

THE SILICATE EMISSION FEATURE IN THE SPECTRUM
OF COMET MUELLER 1993A

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ABSTRACT

An 8-13 μm spectrum of comet Mueller 1993a, a dynamically new comet, was acquired when the comet was at $R = 2$ AU. Strong, structured silicate emission is present, closely resembling that seen in comet P/Halley. For the first time in a new comet, the 11.2 μm peak of crystalline olivine was detected, demonstrating that crystalline olivine particles were widespread in the solar nebula. Although the crystalline olivine particles could have formed in the inner protosolar nebula at temperatures > 1200 K, it is unlikely that they could have been transported to the outer nebula where the cometesimals formed. 'I'bus, we conclude that a presolar origin for the crystalline olivine is more likely.

I. INTRODUCTION

Because comets have remained in the cold outer solar system since their formation, they contain a record of the primitive solar nebula. Differences among comets could reflect processes in the solar nebula or compositional gradients with distance from the protosun or the recent thermal history of the nucleus in the inner solar system. For example, if dust composition varied with position in the solar nebula, then we might expect to see variations among both new and evolved comets but not a correlation with their recent dynamical history.

Silicate grains, being high temperature condensates, may have survived with minimal alteration from the interstellar medium. Silicates are known to be a constituent of comet dust, based on data from the Halley probes (Kissel et al. 1986a,b). The Si-O stretching mode vibration in silicate particles produces a broad spectral feature near 10 μm ; the detailed structure of this band depends upon the composition and crystal structure of the silicate particles.

To date, 10 μm spectra exist for only a few comets, and the picture so far is confusing (see Hanner et al. 1994 for a review). The infrared spectra of comets differ from spectra of interstellar grains, such as the Trapezium (Forrest et al. 1975; Hanner et al. 1994b). Comet Halley displayed a strong silicate emission feature, with a distinct peak at 11.25 μm , attributed to crystalline olivine particles (Bregman et al. 1987, Campins & Ryan 1989). Two long-period comets have shown a similar 11.25 μm peak, Bradfield 1987 XXIX (Hanner et al. 1990, Lynch et al. 1988) and Levy 1990 XX (Lynch et al. 1992).

Yet none of the four dynamically new (Oort Cloud) comets observed to date has exhibited the 11.2 μm feature. Each of these new comets has a different, and unexplained, spectrum (e.g. Hanner et al. 1994). If this result were to persist for a larger sample of comets, it would imply that the composition of the grains in new comets was somehow different from that of more evolved comets, either because the outer layers of the nucleus were somehow altered during their 4.5 billion year exposure or because the evolved comets were thermally altered during perihelion passages in the inner solar system. Thus, it is important to expand our sample of new comet spectra.

Comet Mueller 1993a is a dynamically new comet (Marsden 1993). A centrally condensed coma and a short fan-shaped tail were evident when the comet was discovered at 4.5 AU (Green 1993). This comet has provided an opportunity to study the infrared spectrum of a new comet at $R \approx 2$ AU, where the equilibrium blackbody temperature is ≈ 200 K. We observed comet Mueller eight weeks before perihelion at heliocentric distance $R = 2.06$ AU and geocentric distance 1.72 AU. In this paper we present our 8-13 μm spectrum and discuss the implications for the origin of crystalline silicates in comets.

11. OBSERVATIONS

Comet Mueller 1993a was observed at the NASA Infrared Telescope Facility (IRTF) on November 15-17, 1993, using the Aerospace Corp. broadband array spectrograph (BASS). This instrument spans the wavelength region 3 - 14 μm , using two 58-element blocked impurity band linear arrays (Hackwell et al. 1990). Spectral resolution at 10 μm is about 70. We used a 3.4 arcsec aperture and North-South chopping throw of 15 arcsec. The comet was observed after sunset at air mass 1.4-1.7, bracketed by observations of the K3 II standard γ Aql spanning a similar range in air mass. The flux calibration of γ Aql is based on spectra of γ Aql vs α Lyr taken with the UKIRT CGS3 spectrometer (Hanner & Tokunaga, 1991, unpublished), assuming 10.1 μm flux for α Lyr of $1.17 \times 10^{-12} \text{ W m}^{-2} \mu\text{m}^{-1}$. The wavelength calibration was done using a laboratory grating monochromer. The repeatability and internal consistency of these measurements indicate that the wavelength calibration is accurate to better than $\pm 0.02 \mu\text{m}$.

