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The dust properties of a short period comet: comet P/Borrelly

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Abstract. We have calculated the thermal emission spectrum of the dust of comet P/Borrelly (1994l), a short-period comet (Jupiter family), from 3 μm to 14 μm as well as the 10 μm silicate feature in terms of the comet dust model as porous aggregates of interstellar grains. Compared to comet P/Halley dust, the dust grains of P/Borrelly appear to be relatively more processed (more carbonized), less fluffy, and richer in smaller particles. The fluffy aggregate model of silicate core-amorphous carbon mantle grains with a porosity $\mathrm{P} = 0.85$ can match the observational data. To generalize the dust properties of short-period comets, systematic observations of the thermal emission spectra and the silicate features for a large set of samples are needed.

Key words: ISM: dust – comets: general - comets: individual: P/Borrelly

1. Introduction

In general, comets are divided into two classes in terms of their orbits: long-period comets (with orbital periods ranging from 200 yrs up to 10^7 yrs) and short-period comets (with periods shorter than 200 yrs). Long period (hereafter LP) comets originate in the Oort cloud with an isotropic distribution of inclination. Short period (hereafter SP) comets can be further classified as "Jupiter family" comets and "Halley type" comets. Jupiter family comets, which constitute the majority of the SP comets, have a small inclination and an orbital period $\mathrm{P} < 20$ yrs (Levison 1996). It is commonly believed that Jupiter family comets originate in the trans-Neptune region which is known as the Kuiper Belt. Strong evidence of the evolutionary connection of Jupiter family comets with the Kuiper Belt was provided by the recent detection of "Kuiper Belt Objects" (see e.g. Jewitt & Luu 1995). Halley type comets, with a relatively longer period ($20 < \mathrm{P} < 200$ yrs) and larger inclination, can not come from the Kuiper Belt according to Duncan et al. (1988). However they could originally come from the Oort cloud and then have been scattered into SP type orbits by the perturbation of Jupiter and/or Saturn. For a recent review on SP comets see Weissman & Campins (1993). To first order, all the comets have similar properties. However, since the SP (Jupiter family) comets have passed many times through the inner solar system, one expects the presence of small scale heterogeneity and differentiation, and also the existence of some differences in the chemical composition, size, morphology, and activity of the outer layer of the nucleus among different types of comets. Indeed, P/Halley is much more active than Jupiter family comets. On the other hand, it has also been suggested that the chemical differences may have already existed in the solar nebula for the different types of comets before they formed (A'Hearn et al. 1995). These differences should also be reflected in the nature of the coma dust. In this work we focus on the dust properties of the Jupiter family comets. In the following sections, unless otherwise stated, the term "SP comets" refers to *Jupiter family* comets. It should be noted here that the outer layers of the dynamically new comets (belonging to LP comets) could have also been modified by cosmic-ray processing which may result in less fragile, larger (and thus cooler) grains (cf. Greenberg et al. 1993). Actually, the so-called deficiency of C_2 and CN observed in a new comet, comet Yanaka (1988r), can be explained in terms of cosmic-ray processing and small-aperture-observations (Greenberg et al. 1993).

It has become well recognized that silicates are a major component of cometary dust particles since the 10 μm Si-O stretching emission feature was first detected in comet Bennett (Maas et al. 1970). However, all the previous detections of the silicate emission were restricted to the LP comets. No distinct 10 μm silicate feature had been detected for the SP comets until, most recently, Hanner et al. (1996) for the first time discovered it in two SP comets: comet P/Borrelly and comet P/Faye. The previous lack of detection of any silicate feature in SP comets may have been due to the fact that a substantial fraction of their surfaces are covered by an inert crust and thus SP comets have a much lower activity level and are considerably fainter compared to LP comets so that it is more difficult to make spectroscopic observations of SP comets. It is the purpose of this work to constrain, or at least to obtain some clues of, the dust properties of the SP comets by modeling the observational spectra of comet P/Borrelly from 3 μm to 14 μm including the 10 μm silicate feature. In Sect. 2 we briefly describe the modeling procedure. The model results and the inferred likely dust properties are dis-

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cussed in Sect. 3. Our discussion and conclusion are presented in Sect. 4.

