MID-INFRARED SPECTRA OF COMETS P/BORRELLY, P/FAYE, AND P/SCHAUMASSE

Martha S. Hanner[1,3]*, David K. Lynch[2]*, Ray W. Russell[2]*,
John A. Hackwell[2]*, Robert Kellogg**. and Diana Blaney[1]*

[1] Jet Propulsion Laboratory, M. S. 183-501, California Institute of Technology,
'Pasadena, CA 91109

[2]The Aerospace Corporation, M2/266, P. O. Box 92957, Los Angeles, CA 90009-2957

[3]email: msh@scn 1.jpl.nasa.gov

Submitted to Icarus November 20, 1995

Pages:

Figures:

Tables: 1

key words: Comets: Dust, Cornets: Composition, Infrared observations

*Visiting Astronomer at the Infrared Telescope Facility, operated by the University of Hawaii under contract from the National Aeronautics and Space Administration.

Running title: Mid-Infrared Spectra of Comets

Martha S. Hanner
Mail Stop 183-601
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena CA 91109

Phone: 818-354-4100

ABSTRACT

A 10 µm silicate emission feature has been discovered in the spectra of comets P/Borrelly and P/Faye at R - 1.5 AU. These are the first short period comets in which silicate emission has definite] y been detected. The emission feat ures, about 25% above the continuum, are broad and structureless. No crystalline olivine peak at 11.2 pm is evident. No emission feature was present in the spectrum of P/Schaumasse; it is likely that the nucleus of P/Schaumasse was directly detected. If all of the observed flux originated from the nucleus, then the effective radius is about 3 km.

We present models that show how the shape of' the silicate feature can depend on the way in which silicate and absorbing material are mixed in the grains.

I. INTRODUCTION

Short-period comets, with their low-inclination orbits, most likely originated in the trans-Neptune region from 30-100 AU (Duncan, Quinn& Tremain 1988), whereas the Oort cloud comets probably formed in the region of the giant planets. If there were radial gradients in the composition of the solar nebula due, for example, to the extent of mixing between warm and cold regions, then one might expect to see systematic differences between the short-period comets and the new or long period comets.

An emission feature around 10 μm arising from small silicate grains is seen in a number of new and long-period cornets. Four comets (among the 9 with good spectra) display a strong silicate feature with a distinct peak at 11.25 pm, attributed to crystalline olivine grains: long period comets Levy 1990 XX (Lynch et al. 1992) and Bradfield 1987 XXIX (Hanner et al. 1990, 1994a), new comet Mueller 1993a (Hanner et al. 1994b), and P/Halley (Bregman et al. 1987; Campins & Ryan 1989). Crystalline olivine is a high temperature mineral that is rare or absent in the diffuse interstellar medium. The olivine grains could have annealed in the inner solar nebula, but to transport them to the region of comet formation would have required extensive radial mixing in the solar nebula.

Until now, there have been no spectra with high signal/noise for the fainter short-period comets. No silicate feature is evident in filter photometry of these objects; however, a broad or weak feature could have gone undetected. in this paper we present 8-13 μm spectra for three short-period comets, P/Borrelly, P/Faye, and P/Schaumasse. Two of these comets do show moderate silicate emission, but neither has an obvious 11.2 μm peak.

11. OBSERVATIONS

The infrared spectra were obtained at the NASA Infrared Telescope Facility with the Aerospace Corp. broadband array spectrograph system (BASS). The instrument spans the wavelength range 2-14 μm using two 58-element blocked impurity band linear arrays; all spectral elements are observed simultaneously (Hackwell et al. 1990). 1 'able 1 presents a log of the observations. Standard chopping and nodding were done with a 15-20 arcsec N/S chopping throw. Several 400 sec integrations were summed; the total on-source time is given in the Table. On each night, spectra of the standard star were taken over a range in air mass. Each comet spectrum was divided by the standard star spectrum interpolated to the same air mass; the comets were always observed at air mass < 1.30. The resulting ratio spectra were weighted by their standard deviations and averaged.

'l'he absolute fluxes of β Gem and α Tau are based on measured spectra relative to **a** CMa, assuming **a** CMa to be a 9700 K blackbody, with 1 ().0 μm flux = $4.57\cdot10^{-12}$ $W/m^2/\mu m$. Alpha Tau has an 8 pm SiO feature with a depth of-14Y'0, while the spectrum of β Gem is close to that of a black body.

111. COMPARISON OF 1'1111 SPECTRA

P/Schaumasse

The spectrum of cornet P/Schaumasse is plotted in Fig. 1. Because the spectra showed no significant change from Feb. 7 to Feb. 8, the data from the two nights are combined in the Figure, The error bars represent the difference between the average and the fluxes for the individual nights. The spectrum can be fit by a smooth blackbody continuum with a 265 K color temperature, about 5 % above that of a perfect bl ackbody in equilibrium with the solar radiation at 1.24 AU. There is no evidence for a silicate emission feature; we can set an upper limit of 10% for the strength of any feature relative to the continuum.

