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Sublimation of Interplanetary Dust

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Abstract. Three topics are briefly reviewed to examine evidence for the nature of dust grains and grain alteration by physical processes related to mainly sublimation. Namely, (1) a change of dust flux detected by *in situ* dust measurements beyond $\sim$ 2 AU from the Sun suggests a disappearance of volatile ices due to sublimation below this distance, (2) an elongation angle dependence of Doppler shifts observed in the zodiacal light can be explained by the introduction of a dependence of the orbital velocity on the radiation pressure forces acting on the grains, taking into account a variation of dust structure with heliocentric distance, and (3) the variation of color temperature observed in cometary coma suggests a loss of carbon content from cometary dust grains due to sublimation. This piece of evidence agrees with the generation of carbon-bearing molecules from extended sources, as infered from observations in cometary comae.

1. Introduction

In general, physical processes affecting interplanetary dust cover a large range of topics. Due to a limited space for this review, we focus on topics related to the alteration of grain properties by sublimation. For a greater variety of topics, Gustafson (1994) has recently reviewed light scattering processes and dynamical processes for interplanetary dust. Mendis and Rosenberg (1994) have given a review of physical processes related to the dusty plasma in the solar system. Dwek and Arendt (1992) summarized the dust-gas interactions in the interstellar medium, and the elementary processes described there are closely related to those in interplanetary space. Furthermore, a book on "Interplanetary Dust" (The University of Arizona Press, 1996) will devote one chapter to physical processes, including collisional growth, collisional fragmentation, sublimation, sputtering and electric charging of dust grain.

High energy plasma particles produced in solar flares make tracks inside interplanetary dust grains (e.g. Bradly et al. 1984). Accumulations of plasma particles have recently been found in some grains (Bradley 1994). Furthermore, a significant proportion of interplanetary dust particles have experienced aqueous alteration (see, e.g. Tomeoka 1991). This is an explicit example of grain modification. However, we will be interested in implicit evidence for alteration latent in the data obtained by astronomical observations. Such signatures will be examined in the following sections.

2. Enviromental parameters

In the present solar system, the energy flux of solar radiation ($\sim 1.37\,kW\,m^{-2}$ at 1 AU from the Sun) plays a dominant role in the control of physical process affecting interplanetary dust. Visible light dominates the energy influx and thus affects the equilibrium temperature of the grains. Consequently, it controls the mass loss process through sublimation.

Although the energy flux of plasma particles in the solar wind is negligibly small compared with that of solar radiation, i.e. $2\times10^{-8}\,W\,m^{-2}$ at 1 AU, they can cause mass loss due to sputtering, as well as the alteration of chemical bonds in the grain material. The physical parameters of solar wind at 1 AU in the average phase of solar activity are as follows (e.g. Geiss 1982): number flux=2×10^{12} *particles* $m^{-2}\,s^{-1}$, mean velocity= 400 $km\ s^{-1}$, temperature=$10^5\,K$, number density=$4.5\times10^6\,m^{-3}$ and the number fraction of $protons = 96\ \%$ and of $\alpha - particles = 4\ \%$. A ratio of heating rate by solar particles to that by solar photons is small, i.e. ~ 0.01 even for a small grain with a radius of $0.01\mu m$, consisting of transparent materials in the visible (Mukai and Schwehm 1981).

Solar flares produce high energy ($\geq MeV$) particles. The mean energy flux of flare particles is about 1% of the energy flux of solar wind particles. As noted above, evidence for the incidence of high energy particles has been found in the form of solar flare tracks inside grains collected in the upper atomosphere of the Earth. These explicit evidence for alteration provide information on the duration of the grains' exposure to interplanetary space during the past of the order of $10^4 years$.

Under these circumstance of solar irradiation and solar energetic particle flux, interplanetary dust grains are subject to several kinds of physical processes. We shall discuss one such physical processes; sublimation.

3. The sublimation process

For quantitative discussion of sublimation, we need the knowledge of the optical and thermodynamical properties of dust grains. Sublimation is controled by the grain temperature. The temperature of interplanetary dust is obtained from the balance between the input energy to the grain, i.e., absorption of incident solar radiation, and output energy from it, i.e., emission by thermal radiation and energy consumption by sublimation. The absorption of solar radiation and the emission of thermal radiation strongly depend on the grain size, as well as the optical properties of the grain material. Consequently the resulting temperature of a spherical grain varies with the grain radius. It is well known that the smaller grains, with radii less than nearly $1\mu m$, attain higher temperatures than those with larger radii. Furthermore, it has been shown by Patashnick and Rupprecht (1975) that interplanetary dust grains, consisting of pure water-ice, have relatively low temperatures with minimum temperature at the grain radius of about $10\mu m$. These estimates come from the fact that the absorption and emission of radiation depend on the grain radius.