2. The thermal emission spectrum of comet P/Borrelly: modeling method

Comet P/Borrelly (1994l) is a short-period comet ($\mathrm{P} \simeq 7\,\mathrm{yrs}$, Jupiter family) with an elongated nucleus and fractional active area $\sim 9.4\%$ (Lamy et al. 1995). Its 10 μm silicate excess emission was quite pronounced in the spectrum obtained by Hanner et al. (1996) at a heliocentric distance $\mathrm{r_h} = 1.45\,\mathrm{AU}$. There is no evident indication yet of the presence of the crystalline olivine feature at 11.2 $\mu\mathrm{m}$ which has been observed so far in five LP comets (see Hanner et al. 1994a for a summary), including one dynamically new comet (Hanner et al. 1994b) and the recent fascinating comet Hale-Bopp (Crovisier et al. 1997; Hayward & Hanner 1997) as well as comet P/Halley (Bregman et al. 1987; Campins & Ryan 1989). In addition, the ISO (Infrared Space Observatory) SWS has discovered in comet Hale-Bopp strong far infrared (FIR) emission bands attributable to Mg-rich crystalline olivine and crystalline pyroxene (Crovisier et al. 1997). Although an excess above the amorphous silicate emission appeared at the 11.2 μm point in the Dec. 13 (1994) spectrum of P/Borrelly possibly implying the existence of crystalline silicate, its drop in the spectrum obtained the subsequent night and the relatively low point at 11.1 $\mu\mathrm{m}$ make it difficult to draw a definite conclusion (Hanner et al. 1996). High signal to noise ratio and higher spectral resolution in the 11.2 $\mu\mathrm{m}$ range could help one to make an identification. In this work we confine ourselves to the broad smooth amorphous silicate feature although it is possible that the silicate minerals could have been partially crystallized due to the frequent exposure to the solar irradiation perhaps as a result of the energy released at the interface with radical containing organics (Yamamoto et al. 1998).

The recent ISO observations revealed the presence of crystalline silicate materials in the dust shells of evolved oxygen-rich stars (Waters et al. 1996) and in particular, a close similarity of the crystalline silicate emission spectrum in comet Hale-Bopp (Crovisier et al. 1997) and a young main-sequence star HD 100546 (Waelkens et al. 1996; Malfait et al. 1998). However, it is not reasonable to assume that circumstellar silicates can be the direct precursors of comet silicates without passing through the interstellar medium. Given the comet interstellar grain model which supposes that comet grains are aggregates of interstellar grains rather than solar nebula condensates (Greenberg & Hage 1990), and since interstellar silicates exhibit no crystalline silicate feature, the crystallinity of comet dust silicate must be attributed either to severe heating of interstellar dust in the protosolar nebula or to some phenomena occurring after nucleus formation. Laboratory experiments indicate that prolonged exposure to $\sim 1000\,\mathrm{K}$, i.e., significantly more heating than caused by perihelion passage, can anneal amorphous silicate smokes and produce crystalline features at 11.2 $\mu\mathrm{m}$ (Hallenbeck et al. 1997), but cannot produce the FIR crystalline features seen by ISO in comet Hale-Bopp (Crovisier et al. 1997). In any case severe heating of interstellar grains before incorporation into comet nuclei is inconsistent with the evidence for cold formation of comets. It would require at least 90% of the volatile mantles to have evaporated, allowing for only 10% of the original interstellar molecules to be seen in the coma (Greenberg et al. 1996). This is contradictory to the observations that the general proportions of the coma volatiles are quite similar to those in the interstellar dust mantles and also that the H_2O spin temperature is comparable to that for formation at interstellar grain temperature (see Crovisier 1998 and references therein) rather than having been processed in the protosolar nebula before comet formation.

The dust thermal emission is determined by the chemical composition, morphology, and sizes of the dust grains as well as the solar radiation field. According to the interstellar dust model of comets (Greenberg 1982, 1998) the cometary dust particles are porous aggregates of silicate core-organic refractory mantle interstellar grains. The H_2O dominated ice mantles formed in dense clouds were also incorporated into the aggregates when comets formed, while in the comet coma the volatile ices are evaporated rapidly after being subjected to the solar radiation. On the basis of both non-gravitational forces on comet nuclei (Rickman 1986) and on the properties of comet dust (Greenberg & Hage 1990) it is established that cometary nuclei must be of low density. Furthermore, the splitting of comet Shoemaker-Levy 9 has been interpreted by Sekanina (1996) as most consistent with the properties of a highly fluffy nucleus. From modeling the 10 $\mu\mathrm{m}$ silicate emission band of comet P/Halley, Greenberg & Hage (1990) have concluded that the coma dust should have a porosity in the range of $0.93 < \mathrm{P} < 0.975$. In addition to that, the absorbing carbonaceous material of the organic refractory mantle is required not only to account for the so-called "missing carbon" mystery (Delsemme 1982) but also to heat the dust particles sufficiently to give silicate excess emission since the organic materials are much more absorbing in the UV/visual and much poorer in emitting in the far infrared/submillimeter than silicates.

