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3- to 14-μm Spectroscopy of Comet 55P/Tempel–Tuttle, Parent Body of the Leonid Meteors

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Comet 55P/Tempel–Tuttle was observed between 3 and 14 μm using the Broadband Array Spectrograph System (BASS) on the NASA 3-m Infrared Telescope Facility (IRTF) on Mauna Kea. Observations were made February 8.25 and 9.25 1998 UT when the heliocentric distance of the comet was 1.03 AU and decreasing as the comet approached perihelion (February 28, 1998). The spectra from both nights showed no emission features indicative of silicates or other solid substances, and they showed no difference between the two nights. They were well fit with a 330 K blackbody between 3 and 13 μm. The 330 K color temperature was 60 K above the equilibrium blackbody temperature of 274 K. These results are somewhat unusual for a comet, because most comets show silicate emission, indicative of small olivine- and/or pyroxene-based particles. We present a simple analysis of thermal emission and show that some useful though limited knowledge can be inferred about the particles' radiative properties. © 2000 Academic Press

Key Words: **comets; infrared observations; spectroscopy; meteors.**

I. INTRODUCTION

The Leonid meteor shower occurs annually during the period November 14–November 19 and is spawned by Comet 55P/Tempel–Tuttle, a low-inclination (162°), retrograde comet with a period of 33.25 years (Yeomans 1991, Mason 1995). The shower reaches storm proportions in the first couple of years immediately following the comet's perihelion passage (Yeomans *et al.* 1996, Yeomans 1998), an occurrence that has been reported since A.D. 902. The meteors consist of nonvolatile dust particles whose exact composition is unknown. Comet observations suggest that silicate material like olivines and pyroxenes are important constituents of comet dust (Campins and Ryan 1989, Bregman *et al.* 1987, Hanner *et al.* 1994, Wooden *et al.* 1999), a finding generally confirmed by observations of interplanetary dust particles (Bradley 1984, Sanford and Walker 1985, Bradley *et al.* 1992).

The best way of identifying the composition of the dust is to measure its infrared spectrum. In the region 2–20 μm, there are a number of vibrational, rotational, reststrahlen, and Chistiansen bands that can be used to identify the dust. Additionally, continuum observations reveal the color temperature of the dust, and this can be compared with the equilibrium blackbody temperature to investigate the gross optical properties of the dust.

In this paper we report spectroscopy in the region 3–14 μm and analyze the results in the context of particle size, composition, and temperature.

II. OBSERVATIONS

The comet was observed on February 8.25 and 9.25, 1998 UT, at the NASA Infrared Telescope Facility (IRTF) on Mauna Kea using a 3.2-arcsec-diameter aperture. At this time the comet was 1.03 AU from the Sun and approaching perihelion (February 28, 1998). Observations were made with Aerospace's broadband array spectrograph system (BASS) (Hackwell *et al.* 1990). BASS is an infrared array prism spectrograph that covers the entire spectral region 2.9–13.5 μm simultaneously at a resolving power of 25–120, depending on wavelength. This liquid helium-cooled instrument uses two 58-element Blocked Impurity Band (BIB) linear arrays. End-to-end system performance (chopped) is NEP of 2×10^{-14} W Hz$^{-1/2}$ at 10 μm and around 3×10^{-14} W Hz$^{-1/2}$ at 4.8 μm. The calibration source was Aldebaran (α Tau). The brightness of α Tau was obtained by fitting a polynomial through the photometric points reported by Gezari *et al.* (1993). The magnitude at wavelength λ was magnitude $= -5.69856 + 1.48298\lambda - 2.65771E\text{-}01\lambda^2 + 1.97447E\text{-}02\lambda^3 - 5.29454E\text{-}04\lambda^4$, where λ is in micrometers. The numerical values were within about 0.1 magnitude of -3.0 at all wavelengths.

