grain size distribution and on the identity of the grain material, through $Q_a(a, \lambda, m)$.

Solution of equations (9) and (10) for the flux density (at any wavelength) and for the mass is complicated by the wavelength dependence of $Q_a(a, \lambda, m)$, and in general only numerical solutions are possible. The $Q_a(a, \lambda, m)$ are computed from Mie Theory (van de Hulst 1957; Bohren and Huffman 1983) under the assumption that the thermal emitters are homogeneous spheres. While this assumption is unlikely to be correct in detail, the use of Mie Theory provides a valuable guide to the optical properties of particles as a function of size, wavelength and composition (Bohren and Huffman 1983). We compute submillimeter spectra using complex refractive indices for three materials of astrophysical interest. The refractive indices of "astronomical silicate" were taken from Draine (1985), indices for "glassy carbon" are from Edoh (1983) while those for "tholin" are from Khare *et al.* (1984). The tholin indices exist only for wavelengths $\lambda \leq 0.92$ mm, so the tholin model spectra end at this wavelength. Use of these materials is suggested by ground based spectra of comets which give evidence for silicate grains (from the Si-O stretch vibration at 10 μm (e.g., Ney

1982)) and carbon-rich grains (from the presumed C-H stretch vibration at 3.4 μm (e.g. Brooke *et al.* 1989). Silicate and carbon-rich grains were also detected by *in situ* composition measurements in comet P/Halley (Langevin *et al.* 1987). The choice of these three materials is not meant to imply that other substances do not exist in cometary dust grains. Rather, we use the three materials to explore the dependence of the submillimeter spectrum on the grain composition.

Analytic solutions to equations (9) and (10) may be described in the two limiting cases corresponding to very small grains ($x \equiv 2\pi a/\lambda \ll 1$), and to macroscopic grains ($x > 1$). We will discuss these limits before presenting results for the more general case in which the grains occupy a broad distribution of sizes from very small to very large.

i) *Microscopic (Rayleigh) Limit*

In the Rayleigh limit ($x \ll 1$, $|mx| \ll 1$), for a particle of complex refractive index m, the absorption efficiency tends to

$$Q_a(a, \lambda, m) = -4x \,\mathrm{Im}\left\{\frac{m^2 - 1}{m^2 + 2}\right\} \tag{11}$$

(van de Hulst 1957). In the absence of wavelength-dependent variations in the complex refractive index, equation (11) shows that $Q_a(a, \lambda, m) \propto \lambda^{-1}$, so that $F_\nu \propto \lambda^{-3}$, by equation (9). We substitute equation (11) into equation (9), and then eliminate Γ with equation (10) to find the Rayleigh mass

$$M_R = \frac{\rho\lambda^3\Delta^2\{(m_r^2 - m_i^2 + 2)^2 + 4m_r^2 m_i^2\}F_\nu}{72\pi k T_n m_r m_i}, \tag{12}$$

where m_r and m_i are the real and imaginary parts of the refractive index, respectively, and where we have assumed a grain temperature given by equation (5). Notice that, for a given flux density, M_R is independent of the form of the grain size distribution, and is insensitive to the lower and upper grain sizes provided $x \ll 1$ and $|mx| \ll 1$. The Rayleigh masses are thus reasonably independent of the details of the grain distribution.

Rayleigh-limiting masses were computed from equation (12), using refractive indices for the above-mentioned three materials, and using $F_{0.8}$. The densities of the carbon and tholin grains were each taken to be $\rho = 1000$ kg m^{-3}, while the density of silicates was taken to be $\rho = 2500$ kg m^{-3}. These values are suggested by spacecraft measurements of micron-sized grains in the coma of comet Halley (Maas, Krueger, and Kissel 1990). The densities of larger grains are uncertain due to their likely aggregate structure and unknown porosities. For this reason, the above densities may be regarded as upper limits to the true densities of the larger particles (e.g., Brooks 1990). The masses are in addition rendered uncertain by possible errors in the submillimeter refractive indices (see Draine 1990). Table 3 lists the Rayleigh limiting masses computed from the $\lambda = 0.8$ mm flux density alone on UT 1989 September 10. Evidently, the submillimeter detection implies masses of order 10^{10} kg for each adopted material, under the Rayleigh assumption.