A recent evaluation of the in situ PUMA-1 data of P/Halley indicated that the rock-forming silicates consist of various mineral components: Fe-rich silicates, Mg-rich pyroxenes (not olivines), S-rich silicates, and Fe/Ni particles etc. (Schultz et al. 1997). On the other hand, Colangeli et al. (1995) fitted the twin peak silicate feature in comet P/Halley by three mineral components – amorphous pyroxene for the short wavelength side of the feature, amorphous olivine for the mid- to long-wavelength component of the feature, and crystalline olivine. However amorphous pyroxene and crystalline olivine are not found to be components of interstellar grains (Li & Greenberg 1997). We propose that comet grains are composed of fluffy aggregates of interstellar grains (Greenberg & Hage 1990) of interstellar composition (Li & Greenberg 1997). With this assumption, we will adopt the Halley properties (Greenberg & Hage 1990) as a starting point.

To calculate the dust thermal spectrum, we first obtain the effective indices of refraction of the porous core-mantle aggregates on the basis of the Maxwell-Garnett effective medium theory, and the absorption efficiencies are then calculated by using

Mie scattering theory. It should be noted that the spherical shape assumed for an aggregate of spherical silicate cores coated with organic mantles is a simplifying assumption which makes the calculation tractable. However, it should also be noted that if the required calculations are only for absorption and emission cross sections as needed for determining grain temperatures, the errors are not significant. This has been justified by rigorous calculations (Hage & Greenberg 1990). The next step is to derive the temperatures of the dust grains as a function of grain sizes from the dust energy balance equation. Finally, we can calculate the dust thermal emission by integrating over the full size distribution. The input parameters are the indices of refraction of the core (amorphous silicate), the mantle (organic refractory), the mass ratio of the mantle to the core $\mathrm{m_{or}/m_{si}}$, the porosity P of the porous aggregates, and the grain size (mass) distribution $\mathrm{n(m)}$ of the aggregate. For further details about the calculation we refer to Greenberg & Hage (1990). The dust temperatures and thus the resulting thermal spectrum are dependent on the grain material, the size and fluffiness (porosity) of the aggregate.

3. Modeling results and the possible dust properties

Following Greenberg & Hage (1990), we model the comet dust of P/Borrelly as fluffy aggregates of core-mantle interstellar particles. The optical constants [the complex indices of refraction, $m(\lambda) = m^{'}(\lambda) - i\,m^{''}(\lambda)$] for interstellar grains used in the modeling of comet P/Borrelly are based on the determination of the composition of interstellar core-mantle grains by fitting both the interstellar extinction curve and interstellar polarization (Li & Greenberg 1997). For the 10 $\mu\mathrm{m}$ silicate emission feature, we employ amorphous olivine for the silicate core, using the $m^{''}(\lambda)$ of Dorschner et al. (1995) for amorphous olivine $\mathrm{MgFeSiO_4}$ for wavelengths longward of $2\,\mu\mathrm{m}$. For $0.3\,\mu\mathrm{m} \leq \lambda \leq 2\,\mu\mathrm{m}$, we adopt the $m^{''}(\lambda)$ of Draine & Lee (1984). For $\lambda \leq 0.3\,\mu\mathrm{m}$, we adopt the $m^{''}(\lambda)$ of crystalline olivine from Huffman & Stapp (1973), because both crystalline olivine and amorphous olivine absorb through electronic transitions in the far ultraviolet. Finally, the real part of the optical constants $m^{'}(\lambda)$ is calculated from $m^{''}(\lambda)$ by using the Kramers-Kronig relation. For the grain mantle, we shall first employ the optical constants of H, C, O, N-rich organic refractory residues (Li & Greenberg 1997).