The optical properties of dust grains, including their shape effects, have been widely discussed recently (see, e.g. Huffman 1988, Lien 1991, and Gustafson

1994). The temperature of such irregularly shaped grains, including those with multiple components, such as an icy matrix with refractory inclusions, have been examined by several authors (see, e.g. Greenberg and Hage 1990, Kozasa et al. 1992, Mann et al. 1994, and Gustafson 1994). The sublimation rate at a grain temperature depends on the thermodynamical properties of the grain material. Observations of comets suggest that 90 % of the volatiles are water-ice. Therefore, it seems reasonable to assume that water-ice is the dominant volatile in interplanetary dust. Ices of CO, CO_2 and NH_3 are also important.

The theoretical sublimation rate γ of volatile ices per unit time and per unit area is defined by

$$\gamma = p\sqrt{\frac{m}{2\pi kT}} \tag{1}$$

where p represents the vapor pressure of volatile materials, T and m denote temperature of the volatile ice and the average mass for evaporated molecule, respectively, and k is Boltzman constant. This relation comes from the argument that in the equilibrium state the number of molecules striking a unit surface of volatile ice is equal to that leaving from it. Although, in a vacuum, such as in interplanetary space, no molecules strike the surface, we assume that the sublimation rate is tne same as it would be at equlibrium. Therefore, this rate is called the theoretical sublimation rate.

It is known that the experimental sublimation rate, Γ, is smaller than the theoretical one. An empirical accomodation coefficient α is therefore widely used to reduce the theoretical sublimation rate, i.e. $\Gamma = \alpha\ \gamma$. The value of α depends on the material as well as the temperature of interest. It takes values of the order of one-tenth. However, for simplicity, we assume $\alpha = 1$ in this article.

The vapor pressure of amorphous water-ice is presented by

$$log_{10}\, p = \frac{-2391}{T} + 4\, log_{10}\, T - 5.065{\times}10^{-4}\, T^{1.4} + 3.286, \tag{2}$$

where p and T have the units of $N\, m^{-2}$ and K, respectively. The theoretical sublimation rate for amorphous water-ice is calculated by substituting equation (2) in equation (1).

On the other hand, a simplified expression for $\gamma(T)$, i.e.,

$$log_{10}\, \gamma = \frac{-X}{T} + Y \tag{3}$$

was sometimes used (e.g. Lamy 1974, Yamamoto et al. 1983). The values are $X = 755.7$ and $Y = 9.69$ for CO on H_2O ice, 1242 and $10.49 - 0.5 logT$ for CO_2 on H_2O ice and 1691 and 9.57 for NH_3(Sandford and Allamandola 1993, Draine 1985), where the units of γ and T are $kg\, m^{-2} s^{-1}$ and K, respectively. It should be noted that the values for CO and CO_2 depend on the matrix ices (see, e.g. Sandford and Allamandola 1993). For example, $X = 416.9$ and $Y = 9.69$ for CO on CO ice, and $X = 1168$ and $Y = 10.49 - 0.5 logT$ for CO_2 on CO_2 ice. In general, the sublimation rate of molecules from an ice consisting of the same species is higher than that from an ice made of different molecules.

Figure 1 shows the dependency of γ on heliocentric distance r. It is noted that a large uncertainty exists, because the relation of T to the heliocentric