ii) *Macroscopic Limit*

In the macroscopic limit ($x \gg 1$) the absorption efficiency tends to a constant of order unity (van de Hulst 1957), and the spectrum of the emitted radiation follows the λ^{-2} dependence characteristic of a blackbody (again, ignoring wavelength dependent variations in m). For grains of mean radius $\bar{a}$, the mass in this limit is simply given by

$$M = \frac{4\rho\bar{a}C}{3}, \tag{13}$$

where C is the total geometric cross section of the grains. The macroscopic mass computed from equation (13) with $\bar{a} = 10^{-3}$ m is $M \sim 2 \times 10^9$ kg for carbon and tholin grains and $M \sim 4 \times 10^9$ kg for silicate grains. These masses are considerably smaller than the corresponding Rayleigh masses (Table 3). This is easily understood as a result of the small size of Q_a in the Rayleigh limit, necessitating huge numbers (and large masses) of small grains to supply the measured flux density. By contrast, macroscopic grains with $a \sim \lambda$ are near the peak

TABLE 3

ILLUSTRATIVE MASS MODELS

Model Number	$a-$ (mm)	$a+$ (mm)	Size Index q	Material	Spectral Index α	Mass (kg)
1	Rayleigh Limit (see text)			Silicate	3.96	2.2×10^{10}
2	Rayleigh Limit (see text)			Carbon	3.72	7.9×10^9
3	Rayleigh Limit (see text)			Tholin	6.11	8.9×10^9
4	1	1.1	3	Carbon	2.31	8.3×10^9
5	1	1.1	3	Silicate	2.16	5.0×10^9
6	1	1.1	3	Tholin	3.03	2.6×10^9
7	10^{-5}	1	3	Silicate	2.99	2.1×10^9
8	10^{-5}	10	3	Silicate	2.32	1.1×10^{10}
9	10^{-5}	100	3	Silicate	...	7.8×10^{10}
10	10^{-5}	1	3	Carbon	2.60	1.6×10^9
11	10^{-5}	10	3	Carbon	2.21	1.1×10^{10}
12	10^{-5}	100	3	Carbon	...	8.0×10^{10}
13	10^{-5}	1	3	Tholin	4.60	1.8×10^9
14	10^{-5}	10	3	Tholin	3.71	5.9×10^9
15	10^{-5}	100	3	Tholin	...	3.5×10^{10}
16	10^{-5}	10^{-2}	4	Silicate	3.97	2.0×10^{10}
17	10^{-5}	10^{-1}	4	Silicate	4.11	1.5×10^{10}
18	10^{-5}	1	4	Silicate	5.83	4.8×10^9
19	10^{-5}	10	4	Silicate	2.30	5.3×10^9
20	10^{-5}	100	4	Silicate	...	6.0×10^9

emissivity, and thus are the most efficient radiators of millimeter radiation.

iii) *The General Case*

Neither the Rayleigh nor the macroscopic limits can be used to represent the cometary grains in detail. Instead, it is physically more likely that the grains occupy a broad distribution of sizes, ranging from very small ($a \ll \lambda$) to very large ($a > \lambda$). As noted in § I, spacecraft data at Halley provide direct evidence for particles with radii from 10^{-8} to 10^{-3} m, and larger particles are suspected on the basis of gas drag calculations. Thus, it is reasonable to expect that both small and large grains contribute to the measured submillimeter flux densities. We must solve equation (9) in order to compute the emission from an ensemble of grains with widely different sizes.

The important parameters in equation (9) include the grain size index, q, the grain size lower and upper limits, $a-$ and $a+$, respectively, the grain temperature $T(a)$, and the grain composition. We assume $3 \leq q \leq 4$, as measured for the grains in comet Halley. We assess the effect of the size distribution index in our models by comparing results obtained with different values of q. Likewise, we examine the effect of the grain size limits $a-$ and $a+$ by comparing calculations performed using different limits. The importance of grain composition is estimated from comparisons of models calculated using the silicate, carbon and tholin refractive indices discussed above.

The grain-size dependence of the temperature $T(a)$ in equations (3) and (9) has been retained up to this point to draw attention to two physical effects which might influence the temperature. First the wavelength dependence of the absorption coefficient $Q_a(a, \lambda, m)$ will produce "superheat," as has long been known from thermal infrared observations of comets (Becklin and Westphal 1966; Ney 1982). In particular, grains small compared to a wavelength ($x < 1$) will have small emissivities at thermal wavelengths, and will rise to equilibrium temperatures considerably in excess of the local blackbody temperature. The magnitude of the superheat as determined from thermal infrared ($\lambda \sim 10$ μm) observations is typically $S = T/T_{\rm BB} \sim 1.2$, where $T_{\rm BB}$ is the local blackbody temperature (Ney 1982). However, whereas the thermal infrared flux is a strong and nonlinear function of the temperature, the submillimeter flux is dependent only on the first power of the temperature (c.f. eq. [4]). Therefore, superheat should influence the emitted submillimeter radiation only at the 20% level.