The porosity P is treated as a free parameter with a wide range of P from 0 (compact) to 0.975 being considered. *As a starting point*, we adopted the Halley dust size (mass) distribution obtained by spacecrafts (see Fig. 3a of Greenberg & Hage 1990) which can be expressed by a polynomial function (e.g., see Lamy et al. 1987). Adjustment of the Halley size distribution can be made by modifying one of the coefficients to, for example, enhance the smaller grains. For the mass ratio of the organic refractory mantle to the silicate core, according to the mass spectra of comet P/Halley dust as measured by the PUMA mass spectrometer on board the spacecraft Vega 1 (Kissel & Krueger 1987), we adopt $\mathrm{m_{or}/m_{si}} = 1$. The effects of a lower $\mathrm{m_{or}/m_{si}}$ ratio will be discussed later. The lower mass (size) limit was set at $10^{-14}\,\mathrm{g}$ which is equivalent to an individual tenth micron interstellar grain. Particles with radii smaller than tenth micron contribute very little to the thermal emission in comet P/Halley (Hanner et al. 1987). The upper mass limit was set at the maximum liftable mass $\mathrm{m_{max}}$, the mass of the largest dust grain which can be dragged away from the nucleus. Adopting the nucleus size (equivalent to an $\sim 2.2\,\mathrm{km}$ radius sphere) estimated by Lamy et al. (1995), the gas production rate detected by A'Hearn et al. (1995) [scaled by an $\mathrm{r_h^{-2.7}}$ heliocentric dependence (A'Hearn et al. 1995)], and assuming a nucleus density $0.3\,\mathrm{g\,cm^{-3}}$ (Rickman 1986), a grain mass density $0.07\,\mathrm{g\,cm^{-3}}$ (corresponding to a porosity $\mathrm{P} = 0.975$), we estimated $\mathrm{m_{max}} \approx 2.0 \times 10^6\,\mathrm{g}$ from Eq. 19 in Newburn & Spinrad (1985). For a larger dust mass density (corresponding to a lower porosity), $\mathrm{m_{max}}$ becomes smaller, but one can expect that even a significant variation in $\mathrm{m_{max}}$ will not affect the resulting near infrared (hereafter NIR) emission spectrum because those high mass particles are so cold that their contribution is negligible (as long as the grain size distribution is not too flat).

Our calculations show that, within the Halley size distribution, if the particles (with organic residue mantles) are compact they are then too cold to give excess emission at the silicate band. With the dust size distribution adjusted to be greatly weighted toward smaller grains, the silicate feature is enhanced as expected (Gehrz & Ney 1992) but is then far too narrow compared with the observation of comet P/Borrelly. We have tried to fit the observation by both varying the porosity and adjusting the dust size distribution. It turns out that none of these attempts provides a satisfactory match. In Fig. 1a, b, c we present the "best-fitting" (to the silicate emission) spectra using amorphous olivine cores and organic residue mantles, calculated from $\mathrm{P} = 0.85, 0.90, 0.95$ respectively. The corresponding grain size distributions are plotted in Fig. 1d. It can be seen from these figures that the theoretical spectra are a bit sharper than the observation. In addition, the NIR spectrum (3 – 5 $\mu\mathrm{m}$) is too low compared to the observation. We note that, lower porosity or enhancement of larger particles in the size distribution could broaden the silicate feature, but then, the whole feature becomes too shallow and the peak position shifts to longer wavelengths (the particles are too cold).

Suppose that the chemical composition of organics of SP comets could have been modified by solar irradiation or possibly as proposed by A'Hearn et al. (1996), that the original chemical composition for the solar nebula out of which the SP comets were formed is different from where LP comets were formed. This has led us to consider an extreme case – amorphous carbon, which may be characteristic of the most highly processed organics materials – highly depleted in H, O, N. The indices of refraction of amorphous carbon are adopted from those compiled by Rouleau & Martin (1991). As shown in Fig. 2a, a satisfactory fit to the 10 $\mu\mathrm{m}$ silicate feature and the NIR emission can be obtained by the amorphous carbon model with a porosity $\mathrm{P} = 0.85$. The dust size distribution is enhanced toward smaller particles. The fits provided by other porosities are not as good as that by $\mathrm{P} = 0.85$. It can be seen in Fig. 2b that, although the fit for $\mathrm{P} = 0.90$ is not bad, the theoretical spectrum is a bit deficient in the NIR region. Fig. 2c shows that the predicted NIR spectrum from $\mathrm{P} = 0.95$ is too low compared to the observation.