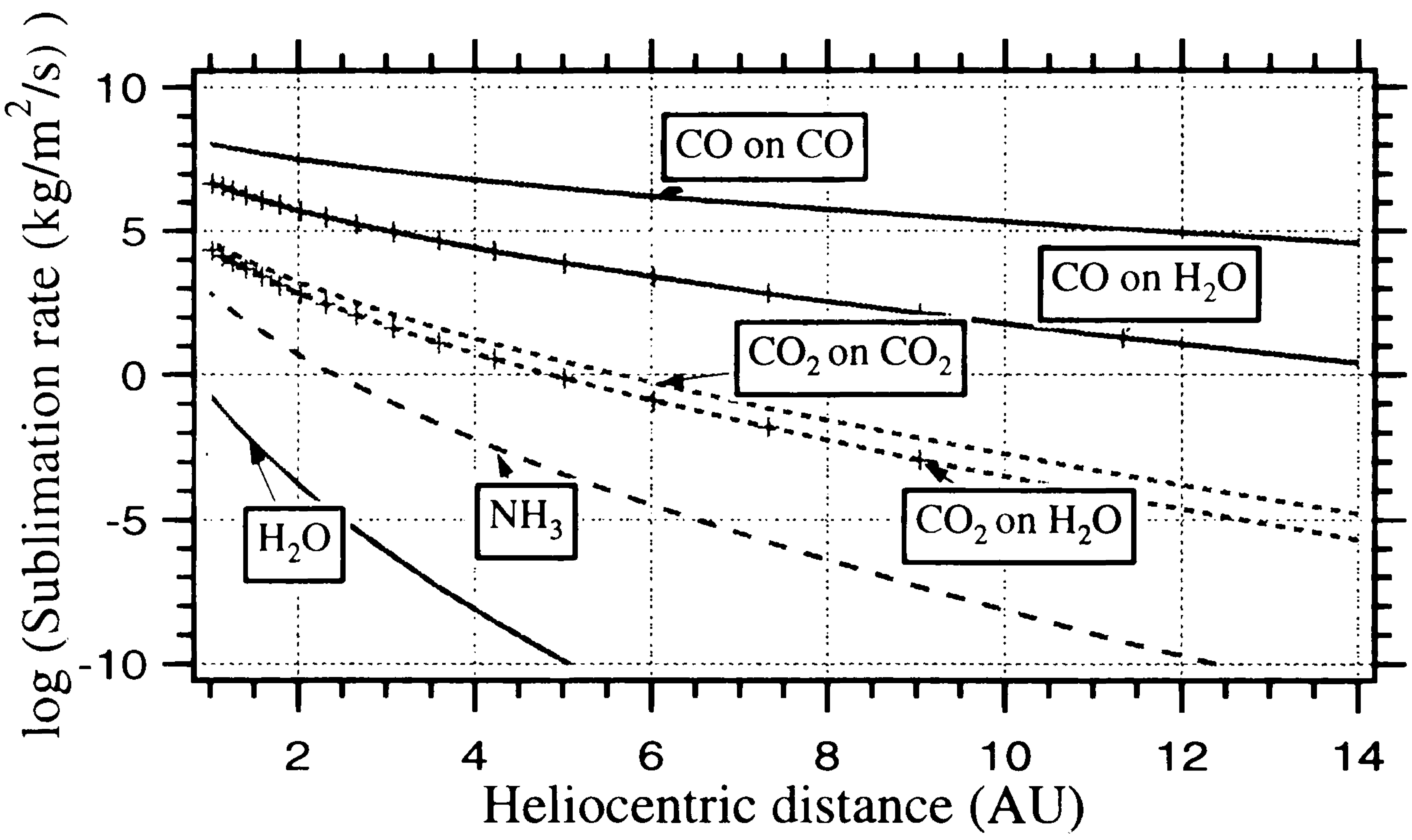

Figure 1. Sublimation rate of volatile ices.

distance r strongly depends on the grain model of interest. In Figure 1, we applied $T = 255r^{-0.35}$, which is the minimum model for the zodiacal emission (Levasseur-Regourd et al. 1991), where $T(K)$ and $r(AU)$. Although some ambiguities in the determination of equilibrium temperature of interplanetary dust still remain, we can conclude from Figure 1 that the sublimation rate quickly increases with decreasing heliocentric distance due to a sharp dependency of p on T In addition, it becomes clear that water-ice is the most stable against sublimation among the ices considered here.

From the sublimation rate obtained above, we can define the survival time t_s of dust grains against sublimation. That is, $t_s = M/(\gamma S)$, where M and S denote the grain mass and total surface area. When the accomodation coefficient $\alpha \neq 1$, γ should be replaced by $\alpha\ \gamma$ The value of $\gamma = 10^{-5} kg\ m^{-2}\ s^{-1}$ corresponds to $t_s = 4\ days$ for a spherical water-ice grain with radius $s = 100 \mu m$. Since the sublimation rate, in general, depends on the grain radius through a size dependence of grain temperature, t_s does not increase in direct proportion to s even for a spherical grain. Further quantitative discussions of lifetimes of icy grains against sublimation, including its size dependence, have been presented in Patashnick and Rupprecht(1975), and Mukai(1986).

