The Dust Trail of Comet 67P/Churyumov-Gerasimenko

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ABSTRACT

We report the detection of comet 67P/Churyumov-Gerasimenko’s dust trail and nucleus in 24 $\mu$m Spitzer Space Telescope images taken February 2004. The dust trail is not found in optical Palomar images taken June 2003. Both the optical and infrared images show a distinct neck-line tail structure, offset from the projected orbit of the comet. We compare our observations to simulated images using a Monte Carlo approach and a dynamical model for comet dust. We estimate the trail to be at least one orbit old (6.6 years) and consist of particles of size $\gtrsim 100$ $\mu$m. The neck-line is composed of similar sized particles, but younger in age. Together, our observations and simulations suggest grains 100 $\mu$m and larger in size dominate the total mass ejected from the comet. The radiometric effective radius of the nucleus is 1.87 $\pm$ 0.08 km, derived from the Spitzer observation. The Rosetta spacecraft is expected to arrive at and orbit this comet in 2014. Assuming the trail is comprised solely of 1 mm radius grains, we compute a low probability ($\sim 10^{-3}$) of a trail grain impacting with Rosetta during approach and orbit insertion.

Subject headings: comets, 67P/Churyumov-Gerasimenko; meteoroids; infrared observations

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1. Introduction

Comet dust trails consist of grains that are ejected from comet nuclei with low velocities and weakly respond to solar radiation pressure. In contrast, dust trails have greater ejection velocities and are strongly influenced by solar radiation. These facts have led investigators to conclude that dust trails are composed of large grains, in excess of 100 \( \mu \text{m} \) (e.g., Sykes and Walker 1992). Trails are so-named because they commonly appear to follow the nucleus along the comet’s projected orbit. Dust trails are long lived (\( \lesssim 100 \text{ yr} \)), a result of normal comet activity, and are the principal mass-loss mechanism of short-period comets, outside of fragmentation and total disruption (Sykes and Walker 1992; Reach et al. 2000, 2007). Over time, planetary perturbations displace a comet’s trail from the nucleus and the trail becomes increasingly tenuous. The trail is then considered to be a meteoroid stream and produces meteor showers if the stream and a planet collide (e.g., the meteor showers associated with comets 2P/Encke and 55P/Tempel-Tuttle). Space-based mid-infrared (mid-IR) observations are readily sensitive to thermal emission from trail particles and the detection rate of trails in Jupiter-family comets is > 80% (Reach et al. 2007), but optical observations of trails from the ground are possible and have been presented for comets 2P/Encke, 22P/Kopff, and 81P/Wild (Ishiguro et al. 2002, 2003, 2007).

The total mass of a dust trail can be estimated from images and dynamic models, assuming the structure and density of the trail dust grains. Comet mass-loss estimates that include trail/large particle production infer dust-to-gas mass ratios that are larger than 1 and that comet nuclei are appropriately described by Sykes and Walker (1992) as “icy mud balls.” For example, Reach et al. (2000) derived a shallow grain size distribution for comet Encke from dynamical simulations of the comet coma and trail at \( r_h = 1.2 \text{ AU} \). Their grain size distribution ranges from \( \frac{dn}{da} \propto a^{-0.7} \) to \( a^{-0.4} \), yielding a dust-to-gas mass ratio of \( \approx 10-30 \). The large derived ratio is mostly due to the dynamics of the coma, best described by large, fast moving particles. Sykes and Walker (1992) deduce a dust-to-gas mass ratio of 3.5 from analysis of Encke’s dust trail and Lisse et al. (2004) posit a value of 2.3 with Infrared Space Observatory photometry of the coma. In contrast, comet Encke’s dust-to-gas mass ratio derived from optical observations suggest the ratio is an order of magnitude lower (e.g., 0.2; Osip et al. 1992). The large dust output from comets imply that comet dust trails are a significant input to the interplanetary dust complex (about half of the dust required to replenish the zodiacal dust complex inside of 1 AU; Sykes et al. 2004).

In the following paper, we present a study of the dust trail of the ecliptic comet 67P/Churyumov-Gerasimenko (67P). Comet 67P is the primary mission target of the European Space Agency’s Rosetta spacecraft, designed to characterize the comet nucleus (morphology, composition) and the comet coma (development of activity, dust-gas interaction, interaction with the solar wind) by following, orbiting, and landing a probe on the nucleus (Glassmeier et al. 2007). Characterization of the comet’s gas and dust environment is important to mission planning (see Colangeli et al. 2004 and references therein; Agarwal et al. 2007).
Fulle et al. (2004) identified this comet to have a neck-line tail structure in optical observations of the comet and concluded that the comet is significantly active dust at 3.6 AU pre-perihelion; Rosetta will enter orbit around the comet at 4–5 AU pre-perihelion. Sykes and Walker (1992) have shown 67P to have dust trail in observations of the comet by the Infrared Astronomical Satellite (IRAS) and estimated this comet’s total dust-to-gas mass ratio to be 4.6. When the trail was observed after the 1982 perihelion, the trail spanned from 0.1° in mean anomaly ahead to 1.1° behind the comet nucleus. Agarwal et al. (2007a) have detected the dust trail at optical wavelengths with the MPG/ESO 2.2 m telescope (4.7 AU post-perihelion). In this paper, we report the detection of 67P’s dust trail and nucleus in Spitzer Space Telescope images taken at 4.5 AU, post-perihelion. We discuss the comet nucleus and dust observed in the mid-IR images and compare our observation to Palomar Observatory ground-based optical images in §3. We model the dust environment of 67P with dynamic models (§4.1-4.2) to estimate the trail grain velocities, sizes, and ages (§4.3-4.5). Finally, we estimate the impact hazard the trail presents to the Rosetta spacecraft (§4.6). We summarize the paper in §5.

2. Observations and Reduction

Spitzer Space Telescope (Gehrz et al. 2007; Werner et al. 2004) images of 67P were taken on 2004 Feb 23 03:44 UT with the Multi-band Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) 24 µm camera ($\lambda = 23.7$ µm, $\Delta \lambda = 5.3$ µm). The observation (Spitzer astronomical observation request key 0006612736) consists of a $3 \times 1$ mosaic of 10 s exposures using the MIPS photometry/super-resolution observation template for a total integration time of 140 s per pixel (one-sigma sensitivity of 0.055–0.077 MJy sr$^{-1}$ per pixel). One targeted pointing of the MIPS photometry/super-resolution mode consists of fourteen dithered images (2.5 arcsec pixel$^{-1}$) providing an $8' \times 5'$ field-of-view, centered on the target. In support of the Spitzer observation, we also imaged comet 67P with the Mount Palomar 5 m Hale telescope Large Format Camera (LFC, a prime-focus camera and mosaic of six detectors spanning a 24' diameter field-of-view) on 25–27 June 2003. Our viewing geometries are summarized in Table 1 and a diagram of the Earth, Spitzer, and 67P is presented in Fig. 1. The IRAS observation geometry is included for comparison. Comet 67P is a Jupiter-family comet with a 6.6 year period (eccentricity = 0.63, semi-major axis = 3.5 AU, inclination = 7.1°) and we observed the comet 312 days ($\lambda = 0.6$ µm) and 554 days ($\lambda = 24$ µm) after the August 2002 perihelion.