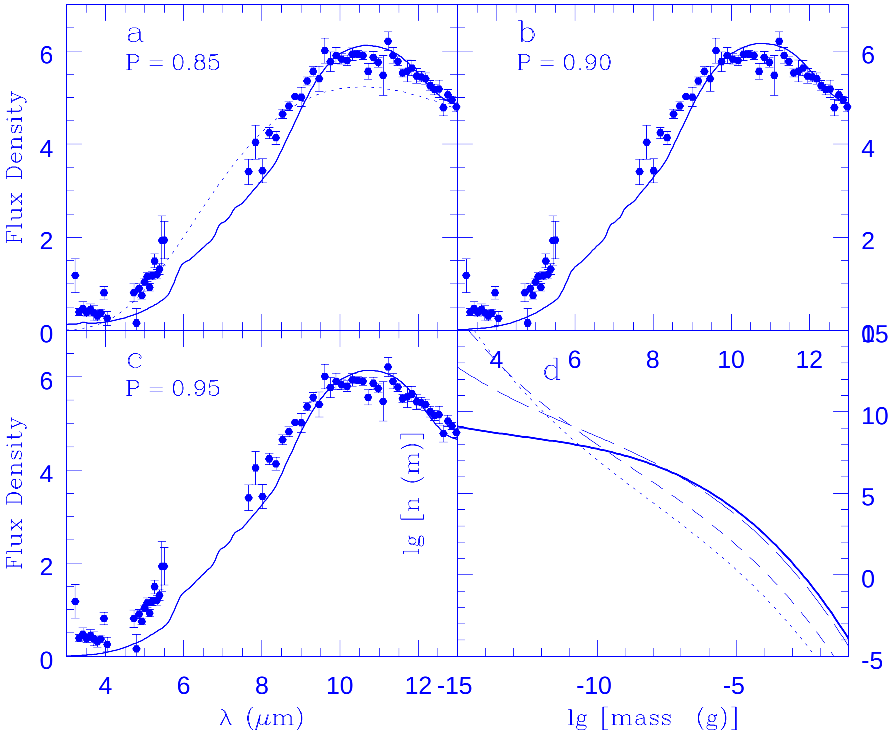

Fig. 1a–d. The infrared thermal emission spectrum of comet P/Borrelly (in $10^{-14}\,\mathrm{W\,m^{-2}\,\mu m^{-1}}$). The observational data (points) are taken from Hanner et al. (1996). The predicted spectra of the porous aggregate comet dust model of silicate core-*organic refractory* mantle interstellar grains with a porosity $\mathrm{P} = 0.85, 0.90, 0.95$ are plotted as solid lines in **a**, **b** and **c**, respectively. The chi-square, $\chi^2 = \sum\{[f_\nu(\mathrm{model}) - f_\nu(\mathrm{obs})]/\sigma_i\}^2/(\mathrm{N}-\mathrm{M})$ (here $\mathrm{N} = 63$, the number of observational data points; $\mathrm{M} = 2$ is the number of free parameters: the porosity and the dust size distribution) which, to some extent, can describe the goodness of the fit, is about 18.4, 18.9, 19.0 for $\mathrm{P} = 0.85, 0.90, 0.95$, respectively. The dotted line in **a** is a blackbody ($\mathrm{T} = 275\,\mathrm{K}$) emission (Hanner et al. 1996). The corresponding dust size distributions are shown in **d**: solid – the Halley dust size distribution; dotted – $\mathrm{P} = 0.85$; short dashed – $\mathrm{P} = 0.90$; long dashed – $\mathrm{P} = 0.95$.

If we increase the weight of smaller particles, the fit to the NIR spectrum improves; however, then the silicate feature becomes too sharp. We have also tried lower porosities ($\mathrm{P} < 0.85$), but then we found that the dust grains are too cold so that the calculated spectra shift the peak positions to longer wavelengths and are deficient in the NIR.

Therefore we conclude that the amorphous olivine core - amorphous carbon mantle model with a porosity $\mathrm{P} = 0.85$ (Fig. 2a) provides the best fit to the observations. Integrating over the mass range of interest in this work, the total dust mass required by the model with $\mathrm{P} = 0.85$ is $\approx 3.9 \times 10^9$ g. If we assume an average outflow velocity $\mathrm{v} = 0.5\,\mathrm{km\,s^{-1}}$ for all the grains rather than taking into account the outflow velocity distribution as a function of grain size, following the formula given by Hanner et al. (1985), we derive the dust production rate to be $\approx 1.5 \times 10^6\,\mathrm{g\,s^{-1}}$. If we adopt the water production rate $\log \mathrm{Q_{H_2O}} = 28.33\,\mathrm{mol\,s^{-1}}$ measured at $\mathrm{r_h} = 1.38$ AU (A'Hearn et al. 1995) scaled by a heliocentric evolution $\mathrm{r_h^{-2.7}}$ (A'Hearn et al. 1995) as the gas production rate, the ratio of dust to $\mathrm{H_2O}$ production rate is then ≈ 2.6. One should keep in mind that the dust production rate deduced from the infrared (IR) emission may not reflect the actual dust mass loss since large particles are too cold to be well constrained by the IR emission (Crifo 1987; Fulle 1998). As long as the size distribution for the large particles are not too flat, some degree of variation in the slope of the large particle size distribution will not affect the IR emission spectrum, but result in considerably differences in the dust mass lose rate. Actually, the IR emission spectrum in the wavelength range considered in this work is contributed only by grains smaller than $\sim 10^{-4}$ g (within the size distribution as derived for $\mathrm{P} = 0.85$). If the upper mass limit is set at $\mathrm{m} = 10^{-4}$ g, the corresponding dust production rate would be $\approx 5.0 \times 10^5\,\mathrm{g\,s^{-1}}$.