3.1. Why does the spatial dependence of dust flux change beyond 2 AU from the Sun?

The dust detectors on board Pioneers 10 and 11, which have a mass threshold at 20 $km\ s^{-1}$ of $2\times10^{-9}\ g$ and $1\times10^{-8}\ g$, respectively, found a decrease of dust flux with increasing heliocentric distance beyond 1 AU. However, the flux was the nearly constant around 2 AU from the Sun, and may have increased beyond about 2 AU (Humes 1980). These observations have recently been confirmed by the Ulysses and Galileo dust measurements (Grün et al. 1992). Both dust detectors have the same mass threshold at 20 $km\ s^{-1}$ of $1\times10^{-15}\ g$, which is significantly smaller than those of two Pioneers. It is natural to assume that the change of dust flux is due to sublimation. Volatile ices produced far from the Sun are gradually approaching the Sun due to the Poynting-Robertson effect. When their temperature reaches some critical value, sublimation causes loss of the volatile material (see Figure 1). Consequently, these materials disappear below some critical distance.

Figure 1 tells us that the critical heliocentric distance is about 2 AU from the Sun for water-ices, and is further from the Sun for other volatile ices. Divine (1993) proposed five populations of interplanetary dust to explain the observed spatial dust distribution, where the "Halo population" seems to correspond to that expected from the spatial distribution of volatile ices ejected from long period comets having a nearly isotropic inclination distribution. Mann and Grün (1995) reported that 50% of the impacts detected in the outer solar system seem to be from grains on randomly oriented orbits of high eccentricity or on unbound orbits, whereas the other half is dust of interstellar origin. It should be noted, however, that the dust supply rate on bound orbits has been estimated to about 30 $kg\ s^{-1}$ from 101 long-period comets. This is roughly 3 % of that from 85 short-periods comets (see, e.g. Mukai 1989). A relatively low supply from long-period comets is due to the fact that solar radiation pressure forces eject most of the grains. On the other hand, dust grains originating in collisions between asteroids may cause an increase of dust flux near the asteroid belt. Therefore, it seems that the origin of grains beyond 2 AU from the Sun is still an open question.

3.2. Why do Doppler shifts suggest a variation of grain properties with heliocentric distance?

Measurements of Doppler shifts of scattered Fraunhofer lines in the zodiacal light have been used to study the motion of interplanetary dust. The shift $\delta\lambda$ is roughly given by $\delta\lambda \sim (v_k \lambda / c)$, where c denotes the speed of light. Since $v_k (\propto r^{-1/2})$ increases as the heliocentric distance r of the grain decreases, the resulting shifts of line profile $\delta\lambda$ increases when we see a direction of smaller elongation angle. This has been confirmed by observations (e.g. Blackwell and Ingham 1961). Fried (1978) reported, based on his observations, that $\delta\lambda$ is larger than expected for dust grains moving on Keplerian orbits. It appears that dust grains within about 0.7 AU from the Sun scatter sunlight as if they have orbital velocities greater than those of circular Keplerian orbits around the Sun. This problem has been reconciled by Mukai and Mann (1993) who applied a model including dust grains with eccentric orbits, and introduced a variation of β with r due to the change of their structure with decreasing a heliocentric distance.

One mechanism that can change a grain's structure, and therefore β, with the heliocentric distance has been proposed by Mukai and Fechtig (1984). Let us consider an aggregate consisting of individual core-mantle particles, where the core is made of a refractory material and the mantle is volatile. Sublimation of volatile materials leads to an anisotropic mass ejection. Temperature difference between constituent particles on the surface illuminated by sunlight and those in the shadow cause the anisotropy. The resulting reaction force acts on the refractory cores in a direction from outside to inside of the aggregate. The refractory cores penetrate into the crevices/cavities of the aggregate, and subsequently the porosity of the aggregate is reduced as a result of the reaction force. It has been shown by Mukai and Fechtig (1984) that a mass loss rate of 5×10^{-12} $kg\ m^{-2}\ s^{-1}$ produces a change of mass density of the aggregate from 8×10^{2} $kg\ m^{-3}$ to 3×10^{3} $kg\ m^{-3}$ within 2×10^{4} *years*, where the aggregate has an initial characteristic radius of $100\mu m$ and is in an orbit with semimajor axis 17.9 AU and eccentricity 0.967 (the orbit of comet P/Halley). An initially loose aggregate structure released from a parent body far from the Sun becomes faily compact within a reasonable time scale, i.e., $\sim2\times10^{4}$ *years*, compared with the Poynting-Robertson time of $\sim2\times10^{5}$ *years* in the above case.