MIPS images were initially processed with the Spitzer Science Center’s pipeline version S11.4.0. Starting with individual basic calibrated data (BCD) frames, we applied a few corrections, as prescribed by the MIPS Data Handbook (Spitzer Science Center 2006), before creating the final mosaic. Our individual frames suffered from what is known as the “jail bar effect,” that is, the readout of one saturated pixel causes a constant offset in every forth
column. We subtracted a constant from each affected column such that the median value matches the median value of the nearby unaffected columns. We added a constant value to each frame to correct for slight background offsets between dither positions. Next, we median combined all data frames to create a clean “delta-flat field.” We divided all frames by the delta-flat field to correct for data variations between the data and the pipeline flat field. Finally, distortions in the MIPS 24 µm focal plane were removed by mapping the frames onto a plane tangent to the celestial sphere using the distortion solution provided by the Spitzer Science Center. The resulting images were mosaicked, accounting for the motion of the comet, to create the final image. The delta-flat field, distortion corrections, and mosaicking were performed with the Spitzer Science Center’s MOPEX software (Makovoz and Khan 2005). The final mosaicked image, rotated to the celestial coordinate system, is presented in Fig. 2.

Optical images were obtained on three nights, 25–27 June 2003 UT, using the Gunn r’ filter (Fukugita et al. 1996). The total integration time on the comet was 55 min, observed at an average airmass of 1.80, and an average seeing of 1.9ʺ. The LFC was placed in 2 × 2 binning mode, for an observed platescale of 0.36 arcsec pixel⁻¹. The images were reduced using standard techniques and the NOAO IRAF (Tody 1993) Mosaic Reduction Package. Color differences between twilight/dome light and the dark sky affected the mosaic flat fielding. Each night’s deep exposure frames were object masked and median combined to create super-flats that mitigate the effect of the color difference. Unaccounted features in the flat-field and slight offsets in the chip-to-chip background matching produced the large scale artifacts apparent in the co-added image. The structure varies on the order of 0.5% of the background and were most apparent in images from the last night of observations for which a complete flat-field could not be derived.

The Palomar images were photometrically calibrated with the Smith et al. (2002) Sloan r’ standard stars SA 107-351, and SA 110-232. A canonical airmass correction of 0.115 magnitudes per airmass was derived from the sky extinction at Palomar and the r’ bandpass. The error in standard star photometry was 1.7%. Altogether, our signal-to-noise ratio limit was ≈ 50, that is, the flat-field artifacts and standard star photometry limited our photometric error to no less than 2%. Our three nights of 67P images were combined in the comet’s rest frame to remove background objects, and the result is presented in Fig. 3.

3. Results

3.1. Comet Morphology

The Spitzer image clearly shows emission in both the forward and backward directions. Throughout the paper, forward refers to the direction of the comet’s projected velocity vector, and backward refers to the anti-velocity direction (see Figs. 2 and 3). In Fig. 2, it
is important to note the asymmetry in the backward direction. The bottom panel of Fig. 2 plots contours to enhance the comet morphology. The bulk of the backward emission is found to the south of the projected orbit, meanwhile the forward emission is centered on the orbit. The ephemeris of comet 67P (computed 2004 Aug 23, solution JPL K023/22) has an observation baseline of 15.96 years and the root-mean-square of the fit residuals is 0.7", or 0.3 pixels. The astrometry of the field was verified with the 2MASS point source catalog. The central point source of 67P is found within 0.4 pixels of the expected position. The alignment of the forward emission with the orbit and the asymmetry of the backward emission with respect to the orbit appear to be true, given the accuracies of the image and orbit solution.

The Palomar image is presented in Fig. 3 and compared to the projected orbit at that epoch. Here the backward emission lies to the north of the projected orbit and is visible to 10' behind the nucleus. With close inspection of the data, dust emission is evident out to 14'. The forward emission observed in the 24 \( \mu \text{m} \) image does not appear to be present in the 0.6 \( \mu \text{m} \) image, at least at this epoch and sensitivity limit. We identify the natures of the forward and backward emissions through comparisons to models of dust comae in §4.5.

### 3.2. Comet Nucleus and Dust Production

The central point source in the 24 \( \mu \text{m} \) image has a full-width at half maximum (FWHM) of 6.5" and a surrounding diffraction ring, similar to point sources in the surrounding field. At the observed distance of \( \Delta = 4.1 \) AU, the point source width is 19,000 km; such a large area may still contain flux from an unresolved coma. This dilemma is typically encountered in observations of comets at large heliocentric distances. At best we can consider the point source to be solely due to emission from the nucleus, and at worst the point source is dominated by an unresolved coma. We assume that the point source flux and the nucleus flux are equivalent but at this point we note that without more information this estimate is truly an upper-limit.

The emission from the nucleus was derived by fitting a point-spread function (PSF) to the comet’s central point source with IRAF’s DAOPHOT package. Upon initial PSF subtraction, it became apparent that the inner 10" of coma (superposed with the nucleus) could either be as faint as the forward emission, or as bright as the backward emission. The flux of the nucleus could be modified to reproduce either case, with both cases being equally viable given the signal-to-noise ratio of our image. We considered the two cases to be upper- and lower-limits to the point source flux. A color-corrected flux density of 3.1 \( \pm 0.2 \) mJy (1\( \sigma \) formal error) was obtained by matching the inner coma to the emission ahead of the nucleus, and a flux density of 2.8 \( \pm 0.2 \) mJy when the inner coma is matched to the backward emission. Together, these values suggest a flux density of 2.95 \( \pm 0.25 \) mJy. A cut across the point source before and after point source subtraction (at 2.95 mJy) is presented in Fig. 4.
The total flux density inside a 10 pixel radius aperture before point source subtraction was $17.53 \pm 0.37$ mJy.

To estimate the effective radius of the comet nucleus we use the near-Earth asteroid thermal model (NEATM) of Harris (1998) with a geometric albedo, $p_v$, of 0.04 and an IR emissivity, $\epsilon$, of 0.9. The NEATM formalism requires the IR-beaming parameter to be fit to the observed color-temperature. In the absence of any color information on the nucleus, we chose the IR-beaming parameter to be 0.756, the same value used for main-belt asteroids (Lebofsky et al. 1986) observed at phase angles less than 30° (our observation is at a phase angle of 12°).

The NEATM only applies to slowly rotating objects. Slow rotator models assume each point on the surface is in instantaneous equilibrium with insolation, i.e., the sub-solar point is the hottest point and the night side is the coldest. In contrast, a fast rotator model applies to surfaces that have no time to radiatively cool through the night side, and, therefore, is isothermal with respect to solar latitude. Following Spencer et al. (1989), we can test if the 67P nucleus may be considered a fast or slow rotator at a given heliocentric distance. The unit-less parameter $\Theta$ determines the applicability of the two models,

$$\Theta = \frac{\Gamma \sqrt{\omega}}{\epsilon \sigma T_{ss}^{3}},$$

where $\Gamma$ is the thermal inertia in MKS units (J K$^{-1}$ m$^{-2}$ s$^{-1/2}$, commonly abbreviated as MKS), $\omega$ is the angular rotation rate of the object, and $\sigma$ is the Stefan-Boltzmann constant. Slow rotators have $\Theta \ll 1$ and fast rotators have $\Theta \gg 1$. For the thermal inertia of 67P’s nucleus, we choose an upper-limit of 100 MKS, constrained by the $\Gamma$ upper-limit of the comet 9P/Tempel nucleus from Deep Impact fly-by and Spitzer Space Telescope observations (A’Hearn et al. 2005; Lisse et al. 2005). Lower values are more probable (Groussin et al. 2006), and $\Gamma \lesssim 20$ MKS has been measured for Centaurs 95P/Chiron, (8405) Asbolus, and (10199) Chariklo (Fernández et al. 2002; Groussin et al. 2004). The rotation period of the 67P nucleus is $12.3 \pm 0.27$ hr (Lamy et al. 2004) and the sub-solar temperature $T_{ss} = 204$ K, derived from our NEATM model. If the 100 MKS upper-limit to the thermal inertia of the 67P nucleus is appropriate, then we calculate a $\Theta$-value of $\lesssim 1.2$, suggesting a slow rotating nucleus, or, less probably, an intermediate case between a fast and slow rotating nucleus. The NEATM is a valid model for the 67P nucleus at 4.5 AU.