Alternatively, we have also tried to model the IR emission spectrum in terms of a power law dust size distribution $\mathrm{n(m)} \sim \mathrm{m}^{-\alpha}$. We found that a model with $\mathrm{P} = 0.85$ and $\alpha = 1.63$ provides a good match. Actually, the modified Halley size distribution (for $\mathrm{P} = 0.85$, see Fig. 2d) can be approximated by two power law distributions (for $\mathrm{m} < 10^{-5}$ g, $\mathrm{n(m)} \sim \mathrm{m}^{-1.53}$; for $\mathrm{m} > 10^{-5}$ g, $\mathrm{n(m)} \sim \mathrm{m}^{-1.81}$).

It is possible that the carbonaceous mantle could have undergone partial evaporation in the coma. We have also taken this into account by considering a model with a thinner mantle, $\mathrm{m_{or}/m_{si}} = 1/2$. Intuitively, we expect that, for a lower $\mathrm{m_{or}/m_{si}}$ which leads to a lower dust temperature, a higher porosity and/or a steeper dust size distribution, which results in a higher temperature, are needed to account for the emission spectrum. In the case $\mathrm{m_{or}/m_{si}} = 1/2$ which implies that half of the mantle has evaporated, the original porosity $\mathrm{P} = 0.85$ then becomes $\mathrm{P} \approx 0.90$. Using the same size distribution as derived for $\mathrm{P} = 0.85$ (see Fig. 2d), our calculations show that the fit by the model with $\mathrm{P} \approx 0.90$ and $\mathrm{m_{or}/m_{si}} = 1/2$ is reasonably good (plotted as dashed line in Fig. 2b), but the silicate feature is slightly too sharp and the NIR emission is a bit too low. Increasing the porosity or enhancing the small particles, the fit to the NIR emission gets better but the silicate feature becomes even sharper. Decreasing the porosity or enhancing the large particles, the silicate feature becomes broader but then the model fails to fit the NIR emission. For a mantle thickness $\mathrm{m_{or}/m_{si}} < 1/2$, the match to the overall spectrum is even poorer.

The modeling results as presented above clearly indicate some differences between the dust properties of P/Borrelly and