When the ratio β of radiation pressure forces on the grain to the solar gravity decreases with decreasing heliocentric distance, the orbital velocity v_k of the grain increases with decreasing distance, because $v_k \propto \sqrt{1-\beta}$. If this occurs, we expect an additional increase of the Doppler shift toward smaller elongation angles. This gives a reasonable fit to the measurements.

How can we expect the decrease of β with decreasing heliocentric distance for the aggregate as a function of the porosity? Mukai et al. (1992) have shown the computed results for β values of fractal aggregates with different porosity. In general, when the radius of an aggregate decreases, the value of β increases monotonously, because $\beta\sim$(grain mass)/(its geometrical cross section). It is found, however, that a decrease in porosity leads to a decrease of β for absorbing materials in the sublimation size range, in contrast with an increase of β for dielectric materials. Sublimation leads to a decrease of both the radius of aggregate and its porosity. This change in the structure of the grain is completed before the spiralling-in to the Sun by the Poynting-Robertson effect. When we apply such fractal aggregate analogues for interplanetary dust, absorbing aggregates might explain the additional enhancement of the Doppler shifts observed at smaller elongation angles.

3.3. Why do the cometary grain properties vary with heliocentric distance?

It is widely known that the color temperature T_c observed in comets is higher than the temperature of a spinning black body T_b at the same heliocentric distance (e.g. Ney 1982). Strictly speaking, the color temperature of the grain is not the same as its real temperature, because the emissivity at infrared wavelengths (where the color temperature is estimated) depends on the wavelength. However, we assume that the wavelength-dependence of emissivity is weak in the middle infrared wavelengths, except remarkable silicate features. Therefore, we can say that the color temperature derived from the flux at midle infrared wavelengths gives a fairly good approximation of the real temperature of the grains. The contribution of small grains has been proposed to explain the enhancement of color temperature (Mukai 1977, Campins and Hanner 1982). When the grain is smaller than the wavelength of thermal emission, the resulting lower emissivity at the infrared wavelengths leads to a higher equilibrium temperature. Consequently, the smaller grain has higher temperature than a black body.

Figure 2 shows that the color temperature observed in comets varies with heliocentric distance (data cited from Walker and Aumann 1984). The ratio of color temperature to that of a black body is always beyond unity and it seems