Second, very small grains might be raised to high temperatures by the absorption of individual photons. This "single-photon" or "spike" heating is very important in the interstellar medium, where the equilibrium temperatures of the small grains (say $T \sim 50$ K) may be increased by a factor of ~ 20 (to $T \sim 1000$ K) by the absorption of a single UV photon (Sellgren 1984). In comets, we expect that single-photon heating should be of considerably reduced importance, since (1) the grain equilibrium temperature is already high ($T \sim 400$ K) and cannot be increased by more than a factor of order 2 without causing sublimation and (2) the Sun is not a copious source of UV photons.

We have evaluated equations (9) and (10) using two approximations for $T(a)$. Comparison of these two approximations provides an empirical measure of the sensitivity of the emitted intensity to the grain temperatures.

Case A.—We have simply put $T(a) = T_n$, as defined by equation (5), corresponding to the complete neglect of both superheat and single-photon heating.

Case B.—We have computed $T(a)$ from the radiation balance equation

$$\int_0^\infty Q_a(a, \lambda, m)\pi a^2 F_\nu^\odot \, d\nu = \int_0^\infty Q_a(a, \lambda, m) 4\pi a^2 \pi B_\nu[T(a)] d\nu \, , \tag{14}$$

in which $F_\nu^\odot$ is the solar flux density at frequency ν incident on a grain, and $B_\nu(T(a))$ is the Planck function at the equilibrium grain temperature, $T(a)$. In equation (14), contributions to the integral on the left-hand side are dominated by radiation with wavelengths in the optical region (corresponding to the peak of the solar spectrum) while the integral on the right-hand side is dominated by radiation with wavelengths near the peak of the grain thermal emission (typically $\lambda \sim 10$ μm). The grain temperature is thus controlled by the ratio of the emissivities at optical and thermal infrared wavelengths. The blackbody temperature at $R = 0.48$ AU is $T = 400$ K. Small grains can be elevated to higher temperatures by the wavelength dependence of the emissivity. As noted above, cometary grains elevated to temperatures much in excess of 1000 K will be promptly destroyed by sublimation. Therefore, in the present calculations, any grains reaching $T \geq 1000$ K were rejected as sources of submillimeter emission by setting their cross sections equal to zero.

For purposes of illustration, two models which are identical in all respects except for the method of grain temperature calculation are presented in Figure 2. From the models, we find that the emitted spectrum is relatively insensitive to the method of grain temperature calculation, as expected from the qualitative arguments given above. Subsequent models in this paper are based on "Case B" temperatures.

In Figure 3 we attempt to illustrate the effect of grain size on the emitted spectrum. The calculations plotted there were performed using refractive indices appropriate to silicates, and assume a size distribution with index $q = 3$. (The major characteristics described below are also found in spectra computed for carbon and tholin.) In order to remove the effects of resonances in Q_a (caused by the spherical geometry of the Mie

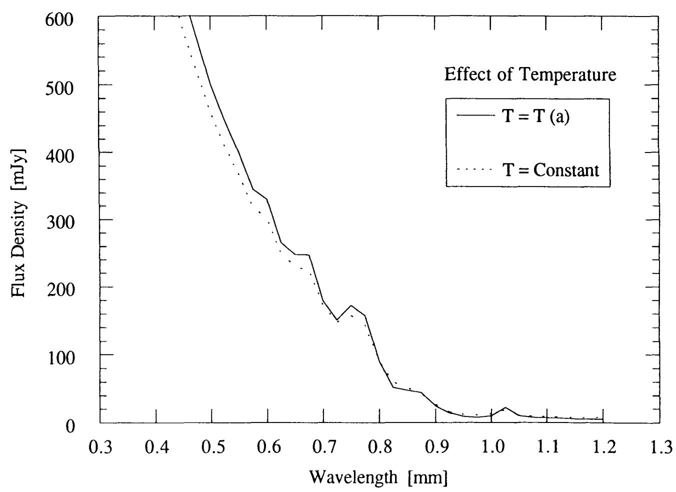

FIG. 2.—Models of the submillimeter spectrum computed with and without the size dependence of the grain temperature. Both models have $a- = 10^{-8}$ m, $a+ = 10^{-2}$ m, $q = 3$ and silicate composition, and both are normalized at 0.8 mm wavelength. The single-temperature model underestimates the flux density at short wavelengths by $\sim 10\%$.