Thus, neither submicron silicate grains, which produce a 10 pm feature, nor hot submicron absorbing grains that give rise to an elevated color temperature are abundant in the coma. Either the thermal emission arises from large grains or we are seeing emission from the nucleus. If the entire observed flux was emitted from the nucleus, then a model for a spherical nucleus at R=1.24 AU, phase angle 50", and emissivity 0.9 yields a nuclear radius of 3.3 km. To be consistent with the observed color temperature, the nucleus must be rapidly rotating; that is, the time required for the surface to come to equilibrium must be long compared to the rotation rate.

P/Faye

The observed spectrum of comet P/Faye is shown as the solid points in Fig. 2a. The spectrum clearl y has a convex shape that differs from a black body. Lamy and Toth (1995) have derived a radius of 2.42 km for P/Faye, based on HST images. A model for the thermal emission from a slowly rotating 2.42 km radius spherical nucleus with emissivity 0.9 was subtracted from the observed fluxes to give the spectrum in Fig. 2b. (A rapidly rotating nucleus would make a smaller contribution to the total flux.) The broad emission feature has a shape typical of silicate emission from non-crystal] i ne grains and a strength of about 250/0 relative to a smooth blackbod y continuum. There is no structure > 1 σ.

P/Borrelly

P/Borrelly is among the dustier short pe period comets and tends to be brighter post-perihelion. We observed the comet about 6 weeks after perihelion. The spectra on Dec. 13 and 14 are presented in Figure 3. The larger errors on Dec 14 are due to the shorter integration time. As in the case of P/Faye, the spectral shape is more convex than a black body, indicating the presence of silicate emission. The single high data point at 11.2 μm on Dec. 13 is at the wavelength of the crystalline olivine peak. However, we consider it to be within the scatter of the data and the corresponding data point is not elevated in the Dec. 14 spectrum. The entire 3- 13 μm spectrum of Borrelly is plotted in Figure 4. A 275 K Planck function fits the continuum from 4.8-13 pm.

Lamy et al. (1 995) have reported that the nucleus of P/Borrelly is extremely elongated, with semi-axes of 4.14 and 1.63 km and a synodic period of 24.7 ±0.5 hr. The period is not well enough determined for us to extrapolate the rotation phase from the HST images on Nov. 28 to Dec. 13-14. Depending on the orientation at the time of our observations, this nucleus contributed 15 - 30°/0 of the observed flux.

Color Temperatures

The 8-20 μm color temperature of the dust in comet P/1 Ialley could be represented by the expression $T =- 3\ 15.5r^{-0.502}$, about 15% higher than a perfect blackbody in equilibrium (Tokunaga et al. 1988). Our 8-13pm temperatures for P/Borrelly and P/Faye are comparable to those for P/Halley at R= 1.48 AU post-perihelion.

Iv. THE I] US-l' GRAINS

The fact that the color temperature is higher than the equilibrium temperature and the presence of even a weak emission feature mean that the grains in the coma do not radiate as blackbodies. Small absorbing grains, radius< 1 μm, cannot radiate efficiently at λ -10 pm, where the Planck function peaks. They will heat up until the energy radiated at shorter wavelengths balances the solar heating. The observed color temperature depends on the weighted emission from grains with a range of sizes, temperatures, and wavelength-dependent emissivities (Hanner 1983; Campins & Hanner 1982).

The strength and shape of the 10 μm silicate emission feature depend on the size distribution, grain temperature, type of silicate, and the manner in which the silicates are mixed with absorbing material. A weak feature does not necessari 1 y imply a lack of silicates in the comet dust. The silicate grains could be too cold for their emission to show up against the emission from hot dark grains, or too large to exhibit a feature, or so well mixed with absorbing material that the feature is masked. Pure silicate grains have almost no absorption at visual wavelengths, yet radiate efficiently at 10 pm; consequently, they will be much colder than a blackbody. However, the particles detected by the dust analyzer on the Halley space probes typically contained both silicates and carbon-rich material. Since it requires only a small percentage of absorbing material to increase the absorption of solar radiation, we expect that most of the silicate grains will be "dirty" and warm.

To illustrate how the way in which silicate and absorbing material are mixed influences the spectral shape, we show three computed models of the thermal emission for a mixture of silicate and absorbing grains. Refractive indices of glassy carbon (Edoh 1983), glassy bronzite (Dorschner et al. 1988) and disordered olivine (Krätschmer & Huffman 1979) were used with Mie theory to compute the emissivities. The equilibrium temperature was computed for each grain size and composition by balancing the total absorption and emission. A size distribution of the form used by Hanner et al. (1985) with peak radius 0.48 μm was adopted.