We derive an effective radius of $1.87 \pm 0.08$ km for the nucleus. The error at the 3$\sigma$ level ($\pm 0.24$ km) encompasses the full 3$\sigma$ range of point source fluxes, 2.2–3.7 mJy, estimated from the two PSF fits above. Our derived effective radius is in agreement with the radius $1.98 \pm 0.02$ km calculated from Hubble Space Telescope observations (Lamy et al. 2006; see also Lamy et al. 2007), also using a geometric albedo of 0.04, although the infrared derived radius is not as sensitive to the chosen albedo as is the optically derived radius. Considering the agreement between effective radii, there likely is little or no unresolved coma in our flux estimate for the nucleus. We can combine the optical and infrared results to derive
the comet’s true geometric albedo and find a value of 0.035 ± 0.005. The calculation of
the albedo assumes the cross-section of the nucleus at the epoch of the Hubble and Spitzer
observations are equivalent. This is not necessarily the case. Indeed, the axial ratio of the
nucleus derived from the Hubble light curve is ≥ 1.55, i.e., the effective cross-sectional area
varies by at least a factor of 1.55 over one 12 hr period, depending on the orientation of the
spheroid. Since the relative phase of the Spitzer observation is unknown (1.87 km could be
a light-curve maximum, minimum, or anything in-between), the solutions to the geometric
albedo range from 0.015 to 0.078, wholly encompassing the known comet nucleus albedo
range of 0.02–0.06 (Lamy et al. 2004). With some confidence we can state that the albedo
of 67P is not radically different from typical comet surfaces.

In the Palomar image, the coma has a radially averaged FWHM of 11′′ (28,000 km) and
is asymmetric with respect to the orbit, with more emission found to the southwest. If the
coma is in a “steady state” then we can estimate the product \( A(\theta) f \rho \). The product \( A(\theta) f \rho \)
is commonly used as a proxy for dust production (A’Hearn et al. 1995), where \( A(\theta) \) is the
dust albedo as a function of \( \theta \), the scattering angle, \( f \) is the filling factor of the dust grains
in the aperture, and \( \rho \) is the radius of the field-of-view (A’Hearn et al. 1984). A steady-
state coma arises from a spherically symmetric, homogeneous outflow of dust, resulting in
an observed coma flux that varies linearly with aperture radius. As a consequence, the
steady-state coma’s \( A(\theta) f \rho \) is independent of radius (A’Hearn et al. 1984). The asymmetry
in the coma morphology of 67P prevents us from assuming a steady state coma (here, the
integrated aperture profile varies as \( \rho^{1.4} \) instead of \( \rho^{1.0} \)), but in order to compare our data
to other investigations we continue with an estimate of \( A(\theta) f \rho \). We derive values of \( A(\theta) f \rho \)
that range from 10.17 ± 0.2 to 25.8 ± 0.4 cm for apertures of radius 3400–68000 km.

Comet 67P’s \( A(\theta) f \rho \) values at 3.23 AU are approximately a factor of 3–5 lower than
extrapolation from the observations of A’Hearn et al. (1995) using the averaged power-law,
\( A(\theta) f \rho = 323 r_h^{-1.34} \) (cm), but the values agree given the error in the slope (±0.81). Kidger
(2003) derives \( A(\theta) f \rho = 1530 r_h^{-5.8} \) (cm), which extrapolates to 2–3 cm at \( r_h = 3.2 \) AU. Our
\( A(\theta) f \rho \) value is approximately 7 times larger. The Kidger (2003) investigation is a collection
of 625 standardized amateur astronomer CCD observations from perihelion to 2.8 AU
post-perihelion (whereas A’Hearn et al. measured 13 observations from perihelion to 1.9 AU
post-perihelion). The visual light curve\(^1\) varies as \( r_h^{-4} \), therefore, the steeper slope (-5.8)
likely indicates the overall dust production trend. Schleicher (2006) measured \( A(\theta) f \rho \) and
the gas production of comet 67P and found the gaseous species (such as OH, a proxy for
water production) follow steep profiles (\( r_h^{-4} \) to \( r_h^{-6} \)) and \( A(\theta) f \rho \) to vary as \( \sim r_h^{-1} \). If \( A(\theta) f \rho \)
truly is the dust production, then the shallow profile implies that as the comet recedes from
the Sun, the volatile gases become increasingly efficient at ejecting dust. A more probable
scenario, as Schleicher (2006) points out, is that slow moving, medium-sized (10–100 \( \mu m \))

\(^1\)Available at S. Yoshida’s Comet Catalog: http://www.aerith.net/comet/catalog/0067P/2002.html
particles are lingering near the nucleus, causing the shallow slope in the post-perihelion $A(\theta)f\rho$ dependence on $r_h$ (the comet is not as well studied at pre-perihelion epochs). The factor of 7 discrepancy between the LFC derived $A(\theta)f\rho$ value at 3.23 AU and the Kidger (2003) extrapolated value could be consistent with a lingering population of medium-sized dust grains. Alternatively, a power-law description of the dust production is likely a simplification. At 3.23 AU post-perihelion, water sublimation continues to decrease, and other ices, such as CO and CO$_2$ become increasingly important as drivers of dust production (Meech and Svoren 2004) and a power-law does not account for discrete, yet prolific, dust production by jet activity related to seasonal temperature changes on the surface and sub-surface. We adopt $r_h^{-5.8}$ as an approximation to the dust production trend for the purposes of dynamical simulations of the coma and trail (§4.1). The dynamical simulations automatically take into account large, slow moving grains by treating the dynamics of dust as a function of grain size.

### 3.3. Surface Brightness Profiles and Albedo

To compare the Palomar and Spitzer data, we binned each image with rectangular apertures (0.6 $\mu$m: 22.5" $\times$ 7.5", 24 $\mu$m: 21" $\times$ 7.4"), where the long dimension is placed parallel to the orbit. Figure 3 presents the profiles, de-projected according to the angle listed in Table 1. The profiles can be approximated by power-laws and the best fits to the profiles, in terms of surface brightness ($S_\nu$) and optical depth ($\tau$), are presented in Table 2. The 0.6 $\mu$m $\tau$ was calculated using the solar spectral energy distribution from Neckel and Labs (1984) and the 24 $\mu$m $\tau$ was calculated using the blackbody temperature at a heliocentric distance of 4.47 AU. The ratio $\tau_{0.6}$ to $\tau_{24}$, the albedo of the grains, ranges from 0.05 to 0.10 at 2$\times$10$^6$ to 0.5$\times$10$^6$ km from the nucleus. The 24 $\mu$m profile is shallower than the 0.6 $\mu$m profile by a factor of $d^{0.5}$, where $d$ is the distance from the nucleus. The difference suggests that the images are sampling two disparate grain populations (either physically or dynamically different) and that a direct photometric comparison (e.g., the albedo calculation) is not appropriate.

