10 μm SPECTRAL STRUCTURE IN COMETS

David K. Lynch*, Ray W. Russell*, and Humberto Campins**

*The Aerospace Corporation, Space Sciences Laboratory
**Planetary Science Institute

Abstract

The 10 μm spectra of comets Halley (1982i), Wilson (1986l), Kohoutek (1973f) and Bradfield (1987s) are presented and compared. The silicate emission profiles of Halley and Bradfield are seen to be remarkably similar in that both contain a sharp break in the spectrum at 11.3 μm. Comet Bradfield does not show the same double peak structure seen in olivine and reported in Comet Halley by Campins and Ryan (1988) and Bregman, et al. (1987). We interpret the 11.3 μm signature as being due to olivine-type dust grains with at least some degree of crystallinity. Olivine alone is not enough to reproduce the shape of the 10 μm structure. However, in view of our past success in fitting interstellar dust features with the emissivity profile obtained from amorphous grains produced by laser-vaporizing olivine, this is a very appealing identification. We note that there are significant variations in olivine spectra due to compositional differences, grain size distribution and related grain temperature variations to make the olivine identification tentative. We further tentatively identify the 9.8 μm feature in Halley as being due to either amorphorous olivine or a phyllosilicate ("layer lattice"). Neither the spectra of Halley, Kohoutek, nor Bradfield exhibited the 12.2 μm feature seen in Comet Wilson, which may prove diagnostic of the composition or thermal history differences between these comets. IR spectra of various mineral samples are discussed in terms of their match to cometary spectra.

I. Introduction

The composition of interstellar dust is so poorly known that, until recently, any statement about its make-up needed to be heavily qualified. Indeed, identifications in the 10 μm thermal window have to date amounted to little more than vague associations of the "silicate" emission feature to grossly similar features in terrestrial (and some lunar) silicates. It was shown theoretically by Gilman (1969) that it is plausible that silicates could condense from a hot cloud as it cools. This work has recently been extended by, for example, Grossman and Larimer (1974). Several workers (e.g. Day and Donn, 1978) obtained laboratory spectra which exhibited absorptivity (i.e., emissivity) peaks which were similar to the astrophysical feature at 9.8 μm, but which either had a central wavelength that did not match that seen in astronomical spectra, or did not have enough of a long wavelength tail. Stephens and Russell (1976), using laser vaporized sample of olivine were able to match the 10 μm feature in the Trapezium, and later the twenty μm feature as well (Cohen, et al., 1980). The first in situ experimental evidence that condensed silicates might indeed be present in comets was obtained by the mass spectrometer on the Halley flyby which samples comet dust (Kissel, et al., 1986).

417

Such compelling results add scientific weight to but not proof of the larger assertion that interstellar material has a large proportion of siliceous material (or any of the other proposed celestial grain materials, such as polycyclic aromatic hydrocarbons, hydrogenated amorphous carbons, etc.). An additional concern is that silicate–to–silicate variations in the type of fine spectral structure (features whose widths $\Delta\lambda$ are of the order of $\lambda/100$) necessary to uniquely identify the composition is complex and subtle. In view of the now well established laboratory demonstration that fine spectral features are often lost when the crystals are heated and become amorphous, the need to proceed carefully cannot be over emphasized.

Comets provide a rare astrophysical opportunity to identify the chemical composition of solar system dust because their thermal emission originates in simple, nearly isothermal, optically thin dust clouds. In this paper we analyze a simple subset of thermal emission from comets near 10 μm. The goal is to identify those features which are: 1) real, 2) present in more than one spectra, in an effort to help identify the mineralogical species responsible for thermal dust emission in comets. As an intermediate step in this analysis one derives temperatures for the cometary grains from the (assumed) grey continuum and compares the results with the blackbody radiative equilibrium temperature for the appropriate heliocentric distance to derive limits on particles sizes.

II. Five Spectra of Four Comets

Figure 1 shows five spectra taken of four comets: two of Halley, and one each of Bradfield (1987s), Wilson (1986l) and Kohoutek (1973f). Although the true shape of the spectra are accurately represented, they have been multiplied by appropriate intensity factors for convenient placement on the graph. Also note the overlay of a 300 K grey body for shape comparison. Table 1 gives the source of data and the continuum color temperature.

Table 1

		T(K)
A.	Bradfield 1987s (Lynch and Russell, 1988)	475
B.	Kohoutek 1973f (Merrill, 1974)	600
C.	Halley 1982i (Campins and Ryan, 1988)	385
D.	Halley 1982l (Bregman, et al., 1987)	320
E.	Wilson 1986s (Lynch, et al., 1988)	300

While it is obvious that the slope of any portion of a spectrum are seriously influenced by the temperature of the blackbody spectral shape it follows, the locations where the slope changes abruptly will be independent of the underlying blackbody temperature. With this in mind, we note two aspects common to most of the spectra of figure 1, and possible additional structure in the spectra of Comet Halley (see also Fig. 3).

