Very small dust grains as a probe for exploring thermal properties of mesoscopic scale materials

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It is well known that interstellar dust grains have a continuous size distribution from several hundred nanometers to less than a nanometer [1]. Among those, dust grains below a few tens of nanometers are classified as Very Small Grains (VSGs). Since the number of molecules, contained in a VSG, ranges from hundreds to tens of thousands [2], the VSG is intrinsically a mesoscopic scale material. For mesoscopic grains, the finiteness of their sizes brings two major effects. One is the quantum interference effect by free electron clouds surrounding each ion of the grains. This effect is no longer negligible since the de Broglie wavelength of the electron clouds is about 10 nanometers when their temperature cools down to 10 K, which is comparable to or larger than their physical sizes. The other is the limitation to the application of physical properties deduced from bulk materials, for which infinitely small size is implicitly assumed, to the modeling of VSGs (e.g., [3]). Both effects have not been satisfactorily taken into account for modeling VSGs. In this paper, we focus on the latter.

The following three facts tell us that significant modifications from the bulk materials must be made for modeling VSGs. 1. When the Debye model is used to describe the thermal properties of a silicate grain that has size < 2 nanometers, the thermal energy of the grain becomes lower than $k_B T$ at T <10 K, where k_B is the Boltzmann constant, and T is the grain temperature. This indicates that the thermal emission from the VSG is truncated by the upper bound due to its thermal energy, and the spectrum, as a result, is significantly modified by the upper bound. Yet, nobody has shown the Spectral Energy Distribution (SED) from the VSGs at wavelengths longer than the submillimeter with the upper bound taken into account. 2. Since the possible longest wavelength of the vibrational modes is limited by their sizes, the energy of the first excitation level of phonons becomes as high as about 0.01 eV corresponding temperature of 100 K for a few nanometer grains. The Debye model is no more appropriate to describe the nature of the VSGs at such low temperatures. 3. The irregularity of the grain shapes and the possible randomness of the shapes may result in breaking the degeneracy of the energy levels of phonons, which causes distributions of energy levels to vary from grain to grain. Draine and Li (2001) [2] have taken into account the first effect. They have also taken into account the second one by modeling the energy levels with no degeneracy. However, they did not take into account the third one, the randomness of the energy level distributions.

In this paper, we model the thermal and radiative properties of the VSGs by taking into account the above three effects, and examine the SED of the thermal emission from the VSGs. Our preliminary model predicts that the VSGs emit not only in the mid-infrared wave bands while they stay at a temperature above 100 K, but also emit a significant amount of flux in the millimeter. Our result predicts a correlation between the intensity of the mid-infrared emission and the millimeter emission. Since VSGs are supposed to be misaligned against magnetic fields, these excess emissions only appear in the intensity SED and do not appear in the polarization SED.

Although there is some observational evidence of the existence of the millimeter excess emission in the dust SEDs [4][5][6], the existence is still under debate [7]. It is expected that force-coming high-precision CMB experiments may provide crucial results on this topic and open the opportunity to explore the thermal properties of mesoscopic scale materials through observations. We believe that revisiting the VSG modeling explicitly by taking into account the mesoscopic scale physics is one of the current topics which should be studied.

Reference

[1] Weingartner J. C. Draine. B. T. 2001. *Astrophys. J.* 548. 296.

[2] Draine B. T. Li A. 2001. *Astrophys. J.* 551. 807

[3] Kubo R. 1962. *J. Phys. Soc. Jpn.* 17. 6

[4] Reach W. T. Dwek E. Fixen D. J. et al. 1995. *Astrophys. J.* 451. 188.

[5] Meisner A. M. Finkbeiner D.P. 2015. *Astrophys. J.* 88. 19.

[6] Galliano F. Galametz M. Jones A. P. 2018. *Annu. Rev. Astron. Astrophys.* 56. 673

[7] Planck Collaboration. 2020. *Astron. Astrophys.* 641. A11