Figure 6 is a plot of cuts from the point source subtracted 24 $\mu$m image. Each cut is perpendicular to 67P’s projected orbit. The emission has an approximate width of 60,000 km ahead of the nucleus and 60,000–120,000 km behind the nucleus. As discussed in §4.5, the peak of the backward emission is not aligned with the orbit.
4. Discussion

4.1. Dynamical Model

Comet dust is ejected from the nucleus by surface and sub-surface volatile sublimation. Once a dust grain decouples from the outward gas flow in the near-nucleus environment, the principal forces remaining are solar gravitational and solar radiation forces. Since both forces are proportional to \( r^{-2} \) and the force of solar radiation \(( F_{\text{rad}})\) opposes the force of gravity \(( F_g)\), the net effect may be considered a reduced solar gravitational force. This effect is commonly parameterized by \( \beta \), the ratio of the radiation force \(( F_{\text{rad}})\) to the gravitational force \(( F_g)\),

\[
F_{\text{net}} = F_{\text{rad}} + F_g = (1 - \beta) F_g,
\]

where \( \beta \) reduces to

\[
\beta = \frac{0.57 Q_{pr}}{\alpha \rho}.
\]

and \( Q_{pr} \) is the efficiency of radiation pressure on the grain, \( \alpha \) is the radius of the grain in units of \( \mu m \), and \( \rho \) is the grain density in g cm\(^{-3} \) (Burns et al. 1979). The \( \beta \) parameterization is used throughout this paper. To approximate the more rigorous treatment to grain structure in thermal emission and light scattering models of comet dust, the dynamic model uses a low dust grain density equal to 1 g cm\(^{-3} \) for materials with bulk densities ranging 2–3 g cm\(^{-3} \) (cf., Lisse et al. 1998; Harker et al. 2002; Kimura et al. 2006). The model also assumes \( Q_{pr} = 1 \). This value is appropriate for large, isotropic scatterers with \( Q_{abs} \approx 1 \) (Burns et al. 1979), i.e., the modeled grains are large with respect to the absorbed light (here, the solar spectrum). To remain within the large particle limit, our simulations only choose particles with \( \alpha \gtrsim 0.5 \mu m \).

Comet grain densities lower than our chosen value of 1 g cm\(^{-3} \) have been deduced by other investigations. For example:

1. Fulle et al. (2000) use in situ observations and dynamic models to constrain comet 1P/Halley’s dust grains to densities ranging from 0.05–0.5 g cm\(^{-3} \), with 0.1 g cm\(^{-3} \) being the favored solution.

2. Lasue and Levasseur-Regourd (2006) model the dust of comet C/1995 O1 (Hale-Bopp) using aggregates and compact spheroidal grains \( (\alpha \leq 20 \mu m) \) and a power-law size distribution slope of -3. The model produces good agreement with optical dust polarization data. Lasue and Levasseur-Regourd and other investigators using light scattering and thermal emission models often describe the porosity of grain aggregates with the fractal dimension of the grain. The density of a grain aggregate of homogeneous composition with fractal dimension \( D \) is described by

\[
\rho(a) = \rho_0 \left( \frac{a}{a_0} \right)^{D-3},
\]

(4)
where $\rho_0$ is the bulk density of grain material, and $a_0$ is the minimum particle size (typically $a_0 \lesssim 0.1 \mu\text{m}$). Lasue and Levasseur-Regourd (2006) found that the scattering properties of their grain aggregates were not significantly affected by aggregates with values of $D$ ranging from 1.5 to 2.9 [for $\rho_0 = 2.5$ g cm$^{-3}$: $\rho(1 \mu\text{m}) \approx 0.08 - 2$ g cm$^{-3}$, $\rho(10 \mu\text{m}) \approx 0.003 - 2$ g cm$^{-3}$].

3. Kolokolova et al. (2007) also find the scattering properties of compact and fluffy grains to be similar, yet the absorption cross sections to be significantly different. They suggest that comets with low semi-major axes have dust comae that are comprised of more compact grains than comets with large semi-major axes. Grain compactness may be independently revealed by the strength of the 10 $\mu$m silicate emission feature. Orbit integrations by K. Kinoshita show the semi-major axis of 67P has ranged from 3.5–4.4 AU in the past 100 yr, and low-resolution spectrophotometry of the coma of 67P by Hanner et al. (1985) reveal no indication of a silicate feature at 10 $\mu$m. Together, these facts indicate comet 67P ejects compact, rather than fluffy, grains. Kolokolova et al. (2007) list the vacuum fraction of compact grains to be $\approx 0.85$ for equivalent volume radii ranging from 0.3–100 $\mu$m.

4. The *Stardust* spacecraft returned more than 10,000 dust particles in the 1 to 300 $\mu$m size range collected from comet 81P/Wild (Brownlee et al. 2006). The spacecraft collected dust grains in a porous silica glass ($\rho \leq 0.05$ g cm$^{-3}$) at a relative speed of 6.1 km s$^{-1}$. This collection method caused many grains to fragment, yet some information on their structure is still retained. The collected grains range in densities from $\approx 3$ g cm$^{-3}$ to as low as 0.3 g cm$^{-3}$ (Hörz et al. 2006).

Equation 3 is valid for spherical grains, but greatly under-dense grain aggregates, such as those discussed above, should not be expected to scatter light in a manner equivalent to spheres. Levasseur-Regourd et al. (2007) computed $\beta$-values of fluffy aggregates using a combination of Maxwell-Garnet effective medium theory and Mie theory (for $2\pi a/\lambda \leq 100$) and geometric optics (for $2\pi a/\lambda > 100$). The authors found that the $\beta$-values of large aggregates ($a \gtrsim 1$ mm) are larger than the $\beta$-value of equivalent volume spheres. The grain composition plays an important role for $a \lesssim 1$ mm: for silicate aggregates $\beta$ is less than or equal to the $\beta$ of equivalent volume spheres; for amorphous carbon aggregates $\beta$ is greater than or equal to the $\beta$ of equivalent volume spheres. Both compositions have $\beta$-values within an order of magnitude of their equivalent spheres. *In situ* evidence from comets 1P/Halley and 81P/Wild suggest comet grains can be heterogeneous in composition (Fomenkova et al. 1992; Brownlee et al. 2006; Hörz et al. 2006; Keller et al. 2006). Heterogeneous grain models by (Kimura et al. 2006) qualitatively reproduce observed light scattering properties of dust.

[http://www9.ocn.ne.jp/~comet/]{http://www9.ocn.ne.jp/~comet/}
Further work incorporating heterogeneous compositions into models of light scattering by trail grains (both aggregate and spheroidal) is needed.

In addition to the differences in $\beta$-values, aggregates should be ejected from the nucleus at speeds different from equivalent spheres due to dissimilar grain surface areas per mass. Altogether, incorporating a mixture of aggregates and compact grains into a dynamical model will imbue a range of sizes and velocities on a set of grains with a given $\beta$-value. Observational data that could reveal the structure and composition of trail grains is limited. We must necessarily take caution when transforming $\beta$-values to grain radii and grain masses, but it appears that order of magnitude estimates are possible.

Equation 2 describes the net force acting on a dust particle orbiting the Sun, although the Sun is not the dynamical center of the solar system. To appropriately treat a dust particle in our solar system, our dynamical model also includes the gravitational accelerations of the planets and, for completeness, the Poynting-Robertson effect. We use JPL’s planetary ephemeris DE-405 \cite{Standish1998} to determine the positions of the planets, and the HORIZONS ephemeris generator \cite{Giorgini1996} for the comet positions and velocities. HORIZONS ephemerides account for perturbations by the planets and for non-gravitational accelerations due to comet outgassing. The net force on each particle is integrated from ejection to the time of observation using the RADAU-15 integrator of Everhart \cite{Everhart1985}, which is accurate to a 15th-order series expansion of the acceleration as a function of time. The final particle positions are projected onto the sky for an arbitrary observer (e.g., Earth or Spitzer).

To test the accuracy of the program, we integrated $\beta = 0$ particles released from a comet with a highly eccentric orbit, 28P/Neujmin ($e = 0.78$, $q = 6.91$ AU), and one with a near circular orbit, 29P/Schwassmann-Wachmann ($e = 0.044$, $q = 5.99$ AU). A $\beta = 0$ particle is the large particle limit ($F_{rad} \ll F_g$) and represents the nucleus of a comet. The JPL orbit solutions for comets Neujmin and 29P/Schwassmann-Wachmann do not include non-gravitational accelerations, therefore, the positions of $\beta = 0$ particles released with $v_{ej} = 0$ should coincide with the ephemeris positions of the nuclei. In 0–20 year integrations the final positions of $\beta = 0$ particles typically agree within 30–150 km, but increase to $\approx 2000$ km after two perihelion passages for comet Neujmin. The accuracy of the program is sufficient for the following simulations ($2000$–$3000$ km corresponds to $\approx 1''$ in the Spitzer image).