Each spectrum of Comet Mueller was divided by the spectrum of γ Aql interpolated to the same air mass. The resulting ratio spectra were weighted by their standard deviations and averaged. The comet was 10% - 1 S % brighter on Nov. 17. The averaged spectrum for each night, converted to flux, is presented in Fig. 1a-1 c and the weighted average of the three nights in Fig. 1 d. A strong emission feature is evident, similar to the silicate emission seen in several other comets at smaller heliocentric distances. The comet was too faint for u scf u] spectra to be obtained in the L and M bandpasses.

III. DISCUSSION

A. Shape of the Silicate Feature

To study the shape of the emission feature, the weighted average spectrum in Fig. 1 d was divided by a 220 K blackbody continuum fitted to the data near 8 and 13 μm . This method assumes that the average emissivity of the grains is the same at 8 and 13 μm . If the small silicate grains producing the feature were the SOIC emitters in the optically thin coma, then the observed flux divided by the appropriate blackbody flux would yield the average emissivity of the grains. If thermal emission from large, featureless grains (or small carbonaceous grains) contributes to the observed flux, then the observed feature/continuum ratio will be a lower limit to the emissivity of the silicate grains. For further discussion of this point, see Hanner et al. (1994a).

The resulting flux/continuum spectrum is plotted in Fig. 2. The emission feature has a broad maximum near 9.8 μm and a narrower peak at 11.21 μm , closely resembling the silicate features in comets P/1 Halley (Bregman et al. 1987; Campins & Ryan 1989), Levy 1990 XX (Lynch et al. 1992), and Bradfield 1987 XXIX (Hanner et al. 1990; Lynch et al. 1988). The FWHM (2.85 μm) and the wavelengths of half-maximum $\lambda_1 = 8.85 \mu\text{m}$, $\lambda_2 =$

11.7 μm) agree with Halley at 0.79 AU and Bradfield at 0.99 AU (Janner et al. 1994, Table 2). The emission band in amorphous (or crystalline) pyroxenes generally occurs at shorter wavelength than the band in amorphous (or crystalline) olivine (Stephens & Russell 1979). The similar λ_1 and λ_2 indicate that a similar mix of olivines and pyroxenes is present in comets Mueller, Bradfield, and Halley.

The peak at 11.2 μm is probably due to small grains of crystalline olivine. It is seen in comets only in conjunction with strong silicate emission. Olivine crystals are present in interplanetary dust particles of possible cometary origin. The peak wavelength and shape agree with laboratory spectra of Mg-rich olivine (Stephens & Russell 1979; Koike et al. 1993),

B. Origin of the Crystalline Olivine

Comet Mueller is the first Oort Cloud comet in which this signature of crystalline silicates has been seen. That the 11.2 μm peak has now been detected in a new comet, two long period comets, and P/Halley, indicates that crystalline olivine must be a common constituent in cometary dust (although the crystalline olivine constitutes only a fraction of the silicate material; Janner et al. 1994a),

Crystalline grains can form by direct condensation from the vapor phase with very slow cooling or by annealing [heating] of amorphous silicate particles. Day and Dorm (1978) converted amorphous magnesium silicate smoke to crystalline olivine by heating at $T = 1270$ K for 1 hour. Koike and Tsuchiyama (1992) created crystalline olivine by heating glassy silicate particles for 105 hours at $T = 875$ K, corresponding to the blackbody temperature at heliocentric distance $R \approx 0.1$ AU. The annealing rate drops by orders of magnitude at lower temperatures, but laboratory data to quantify this are not available.