1. A break in spectra A,C,D and possibly B at about 11.3 μm.
2. A break in spectra A,B,C and possibly D at about 9 μm.
3. Double–peak structure (9.8 and 11.3 μm) in C and D.

The meaning of these features depends on where the continuum is drawn. They could be either: a) two broad emission features at 9 or 9.8 and 11.3 μm, or b) a single broad dip at 10 μm. Campins and Ryan (1988) have proposed that olivine interplanetary dust particles (IDPs) can explain the shape of the Halley spectra longward of 10 μm.

418

III. Spectra of Olivine

   Olivine is common rock–forming mafic (rich in Mg and Fe) mineral occurring widely
on Earth. Its composition varies within two well–defined limits, being an isomorphous
solid solution between forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4).
From the low pressure gas phase olivine condenses at around 1300 K (Grossman and
Larimer, 1974) although lower temperature condensates with closely related chemical
composition occur down to around 800 K. Figure 2 shows several IR spectra of olivine
digitized from publications of A. Hunt and Salisbury (1974), B. Zaikowski (1975), C. Day
(1975), and D. Koike, et al. (1981). Several properties of the spectra are evident:

   1.   Two prominent peaks occur in the 10 µm region, at around 10.1 and 11.4 µm.
   2.   The peaks occur at somewhat different wavelengths in different samples.
   3.   The shapes of the peaks are different in different samples.

These spectra, though showing some differences, suggest that the spectra of olivine could
be used to identify mineralogical content of cometary dust, providing that olivine's
spectral variations cannot be duplicated by spectra of other minerals.

IV. Is Comet Halley's Dust Made of Olivine?

   Figure 3 shows Campins and Ryan's fit of the IRTF Halley spectrum to Sandford and
Walker's (1985) olivine interplanetary dust particle. It is evident that:

   a.   Halley's spectrum's peaks .... $\simeq$ 9.8 and $\simeq$ 11.3 µm
   b.   Olivine IDP spectrum's peaks .... $\simeq$ 10.3 and $\simeq$ 11.3 µm
   c.   Olivine (Fig. 2) spectrum's peaks ...... $\simeq$ 10.1 and $\simeq$ 11.3 µm

From this analysis we see that the structure of Halley's spectrum and olivine's spectrum,
though similar, are significantly different, shortward of 10 µm. Although the 10.1 to
10.3 µm olivine features are observed to change wavelength in various samples, no
crystalline olivine sample was found that had the short wavelength peak shifted to
$\simeq$ 9.8 µm. The discrepancy is enough to suggest that olivine is either not the sole
content of the dust, or if it is, it's lattice structure (and thus spectral structure) has been
altered in a significant manner. An equally plausible scenario involves a mineral
component as yet unidentified. The main appeal of olivine as a major constituent in
cometary dust is that a large fraction of IDPs contain olivine–like material and comets
are believed to be the main source of IDPs (Sandford and Walker 1985). Furthermore, an
amorphous olivine emission spectrum has been shown to match the 10 and 20 µm
emission profile (Stephens and Russell, 1979).

V. What Causes the 9.8 µm Feature?

   Our approach to identifying the 9.8 µm feature in Comet Halley's spectrum is
two–fold: 1) locating minerals with known 9.8 µm emission features and compositions
similar to olivine, and 2) locating minerals with the 9.8 µm feature that occur in IDPs.

   Taking our cue from the tentative olivine identification of the 11.3 µm feature, we
have searched for minerals whose spectra show the similar structure and which would be
expected to condense from a low density plasma around 1300 K as olivine does. The
following minerals are possible candidates for the mineral responsible for the 9.8 µm
feature.

419

1. Andalusite .... $AlSiO_5$
2. Pectolite .... $NaCa_2Si_3O_8OH$
3. Cordierite .... $(Mg,Fe^{3+})_2Al_4Si_5O_{18}$
4. Garnierite .... $(Ni,Mg)_3Si_2O_5(OH)_7$
5. Hisingerite .... $Fe_2Si_2O_5(OH)_4 \cdot 2H_2O$

The spectra of these minerals are shown in figure 4.

Andalusite is considered a metamorphic mineral and, being trimorphic with neosilicates kyanite and sillimanite, would not normally be expected to form directly from a low density plasma. However, it is not known what changes would take place in corundum (Al_2O_3) to alter it to andalusite on solar system time scales. Kyanite shows a feature too broad to reproduce the 9.8 μm cometary feature and sillimanite has a completely different 10 μm spectrum. Pectolite is an inosilicate which has both 9.8 and 11.3 μm features. Cordierite is a cyclosilicate and is commonly found with polymorphs of Al_2O_5 (see #1 andalusite above). Except for being metamorphic, cordierite might be considered a suitable candidate. Garnierite, though possessing the proper spectral shape, is probably too rare to be seriously considered because of the low nickel abundance in the solar system. Little is known about hisingerite.