Figure 5a shows the thermal emission for a model with 50% carbon and 50% dirty bronzite, computing the flux for each component separately and then averaging. The bronzite grains arc assumed to have a temperature equal to the equilibrium blackbody temperature of 232 K (e.g. Hanner 1983). The same size distribution was used for both components. This model produces a broad silicate feature similar to that observed, but the short-wavelength side is offset from the observations,

If two materials are mixed on a scale small compared to the wavelength, one can approximate the optical constants of the mixture via effective medium theory (Bohren & Huffman 1983). We used the Bruggeman formula to compute effective optical constants for mixtures of carbon and bronzite or olivine. Fig. 5b shows the results for a mixture of 50°/0 carbon and 50°/0 bronzite by volume, with the same size distribution as the model in Figure 5a. Comparing Fig. 5a and 5b, one sees that the shape of the silicate feature can be different for the same relative abundances of the same components with the same size distribution, simply mixed in a different way. A model for a Bruggeman average of 50°/0 carbon and 50°/0 disordered olivine is plotted in Fig. 5c. The olivine produces a slightly stronger feature and a narrower peak at *9.8* μm than the bronzite. (Note that the maximum difference between data and models is <1O%.)

The strength of the silicate feature is comparable in the three examples illustrated, Shifting the size distribution towards smaller sizes would cause the silicate feature to be too strong . A higher relative abundance of silicate to absorbing material would also increase the strength of the observed feature.

Differences in the abundance of submicron grains in the coma are the simplest explanation as to why the silicate feature in comets is variable. Many comets show a stronger silicate feature when closer to the Sun (e.g. Ney 1982), perhaps the result of grain fragmentation when an organic component volatilizes. We note that P/Halley did not have a silicate feature larger than about 1 So/O of the continuum flux at 1.5 AU post-perihelion, a distance comparable to that of P/Faye and P/Borrell y (Tokunaga et al. 1988). Yet, Mueller 1993a showed a strong silicate feature at 2 AU and short-period cornets near the sun, such as Encke have not displayed an obvious feature. Apparently, only “fresh” icy surfaces or vents that reach the “fresh” subsurface ice layers of the nucleus release the original size distribution of small grains. Stronger silicate emission, higher polarization, stronger scattered light continuum and less red color, all characteristics of small grains, were associated with the jet activity in Halley, presumably coming from deep vents. Further studies which correlate the strength of the silicate feature with other signatures of sub-micron sized grains are needed.

V. SUMMARY

We have discovered 10 μm silicate emission in two short period cornets, P/Faye and P/Borrelly, at R -1,5 AU. The emission features are broad and structureless; there is no 11.2 μm peak of crystalline olivine larger than the scatter in the data. These are the first short period comets in which silicate emission has definitely been detected.

A grain model comprising equal amounts of glassy silicate and absorbing grains gives a feature of comparable strength to that observed for a size distribution favoring micron-sized particles; however, the shape of the silicate feature depends on the way in which the silicate and absorbing material are mixed as well as on the silicate mineralogy and size distribution.

No silicate feature was present in the spectrum of P/Schaumasse. We can set an upper limit of 3.3 km for the effective radius of the nucleus, if all of the observed 8- 13 pm flux was from the nucleus. The color temperature implies that the nucleus must bc rapidly rotating.

ACKNOWLEDGEMENTS

We thank the IRTF staff for their support, particularly telescope operators Bill Golisch, Dave Griep, and Charlie Kaminski. Dr. Glenn Veeder computed the nucleus models for us. Ann Mazuk assisted with the data reduction and Bob Young assisted with the instrument shipping and setup. This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (Planetary Astronomy Program). This work was supported at the Aerospace Corporation by the Aerospace Sponsored Research Program.

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Table I.

Short-Period Comets Observed with BASS

Name	q, AU	Dates Observed	R, AU	Δ, AU	θ deg	Beam, arcsec	Chopping Throw, "	τ, min	Standard Star
P/Faye	1.593	11/17.3/91	1.59	0.653	17	3.4	20 N/S	25	a Tau
P/Schaumasse	1.202	2/7.25/93 2/8.24/93	1.24	0.545	50	3.5	16 N/S		α Tau
P/Borrelly	1.365	12/13.6/94 12/14.5/94	1.45	0.626	33	3.0	18 N/S	67 30	β Gem

q = perihelion distance

R= heliocentric distance

A = geocentric distance

e = phase angle

τ = total on-source integration time

FIGURE LEGENDS

Fig. 1: BASS spectrum of P/Schaumasse 2/7-8/93 at R = 1.?.4 AU. ____'T' = 265 K blackbody

Fig. 2: BASS spectrum of P/Faye 11/1 7/91 at R = 1.59 AU. 2a: total observed flux, T = 265 K blackbody; 2b: residual flux after subtracting computed flux from 2.42 km radius slowly rotating nucleus, _.._ T = ?50 K blackbody

Fig. 3: BASS spectrum of P/Borrelly at R = 1.45 AU. 3a: 12/13/94; 3b: 12/14/94

Fig. 4: 3-13 μm spectrum of P/Borrelly, average of 12/13 and 12/14. ---T = 275 K blackbody

Fig. 5a: Model for mixture of 50% glassy bronzite, 50% carbon, separate components, fit to Borrelly data from Fig. 4

Fig. 5b: Model for mixture of 50% glassy bronzite, 50% carbon using effective medium theory, fit to Borrelly data

Fig. 5c: Model for mixture of 50'% disordered olivine, 50% carbon using effective medium theory, fit to Borrelly data

