DEBRIS FROM COMET P/SWIFT-TUTTLE

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ABSTRACT

We present continuum observations of comet P/Swift-Tuttle taken at 850 μm wavelength using the James Clerk Maxwell Telescope. Near perihelion, it exhibited the largest submillimeter cross-section of any comet yet studied. We attribute the submillimeter emission to thermal radiation from large, near-nucleus particles destined to populate the Perseid meteor stream. The perihelion production of dust is estimated at 5×10^4 kg s^{-1}, and the dust to gas production ratio at ~2.8. © *1996 American Astronomical Society.*

1. INTRODUCTION

Comet P/Swift-Tuttle became a bright and well-observed object when near perihelion (q=0.958 AU) in 1992 December, with a peak water production rate of 6×10^{29} s^{-1} (Bockelee-Morvan *et al.* 1994). The coma displayed a complex set of jets at optical continuum and molecular emission band wavelengths, with evidence for nucleus rotation with a period near 2.9 days Sekanina 1981; Yoshida *et al.* 1993; Boehnhardt & Birkle 1994; Jorda *et al.* 1994). The comet is of special interest as the parent of the Perseid meteoroid stream (cf. McIntosh 1991) and the high activity of this stream suggests that Swift-Tuttle is a copious source of millimeter sized meteoroids. These large particles may present a negligible fraction of the total geometrical cross section in dust, and yet contain a significant fraction of (or even dominate) the dust mass.

Submillimeter wavelength continuum observations are ideally suited to the study of large cometary particles (Altenhoff *et al.* 1986, 1989; Jewitt & Luu 1990, 1992). In our previous work, we have reported observations of submillimeter emission from active comets and interpreted the observations in terms of thermal radiation from cometary solids. In this paper we extend our submillimeter investigations to P/Swift-Tuttle.

2. OBSERVATIONS

Comet P/Swift-Tuttle was observed using the 15 m diam James Clerk Maxwell Telescope (JCMT) located on Mauna Kea, Hawaii. The observations were taken by Rachel Padman of the University of Cambridge on behalf of Dominique Bockelee-Morvan and Jacques Crovisier of the Observatoire de Meudon, Paris. The facility bolometer UKT14 was employed with broadband filters centered at λ_c=450 and 850 μm wavelength, each having fractional full width at half maxima (FWHM) $\delta\lambda/\lambda_c \sim 0.25$ (Duncan *et al.* 1990). The circular bolometer entrance aperture was θ=9 arcsec in radius, corresponding to $\ell=1.0\times10^7$ m at the comet. Sky subtraction was achieved by chopping the UKT14 aperture a distance ϕ=60 arcsec in azimuth at 7.8 Hz, while nodding the telescope in azimuth by the same distance at 0.1 Hz. Previous experience has shown that this procedure gives extremely good sky cancellation (e.g., Jewitt & Luu 1992). It is likely that the "sky" positions used for background subtraction were weakly contaminated by emission from the extended dust coma, leading to a small degree of self-subtraction. However, we believe this contamination to be small. For instance, if the surface brightness fell in proportion to the inverse projected distance from the nucleus (cf. Jewitt 1991), the ratio of the flux densities would be $S_\nu(60'')/S_\nu(0'') \sim \theta/(2\phi) \sim 0.08$. This small contamination does not substantially affect the conclusions reached in this paper. Photometric calibration was obtained from observations of Uranus, for which the 850 μm flux density was taken to be 65.9 Jy.