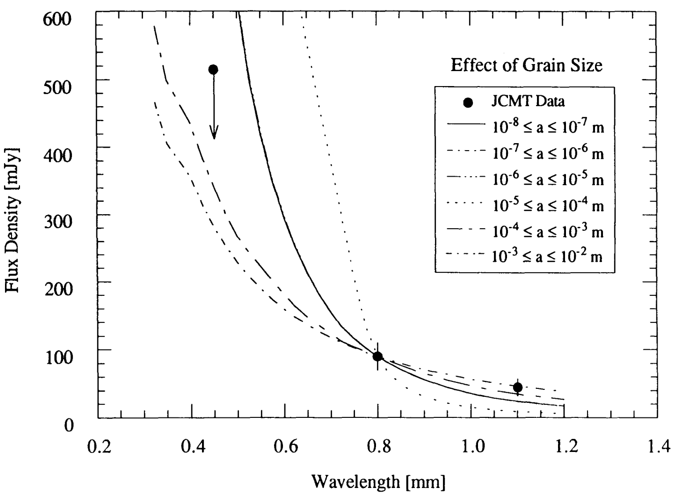

FIG. 3.—Effect of grain size on the emission from a $q = 3$ distribution of silicate grains. The lower and upper size limits, $a-$ and $a+$, respectively, are indicated in the figure. All models are normalized to the measurement at $\lambda = 0.8$ mm.

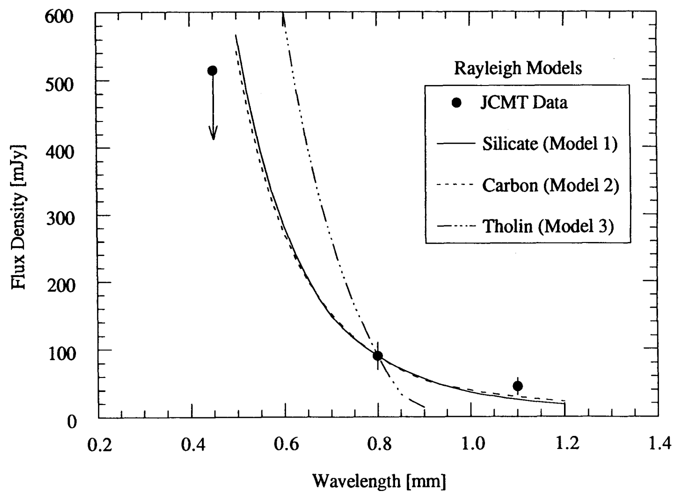

FIG. 4.—Model submillimeter spectra computed for particles small compared to the wavelength of observation (i.e., Rayleigh spectra). Spectra for silicate, carbon and tholin grains are marked. Points represent the data shown in Fig. 1.

scatterers), the emission in each model has been integrated over a range of grain sizes such that $a+/a- = 10$. The geometric mean grain size increases by one order of magnitude between models—the minimum and maximum sizes in each model are noted in the figure. All models are normalized to the $F_{0.8}$ measurement of Brorsen-Metcalf, for easy comparison with the data. Examination of Figure 3 shows that three of the models, specifically, the three with $a+ \le 10^{-5}$ m, are indistinguishable at the scale of the plot. The physical explanation is that the grains in all three models fall in the Rayleigh regime ($x \ll 1$), in which the submillimeter spectral shape is essentially independent of the grain size. The Rayleigh spectra have indices $\alpha \sim 4$, and thus fail to fit the data (c.f. eq. [2]). The spectra of the two largest grain distributions have smaller spectral indices, corresponding to the large-particle regime in which $x \geq 1$. These large particle spectra are compatible with the JCMT data.