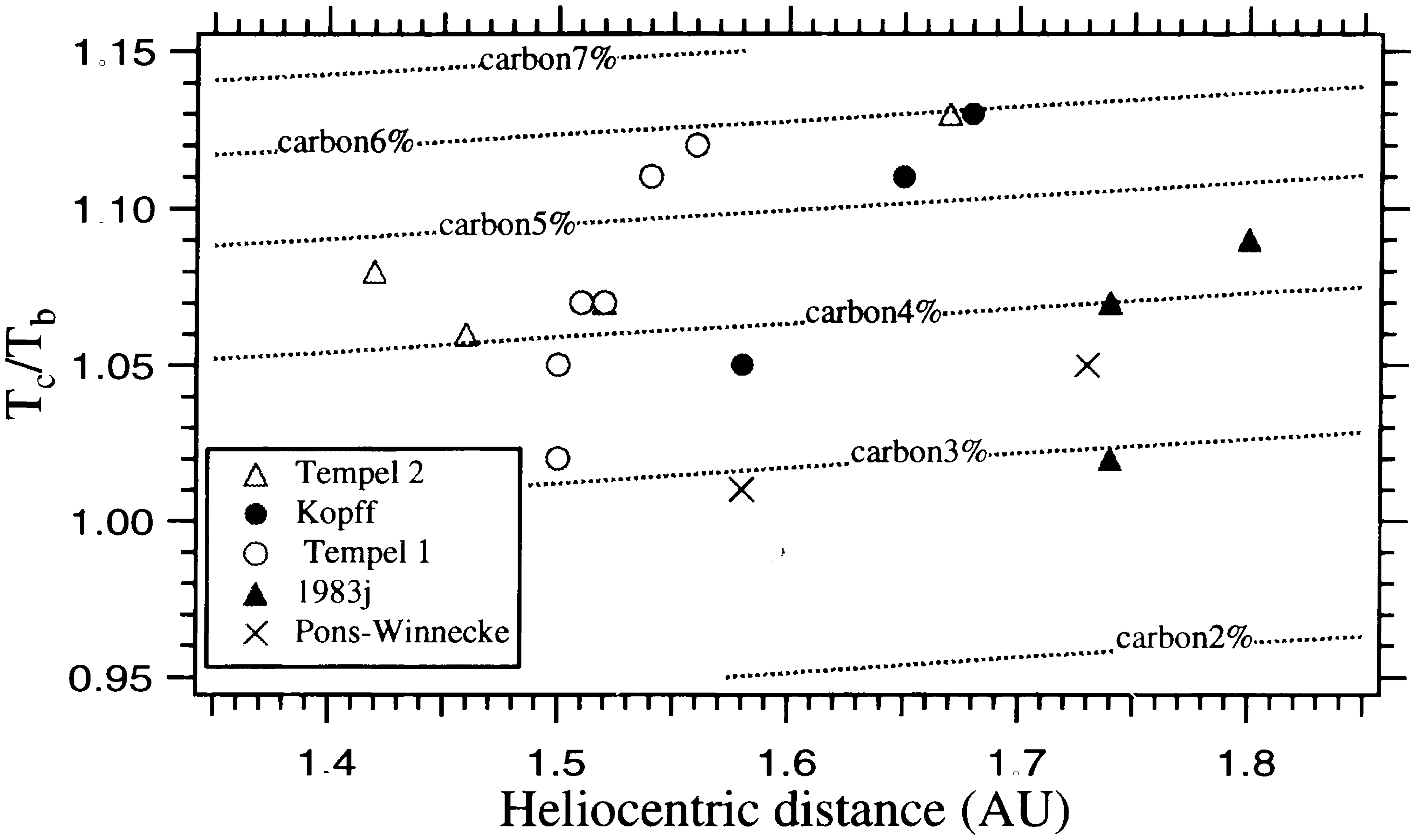

Figure 2. A ratio of color temperature T_c to black body temperature T_b observed in several comets (after Walker and Aumann 1984). Dotted curves indicate the ratio computed for the grain model of a silicate-carbon aggregate with varying volume fraction of carbon, and its radius of 10 μm.

that the ratio is lower when the heliocentric distance of the comet is smaller. This suggests a variation of coma grain properties with heliocentric distance.

The variation of grain's properties inside the coma of P/Halley has been investigated, i.e., (1) the neutral gas mass spectrometer on the Giotto spacecraft has reported that CO molecules were produced from an extended source, such as cometary dust grains, in the inner coma (Eberhardt et al. 1987), and (2) gaseous jets, such as CN, observed from the ground suggest that these radicals are produced from grains ejected from the cometary nucleus (A'Hearn et al. 1986). These evidence leads to the suggestion that dust grains in cometary comae sublimate.

What change occurs in the temperature of grains when they loose their carbon content? The temperature of aggregate grains consisting of silicate and carbon materials with $s = 10\,\mu m$ is presented in Figure 3 (the details of the derivation of these results are discussed in Mann et al. 1994). As the carbon content decreases, the ratio of the temperature of the aggregates to that of a black body decreases. This result seems to agree with the observed variation of color temperature in cometary comae. The carbon content of cometary dust grain, as suggested by their temperature, i.e., 3 % to 6 % by volume (see Figure 2), agree with those estimated from the analysis of the particle population in comet P/Halley by Clark et al. (1987). In conclusion, we suggest that even if the properties of grains ejected from the cometary nucleus are constant with changing a heliocentric distance, grains observed in the cometary coma have a different temperature due to sublimation.