2.1 Results

The submillimeter results are summarized in Table 1. A 5σ detection was achieved at 850 μm, while at 450 μm it was possible only to place an upper limit to the flux density. The non-detection at 450 μm is clearly the result of higher sky noise and lower sensitivity at this shorter wavelength. The two points taken together limit the submillimeter spectral index to $\leqslant$5.6, which is not physically constraining (Jewitt & Luu 1990). Therefore, we ignore the 450 μm datum in the following discussion and, to properly interpret the 850 μm measurement, we make recourse to observations taken at a variety of shorter wavelengths. We reject the possibility that the continuum signal is due to a background source. Such a source would cross the JCMT photometry beam (at 167 arcsec per hr) in <7 min. Sensitivity across the beam is centrally peaked, so that in all probability, the source would rise and fall measurably on a timescale of 2 or 3 min. The data instead show that the signal was persistent, consistent with a source that is fixed within the tracked telescope beam.

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TABLE 1. JCMT photometry of P/Swift-Tuttle.

UT Date	R [AU]	Δ [AU]	α [deg]	λ [μm]	S_ν [mJy]
1992 / 12 / 08.1771	0.96	1.50	40	850	132 ± 28
1992 / 12 / 08.1875	0.96	1.50	40	450	≤ 4634

Furthermore, near-simultaneous spectroscopic observations showing very bright rotational lines (Bockelee-Morvan *et al.* 1994) prove that the comet was in the JCMT beam, and that it was held there.

The cross section (km^2) of a spherical blackbody located at the comet and giving the observed submillimeter flux density is (Jewitt & Luu 1992)

$$C_{BB} \sim 28.3 \lambda^2 \Delta^2 S_\nu R^{1/2}, \quad (1)$$

where λ is the wavelength expressed in millimeters, Δ and R are the geocentric and heliocentric distances expressed in AU, and S_ν is the flux density in mJy. For P/Swift-Tuttle, substitution gives $C_{BB}=(6.0\pm1.3)\times10^3$ km^2. The effective blackbody radius is $(C_{BB}/\pi)^{1/2} \sim 44\pm5$ km. The resulting mean optical depth inside the JCMT beam is $\tau_{850} \sim (C_{BB}/\pi \ell^2) \sim 2\times10^{-5}$, which is extremely optically thin.

The above cross section is far larger than can plausibly be ascribed to the central nucleus. Optical photometry of P/Swift-Tuttle at large heliocentric distance is summarized in Table 2, together with the derived nuclear cross-sections and effective radii. The listed measurements are compatible with a product of the optical albedo times cross-section in the range 15–20 km^2, far smaller than the submillimeter cross section in Eq. (1). If interpreted as the scattering cross section of the nucleus with albedo $p=0.04$, the optical photometry suggests a nuclear radius $r_e \sim 10.5$–12.5 km. This is large compared to the nuclei of most other well-studied comets, including P/Halley (effective radius $r_e \sim 5$ km). However, the negligible nongravitational acceleration exhibited by this comet is compatible with a nucleus of unusually high mass (Yau *et al.* 1994). It is likely that the comet retains a residual coma at $R=5$ AU, and possibly even at $R=8$ AU, which contaminates the light scattered from the bare nucleus. Therefore, Table 2 strictly sets only *upper limits* to the nuclear dimensions. In any event, the optical data show that $\pi r_e^2 \ll C_{BB}$, and hence justify the assumption that the bulk of the submillimeter emission originates in the dust coma rather than from the monolithic nucleus.

2.2 Thermal Infrared Data

Infrared thermal emission from P/Swift-Tuttle was observed at 8.8±0.87, 9.8±0.96, 11.7±1.13, and 12.5±1.16 μm wavelength by Deutsch *et al.* (1992 and 1994). They observed at the Steward Observatory 2.2 m on UT 1992 Dec 09.04–09.09, about 1 day after the 850 μm JCMT observations reported here. The Steward and JCMT observations are not simultaneous, and thus should be compared with caution. However, visual photometry at this epoch shows that day to day variations in P/Swift-Tuttle amount to only ~30% (Marsden 1992), and this is too small to affect the general conclusions reached below. Accordingly, we compare the infrared and submillimeter photometry in Fig. 1. The 450 and 850 μm flux densities have been scaled by the ratio of the photometry apertures (Steward/JCMT=6″/18″) in order to correct for the different volumes of the coma sampled by the two telescopes.