The result that the Rayleigh spectra in Figure 3 are steeper than the Brorsen-Metcalf data allow is independent of the grain composition. This is shown by Figure 4, in which we plot the submillimeter spectra from Rayleigh particles (the distribution used to compute the models in Fig. 4 had $a- = 10^{-8}$ m, $a+ = 10^{-7}$ m and $q = 4$) having silicate, carbon, and tholin compositions. Evidently, the Rayleigh spectra of these three materials are steeper than $\alpha = 3$, due to the wavelength dependences of the complex refractive indices. Thus, we conclude that the spectrum of Brorsen-Metcalf is incompatible with an origin in spherical particles much smaller than a wavelength. This is an important conclusion, since it implies the existence of particles of size comparable to a wavelength in abundance great enough to influence the submillimeter emission. It also shows the diagnostic value of multiwavelength observations. Based on data at a single wavelength, we could not reject Rayleigh grains as the source of the flux density (c.f. § III*b* i).

The macroscopic grain model (§ III*b* ii) survives detailed evaluation of equation (9). Figure 5 shows that the data and the large grains model are compatible, regardless of the grain composition.

Table 3 summarizes a subset of the models computed, and indicates for each model the total mass (determined by normalization to the 0.8 mm measurement) and the best-fit spectral index, determined in the wavelength range $0.4 \le \lambda \le 1.2$ mm ($0.4 \le \lambda \le 0.9$ mm for the tholin models). A subset of the models listed in Table 3 is plotted in Figures 6 and 7. From the Table, it may be seen that the masses are of order 10^9–10^{10} kg, comparable to the masses estimated from the Rayleigh (§ III*b* i) and macroscopic (§ III*b* ii) limits. The consistency of the grain masses to within an order of magnitude is remarkable in view of the wide range of models considered.

IV. DISCUSSION

a) Results

Three results of probable significance may be drawn from inspection of the Figures, from Table 3 and from the preceding discussion.

1. The total grain mass falls in the range $10^9 \le M \le 10^{10}$ kg, and is a relatively insensitive function of the adopted grain composition and size distribution.

2. Size distributions in which the grains are all small compared to a wavelength ($a-$, $a+ \ll \lambda$) in general produce thermal spectra too steep to fit the Brorsen-Metcalf data. By

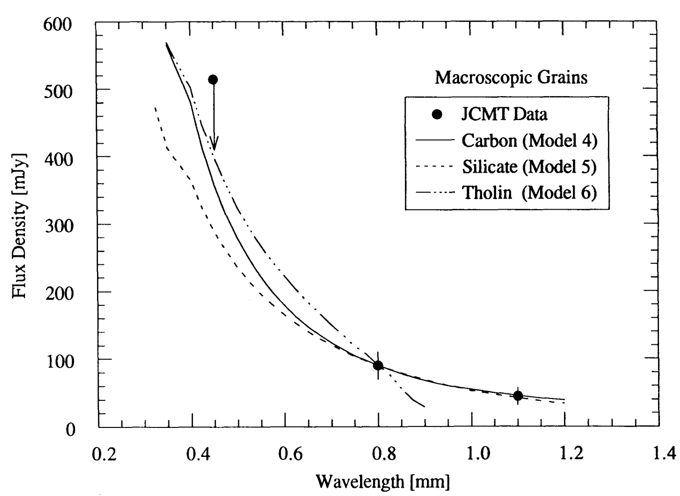

FIG. 5.—Models of submillimeter thermal emission from macroscopic particles $a \sim \lambda$. All three model compositions are compatible with the data.

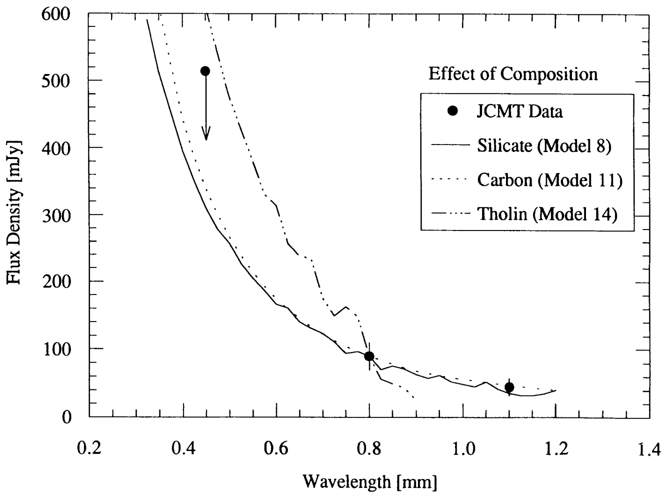

FIG. 6.—Representative submillimeter models from broad size distributions of grains. Three models are shown for silicate, carbon and tholin grains. All models have $a- = 10^{-8}$ m, $a+ = 10^{-2}$ m, and $q = 3$. The silicate and carbon models are completely consistent with the submillimeter data, while the tholin emission is too steep.

implication, the submillimeter spectra provide evidence for large grains ($x \sim 1$, $a \sim 1$ mm) in this comet. Interestingly, submillimeter measurements of circumstellar dust around yound stars reveal relatively flat spectra, consistent with large grains (Weintraub, Sandell, and Duncan 1989).