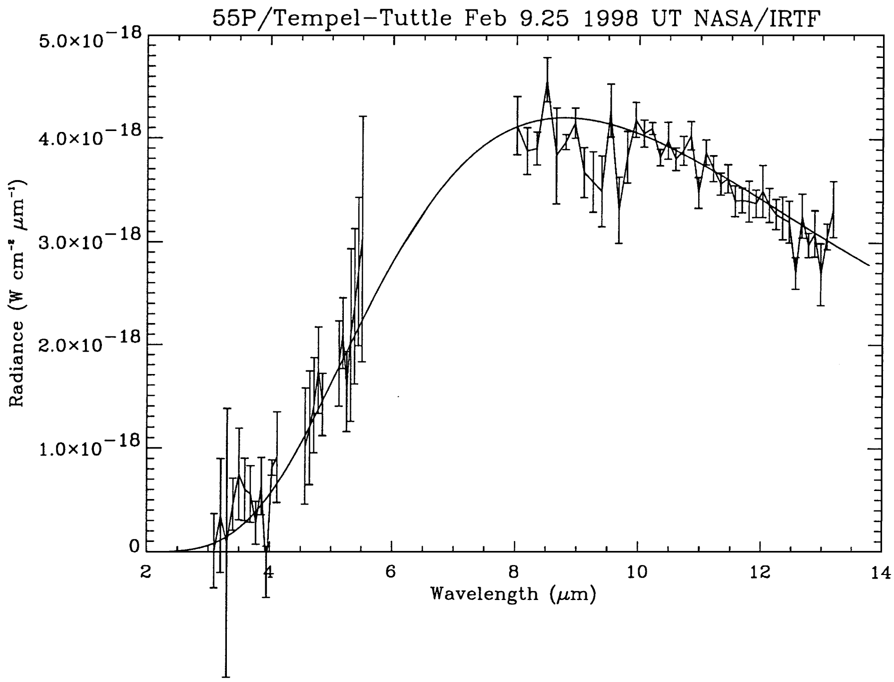

FIG. 1. Infrared spectrum of Comet Tempel–Tuttle, February 8.25, 1998 UT.

Magnitudes were converted to radiance using the assumption that α Lyr was 0.0 magnitude throughout the range and that its radiance at 10.0 μm was 1.26E-16 W cm$^{-2}\mu$m^{-1} at 10.0 μm.

Figures 1 and 2 are spectra of the comet on February 8.25 and February 9.25, 1998 UT, respectively. The spectra show a smooth, featureless, blackbody-like continuum. There is little evidence of silicate emission or any other departure from the continuum that would indicate the presence or composition of small, spectrally structured particles. The spectrum was well fit by a single 330 K Planckian graybody between 3 and 13 μm. The resulting color temperature T_C was approximately 60 K above the equilibrium blackbody temperature T_{BB} of 274 K ($=278/R^{1/2}$ K) for a perfect blackbody at the distance from

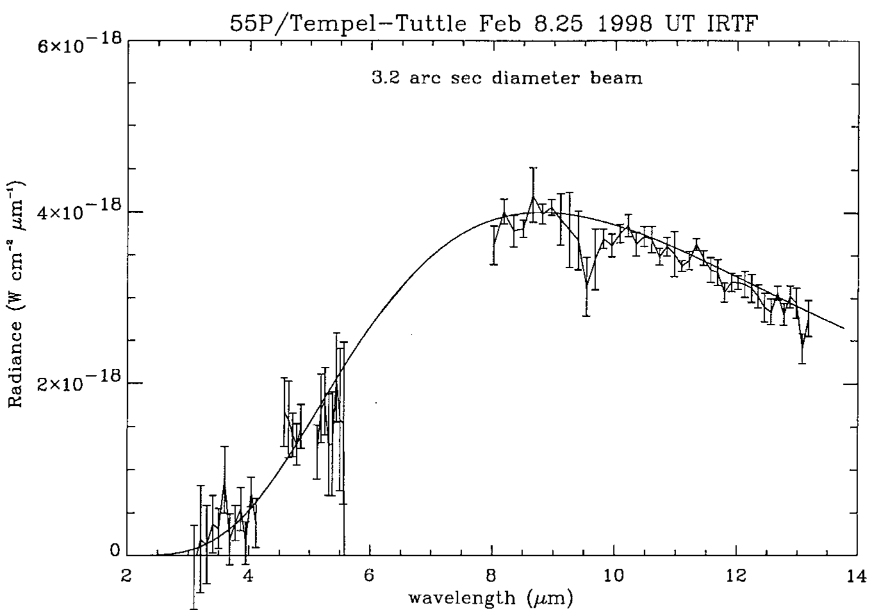

FIG. 2. Infrared spectrum of Comet Tempel–Tuttle, February 9.25, 1998 UT.

the Sun of $R = 1.03$ AU. A weak silicate feature with a contrast of about 5% could have been present but hidden in the noise.