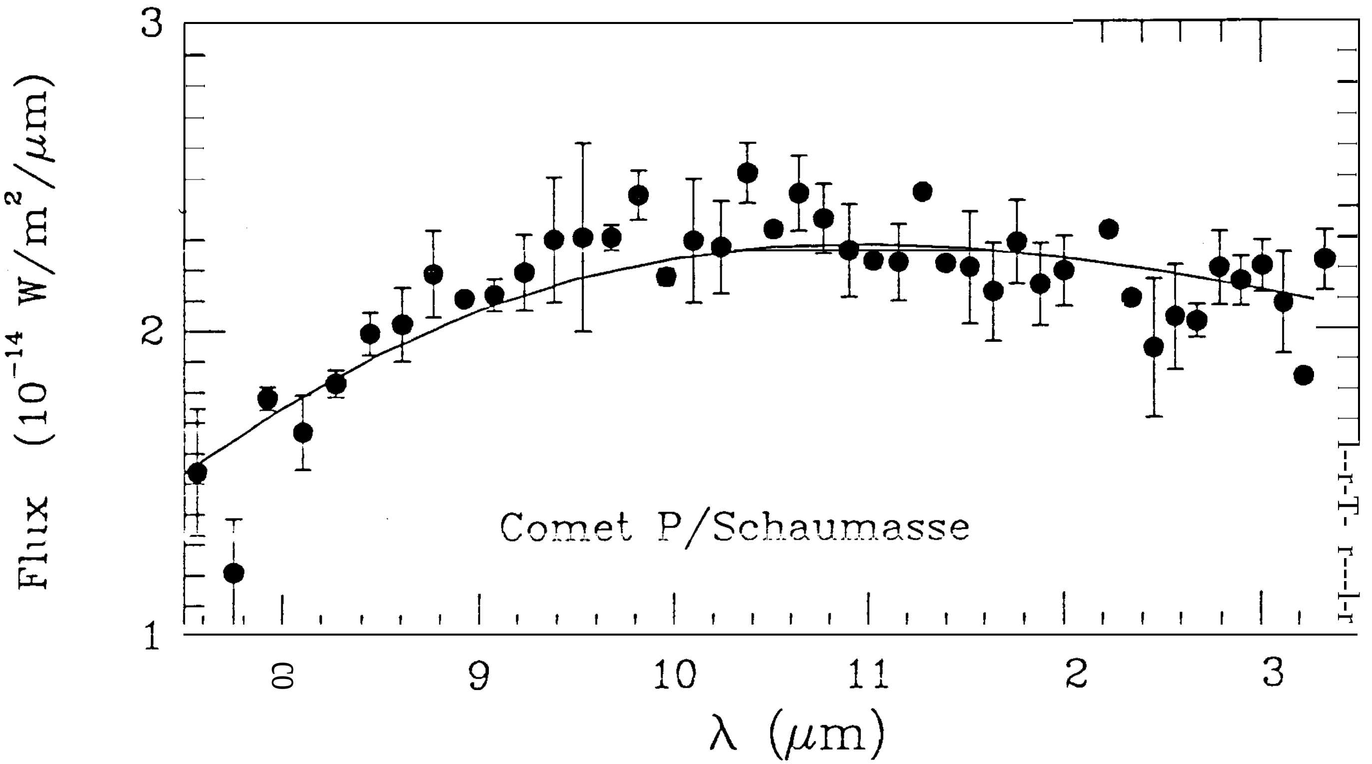


Fig. 1