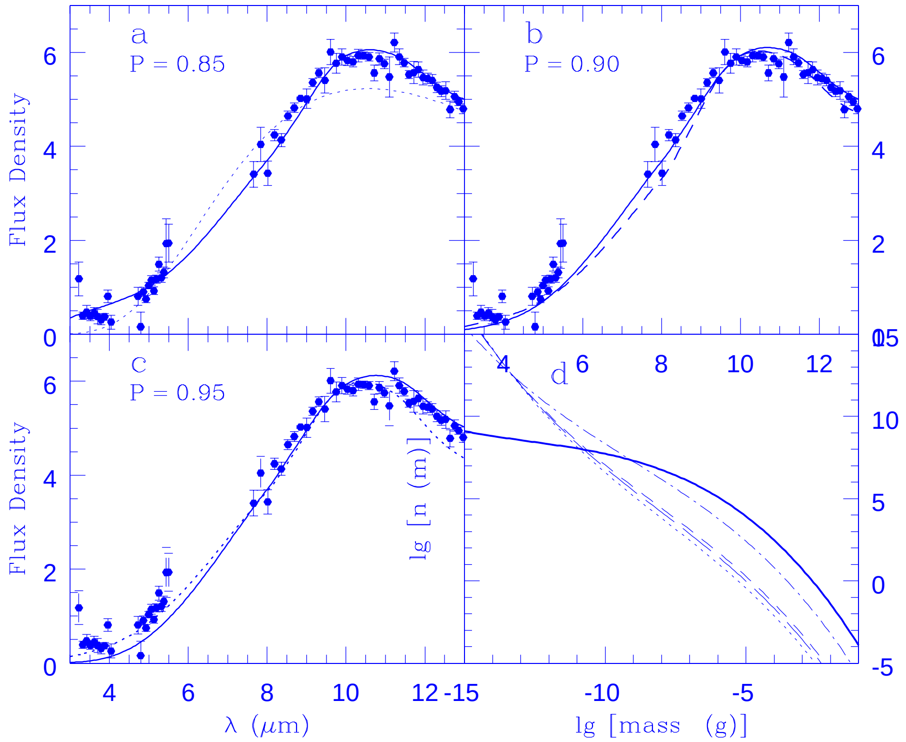

Fig. 2a–d. The theoretical spectra calculated for the porous aggregate comet dust model of silicate core-*amorphous carbon* mantle grains with a porosity $\mathrm{P} = 0.85$ (**a**, $\chi^2 \simeq 4.5$), 0.90 (solid line in **b**, $\chi^2 \simeq 6.6$), and 0.95 (**c**). The dotted line in **a** is a blackbody ($\mathrm{T} = 275\,\mathrm{K}$) emission (Hanner et al. 1996). Also plotted in **b** (dashed line, $\chi^2 \simeq 10.5$) is the spectrum produced by the $\mathrm{P} = 0.90$ model with a thinner mantle ($\mathrm{m_{or}/m_{si}} = 1/2$) and with the same size distribution as for the $\mathrm{P} = 0.85$ model (dotted line in **d**). In **c**, both the solid line ($\chi^2 \simeq 7.8$) and the dotted line ($\chi^2 \simeq 9.1$) are model spectra for $\mathrm{P} = 0.95$. The corresponding dust size distributions are shown in **d**: solid – the Halley dust size distribution; dotted – $\mathrm{P} = 0.85$; short dashed – $\mathrm{P} = 0.90$; long dashed – $\mathrm{P} = 0.95$ (corresponding to the dotted curve in **c**); dotted - short dashed – $\mathrm{P} = 0.95$ (corresponding to the solid curve in **c**).

those of P/Halley. First of all, the dust aggregates of P/Borrelly are somewhat more compact compared to P/Halley. The best fit to the P/Borrelly observation is provided by $\mathrm{P} = 0.85$, while Greenberg & Hage (1990) have shown that, a higher porosity, in the range of $0.93 < \mathrm{P} < 0.975$, fits the silicate emission of P/Halley well. Moreover, the dust size distribution of P/Borrelly is steeper (weighted toward smaller size grains) than that of P/Halley. Furthermore, the organic mantle materials of P/Borrelly, best fit by amorphous carbon, appear to have been strongly processed and are depleted in H, O, N compared to P/Halley.

These differences are not surprising. Actually, there is no reason to expect the dust properties of P/Borrelly to be identical to those of P/Halley. Since P/Borrelly has passed through the inner solar system many more times than P/Halley and therefore been subjected much more to the solar irradiation, the dust grains *within the surface layer* of the nucleus could have been significantly modified. In particular, the organic refractory materials formed in the interstellar medium and then incorporated into the protosolar nebula and finally aggregated into comets could have undergone further carbonization. Here the term "carbonization" means that the organic materials, subjected to the processing of solar ultraviolet photons, would partially lose their H, O, N atoms and thus become carbon-rich (Jenniskens et al. 1993). In other words, the elements H, O, N relative to C would be more depleted than in comet P/Halley organics. Observations do show that some SP (Jupiter family) comets are depleted in $\mathrm{C_2}$ and $\mathrm{C_3}$ (however, CN is approximately constant, see A'Hearn et al. 1995 for details). This can be explained by attributing the "missing carbon" to the carbonization of the original interstellar organics. The fact that some $\mathrm{C_2}$ and $\mathrm{C_3}$ come directly from the volatile nuclear ices (which are relatively depleted in SP comets) while CN is mostly produced from grains (A'Hearn et al. 1995) is consistent with the idea of carbonization. While this is supported by the results of the EURECA space experiments which have indicated the carbonization of the "first generation" organic refractory materials by solar irradiation (Greenberg et al. 1995) there may be other ways of explaining the $\mathrm{C_2}$ and $\mathrm{C_3}$ depletion. For example, it has also been suggested that the chemical abundance in the solar nebula out of which the SP comets formed was different from that of LP comets (A'Hearn et al. 1995). This is not easy to understand because SP comets are *formed further* out than LP comets (see e.g. Levison 1996) so are *closer* to interstellar medium composition. On the other hand, if it is the case that the crystalline silicates formed in the hot, inner region of the solar nebula, *extensive radial mixing would have occurred* so that these materials could have been transported to the outer region where the cometesimals were forming (Hanner et al. 1994a, 1994b), although where and how the crystalline silicates formed is still not known (see e.g. Greenberg et al. 1996). The solar irradiation can also lead to a lower porosity than that of Halley dust due to the packing effect (Mukai & Fechtig 1983; also see Smoluchowski et al. 1984). The dust size distribution could be weighted toward smaller grains; i.e., smaller grains are enhanced as a consequence of evaporation and subsequent fragmentation in the coma. There are both observational and theoretical indications of dust fragmentation in the coma of comet P/Halley. As the volatile ice sublimates from the nucleus, it leaves behind the refractory particles and loosens the aggregates. If the fragmentation indeed results from the sublimation of volatile materials which act as "glue", one may expect relatively more drastic and more complete fragmentation in the coma of SP comets since volatiles are relatively depleted in SP comets (Weissman & Campins 1993). A statistical study of the cometary dust size distribution indeed seems to suggest that the dust size distribution of short-period comets is somewhat steeper than that for long-period comets (Fulle 1998).