Two observations may be made from Fig. 1. First, no single blackbody can simultaneously fit the 10 and 850 μm measurements. For example, the middle curve in Fig. 1 shows Deutsch *et al.*'s 345 K blackbody best fit to the 10 μm data. The flux density at 850 μm is three times smaller than predicted from this and other blackbody extrapolations from the 10 μm data. A threefold decrease in emissivity from 10 to 850 μm wavelength corresponds to emissivity index β=0.25, where $\epsilon(\lambda)\propto\lambda^{-\beta}$ is assumed. This remarkably small emissivity index is incompatible with thermal emission from optically small grains, for which $\beta\sim1$ or 2 would be expected. Instead, it is suggestive of large grains, $a>1$ mm, as the source of much of the infrared and submillimeter flux.

Second, the infrared observations show, at best, muted evidence for the 10 μm silicate feature. In part, this is because the range of wavelengths observed by Deutsch *et al.* barely spans the silicate emission band (8.0–12.5 μm according to Bregman *et al.* 1987), so that the continuum is poorly defined. Even in view of this limitation, however, there is little room for as strong a silicate band as observed in some other comets (Ney 1982; Gehrz & Ney 1992). This suggests that if silicates are present, the emitting grains are individually optically thick at this wavelength and so imposes a lower limit on the effective grain size (e.g., Ney 1982; Gehrz & Ney 1992). With 10 μm silicate opacity $\kappa_{10}\sim10^2$ m^2 kg^{-1} (Pollack *et al.* 1994) we find that grains larger than $a>(\rho\kappa_{10})^{-1}\sim10$ μm would be individually optically thick. Note that Lynch *et al.* (1992) reported a similarly

TABLE 2. Optical photometry.

UT Date	R [AU]	Δ[AU]	α [deg]	m_R	$m_R(1,1,0)^1$	pC_e[km^2]	r_e [km]	Reference
1994 / Feb / 14	5.30	5.09	10.7	19.17±0.02	11.59±0.02	17.6±0.6	11.8±0.2	O'Ceallaigh *et al.* (1995)
1994 / Apr / 14	5.82	5.41	9.4	19.67	11.80	16.2	11.4	Boehnhardt (1995)
1995 / May / 01	8.76	8.39	6.3	21.50±0.05	11.92±0.05	14.5±0.7	10.8±0.3	Luu (1995)

1 $m_R(1,1,0) = m_R - 5\log(R\Delta) - \beta\alpha$. We adopt phase coefficient $\beta = 0.04$ mag. (deg)$^{-1}$ (see Jewitt 1991).

2 $pC_e = 2.25 \times 10^{22}\,\pi\,10^{0.4(m_R(\mathrm{sun}) - m_R(1,1,0))}$, with $m_R(\mathrm{sun}) = -27.3$ (Jewitt 1991).