Since comet Mueller presumably has not previously passed through the inner solar system, the crystalline grains could not have formed by heating on the nucleus surface during prior perihelion passages at small R . Moreover, the other detections were in comets at $R \geq 1$ AU, where the blackbody temperature is < 300 K, so that solar heating would have been insufficient for annealing. Nor is it plausible that the crystalline grains were created during exposure of the nucleus to the cosmic ray flux in the Oort Cloud. Irradiation by energetic charged particles will destroy molecular bonds, producing disordered structure (e.g. Krätschmer & Huffman 1979). Furthermore, a periodic comet such as Halley has long ago lost the original surface layers of the nucleus.

~'bus, the Crystalline particles must have been present in the solar nebula where the comet nuclei formed.

The comets that populate the inner and outer Oort Cloud are thought to have formed in the Uranus- Neptune region, from whence they were dynamically scattered to the Oort

Cloud (Safronov 1972, Mumma et al, 1993). The Oort Cloud is the source of "new" and long period comets. Short-period comets are thought to have originated in the region at $\sim 35-50$ AU, the Kuiper belt (Duncan, Quinn & Tremaine 1988). With its high inclination, retrograde orbit, and strong level of activity, P/Halley may well be a captured long period comet. Thus, our sample of 4 comets most likely all came from the Uranus-Neptune region via the Oort cloud,

If the crystalline silicate grains formed in the solar nebula, we have several questions: Did the grains condense directly from a high-temperature gas or did they form by annealing of amorphous grains? What was the source of heating? Where did they form? If formed in the hot, inner region of the nebula, how were they transported to the outer region where the comet nuclei were accreting?

The crystalline olivine grains could not have been created by the short-term heating events that produced the chondrules. These mm-sized components of chondritic meteorites required heating to ~ 1800 K followed by rapid cooling, on the order of 1000 K/hour (Hewins 1988).

Supporting evidence for direct vapor condensation comes from grains embedded in chondritic porous interplanetary dust particles (IDPs). Bradley et al. (1983) discovered enstatite whiskers and platelets up to a few microns in length in these IDPs that bear the signatures of direct vapor phase condensates. Their unusual shapes and growth patterns, such as axial screw dislocations, point to growth from the vapor phase at low pressures. Their morphologies are not consistent with fragmentation of larger crystals or annealing of amorphous silicate particles. These porous, fragile IDPs may have been released from comets (see discussion in Hanner et al, 1994), Bradley et al. emphasize that the enstatite crystals are relatively rare. Nevertheless, they are evidence that at least some primary silicate condensates were present in the solar nebula,

Conditions for vapor condensation and slow cooling of silicate grains would have existed in the hot inner solar nebula. The condensation temperature of Mg olivine (forsterite) under solar nebula conditions is ~ 1400 K (Kerridge 1993). The evidence from meteorites (e.g. Palma & Boynton 1993) and from consideration of the collapse of the protosolar nebula (e.g. Tscharnuter & Boss 1993) indicate temperatures $\sim 1300-1500$ K could have been reached at $\sim 1-2$ AU.

Whether micron-sized particles could have been transported from the inner nebula, ~ 1 AU, to 20-30 AU is problematical. Cuzzi et al, (1993) have computed that small grains entrained in the outflowing gas near the mid-plane of the solar nebula could drift radially outward $\sim 2-5$ AU before being accreted onto larger particles. Stevenson (1990) concluded that there was little mixing between the inner and outer regions of the nebula. Grain growth by aggregation was apparently a relatively rapid process, in a time scale short compared to the lifetime of the solar nebula (Weidenschilling 1988, Mizuno 1989), limiting the time available for diffusion.

↑
radial

Thus, it seems unlikely that particles formed near 1 AU were transported to the region where cometsimals were accreting. We consider next whether an interstellar origin of the crystalline grains is plausible.

C. The Astronomical Evidence

At the distance of Uranus-Neptune (-20-30 AU), the solar nebula was probably never hot enough to anneal or destroy interstellar silicate grains. Tscharnuter & Boss (1993) and Boss (1994) predict that the temperature in the protosolar nebula was $\lesssim 150$ K at the distance of Saturn-Neptune. The high deuterium ratios in an organic phase of interplanetary dust particles and primitive meteorites is evidence that even some moderately volatile species survived from the interstellar medium (Kerridge 1993). Ibus, intact interstellar silicate particles could have been incorporated into the growing icy planetesimals.