3. The imaginary part of the refractive index of tholin material is a steeply decreasing function of increasing wavelength in the submillimeter range (Khare *et al.* 1984). As a result, tholin grains are inefficient radiators at $\lambda \geq 0.7$ mm, and the spectral indices tend to be steeper than those of corresponding silicate and carbon models (see Figs. 4–7). In this sense, the tholin models are generally the least successful at fitting the submillimeter data, although acceptable fits can sometimes be found (e.g., Fig. 5).

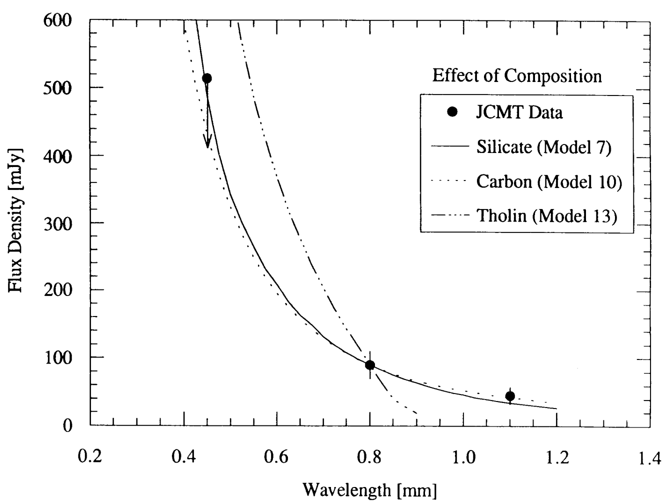

FIG. 7.—Same as Fig. 6 but with $a- = 10^{-8}$ m, $a+ = 10^{-3}$ m, and $q = 3$. Figs. 6 and 7 may be compared to examine the effect of $a+$ on the emitted spectrum. All three spectra are steeper than their counterparts in Fig. 6. The silicate and carbon grain models are still consistent with the data, though only at the 3 σ level (see the 0.45 mm point). The tholin grain model does not match the data.

Table 2 shows that the submillimeter mass was liberated from the nucleus on a time scale of order 1 day (10^5 s). The implied mean mass-loss rate, 10^4–10^5 kg s^{-1}, is large but not unprecedented in the study of comets. For comparison, comet Halley lost $\sim 10^4$ kg s^{-1} in dust near $R \sim 0.7$–0.8 AU, as determined from infrared observations (Hanner *et al.* 1987). It is not obvious, however, that estimates of the mass from infrared observations can be reliably compared with estimates from submillimeter data, since grains of a given size do not contribute equally at different wavelengths. Neither is it obvious that the impulsive dust production observed in the submillimeter is representative of Brorsen-Metcalf at later times. Unfortunately, we know of no simultaneous measurements of the gas production rates, so the gas/dust production rate ratio cannot be calculated from our data.

What might be the origin of millimeter- and centimeter-sized grains in comets? Such grains are unlikely to grow in molecular clouds, where growth times for centimeter sized particles are in excess of the cloud collapse times. Instead, it seems likely that the large particles are produced in the solar system, perhaps at the time of formation of the cometary nuclei. Suitably short growth times are to be found in the protoplanetary disk. Growth by agglomeration in the proto-planetary disk would tend to produce fragile particles with an open, possibly fractal structure. Such particles are presumably weak, and present a cross section per unit mass larger than that of an equal-mass sphere (Meakin and Donn 1988; Wright 1989). Evidence from some meteor streams is compatible with low-strength aggregate structure in cometary meteoroids (Williams 1990), directly suggesting the nature of the large particles in Brorsen-Metcalf.