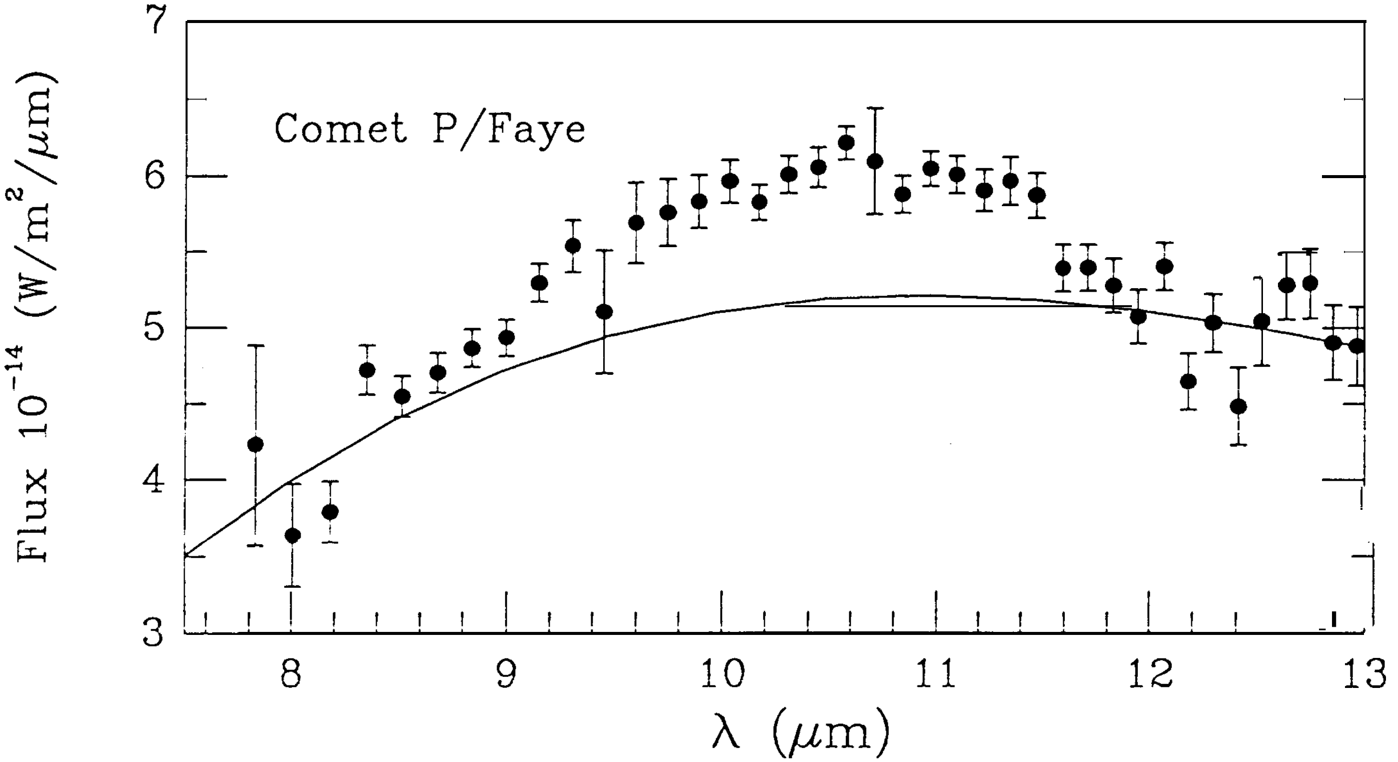
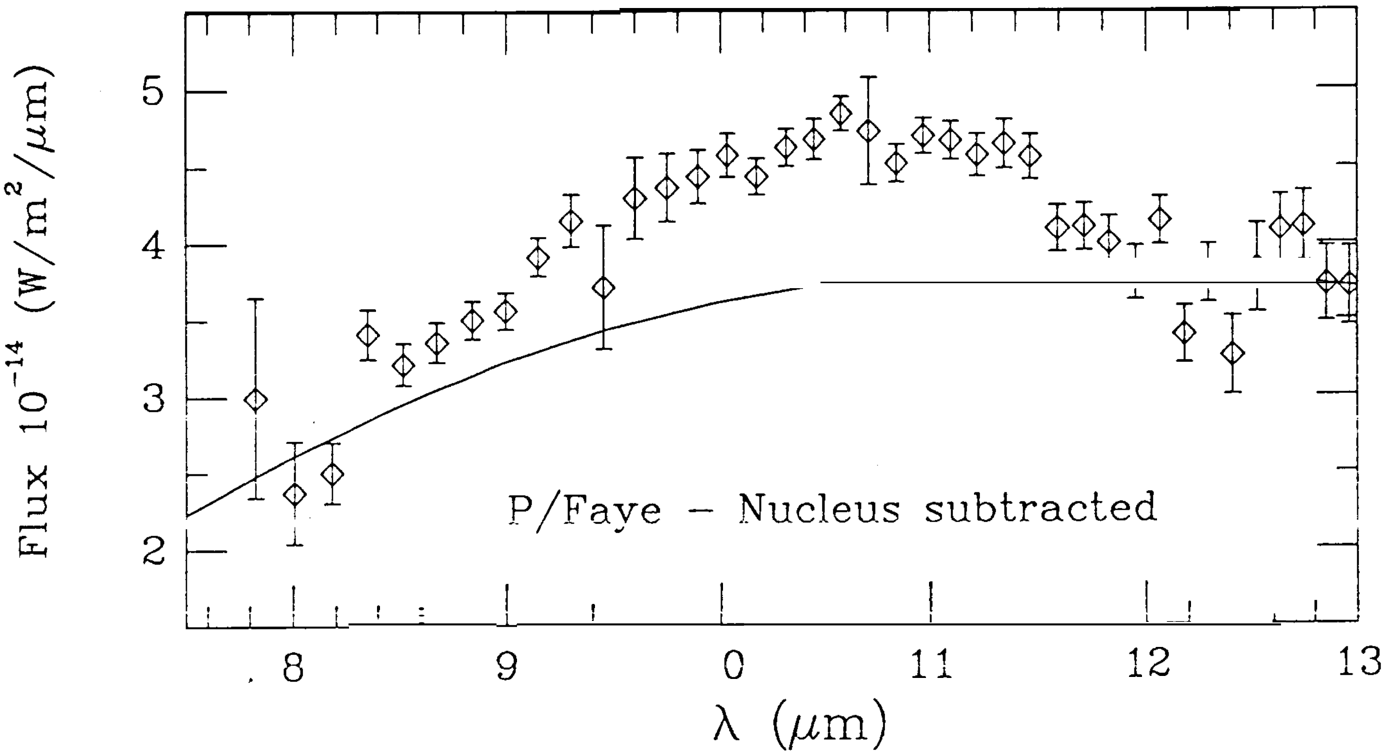