4. Discussion and conclusion

Hanner et al. (1996) have modeled the thermal emission spectrum of comet P/Borrelly in terms of either a mixture or a simple combination of two *separate* components of compact amorphous silicate (bronzite or olivine) and glassy carbon grains. Their models, using the Hanner size distribution form (Hanner et al. 1985), fit the observations reasonably well (within 10%) except for some deficiencies in reproducing the silicate feature. The spectrum produced by the model with two separate components is both a bit deficient in the short wavelength wing of the silicate feature as well as having a peak emission at a longer wavelength. These effects imply that the silicate grains are a bit too cold. This may be due to the fact that the pure silicate materials are rather transparent in the near ultraviolet, visual and the near infrared so that they can not be heated sufficiently. While other investigators have attributed the short wavelength side of the silicate feature in comets to amorphous pyroxene (see, e.g., Colangeli et al. 1995; Hanner et al. 1998; Wooden et al. 1998), the fluffy aggregate interstellar grain model attributes the short wavelength shoulder to the effects of grain porosity and particle size distribution. The model with a mixture of two components gives too sharp a silicate feature which indicates that the particles are too small (although they are sufficiently hot). One could expect to broaden the silicate feature by including larger particles, however, the particles would then be too cold. A possible solution to this dilemma is to adopt the model consisting of porous aggregates of interstellar dust. As shown in the preceding section, the fluffy aggregate model indeed leads to an improved fit: both the NIR continuum and the silicate feature are well reproduced. This is because, for a highly fluffy aggregate, its mass absorption coefficiency is much higher than that of its equal-mass compact counterpart, and it approaches that of the individual small particle unit in the case of extreme porosity $\mathrm{P} \rightarrow 1$. Thus a highly fluffy aggregate, as explicitly demonstrated in Fig. 6b and Fig. 7 of Greenberg & Hage (1990), not only is much hotter, but also emits much more effectively above the continuum at 10 $\mu\mathrm{m}$ than its equal-mass compact counterpart. Note that, as long as $\mathrm{P} \not\rightarrow 1$, the silicate emission feature of a porous aggregate is not as sharp as that of its individual particle unit (but of course, much sharper than that of its equal-mass solid counterpart).

The sudden jump at $\sim 5.5\ \mu\mathrm{m}$ of the spectrum of the *organic refractory* model (see Fig. 1) is attributed to the C=C, C=O, C-OH, C≡N, C-NH_2 etc. stretches, CH, OH, and NH_2 deformations, and H wagging in the organic molecules (Greenberg et al. 1995). This jump will become weaker and even disappear if the organics are subject to further ultraviolet photoprocessing which results in photodissociation and depletion of H, O, N elements and thus higher visual absorptivity. The optical properties of the heavily processed organics would ultimately resemble those of amorphous carbon.

The solar irradiation not only results in the sublimation of volatile ices, depletion of H, O, N elements, but also creates an inert crust on the nucleus surface. The inert crust grows with the age of a comet and progressively lowers the activity level. Finally some SP comets which have exhausted all of their volatiles or whose nucleus surfaces are completely covered by crusts will possibly evolve into extinct asteroid-like objects (Weissman & Campins 1993). Thus it is natural to expect the existence of various degrees of carbonization and activity level among SP comets due to different degrees of physical evolution (different passage frequency through the inner solar system). Admittedly, it is still too early to conclude that all SP comets show the same behavior as comet P/Borrelly. In the observations of Hanner et al. (1996), another SP comet, comet P/Schaumasse, shows no silicate emission at all. This may indicate some variations among SP comets: either dust size (see Fig. 5 of Greenberg & Hage 1990 and Fig. 6 of Hanner et al. 1994b) or activity level (or both). Systematic investigations on the thermal emission spectrum as well as the 11.2 $\mu\mathrm{m}$ crystalline silicate feature of SP comets are needed to confirm or reject the above results. We stress here that the highly processed dust grains make up only a minor fraction of the nucleus, in other words, on a global scale, the comet nucleus is still expected to maintain the original (chemical) properties of interstellar dust. As shown by Kouchi et al. (1992), the effect of solar heating on the comet nucleus is negligible below the outer several centimeters.

Our conclusion is that, a fluffy aggregate model of silicate core-amorphous carbon mantle grains with a porosity $\mathrm{P} = 0.85$ best reproduces the observed thermal emission spectrum of comet P/Borrelly from 3 $\mu\mathrm{m}$ to 14 $\mu\mathrm{m}$ as well as the 10 $\mu\mathrm{m}$ silicate feature. Compared to the comet P/Halley dust, the dust grains of P/Borrelly appear to be relatively more processed, more carbonized, less fluffy, and richer in smaller particles. At this point we are not able to generalize the dust properties of SP comets. Observational data are needed for a larger set of SP comet samples.

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