\section{4.2. Model Images}

We employ our dynamical model and a Monte Carlo technique to create simulated images of comets. Our simulations consist of 500,000 test dust particles ejected from comet 67P. The dust particles are ejected from the sunward hemisphere of the comet. The dynamical
The model’s ejection velocity is
\[ v_{ej} = C v_0 \sqrt{\beta / r_h}, \quad (5) \]
where \( v_0 \) and \( v_{ej} \) are in units of km s\(^{-1}\), \( r_h \) is in units of AU, and \( C \) is an optional scaling factor dependent on insolation. The \( \sqrt{\beta / r_h} \) parameter has been successfully used in other comet models \cite{Lisse1998, Reach2000, Ishiguro2007} and represents varying insolation with \( r_h \) and the changing effect of gas drag with \( \beta \). \cite{Lisse1998} used a variety of other velocity models and found Eq. 5 to best reproduce the COBE observations of comet comae.

The Monte Carlo model picks particles from a uniform distribution in time and a logarithmic distribution in \( \beta \) \( (dn/d \log \beta \propto 1) \). The distributions assure we have useful statistics for all particle sizes and ages. For example, if we instead chose a very steep particle size distribution (PSD) of \( a^{-3} \) \( (dn/d \beta = \beta) \) where \( a \) ranges from 1–10\(^4\) \( \mu m \), the probability of picking a particle with size \( > 10^3 \mu m \) is roughly \( 1 \times 10^{-6} \). The simulated image from a \( 10^6 \) particle simulation would include only a few \( > 10^3 \mu m \) sized particles. The absence of large particles might lead the modeler to conclude that they do not contribute to the thermal emission from the coma. Particles of size \( 10^3 \mu m \) have a larger surface area than particles of size 1 \( \mu m \); at the same temperature they emit \( \sim 10^6 \) times more energy in the thermal infrared. In addition, dynamical effects quickly disperse small particles from the vicinity of the nucleus as the larger particles accumulate. A simulation that does not carefully pick particle sizes may misrepresent the relative contributions of large and small particles.

We also simulate comet dust ejection as constant with heliocentric distance. Similar to the PSD of the simulation, this choice ensures that low levels of activity are appropriately treated. Our chosen age distribution (uniform) and PSD \( (dn/d \log \beta \propto 1) \) are transformed into more appropriate distributions when we generate simulated images. The synthetic imager weights each particle so that the simulated image is representative of a realistic dust production and PSD (as detailed below).

Simulated observations are necessary to compare the model to the 67P observations in order to determine if the chosen parameters \([v_{ej}, \text{dust production } (Q_d), \text{grain parameters}]\) describe the images. After the simulation is complete, the final particle positions are projected onto the sky and observed by an imaginary detector, i.e., the total emission along a line of sight is recorded into an array of pixels. The simulated image may then be treated and processed as any other observation, e.g., it may be Gaussian smoothed or unsharp masked.

The projection of the simulation onto the sky gives us the number of particles in a pixel, \( n_g ds \), where \( n_g \) is the density of grains and \( ds \) is distance along the line of sight. The thermal emission from a collection of particles of uniform temperature, \( T \), and size, \( a \), is given by
\[
I_\lambda = \int_0^\infty \pi a^2 Q_{em}(\lambda, a) \ B_\lambda(T) \ n_g \ ds, \quad (6)
\]
where \( B_\lambda(T) \) is the Planck function. The emission coefficient, \( Q_{em} \), is roughly \( 2\pi a/\lambda \) for \( a \lesssim 10^3 \mu m \).
\(\lambda/2\pi\), and of order unity for \(a \gtrsim \lambda/2\pi\). The dependence of \(Q_{em}\) on mineralogy and structure is beyond the scope of this treatment. Combining all constant factors and transforming our integral into a summation, we now have

\[
I_\lambda \propto \sum_{i=1}^{N} a_i^2 \begin{cases} 
2\pi a_i/\lambda & \text{for } a_i \lesssim \lambda/2\pi \\
1 & \text{for } a_i \gtrsim \lambda/2\pi,
\end{cases}
\]

(7)

where \(N\) is the number of particles along the line of sight.

Real comets do not eject particles with \(dn/d\log \beta \propto 1\) or \(dn/dt \propto 1\). We remove the \(dn/d\log \beta\) bias and weight each particle by the overall dust production trend and an ejected PSD. The dust production will commonly be a power-law of the form, \(Q_d \propto r_h^{-k}\) (e.g., A'Hearn et al. [1995]), where \(r_h\) is the heliocentric distance at particle release and \(k\) is the logarithmic slope of the heliocentric dust production (nominally, -4). For now, we leave the PSD as an arbitrary function, \(n(\beta)|_{PSD}\). Each test particle, \(i\), now represents a collection of particles, \(n_i\):

\[
n_i \propto n(\beta_i)|_{PSD} = \frac{\int \frac{dn}{d\beta} d\beta}{\int \frac{dn}{d\beta} d\beta}|_{PSD,i} \approx \frac{\int \frac{dn}{d\beta} d\beta}{\int \frac{dn}{d\beta} d\beta}|_{sim,i} = \beta_i \frac{dn}{d\beta}|_{PSD,i},
\]

(8)

where \(n(\beta)|_{sim}\) is the PSD of the simulation (here, \(dn/d\log \beta\)). Combining Eq. 7 and 8 yields the intensity of thermal emission falling onto a pixel,

\[
I_\lambda \sim \sum_{i=1}^{N} n_i Q_{d,i} Q_{em,i}(\lambda, a_i) A_i \approx \sum_{i=1}^{N} r_{h,i}^{-k} \beta_i \frac{dn}{d\beta}|_{PSD,i} \begin{cases} 
2\pi/(\beta_i \lambda) & \text{for } a_i \lesssim \lambda/2\pi \\
1 & \text{for } a_i \gtrsim \lambda/2\pi.
\end{cases}
\]

(9)

In §4.4 we consider various PSDs for the comet. At present, we apply an interstellar medium PSD, \(dn/da \sim a^{-3.5}\) (Mathis et al. [1977]), and use \(\rho = 1\) g cm\(^{-3}\) to transform between \(a\) and \(\beta\).

4.3. Ejected Dust Velocity

The forward emission along the trail of 67P can be explained by one of two possibilities. The emission consists of: 1) very old trail particles that will soon be lapped by the nucleus, or 2) grains ejected at some appreciable velocity from the nucleus that fall ahead of the comet. \textit{IRAS} observations of 67P show a forward trail extending \(0.42 \times 10^6\) km (Sykes and Walker [1992]) and \textit{Spitzer} (Fig. 5) shows forward emission \(1.2 \times 10^6\) km in length. If very old trail particles fill the entire orbit and are being lapped by the comet nucleus, then a
longer extension, continuing around the orbit, should have been observed by both IRAS and Spitzer. Moreover, filling an entire cometary orbit with trail particles could take hundreds of years (Reach et al. 2000). Over this time, the planets will have many opportunities to separate the comet nucleus and trail particles through minor and major gravitational perturbations. The separation of trail and nucleus has been observed through meteoroid stream studies of comet 8P/Tuttle and 55P/Tempel-Tuttle (Jenniskens et al. 2002; Jenniskens and Betlem 2000) and modeled in a study of 67P’s meteoroid stream (Vaubaillon et al. 2004). We also note that comet 67P’s last encounter with Jupiter occurred in 1959 (at an encounter distance of 0.05 AU). We conclude that it is highly unlikely that very old trail particles are being lapped by the nucleus.