The question of the origin of the large grains is closely connected with the cause of the temporal variability implied by the sudden appearance of submillimeter flux on September 10. A simple interpretation would be that large grains are emitted from the nucleus continuously but at a variable rate. Mass loss variations on time scales of days are common (if not usual) in near-Sun comets, where they are caused by nucleus rotation and by poorly understood stochastic processes on the nucleus (see Jewitt 1990). Among the latter are included the sudden exposure of buried pockets of volatiles and the possible effects of spontaneous phase changes in water ice. We have no evidence to contradict the hypothesis that the emission of large grains from Brorsen-Metcalf is continuous but temporally modulated. A more interesting speculation can be based on the observation that short period comet nuclei possess mantles composed of low-albedo, refractory matter (e.g., A'Hearn 1988). The mantles grow by the selective depletion of volatiles and small refractory particles due to sublimation and ejection and probably consist of large particles too heavy to be removed by gas drag. Numerical experiments suggest that mantles may be unstable near perihelion due to strong sublimation of underlying volatiles (e.g., Brin and Mendis 1979; Horanyi *et al.* 1984; Rickman, Gustafson, and Fernandez 1990), so that mantles must be regarded as temporary but recurrent features of some cometary nuclei. Perihelion mantle removal suggests a simple, self-consistent explanation of the present submillimeter outburst. Specifically, we hypothesize that part of the mantle on Brorsen-Metcalf was ejected shortly before perihelion, and that fragments of the ejected mantle are responsible for the submillimeter emission observed on UT September 10. Typical mantle thicknesses estimated from the above models are of order $d = 10^{-1}$ m. The surface area of the mantle containing mass M is $A = M/(d\rho)$. With $M \sim 10^9$–10^{10} kg and density $\rho \sim 1000$ kg m^{-3}, we estimate $A \sim 10^7$–10^8 m^2, corresponding to 3%–30% of the surface area of a 5 km radius nucleus. Coincidentally, this area fraction is similar to the typical fraction of the total nucleus surface area occupied by vents on short period comets (A'Hearn 1988). The hypothesis is thus compatible with the impulsive nature of the submillimeter radiation, with its sudden appearance near perihelion, and with the unstable behavior of mantles predicted from models. An expected consequence of the ejection of part of the mantle would be a sudden rise in the gas mass loss rates due to the exposure of subsurface ices. Depending on the active area prior to the ejection, the increase could be as much as a factor of 2, or as little as 10%. Unfortunately, we are not aware of independent measurements of the gas mass-loss rates in Brorsen-Metcalf at the time of the hypothesized mantle ejection. A second consequence would be the persistence of the submillimeter emission for a period of days to weeks, due to the small ejection velocities and large diaphragm transit times anticipated for large grains. Unfortunately, we possess no submillimeter observations taken after September 10, and the unstable mantle hypothesis remains as a non-unique interpretation of the data.

While it is at first sight remarkable that we should have witnessed the disruption of part of the mantle, it is likely that such events are common in periodic comets, and are concentrated in time near perihelion (e.g., Rickman *et al.* 1990). Future radio continuum observations will show whether impulsive submillimeter emission is correlated with perihelion passage, as this hypothesis predicts.

b) *Comparison with Earlier Work*

Numerous earlier attempts at millimeter and centimeter wavelength continuum observations of comets have been reported in the literature (e.g., Hobbs *et al.* 1975; Hobbs, Brandt, and Maran 1977; Snyder, Palmer, and Wade 1983; Irvine *et al.* 1984; Hoban and Baum 1987; Altenhoff *et al.* 1986, 1989). A great many of these attempts proved unsuccessful, and many of the reported detections remain controversial to this day. With the benefit of hindsight, we suggest two plausible reasons why most previous radio continuum observations have yielded no detections. First, the radio continuum is exceedingly weak and is a steep power-law function of wavelength (at least, in Brorsen-Metcalf). Observations at millimeter and, especially, centimeter wavelengths suffer from the steep decline in the emitted flux density with increasing wavelength. Submillimeter observations, on the other hand, benefit from the high flux densities at shorter wavelengths. Second, some of the earlier observations are known to have employed inaccurate ephemerides, whereas (as noted in § II) the Brorsen-Metcalf ephemeris and the JCMT pointing are known to be accurate to a small fraction of a beam width.