3 Computed from $pC_e = p\,\pi\,r_e^2$ with $p = 0.04$ (Jewitt 1991).

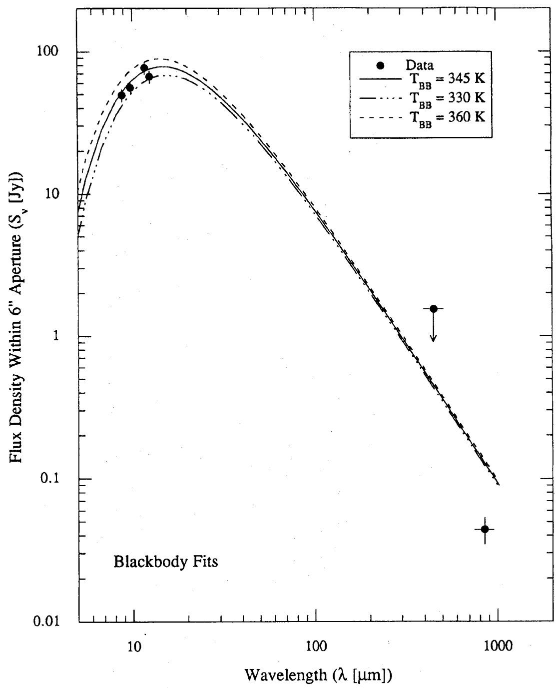

FIG. 1. Thermal infrared and submillimeter measurements of P/Swift-Tuttle are shown as a function of wavelength. The measurements near 10 μm are from Deutsch *et al.* (1992), while those at 450 and 850 μm are from the present work (Table 1). The submillimeter measurements have been scaled down by a factor of 3 to compensate for the larger photometry aperture employed at the JCMT. Error bars on the data do not include an estimated $\pm 30\%$ uncertainty in the scaling between the 10 μm and submillimeter data, due to possible cometary variability in the time between the two sets of measurements. The 450 μm measurement is a 3σ upper limit. Spectra of blackbodies at temperatures T_{BB}=330, 345, and 360 K are also shown. Notice that the blackbody spectra all predict more flux at 850 μm than is observed.

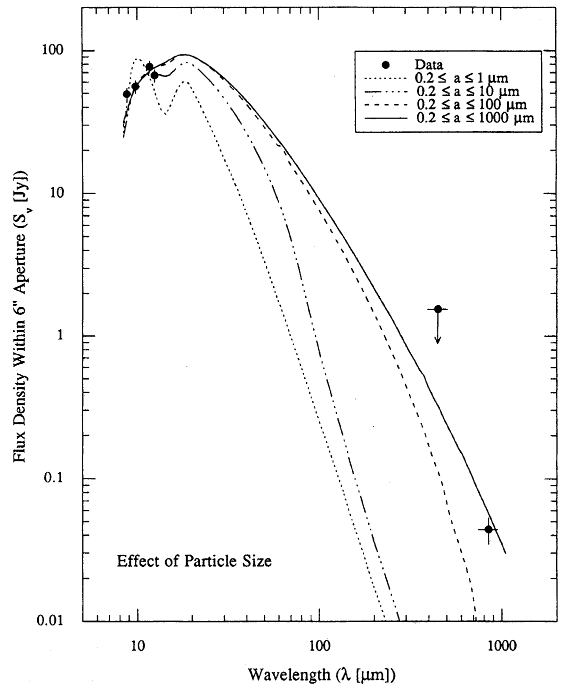

FIG. 2. Thermal emission models (see text) are compared with the infrared-submillimeter photometry to illustrate the effect of particle size on the thermal emission continuum. The particular models shown have differential size index α=3, silicate refractive indices from Draine (1985), and size limits as indicated in the figure. Only models including large particles ($a \sim 1$ mm) supply enough 850 μm flux density to match the data.

small silicate excess in comet P/Brorsen-Metcalf, and suspected the presence of optically large particles.

Accordingly, we pursue an interpretation of the submillimeter emission as thermal radiation dominated by macroscopic solids. To test this idea, we used our previously developed numerical model to compute the emission spectrum from broad size distributions of cometary dust particles (the model is described in Jewitt & Luu 1992). The free parameters of the model include the adopted form of the grain size distribution, the upper and lower limiting particle sizes, and the grain composition expressed as a wavelength-dependent, complex refractive index. Additional uncertainties are due to the physical form of the candidate grain materials (e.g., amorphous versus crystalline). The large number of free parameters makes it impossible to define a unique fit to the observational data, but important general features may be identified from the model. In particular, we seek models that account for the muted 10 μm silicate feature and for the 10–850 μm spectral index.