Fig. 2a



Flux 10^{-14} (W/m^2/μm)
5
4
3
2
P/Faye – Nucleus subtracted
. 8
9
0
11
12
13
λ (μm)

Fig. 2b

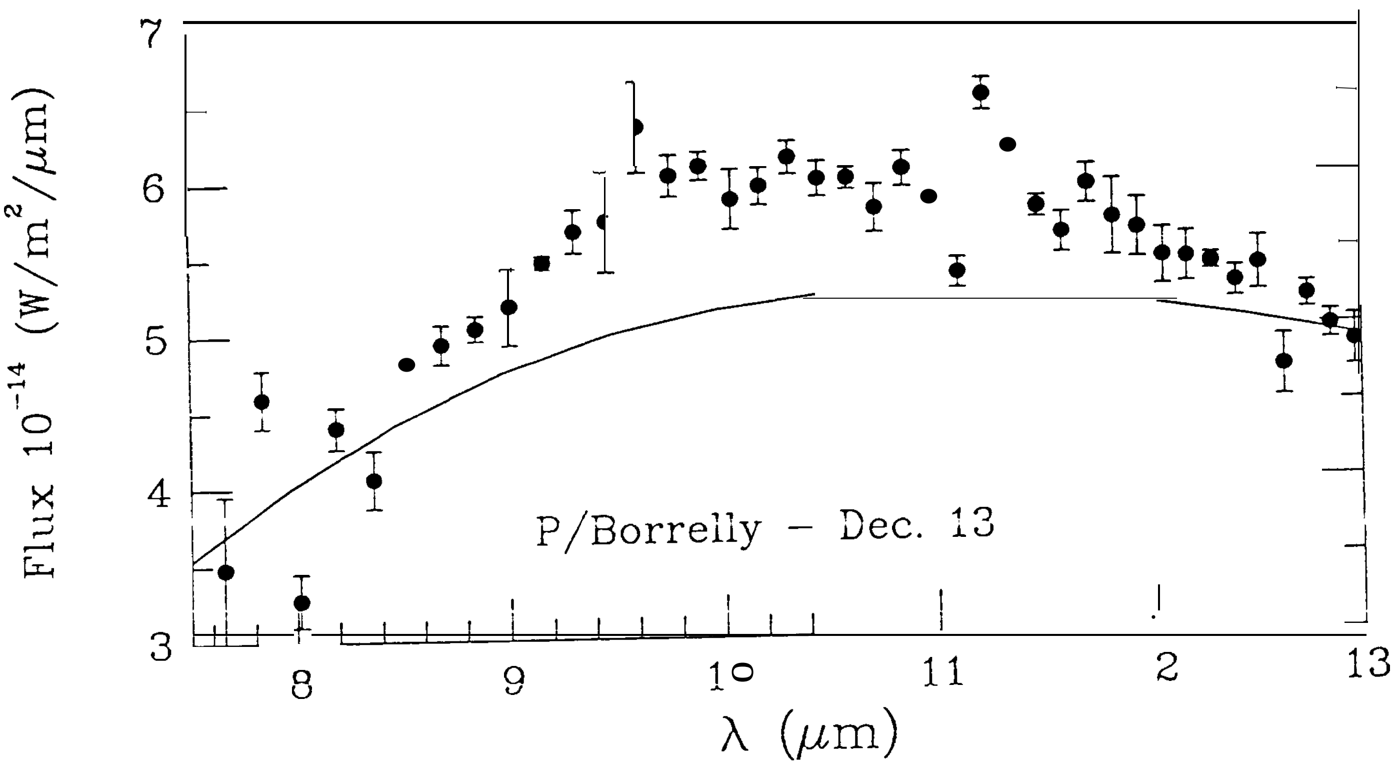


Fig. 3a

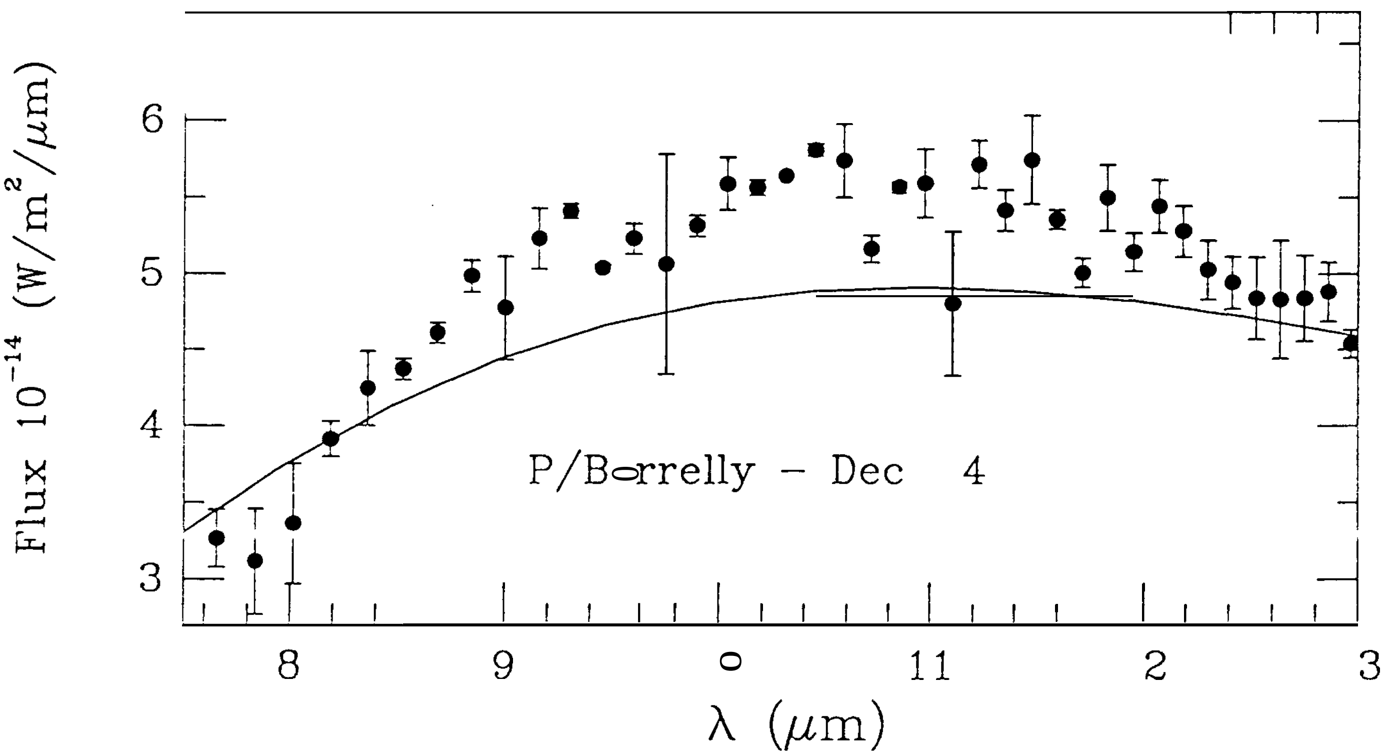


Fig. 3b