If crystalline olivine was abundant in the interstellar cloud from which the solar nebula formed, we might expect to see the signature of olivine in other molecular clouds or star-forming regions. Yet, the 11.2 μm peak is not seen in the spectra of diffuse interstellar dust (Roche & Aitken 1984,1985). Nor is it present in the Trapezium, typical of molecular cloud dust (Hanner, Brooke & Tokunaga 1994b).

A search of both emission and absorption spectra of young stellar objects has so far failed to find any spectra similar to the comets (Cohen & Witteborn 1985; Hanner, Brooke & Tokunaga 1994b). Schutte et al. (1990) proposed that the 11.2 μm peak in the Herbig Ae star Elias 1 in the Taurus dark cloud was due to crystalline olivine. However, Elias 1 displays the series of infrared aromatic hydrocarbon emission bands and the 11.2 μm peak arises primarily from the aromatic hydrocarbon emission band at that wavelength (Hanner, Brooke & Tokunaga, in preparation). Aitken et al. (1988) have detected an 11.2 μm signature of crystalline grains in the polarization of AFGL 2591, a compact molecular cloud source; the feature is marginally visible as a change of slope in the extinction curve. et al.

Mass-losing AGB stars are thought to be a source of interstellar dust. A prominent peak at 11.2 μm is seen in the spectra of some AGB stars. Whether this peak is due to olivine (Little-Marein & Little 1990) or to the aromatic hydrocarbon emission feature (Sylvester et al. 1994) is ambiguous at present. Complete 3-13 μm spectra of these objects are needed in order to clarify the origin of the 11.2 μm feature.

A silicate feature resembling that in comets Halley and Mueller has been detected in the disk surrounding β Pictoris (Knacke et al. 1993). The age of β Pic is estimated to be 1-2 $\times 10^8$ years (Backman & Paresce 1992). Since the age greatly exceeds the dynamical lifetime of small particles in the disk, the particles must have been resupplied from some reservoir, such as comets (e.g. Weissman 1984).

In summary, there is not a clear spectral link between silicate grains in comets and those in interstellar clouds or surrounding young stellar objects. Crystalline silicates are apparently rare in the ISM. While a presolar origin is plausible based on the maximum temperatures in the outer solar nebula, the existing astronomical data ^{does} is not help to support an interstellar origin for the crystalline silicates in comets.

IV. CONCLUSIONS

We have discovered the spectral signature of crystalline olivine at 11.2 μm in the spectrum of the dynamically new comet Mu eller 1993a. The presence of crystalline olivine in both new and evolved comets indicates that these grains must have been widespread in the solar nebula, While the required temperatures for formation of crystalline grains in the solar nebula were attained at $R \lesssim 1$ AU, the difficulty in radial transport of grains from 1 - 2 AU to 20-30 AU makes a presolar origin a more likely alternative. Yet, the lack of an olivine signature in spectra of the interstellar medium and young stellar objects is puzzling.

Several kinds of future observations will be required to clarify the origin of crystalline silicates in comets:

1. Spectra of a larger sample of comets are needed to understand the heterogeneity among comets. At present, only 20% of the new comets with high signal/noise spectra exhibit a silicate feature similar to P/Halley's.

2. Analysis of the matrix material in primitive meteorites at the submicron level, similar to the analyses of IDPs, promises to reveal new information about the mix of high and low temperature condensates in the solar nebula and the presence of interstellar material.

3. Study of interstellar and circumstellar dust with higher spectral resolution ^{or} may lead to detection of weak olivine features and may distinguish between the olivine peak and the aromatic hydrocarbon band which falls near the same wavelength.