Sample models are shown together with the thermal emission data in Fig. 2. We used the complex refractive indices for astronomical silicates tabulated by Draine (1985). The differential grain size distribution is taken to be a power law, $n(a)da = \Gamma a^{-\alpha} da$, with Γ constant and α=3, and we show the effect of particle size on the character of the emitted spectrum. Small grains ($0.2 \leqslant a \leqslant 1$ μm) are optically thin at 10 μm and show a strong Si–O stretch feature near 10 μm which is not present in the data. As noted above, the absence of a clear Si–O band in the data leads us to conclude that silicate grains with $a \geqslant 10$ μm dominate the cross section. The small particle models also predict flux densities at 850 μm that are orders of magnitude too small to fit the data, strengthening the case against them. Models (Fig. 2) including larger grains show a progressive dilution of the silicate bands (consistent with the IR data), combined with a dramatic increase in the flux density at long wavelengths. The upper model in Fig. 2 has maximum particle radius $a \sim 1$ mm. It successfully matches the observed emissivity decrease from 10 to 850 μm, and provides a plausible fit to the four points in the 10 μm window. The models plotted in Fig. 2 are nonunique, but they serve to demonstrate that large particles provide a natural explanation for both the muted silicate feature and the emissivity drop from 10 to 850 μm observed in P/Swift-Tuttle.

3. DUST MASS AND MASS LOSS RATE

The interpretation of submillimeter continuum photometry hinges crucially on knowledge of the opacity (cross section per unit mass) of the dust, $\kappa(\lambda)$ (m^2 kg^{-1}). The opacity is a wavelength-dependent function of the size, shape, porosity, and composition of the grains, and of their size distribution. Previously, we computed effective opacities for comet-like power-law size distributions of dust grains (Jewitt & Luu 1992). For a wide range of grain compositions and size distributions, we found opacities $0.1 \leq \kappa(1\ \mathrm{mm}) \leq 1\ \mathrm{m^2\,kg^{-1}}$. However, our calculations were based on the assumption that cometary grains are homogeneous spheres with zero porosity and must therefore be regarded as simplistic. Recently, a more comprehensive set of theoretical opacities has been presented by Pollack *et al.* (1994). These authors considered a wide range of compositions, grain shapes and porosities. Their results yield $\kappa\ (1\ \mathrm{mm}) = 0.05\ \mathrm{m^2\,kg^{-1}}$, and they estimate this value to be accurate to within a factor of 4. For comparison, Beckwith *et al.* (1990) adopted $\kappa(1\ \mathrm{mm}) = 0.3\ \mathrm{m^2\,kg^{-1}}$ for circumstellar dust around pre-main-sequence stars, while Hildebrand (1983) favored $\kappa(1\ \mathrm{mm}) = 0.06\ \mathrm{m^2\,kg^{-1}}$. We adopt Pollack *et al.*'s estimate of the opacity

$$\kappa(\lambda) = 0.05/\lambda(\mathrm{m^2\,kg^{-1}}), \quad (2)$$

while recognizing that this value is uncertain by a factor of about 4 (the results we derive may be easily scaled to other values of κ should new constraining evidence be obtained).

Combining Eqs. (1) and (2), we obtain the mass of the near-nucleus debris $m = (1.0 \pm 0.2) \times 10^{11}$ kg, which is equivalent to a sphere of density $\rho = 500\ \mathrm{kg\,m^{-3}}$ and of radius $a = 0.36$ km. For comparison, from the minimum nucleus radius $r_e = 10.8$ km (Table 2), we estimate nuclear mass $\mathscr{M} = 2.6 \times 10^{15}$ kg. The ratio $m/\mathscr{M} \sim 4 \times 10^{-5}$ shows that the near-nucleus debris contains only a small fraction of the nuclear mass.