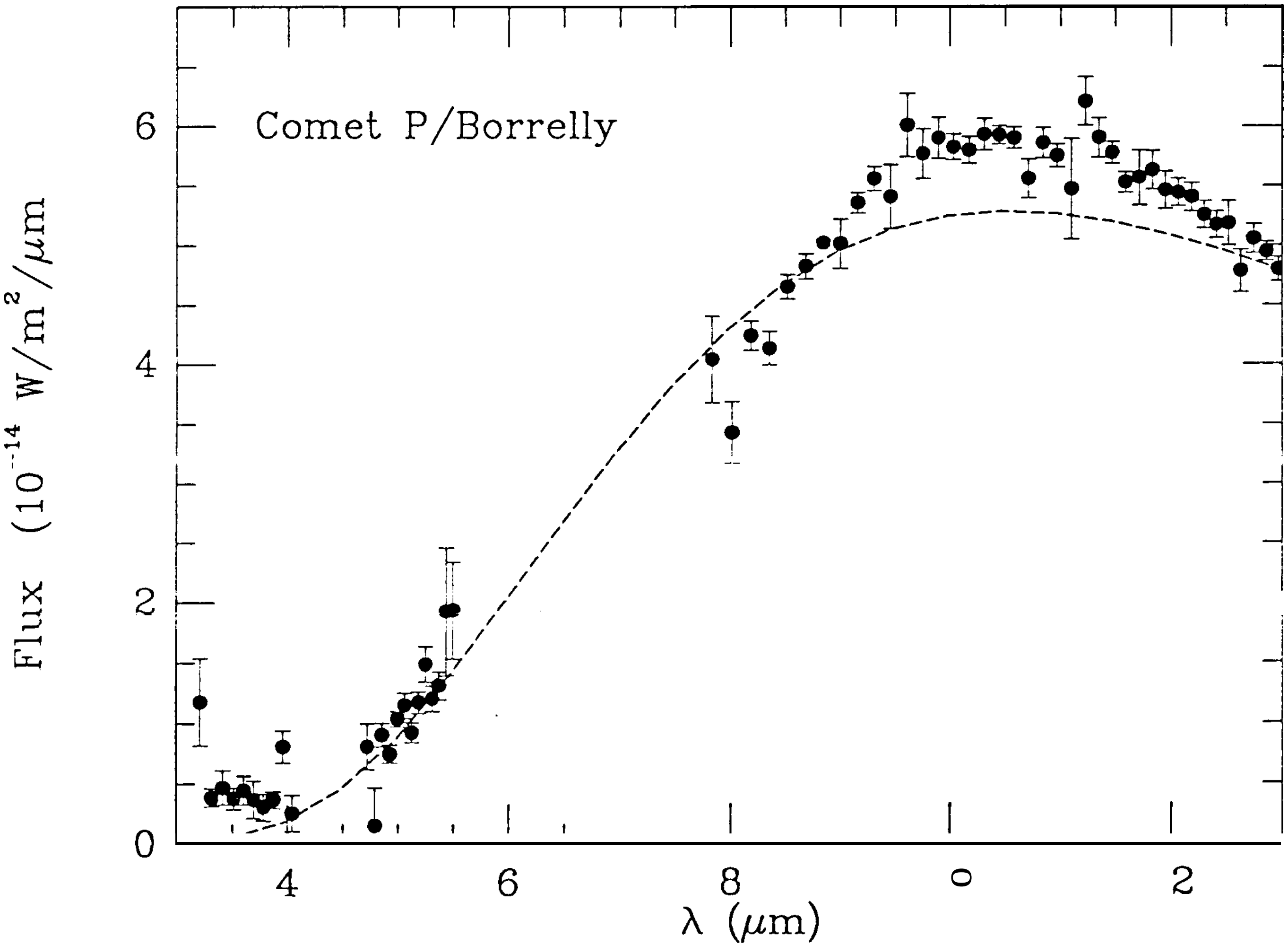


Fig. 4

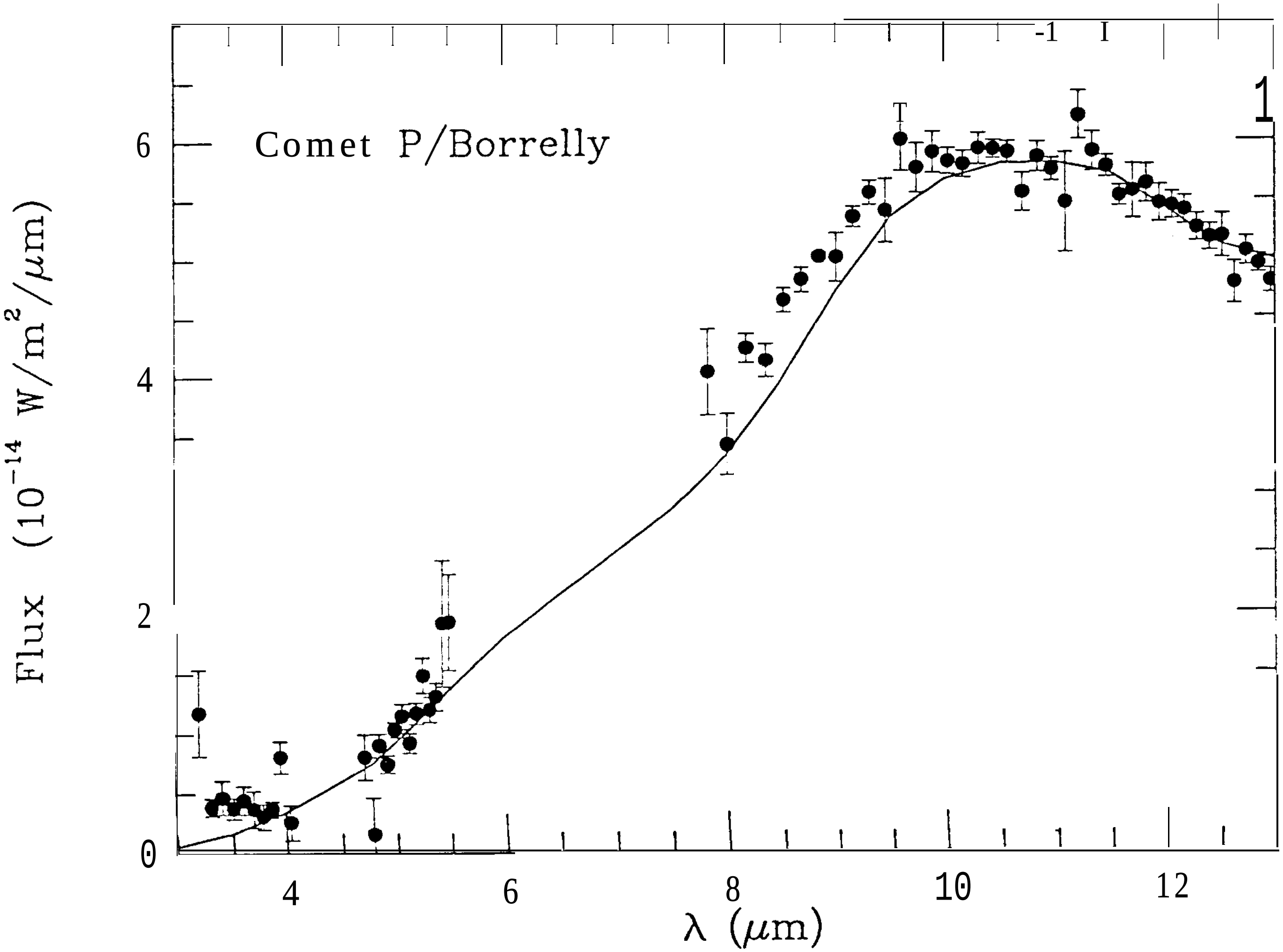


Fig. 5a