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FIGURE LEGENDS

- Figure 1. Spectrum of Comet Mueller 1993a at $R=2.06$ AU. a: Nov. 15, 1993 b: Nov. 16, 1993 c: Nov. 17, 1993 cl: average of Nov. 15-17.
- Figure 2. The silicate feature in Comet Mueller, Nov. 15-17. Flux divided by 220 K blackbody continuum, Comet P/J Halley flux/continuum (Campins & Ryan 1989; Hanner et al. 1994a).

Comet Mueller 1993a Nov 15, 1993

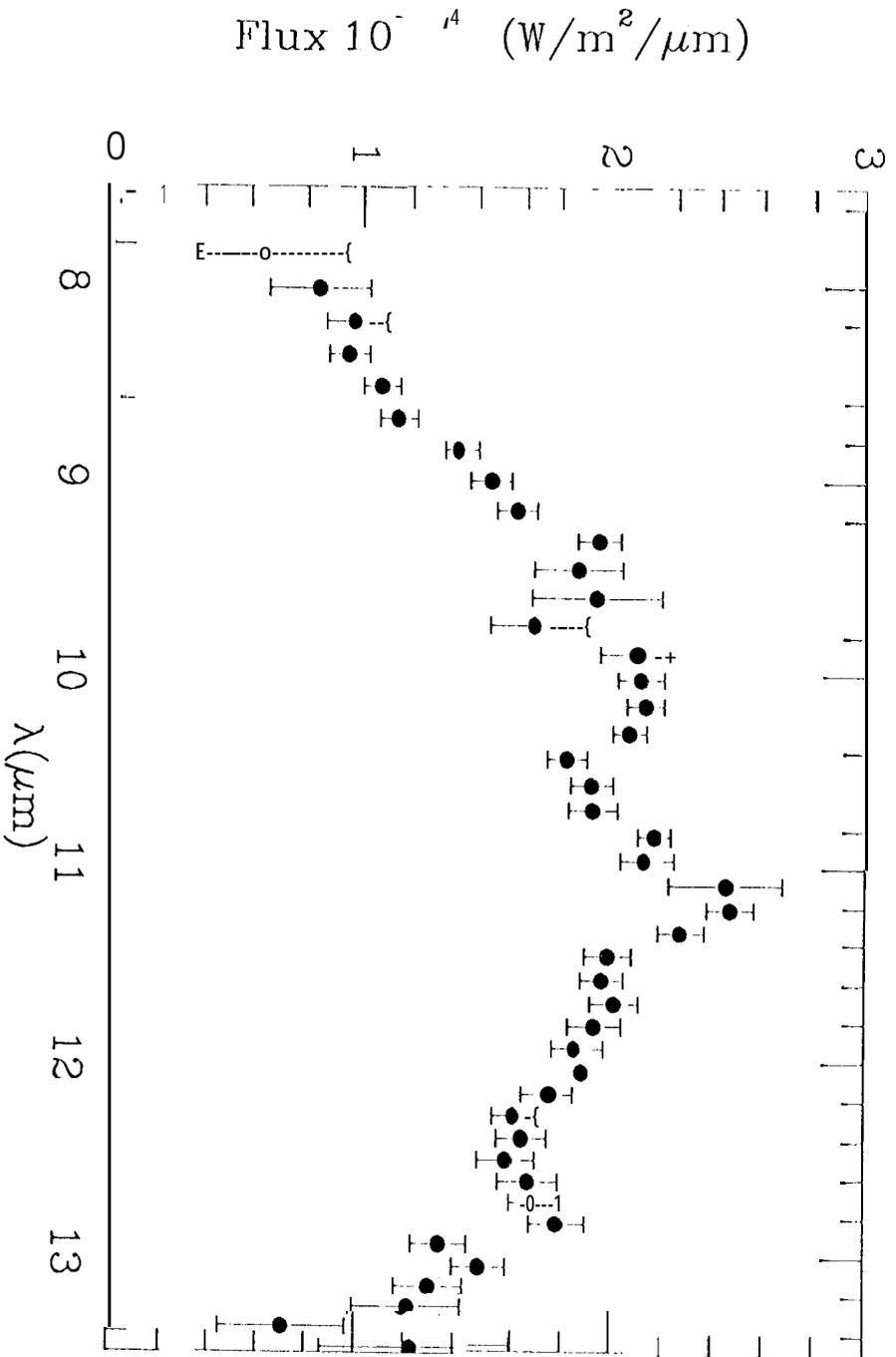
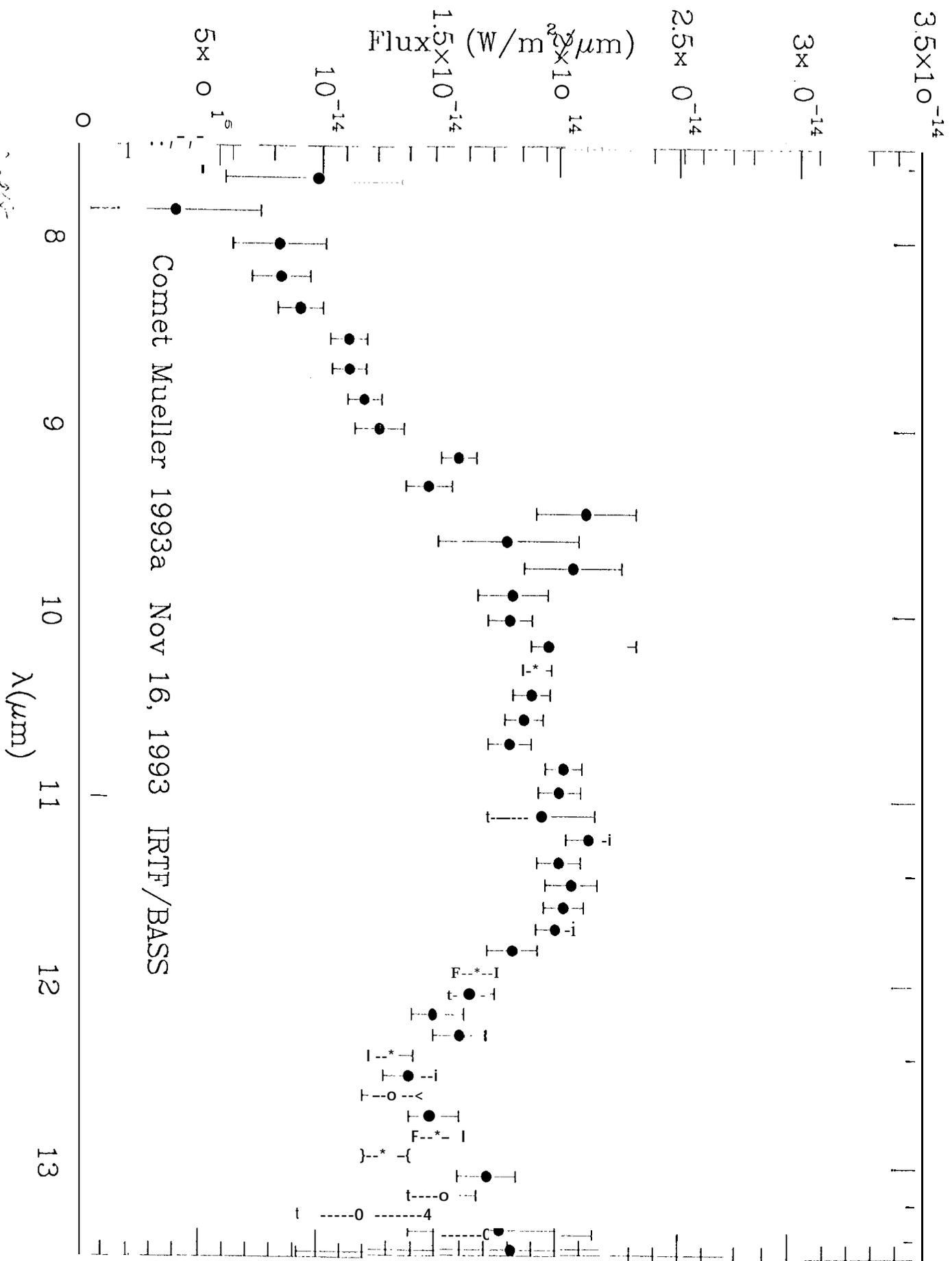