To better understand the effect of ejection velocity on ejected dust grains, we use our dynamical model to simulate observations of comet 67P at the same observation time, viewing geometry, and wavelength as our 24 $\mu$m image. Particle ages range from 0–4000 days and the $\beta$ parameters range from $10^{-5}$–$10^{-1}$ ($a \approx 6$ to $6 \times 10^4 \rho^{-1} \mu m$). A maximum age of 4000 days corresponds to 1.7 orbital periods (March 1993, $r_h = 5.65$ pre-perihelion). Including the previous orbit allows us to place limits on trail ejection velocity and dust production, if we consider that one orbital period is the minimum age of a particle to be considered a trail particle. We test three approaches to represent the ejection velocity ($v_{ej}$) and dust production ($Q_d$) from the surface of the nucleus (via parameter $C$ in Eq. 5): 1) $Q_d$ and $v_{ej}$ are uniform across the sunward hemisphere, 2) $Q_d$ and $v_{ej}$ are proportional to insolation, $\cos z_{\odot}$, where $z_{\odot}$ is the Sun-zenith angle, and 3) $Q_d$ and $v_{ej}$ are proportional to the surface temperature of a slowly rotating nucleus, $\cos^{1/4} z_{\odot}$. An example of each approach is presented in Fig. 7 for $v_0 = 0.5$ km s$^{-1}$ (Eq. 5) and $dn/da \sim a^{-3.5}$.

The uniform model (method 1) produces an abundance of dust with an ejection velocity perpendicular to the orbital plane and causes the observed dust morphology to be dispersed perpendicular to the projected orbit. A lower $v_0$ can be used to suppress this effect, but lower velocities do not eject dust in the forward direction to the extent observed by Spitzer in 4000 day simulations (Fig. 2). The introduction of a cosine term into $Q_d$ and $v_{ej}$ (methods 2 and 3) reduces the extent of the dust emission in the perpendicular direction, by 1) reducing $Q_d(z_{\odot} = 90^\circ)$ to zero, and 2) reducing $v_{ej}(z_{\odot} \gtrsim 30^\circ)$ to lower velocities. Both ($Q_d, v_{ej} \propto \cos z_{\odot}$ and $\propto \cos^{1/4} z_{\odot}$) exhibit a smaller coma width in Fig. 7 and are preferred over the wide comae produced in the uniform production approach. The $\cos z_{\odot}$ and $\cos^{1/4} z_{\odot}$ approaches appear equally viable, but for simplicity we elect to adopt $\cos z_{\odot}$ ($Q_d$ and $v_{ej}$ proportional to insolation) for the duration of the analysis.

We calculated our $C = \cos z_{\odot}$ model with a range of ejection velocities, $v_0 = 0.1, 0.2, 0.3, 0.5, 1.0, \text{ and } 1.5$ km s$^{-1}$ (Fig. 8). Varying $v_0$ affects the extent and profile of the forward emission and the width and intensity of the backward emission. The 0.5 km s$^{-1}$ model best matches the 24 $\mu$m forward emission, backward emission, and the small inner-coma, although the inner-coma is not exactly reproduced. The lowest ejection velocity did not
produce the forward emission in 4000 days and larger velocities created broad coma and backward emission.

4.4. The Particle Size Distribution

We simulated images for a variety of power-law PSDs (Fig. 9) to examine the effect of the comet’s ejected PSD on the dust morphology. A single power-law may not represent the comet’s ejected PSD, but it suffices as a first approximation. We chose the PSD to be $dn/da \propto a^k$, where $k = -5.0$ to $-0.5$ in steps of 0.5 ($dn/d\beta \sim \beta^{-(k+2)}$). Note that the chosen PSDs represent the ejected dust and not the observed dust. The observed PSD is a result of the dynamical separation of dust after ejection, i.e., the observed PSD has an enhanced large particle portion as small particles are quickly removed from the coma and large particles accumulate over time. The ejected PSD that best matches the observed 24 \( \mu \)m image (Fig. 2) is $dn/da \sim a^{-3.5}$. The $a^{-3.5}$ model reproduces the observed: 1) forward emission, 2) backward emission, which increases in width with distance behind the nucleus, and 3) approximately flat perpendicular surface brightness profile at $\approx 500''$ from the nucleus. Fulle et al. (2004) found a time-dependent power-law index best-fit the 67P photometry using the inverse tail approach (Fulle 1989), but their derived time-average of $k = -3.4$ is very close to our derived $k \approx -3.5$. Other comets have $k = -3.0$ to $-4.1$ as determined with the inverse tail approach (Fulle 2004). A summary of our best model’s parameters is presented in Table 3.

We also simulated the coma of 67P at the epoch of our Palomar observation. Figure 10 presents the simulation with the same viewing geometry as the 0.6 \( \mu \)m image (Fig. 3). The model parameters were the same as the best 24 \( \mu \)m simulation (Table 3), but the image is simulated at a wavelength of 0.6 \( \mu \)m, instead of 24 \( \mu \)m (since we are assuming isothermal grains and limit $a > 0.5 \mu$m, Eq. 7 also serves as a rough approximation for scattered light). The resulting simulation shows a coma, and two thin dust structures: one structure is located along the comet’s projected orbit, and the other is located to the north of the projected orbit. The 0.6 \( \mu \)m image does not does not show the emission along the projected orbit, but does exhibit the thin line of emission to the north. The emission along the projected orbit is comprised of particles with a lower $\beta$-value than the thin line of emission just to the north of the orbit. Slightly decreasing the PSD slope from $k = -3.5$ could make the lower $\beta$ structure undetectable in the 0.6 \( \mu \)m images. Alternatively, the PSD could be better described by a multi-component power-law, such as those measured in situ at comets 1P/Halley and 81P/Wild (McDonnell et al. 1987; Green et al. 2004). Modifying the PSD would have important effects on the morphology at the 24 \( \mu \)m image epoch, but varying the dust production or ejection velocities may recover the simulated emission. In a third option, we could simply vary the dust production at the epoch when the northern dust feature is ejected. As is, the parameters of Table 3 adequately represents both the 0.6 and 24 \( \mu \)m images to within their quality.
4.5. The Nature of the Simulated and Observed Emissions

We compared the photometry profiles derived from the 24 $\mu$m image to profiles derived from the best simulated 24 $\mu$m image (Fig. 11) and found that the 24 $\mu$m profile parameters listed in Table 2 approximate the simulated image profile. This gives confidence in the simulation and that one may draw qualitative conclusions on the nature of the observed emission.

[Fulle et al. (2004)] identified comet 67P to have a persistent neck-line tail structure beginning $\approx 60$ days after the August 2002 perihelion passage. The neck-line structure is a thin enhancement of the projected dust surface density in the tail created when dust ejected perpendicular to the plane of the orbit crosses the plane again at the node 180° away (i.e., a true anomaly, $f$, difference of 180°) from its point of emission. The enhancement can only be detected when the observer is located fairly close to the orbital plane of the comet. Comet 67P’s orbit inclination is 7°, which is very favorable for neck-line observations. The age of dust ejected at $\Delta f = 180°$ from the Spitzer observation (neck-line dust) is 590 days. This age corresponds to dust ejected 36 days before the August 2003 perihelion, during significant coma activity ($A(\theta)f\rho \approx 1000$ cm). We decomposed our best 24 $\mu$m simulation into three age bins (Fig. 12): 1) dust ejected before the May 2000 aphelion, 2) dust ejected at 16–56 days before the August 2003 perihelion, and 3) the remaining dust. Bin 1 corresponds to trail particles, is centered on 67P’s projected orbit, has a mean $\beta$-value $\beta = 1.03 \times 10^{-4}$ and a mean radius $\bar{a} = 8470$ $\mu$m. Bin 2 corresponds to the neck-line tail structure located to the south of the projected orbit and has similar sized particles as the trail: $\bar{a} = 1.03 \times 10^{-4}$, $\bar{a} = 7790$ $\mu$m. A comparison of Figs. 2, 6, and 12 reveals that the forward emission in the Spitzer/MIPS image is the dust trail, and the backward emission has contributions from both the dust trail and neck-line. We also examined the 0.6 $\mu$m image and simulation (Fig. 10) and identify the thin line of emission to the north of the projected orbit as a neck-line. The LFC image was not sensitive enough to detect the dust trail.