The cometary feature at around 9.8 ± 0.2 μm (figure 3) may well be due to the Si–O stretching mode in phyllosilicates (Farmer, 1974). Such a feature has been seen in IDPs (Sandford and Walker, 1985), some classes of which also show the 11.3 μm feature attributed to olivine (Campins and Ryan, 1988).

Sandford and Walker found that the best IDP fit to Merrill's Kohoutek spectrum was a roughly equal mixture of layer–lattice silicates and pyroxenes (phyllosilicates and inosilicates). We find the best fit to Campins and Ryan's spectrum of Comet Halley would be roughly equal mixtures of phyllosilicates and neosilicates (olivines).

Finally, we note that amorphous olivine (Stephens and Russell, 1979) has a single feature at ≃ 9.8 μm (see Fig. 5). In view of the identification of the 11.3 μm feature with crystalline olivine, it is reasonable to suggest that both peak in Comet Halley's spectrum can be explained by a mixture of amorphous and crystalline olivine.

VI. Conclusions

Five spectra of four comets are shown to contain enough common spectral features to begin making tentative mineralogical identifications of the dust. Crystalline olivine is a likely candidate for reproducing the 11.3 μm feature in some comets. Other minerals acting together (possibly amorphous olivine and phyllosilicates similar to those identified in IDP must be present to explain the 9.8 μm feature in Comet Halley's spectrum.

References

Bregman, J.D., et al., 1987, Astron. and Astrophys., 187, 616.

Campins, H. and Ryan, E.V., 1988, (preprint).

Cohen, N.L., McCarthy, J.F., Russell, R.W. and Stephens, J.R., 1980, B.A.A.S., 11, 610.

Day, K.L., 1975, Astrophys. J., 199, 660.

Day, K.L., and Donn, B., 1978, Astrophys. J. (Letters), 222, L45.

Farmer, V.C., 1974, The Infrared Spectra of Minerals, Mineralogical Society of London.

Ferraro, J.R., 1982, The Sadtler Infrared Spectra Handbook of Minerals and Clays,
    Sadtler Research Laboratories, Philadelphia.

Gilman, R.C., 1969, Astrophys. J. (Letters), 155, L185.

Grossman, L. and Larimer, J.W., 1974, Rev. Geophys. and Space Phys., 12, 71–101.

Hunt, G.R. and Salisbury, J.W., 1974, AFCRL-TR-74-0625.

Kissel, J., et al., 1986, Nature, 321, 280–282.

Koike, C., Hasegawa, H., Asada, N. and Hattori, T., 1981, Astrophys. Space Sci., 79, 77.

Lynch, D.K., et al., 1988, (preprint).

Merrill, K.M., 1974, Icarus, 23, 566–567.

Russell, R.W., Lynch, D.K., and Chatelain, M., 1988, Bull. A.A.S., 20, 724.

Sandford, S.A. and Walker, R.M., 1985, Astrophys. J., 291, 838.

Zaikowski, A., Knacke, R., and Porco, C.C., 1975, Astrophys. Space Sci., 35, 97.