Fig. 1a



Flux 10^{-14} ($\text{W}/\text{m}^2/\mu\text{m}$)

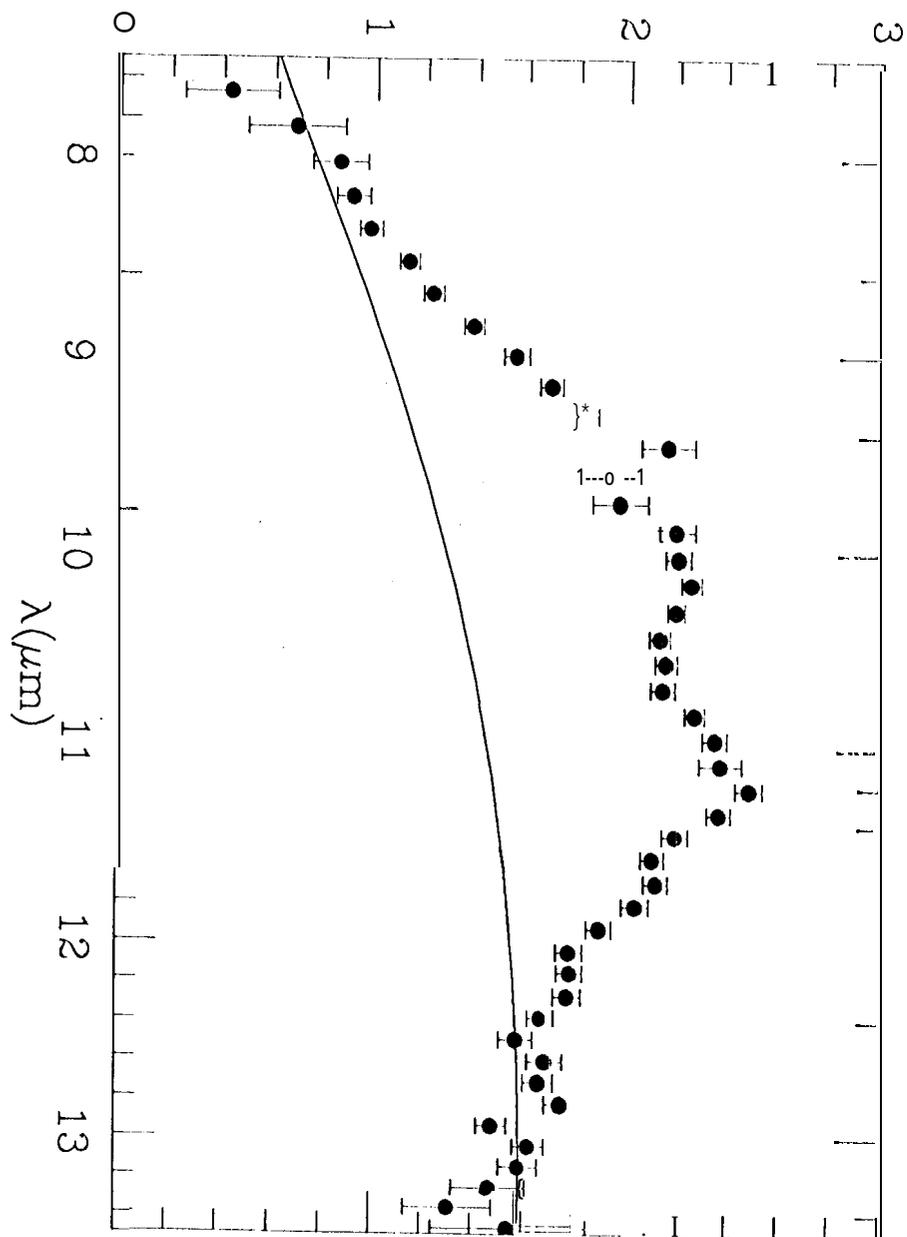