III. DISCUSSION

The absence of silicate emission is a little unusual because most comets display silicate emission at one time or another in their life (Hanner *et al.* 1994). Comets that did not show silicate emission include Brorsen–Metcalf (Lynch *et al.* 1992), Schaumasse (Hanner *et al.* 1996), and 1998 K5 LINEAR (Wooden *et al.* 1998). Tempel–Tuttle's elevated color temperature is not at all surprising because it is almost invariably present when deduced from infrared measurements (Lynch and Mazuk 2000). Without any spectral structure to suggest mineralogy, we can deduce little or nothing about the dust's composition. Indeed, blackbody radiation carries no information about composition, particle size, or any other aspect of the emitting dust.

We can, however, draw some general conclusions about the particles' optical properties based on the elevated color temperature. Although T_C need not actually be the kinetic temperature of the particles, it is probably a reasonable supposition when the spectra are so nearly Planckian. Lynch *et al.* (1989) and Lien (1990) have shown that

$$T_C/T_{BB} \approx (Q_{VIS}/Q_{IR})^{1/4},$$

where Q_{VIS} and Q_{IR} are the wavelength-averaged visible and IR emissivities of the particles. Both emissivities are also averaged over particle size distribution. Taking $T_C = 330$ and $T_{BB} = 274$ from above, we find that $Q_{VIS}/Q_{IR} \approx 2.1$. Using an albedo of 0.04 (see below) and assuming that visible emissivity $= 1.0 -$ albedo, then $Q_{VIS} = 0.96$, leading to $Q_{IR} \approx 0.46$.

The absence of silicate emission, or alternatively the presence of blackbody-like emission, is often interpreted in one of two ways: (1) The particles must be "large" and therefore emit in a grossly Plankian manner. Such emission does not exhibit spectral structure that is indicative of the dust's optical constants. (2) The particles are composed of a substance that lacks discrete absorption bands in the observed wavelengths such as graphite. The emissivity of such particles changes slowly with wavelength and therefore no localized spectral structures are apparent.

Either explanation is possible. Indeed, using olivine, enstatite, and graphite with an appropriate choice of particle sizes, we computed a number of spectra that were able to fit the observations satisfactorily. Such fits, however, do nothing to narrow the range of possible minerals responsible for the comet's emission because, regardless of composition, all the spectra resembled blackbodies. Such fits could as easily have been obtained using almost any substance.

Some of the emission we observed might have been from the nucleus. Lamy *et al.* (1998) reports Hubble Space Telescope imaging of the nuclear region that suggests a radius of 1.8 km for an assumed albedo of 0.04. Independently Hainaut *et al.* (1998) obtained the same value from ground-based imagery. If we treat the nucleus as a blackbody ($Q_{IR} = 1.0$), then the fraction of the observed flux that would be due to the nucleus at 330 K (color temperature) and 274 K (radiative equilibrium temperature) would be 25 and 10%, respectively. If we adopt the value of $Q_{IR} = 0.46$ as found above, then the fraction of the observed flux that would be due to the nucleus at 330 K (color temperature) and 274 K (radiative equilibrium temperature) would be 12 and 5%, respectively. Thus it appears that most of the emission originated from dust in the coma.

With no estimates of the actual albedo or emissivity, and with significant uncertainty in the phase relation, it is conceivable that all of the radiation could have come from the nucleus. Assuming that the nucleus is a blackbody, we can compute the irradiance as a function of nuclear radius by assuming the entire (spherical) nucleus is at the observed color temperature. For a blackbody at $T = 330$ K the observed emission would correspond to a radius of 4 km. For $T = 274$ K, the radiative equilibrium temperature, the radius would be about 6.5 km. The fractional illumination of an assumed spherical nucleus at the time of the observations was 74%. Since irradiance varies as the area, which itself varies as the square of the radius, a 74% illumination fraction would mean that the radius necessary to produce the same observed radiance would have to be $1/(0.74)^{1/2} = 1.16$ times larger, or radii of 4.6 and 7.5 km, respectively.

Thus it seems likely that some of the radiation came from the nucleus. If we accept earlier estimates of the radius, then most of the radiation coming from the comet originates in a coma whose constituents do not show silicate emission.

IV. SUMMARY AND CONCLUSIONS

The 3- to 14-μm spectrum of Comet Tempel–Tuttle was remarkable because it was unremarkable. Its spectrum was indistinguishable from that of a blackbody at 330 K. The elevated color temperature compared with the blackbody equilibrium temperature (274 K) suggests that the particles are not true blackbody emitters but behave as though $Q_{VIS}/Q_{IR} \approx 2.1$. During the one day between observations, there was no brightness change. A certain fraction of the emission could have come from the nucleus.

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