To estimate the mass production rate we need to know the time of residence of the debris within the JCMT beam. The ejection speed of cometary dust at a given heliocentric distance is a strong function of the dust particle size. From a consideration of the momentum transfer between gas molecules and dust grains, we find that grains smaller than a critical size $a_{\mathrm{crit}} \sim \mu m_H Z r_n/(v_{\mathrm{th}}\rho)$ are dynamically well coupled to the outflowing gas. Here, μ is the molecular weight, $m_H = 1.67 \times 10^{-27}$ kg is the mass of hydrogen, $Z(\mathrm{m^{-2}\,s^{-1}})$ is the sublimation gas flux, r_n is the nucleus radius, $\rho(\mathrm{kg\,m^{-3}})$ is the grain density, and v_{th} is the speed of the gas. We compute Z from the energy balance equation applied to water sublimating at the surface of the nucleus. For P/Swift-Tuttle at perihelion, we take $\mu m_H Z = 5 \times 10^{-4}\ \mathrm{kg\,m^{-2}\,s^{-1}}$, $r_n = 10^4$ m (Table 2), $v_{\mathrm{th}} = 10^3\ \mathrm{m\,s^{-1}}$ (Bockelee-Morvan *et al.* 1994) and $\rho = 500\ \mathrm{kg\,m^{-3}}$ to find $a_{\mathrm{crit}} \sim 5\ \mu$m. The micron-sized optically dominant grains in this comet's distinctive spiral arms, for example, are ejected at or close to the velocity of the escaping sublimated gas (Schulz *et al.* 1994). Millimeter sized and larger grains responsible for the submillimeter emission, however, will be ejected at a much lower speed (e.g., Whipple 1951). The largest escaping particles will leave the nucleus at close to the gravitational escape velocity $v_e = (2GM_n/r_n)^{1/2} \sim 5\ \mathrm{m\,s^{-1}}$, and we take this as a crude estimate of the expansion velocity of the near-nucleus debris. Radar observations of comet *IRAS*-Araki-Alcock show Doppler shifts in its debris sheet which are of this order (Harmon *et al.* 1989; Goldstein *et al.* 1984). Independently Kresak (1993) has estimated ejection velocities $\sim 5\ \mathrm{m\,s^{-1}}$ from the dynamics of meteor streams and *IRAS* dust trails. With $v_e = 5\ \mathrm{m\,s^{-1}}$, the residence time within the JCMT beam is $\tau_{\mathrm{res}} = \ell/v_e \sim 2 \times 10^6$ s (23 days), and the mean dust production rate $m/\tau_{\mathrm{res}} = 5 \times 10^4\ \mathrm{kg\,s^{-1}}$. The OH production rate is sharply peaked near perihelion, and varies on time scales that are short compared with τ_{res} (Bockelee-Morvan *et al.* 1994). We adopt the instantaneous OH production rate $\tau_{\mathrm{res}}/2 \sim 12$ days before the date of the JCMT observations, namely, $Q_{\mathrm{OH}} \sim 6 \times 10^{29}\ \mathrm{s^{-1}}$ ($1.8 \times 10^4\ \mathrm{kg\,s^{-1}}$). The corresponding ratio of dust to gas production rates is $\mathscr{R} = 50/18 \sim 2.8$ (with an uncertainty of a factor of 4). Values of $\mathscr{R} > 1$ have been measured by *in situ* spacecraft at comets P/Halley and Grigg-Skjellerup (McDonnell *et al.* 1991, 1993). At both comets, the dust mass was controlled by the largest particles, just as we found for P/Swift-Tuttle. We compare other parameters of P/Swift-Tuttle and P/Halley nuclei in Table 3.

TABLE 3. Comparison with Comet Halley.

Property	Symbol	P/Swift-Tuttle	P/Halley
Effective Radius	r_n [km]	10.8[a]	5[b]
Mass ($\rho \cong 500\ \mathrm{kg\,m^{-3}}$)	M [kg]	2.6×10^{15}	2.6×10^{14}
Cross-section	C_{BB} [km^2]	$(6.0 \pm 1.3) \times 10^3$ [a]	$(8 \pm 1) \times 10^2$ [c]
Gas Production at 1 AU	Q_{OH} [s^{-1}]	6×10^{29} [d]	2.5×10^{29} [e]
Dust/Gas	$\mathfrak{R}$	2.8 [a]	2 to 3 [f]