Neither of these conjectures can account for the strong *positive* detections reported in comets Kohoutek 1973f (Hobbs *et al.* 1975) and West 1975n (Hobbs *et al.* 1977), at 28 and 37 mm, respectively. If real, these detections would suggest 1 mm flux densities $F_\nu \gg 1000$ mJy, for any physically reasonable spectral index ($\alpha \geq 2$). It seems unlikely that thermal emission can be responsible for the reported comet Kohoutek and West flux densities. Perhaps another emission process can operate in some comets at some times (?). By contrast, the detection of comet Halley by Altenhoff *et al.* 1986 and 1989 is clearly consistent with a thermal origin in large particles.

c) *Future Submillimeter Work*

The present observations raise a number of questions concerning the grains responsible for the submillimeter continuum radiation, and highlight the need for more extensive submillimeter observations of comets. As we have seen, the quantity best constrained by the submillimeter photometry is the total grain mass, M, and this quantity is determined probably to within an order of magnitude from the present data. Additional constraints (notably the finding that the emission cannot be attributed to Rayleigh particles) are based essentially on the submillimeter spectral index. Evidently, the most practical route to stronger constraints on the properties of the grains can reasonably be anticipated from *simultaneous* optical, thermal-infrared and submillimeter photometry. Therefore, future submillimeter observations should be taken in conjunction with simultaneous observations at shorter wavelengths.

Many or all active comets should emit millimeter-sized or larger particles. Impulsive events of the kind observed in Brorsen-Metcalf and hypothesized to be caused by mantle failure should be most common near perihelion. Steady emission due to ejection of large grains through active vents may also occur (see Altenhoff *et al.* 1986). Future observations should be directed towards the elucidation of the spectral, temporal and spatial characteristics of the radiation emitted by these particles. Vaidya and Desai (1986) have suggested that large grains might be detected in the optical via forward scattered radiation during stellar occultations—an observation which is at least as difficult as the submillimeter observations reported here. Submillimeter photometry, supplemented by thermal infrared, millimeter wavelength and radar observations (when possible), seems to be the most direct route to an understanding of the large-particle populations in comets.

Lastly, there is an urgent need for more laboratory measurements of the submillimeter refractive indices of astrophysically significant materials (see Draine 1990). Experimental and theoretical research into the optical effects of fractal structure in the large grains might usefully test our confidence in the use of the Mie Theory for the interpretation of future submillimeter data.

V. SUMMARY

1. Submillimeter continuum emission has been detected from comet P/Brorsen-Metcalf at perihelion ($R = 0.48$ AU, $\Delta = 1.10$ AU, $\alpha = 67°$). The submillimeter spectral index is in the range $1 \leq \alpha \leq 3$. The 0.8 mm emission is variable on a time scale of 1 day.

2. We interpret the submillimeter radiation as thermal emission from a coma of solid grains. The estimated total mass of the grains responsible for the submillimeter emission is $10^9 < M < 10^{10}$ kg, and is weakly dependent on the details of the particular model employed to fit the spectrum.

3. The shape of the submillimeter spectrum can be reproduced using a suite of models with various grain size distributions and compositions (i.e., the submillimeter spectrum imposes no *unique* constraints on the size distribution or grain compositions). However, the measured spectral index is too small to be compatible with an origin in small ($2\pi a/\lambda \ll 1$, where a is the radius) spherical particles composed of either astronomical silicate, glassy carbon or tholin. Instead, the present observations are consistent with models based on large grains, either alone, or in Halley-like size distributions from $a \ll 1$ μm to $a \geq 1$ mm.

4. The submillimeter mass was liberated impulsively from the nucleus on a time scale ≤ 2 days, yielding an average mass

production rate $dM/dt \sim 10^4$–10^5 kg s^{-1} in this interval. The submillimeter observations are consistent with ejection of a small part of the nucleus mantle in response to heating at perihelion. This interpretation is also consistent with theoretical models which suggest that periodic mantle formation (and ejection) should be common on the nuclei of short-period comets.

5. Interpretation of the submillimeter observations is dependent on the availability of accurate submillimeter complex refractive indices of materials likely to be abundant in comets. There is an urgent need for laboratory studies of the optical properties of such materials in the submillimeter wavelength range.

We are thankful to Henry Matthews for a positively jolly introduction to UKT 14. We also greatly appreciate the competent assistance of telescope operator Charles Cordell, and we especially thank him for allowing us to extend our observing time beyond the end of the formal shift on September 10, so as to take advantage of the good atmospheric conditions and the sudden activity in P/Brorsen-Metcalf. Tim Brooke kindly supplied his near-IR photometry from UT September 9 in advance of publication. We thank W. Altenhoff, S. Maran, S. Ridgway, and G. Wynn-Williams for comments on the manuscript. This work was supported in part by funds from the National Science Foundation.

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