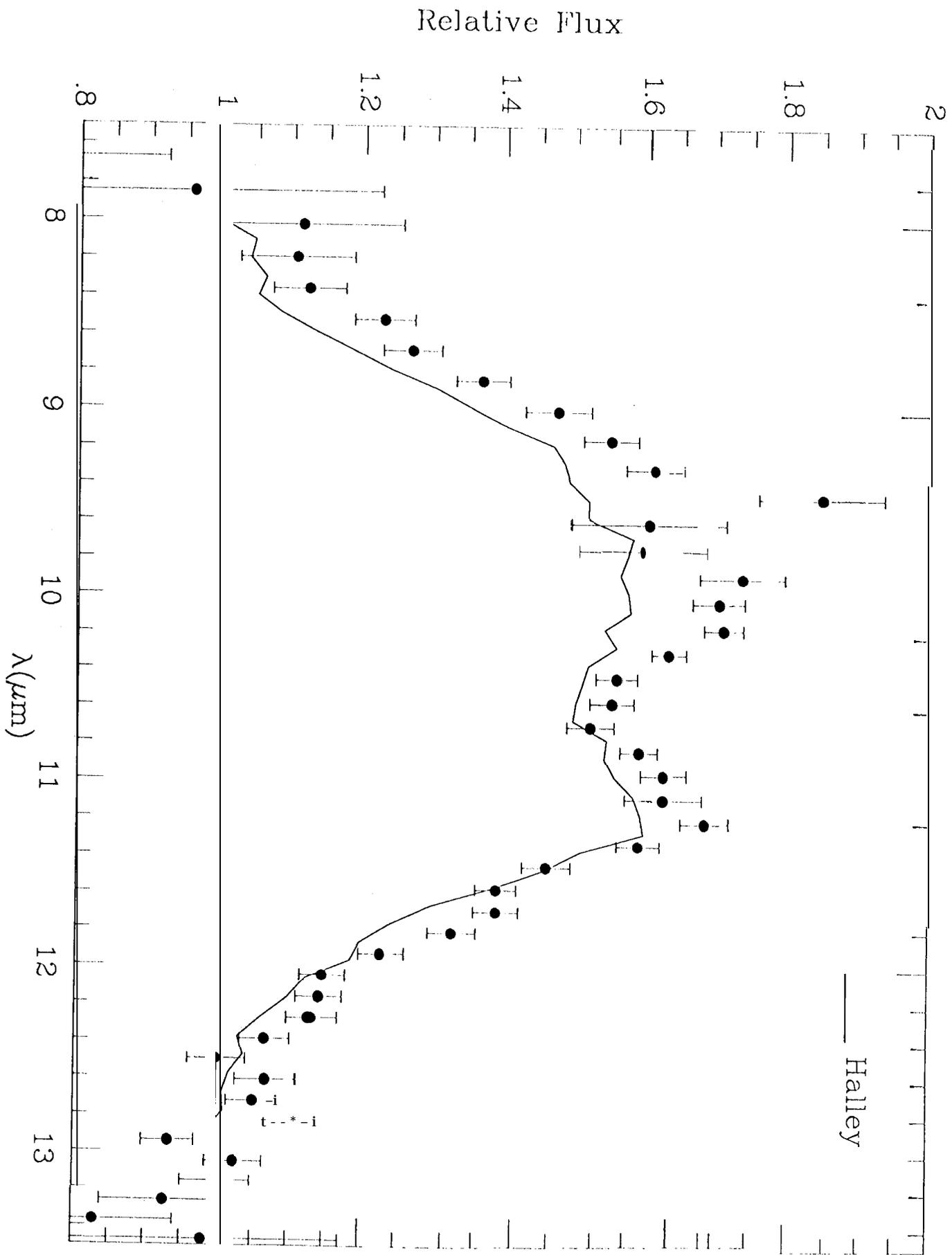


Fig. 1a



Comet Mueller 1993a Nov 15-17, 1993 / 220 K blackbody

Fig. 2