Notes
a - This work
b - Keller *et al.* (1987)
c - Jewitt and Luu (1992)
d - Bockelee-Morvan *et al.* (1994)
e - Schloerb *et al.* (1987)
f - McDonnell *et al* . (1991)

Hughes & McBride (1989) have indirectly estimated the mass of the Perseid meteor stream as 3×10^{14} kg (i.e., roughly 10% of the nucleus mass). The JCMT observations allow us to independently assess the total mass of debris released into the Perseid meteor stream. To do this, we note that the production rate of OH is strongly peaked around perihelion, decreasing by a factor of 10 as the comet moves from perihelion to $R = 1.3$ AU (Bockelee-Morvan *et al.* 1994). P/Swift-Tuttle spends about four months of its orbit inside 1.3 AU. To place an upper bound to the debris mass, we suppose that the perihelion loss rate ($5 \times 10^4\ \mathrm{kg\,s^{-1}}$) is sustained for all of the four months near perihelion during which the comet is closer to the sun than 1.3 AU. Then the dust production per perihelion (and per orbit) is about 5×10^{11} kg. Independently, Fulle *et al.* (1994) obtained 7×10^{10} kg of debris per orbit by modeling the isophotes of the cometary dust coma. The agreement, to within a factor of 7, gives us confidence that at least the correct order of magnitude has been reached.

The Hughes & McBride Perseid stream mass represents about 600 orbits of accumulation at the rate measured from the JCMT photometry. However, numerical integrations show large variations in the perihelion distance and other orbital parameters of P/Swift-Tuttle on timescales short compared to 600 orbits (Levison & Duncan 1994). Therefore, it is not obvious that the measured rate of dust production is sufficient to supply the Hughes & McBride stream mass on these shorter timescales. Given that stream masses are highly uncertain (McIntosh 1991) and that the mass loss rate may vary from orbit to orbit, however, we see no immediate contradiction between the various estimates.

4. CONCLUSIONS

(1) Comet P/Swift-Tuttle was detected near perihelion at 850 μm wavelength using the James Clerk Maxwell Telescope. The measured signal, $S_\nu = 132 \pm 28$ mJy, is the strongest yet recorded from any comet. The emitting cross section, $C_{BB} = (6.0 \pm 1.3) \times 10^3$ km^2, is too large to be identified with the solid nucleus. Instead, we identify C_{BB} with the cross section of debris in the near-nucleus coma.

(2)The strong submillimeter signal and the muted appearance of the Si–O stretch band at 10 μm are both consistent with a high abundance of large particles in P/Swift-Tuttle. The derived perihelion dust mass production rate of 5×10^4 kg s^{-1} corresponds to an instantaneous dust to gas production ratio ~2.8. Because of uncertainties in the submillimeter opacity of cometary debris, the derived mass loss rate and the dust to gas ratio may be uncertain by a factor of ~4. Within the measurement uncertainties, the dust to gas ratio in P/Swift-Tuttle is compatible with that measured *in situ* in P/Halley.

(3) Millimeter sized and larger grains are the presumed precursors of meteoroids in the Perseid stream. The meteoroid stream mass estimated by Hughes & McBride (1989) is equal to the total dust mass lost from P/Swift-Tuttle in 600 orbits.

Note Added in Proof: Independent observations of P/Swift-Tuttle at 10 μm wavelength have been recently reported by Fomenkova, M., Jones, B., Pina, R., Puetter, R., Sarmecanic, J., Gehrz, R., and Jones, T. (1995) AJ, 110, 1866–1874. These authors deduce a perihelion dust mass production rate of 1000 kg s^{-1}, about a factor of 50 smaller than derived from the submillimeter observations. The discrepancy with the present work is most likely an artifact of the short wavelengths employed by Fomenkova *et al.*, and their resulting insensitivity to the large particles which dominate the comentary dust mass distribution.

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