4.6. Rosetta’s Dust Impact Hazard

During encounters with comets, spacecraft are vulnerable to dust impacts. The Rosetta spacecraft is designed to follow and approach comet 67P and subsequently orbit the comet nucleus at distances of 5 to 25 nucleus radii. Orbit insertion missions have a lower impact hazard than typical flyby missions due to the lower encounter velocities (m s$^{-1}$ versus km s$^{-1}$). The largest particles ($a > 10^3$ $\mu$m) pose the greatest threat to spacecraft health, but typical comet PSDs suggest these particles are fewest in number. To predict the large particle impact hazard to Rosetta, we estimate the surface brightness of 67P’s dust trail near the comet nucleus and then calculate a trail grain density. The 24 $\mu$m image at the nucleus has a surface brightness of 0.61 ± 0.10 MJy sr$^{-1}$ (Fig. 4). Rosetta will encounter 67P while
the comet is approaching the Sun at \( r_h = 4 - 5 \) AU. At orbit insertion, the nucleus will be surrounded by persistent trail dust, but, since little or no dust production is expected near aphelion, the transient neck-line and coma dust will have dissipated. According to our best model, the trail comprises 12\% of the total dust emission near the nucleus, or \( 0.07 \pm 0.01 \) MJy sr\(^{-1} \) in the 24 \( \mu \)m image. The error quoted for the trail component arises from the formal measurement uncertainty of the dust surface brightness. The error due to model uncertainties is difficult to estimate. We find a comparable surface brightness in the forward trail (\( \approx 0.1 \) MJy sr\(^{-1} \)), which suggests that we have the correct order of magnitude. A trail surface brightness \( \approx 0.1 \) MJy sr\(^{-1} \) serves as a useful estimate near the nucleus. This value corresponds to a grain number density of \( \approx 10^{-11} \) m\(^{-3} \). We have assumed the trail consists entirely of 1 mm sized grains, the dust temperature is 300\( \sqrt{r_h} \) K, derived from IRAS color-temperatures of comet dust trails (Sykes and Walker 1992), and the near-nucleus volume is 22,000 \times 22,000 \times 60,000 km. The volume corresponds to the spatial resolution of the MIPS instrument and the trail width measured in \( \S 3.3 \). Using a spacecraft cross-section of 4 m\(^2 \) (European Space Agency 2007) and a path length of half the trail width (30,000 km), we calculate that Rosetta has a \( \approx 0.1\% \) chance of encountering a 1 mm sized trail particle during orbit insertion. The low probability is expected. During comet flyby missions, spacecraft typically encounter a few \( 0.1 - 1 \) mg (\( a \approx 500 \) \( \mu \)m) dust grains (Green et al. 2004; McDonnell et al. 1987, 1993), but these encounters occur during vigorous coma activity, which enhances the probability of large particle impacts.

5. Conclusions

Comet 67P/Churyumov-Gerasimenko’s dust trail was detected in Spitzer/MIPS images when the comet was at 4.5 AU post-perihelion. By comparison of a 24 \( \mu \)m image to dynamic models, we estimate that the trail particles are large (\( \gtrsim 100 \) \( \mu \)m) and old (at least 1 orbit or 6.6 years). They are ejected at relative velocities of \( \approx 0.5\sqrt{\beta/r_h \cos z_0} \) km s\(^{-1} \), or of order 1 m s\(^{-1} \) at perihelion, although we note that the ejection velocity may be lower, if older, and slower, particles are included in the dust trail. The simulations show two distinct features. One feature is centered on the projected orbit of the comet and extends in the forward and trailing directions. Given the low average \( \beta \) (10\(^{-4} \)) and large age (up to the limits of the simulation) we identify the feature to be the comet’s dust trail. The other feature is located at a few degrees south of the trail in position angle (at the Spitzer epoch/viewing geometry) and extends behind the comet. This feature is the “neck-line” structure and is also comprised of low \( \beta \) (10\(^{-4} \)) grains, but the orientation and age (590 days at the Spitzer epoch) preclude it from being identified as a dust trail. The morphology of the Spitzer (24 \( \mu \)m) and Palomar (0.6 \( \mu \)m) images agree with our dynamical model. In particular, the forward trail is observed in the 24 \( \mu \)m image, and the neck-line is observed in both images. The dust trail is found behind the comet, but is overwhelmed by emission from the neck-line dust. The dust trail is below the detection limit of our optical image.
Comet dust particle size distributions favor small particles \((a \lesssim 10 \, \mu m)\) by number, although larger particles may still dominate the ejected dust mass. Consequently, small particles are more readily detected in optical images and typical 10 \, \mu m spectra of comets. Observations of large particles, dynamically separated from comet comae and tails, allow for a detailed study of large dust grains ejected from comet nuclei. In the study of comet 67P’s dust trail, we find that the ejected dust grain size distribution is approximately a power-law (slope \(-3.5\)) for particle sizes from 1 to 10 \, \mu m, or more. Thermal infrared spectra \cite{Harker2005, Lisse2006} and dust collectors on-board comet flyby spacecraft \cite{McDonnell1987, Green2004} also measure grain size distributions with power-law slopes in the \(-3\) to \(-4\) range, with some variation between models and particle size bins. Such power-law slopes have important implications on the total mass ejected from comet 67P. With our PSD derived for 67P, the mass of particles studied by thermal models of mid-IR spectra \((a = 0.1 \text{ to } \approx 20 \, \mu m)\) comprise approximately 10\% of the total ejected dust, when particles up to 10\(^3\) \, \mu m are considered. Using our dynamical model, we estimate the surface brightness of the dust trail near the nucleus and find \textit{Rosetta}’s probability of impacting a dust trail grain to be \(\sim 10^{-3}\), assuming the grains are all \(10^3 \, \mu m\) in radius. The low probability of impact coupled with the low relative velocities required for orbit insertion suggests that 67P’s dust trail poses a minor threat to the \textit{Rosetta} spacecraft.

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Table 1. Comet 67P/Churyumov-Gerasimenko trail observation details.

| Observatory | Date / Time (UT) | \( T - T_p^a \) (days) | \( r_h \) (AU) | \( \Delta^b \) (AU) | Phase Angle (degrees) | Projection Angle (degrees) |
|-------------|------------------|------------------------|----------------|---------------------|----------------------|--------------------------|
| IRAS        | 1983 May 05 13:00| 174.4                  | 2.28           | 2.09                | 26                   | 8                        |
| Palomar     | 2003 Jun 26 04:36\(^d\) | 312.0 | 3.23 | 3.35 | 18 | 20 |
| Spitzer     | 2004 Feb 23 03:44 | 553.9 | 4.47 | 4.06 | 12 | 48 |

\(^a\) Time since the closest perihelion.

\(^b\) Observer-comet distance.

\(^c\) Angle between the comet’s heliocentric velocity vector and the image plane.

\(^d\) Average of three observations: June 25.1840, 26.2049, 27.1861.