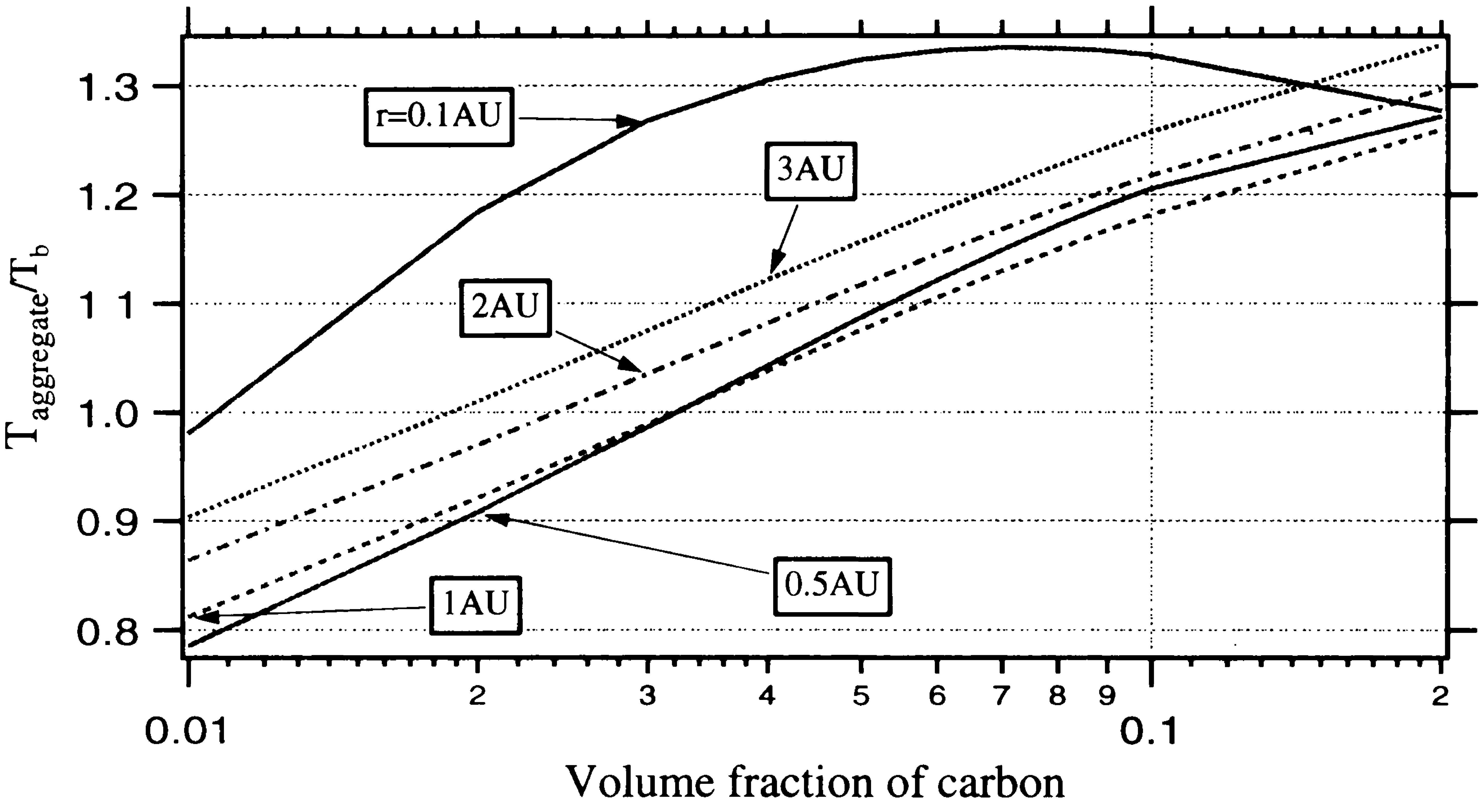

Figure 3. Ratio of the temperature of an aggregate to the black body temperature T_b computed for a silicate-carbon aggregate with an average radius of 10 μm at a range of heliocentric distances r.

3.4. Summary

The change of grain properties due to sublimation can explain the observed evidence, such as a change of dust flux beyond 2 AU from the Sun, the extra enhancement of Doppler shifts in the zodiacal light at smaller elongation angles, and a variation of enhanced color temperature of cometary grains within the cometary coma. These observed evidence strongly suggest that the properties of interplanetary dust are continuously affected by physical processes in interplanetary space. Future *in situ* measurements of grain's physical properties, including the sample return mission from primitive bodies, are highly desired to investigate the physical processes affecting interplanetary dust grains in detail.

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