Figure 1
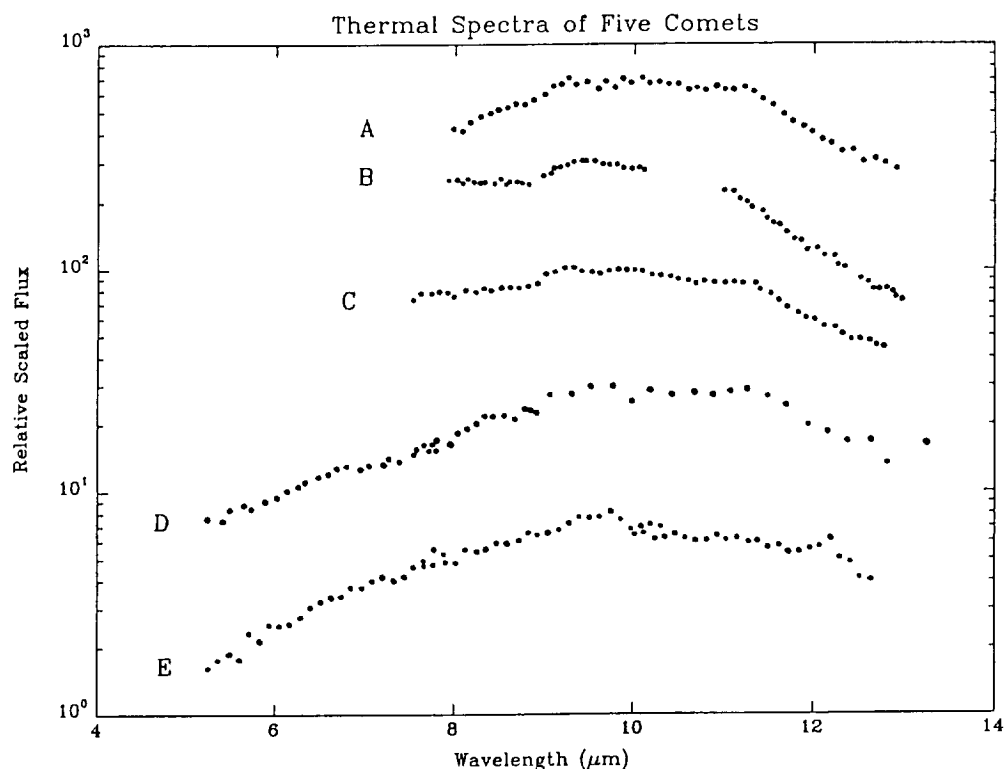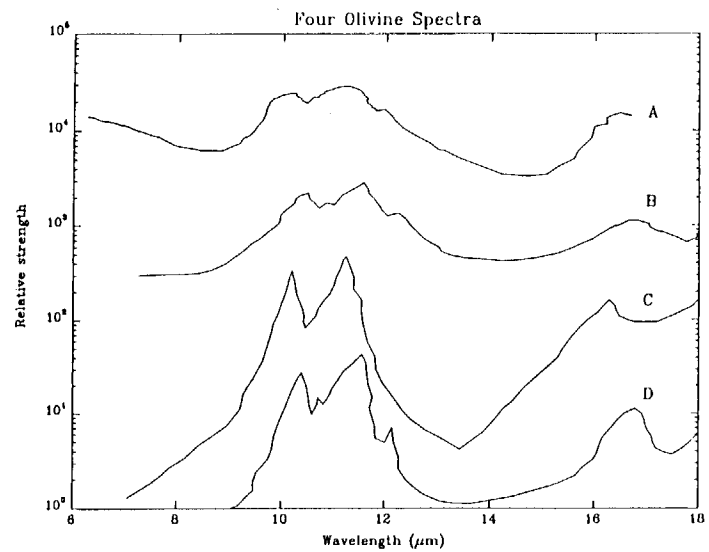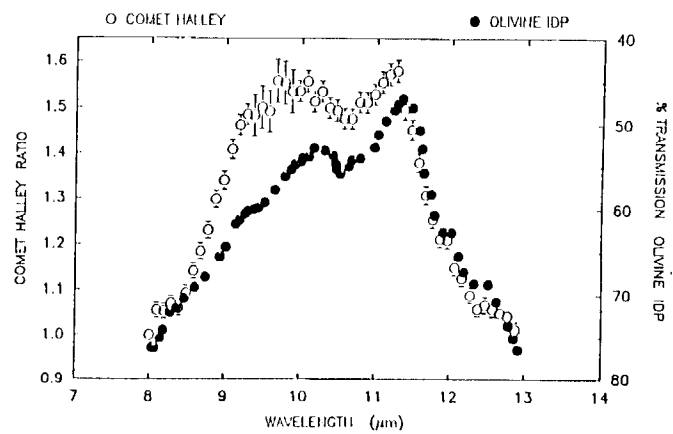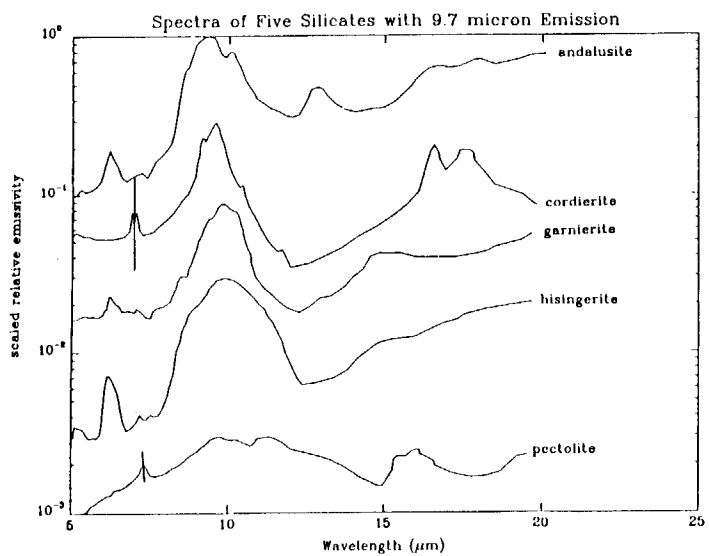
Four Olivine Spectra

Figure 2

Spectra of Five Silicates with 9.7 micron Emission

Figure 5

O COMET HALLEY   ● OLIVINE IDP

Figure 3

Stephens and Russell (1979)