Table 2. Best-fit, de-projected dust profiles of the comet 67P/Churyumov-Gerasimenko Spitzer/MIPS observation (Fig. 5).\(^a\)

| Emission       | Slope, \( k \) | Scale, \( S_\nu \) (MJy sr\(^-1\)) | Scale, \( \tau \) | \( \chi^2_\nu \) |
|----------------|---------------|------------------------------------|-----------------|-------------|
| 0.6 \( \mu \)m backward | -1.03 ± 0.02  | 2200 ± 400                         | 130 ± 20        | 4.6         |
| 24 \( \mu \)m backward    | -0.50 ± 0.05  | 350 ± 20                           | 1.23 ± 0.08     | 20.2        |
| 24 \( \mu \)m forward     | -0.85 ± 0.04  | 7000 ± 3400                        | 25 ± 12         | 0.7         |

\(^a\) Profile = \( C d^k \), where \( d \) is in units of km, and \( C \) is the scale factor.

Table 3. Simulation (Fig. 12) parameters that best reproduce the Spitzer/MIPS image of comet 67P/Churyumov-Gerasimenko (Fig. 2).

| Parameter               | Value\(^a\) |
|-------------------------|-------------|
| Dust production, \( Q_d \) | \( \sim r_h^{-5.8} \cos z_\odot \) |
| Particle size distribution, \( dn/da \) | \( \sim a^{-3.5} \) |
| Ejection velocity, \( v_{ej} \) | \( 0.5\sqrt{\beta/r_h \cos z_\odot} \) (km s\(^{-1}\)) |

\(^a\) The parameter \( z_\odot \) is the Sun-zenith angle, dust production is zero on the night hemisphere (\( z_\odot > 90^\circ \)).
Fig. 1.— Observer-comet 67P/Churyumov-Gerasimenko viewing geometries for the IRAS, Palomar, and Spitzer epochs, as seen from the north ecliptic pole. The observer positions (filled and open circles) are labeled with the telescope names and the respective comet positions (triangles) are labeled with the telescope names in parentheses. The orbits of Earth, Jupiter, and 67P/Churyumov-Gerasimenko are also shown.

Fig. 2.— Spitzer/MIPS 24 $\mu$m image of comet 67P/Churyumov-Gerasimenko (top) and smoothed contours (bottom). The observation was taken on 2004 February 23 at 03:44 UT. The neck-line tail structure and dust trail (identified in §4.5) are indicated by the arrows. The first contour is 1.5$\sigma$ above the background and the second contour is selected to enhance the neck-line. Short arrows denote the projected heliocentric velocity ($v$) and sunward direction ($\odot$).

Fig. 3.— Mt. Palomar 5 m/Large Format Camera $r'$ (0.6 $\mu$m) image of comet 67P/Churyumov-Gerasimenko taken on 2003 June 26 at 04:36 UT. Arrows mark the projected heliocentric velocity ($v$) and sunward direction ($\odot$).

Fig. 4.— Cuts along the orbit of comet 67P/Churyumov-Gerasimenko centered on the nucleus at 24 $\mu$m for both the original image (solid line) and the point source subtracted image (dashed line). Each line represents a 3 pixel width average. The total point source flux used was 2.95 mJy, the mid-point of our upper- and lower-limits on the flux from the nucleus. Inset: A 40 $\times$ 40 pixel close-up of the nucleus.

Fig. 5.— Peak surface brightness of comet 67P/Churyumov-Gerasimenko as a function of distance along the de-projected dust emission for the 0.6 $\mu$m (left) and the 24 $\mu$m (right) images (see §3.3 for details). The plotted profiles are described in Table 2. All data points have a signal-to-noise ratio greater than 3 with the exception of the three data points on the far left of the 0.6 $\mu$m figure.

Fig. 6.— Cuts perpendicular to the projected orbit of comet 67P/Churyumov-Gerasimenko in the point source subtracted Spitzer/MIPS image. Labels denote distance from the nucleus, positive values are in the trailing direction. The emission ahead of the nucleus is centered on the projected orbit, meanwhile the emission behind the nucleus widens as the neck-line structure separates from the orbit and trail in projection (§4.5).
Fig. 7.— Simulated 24 µm images of comet 67P/Churyumov-Gerasimenko with the same viewing geometry as Fig. 2. The dust production ($Q_d$) and the magnitude and direction of $v_{ej}$ is varied between the three panels, but $v_0$ (Eq. 5) is held constant at 0.5 km s$^{-1}$: top panel, uniform $Q_d$ and $v_{ej}$ across the sunlit hemisphere; center panel, $Q_d$ and $v_{ej}$ are proportional to $\cos z_\odot$, where $z_\odot$ is the Sun-zenith angle; and bottom panel, $Q_d$ and $v_{ej}$ are proportional to the surface temperature of a spherical nucleus ($\cos^{1/4} z_\odot$). The images are plot with the same logarithmic scale and have been Gaussian smoothed (3 pixel Gaussian full-width at half-maximum at 2.5 arcsec pixel$^{-1}$). The dust production varies as $r^{-5.8}$ and the particle size distribution is $dn/da \propto a^{-3.5}$. See §4.3 for a discussion.

Fig. 8.— Same as Fig. 7 but only the $\cos z_\odot$ model is shown and $v_0$ is varied (Eq. 5). See §4.3 for a discussion.

Fig. 9.— Same as Fig. 8 but only the $v_0 = 0.5$ km s$^{-1}$ model is shown and the ejected particle size distribution is varied ($dn/da \sim a^k$). See §4.4 for a discussion.

Fig. 10.— Simulated image (top) for the same viewing geometry as the 0.6 µm Palomar/LFC image (bottom) using the parameters of the best 24 µm model (Table 3). The image is simulated for a wavelength of 0.6 µm at 0.7 arcsec pixel$^{-1}$ (see §4.4). Both images have been convolved with a 12" full-width at half-maximum Gaussian and are plot on a linear scale. The projected orbit of comet 67P/Churyumov-Gerasimenko is shown as a solid line. The trail (along the orbit) and neck-line (north of the orbit) are both visible in this simulated image but only the neck-line appears to be visible in the LFC image (§4.5).

Fig. 11.— Surface brightness profile of the best simulated 24 µm image (Fig. 12). The dotted lines are scaled versions of the best-fit forward and backward 24 µm profiles (Table 2). The scaling factors used were 0.021 for the backward emission, and 0.026 for the forward emission.

Fig. 12.— Same as Fig. 8 but only for $v_0 = 0.5$ km s$^{-1}$ and the emission has been enhanced by a factor of 2 to increase the image contrast. The projected orbit is plot as a solid line. The top panel shows the thermal emission from particles released during the 1996 perihelion (particle age $> 1750$ days, or 4.8 years), i.e., trail particles. The center panel shows the thermal emission from particles released at a true anomaly 180° prior to the 24 µm observation ($570 <$ age $< 610$ days), i.e., particles that form a neck-line tail structure. Both of the trail and neck-line components are visible in the 24 µm image, Fig. 2. The bottom panel shows the remaining dust after removing the neck-line and trail components.
Fig. 1.— Kelley et al., The Dust Trail of Comet 67P/Churyumov-Gerasimenko
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Fig. 4.— Kelley et al., The Dust Trail of Comet 67P/Churyumov-Gerasimenko
Fig. 5.— Kelley et al., The Dust Trail of Comet 67P/Churyumov-Gerasimenko
Fig. 6.— Kelley et al., The Dust Trail of Comet 67P/Churyumov-Gerasimenko
Fig. 7.— Kelley et al., The Dust Trail of Comet 67P/Churyumov-Gerasimenko
Fig. 8.— Kelley et al., The Dust Trail of Comet 67P/Churyumov-Gerasimenko
Fig. 9.— Kelley et al., The Dust Trail of Comet 67P/Churyumov-Gerasimenko
Fig. 10.— Kelley et al., The Dust Trail of Comet 67P/Churyumov-Gerasimenko
Fig. 11.— Kelley et al., The Dust Trail of Comet 67P/Churyumov-Gerasimenko
Fig. 12.— Kelley et al., The Dust Trail of Comet 67P/Churyumov-Gerasimenko