Infrared Observational Manifestations of Young Dusty Super Star Clusters

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Sergio Martínez-González, Guillermo Tenorio-Tagle, Sergiy Silich

Instituto Nacional de Astrofísica, Óptica y Electrónica, Puebla, México

sergiomtz@inaoep.mx

Abstract

In light of the growing evidence pointing at core-collapse supernovae as large dust producers, and given their immense number in young massive stellar clusters (SSCs), this work is devoted to address the influence of stochastic injection, sputtering and outflow of dust grains on their emission properties inside the hot and dense intracluster medium. The theory of dust radiative cooling, which considers time-dependent dust size distributions and chemical composition, is combined with a self-consistent semi-analytic method, in order to study the hydrodynamics of spherically symmetric winds driven by SSCs with a generalized Schuster stellar density profile.

Star Cluster Winds and Stochastic Dust Heating

We consider young and massive star clusters in which massive stars follow a generalized Schuster stellar density distribution, $\rho_* \propto [1+(r/R_c)^2]^{-\beta}$, Tenorio-Tagle et al. (2013) with $\beta = 1.5$, where r is the distance from the cluster center and R_c is the core radius of the stellar distribution. This stellar distribution is truncated at radius R_{SC}. Other input parameters are: the star cluster mechanical luminosity, L_{SC}, and the adiabatic wind terminal speed $V_{A\infty}$. Supernovae are considered to inject dust uniformly throughout the star cluster with a standard Mathis et al. (1977) grain size distribution. Right after injection, the dust size distribution will evolve due to the action of thermal sputtering and the exit of dust grains from the star cluster as part of the star cluster wind.

The values of the total dust mass injected by a single supernova and the interval between supernova events were selected pseudo-randomly from a Gaussian distribution. The mean value for $M_{dSN}^{(m)}$ was set to 0.5 M$_\odot$ with a standard deviation 0.15 M$_\odot$.

The prevailing conditions inside the star cluster volume (i.e. average values for the gas number density, n, and temperature, T) are calculated by making use of the hydrodynamical model discussed in Silich et al. (2011) and Palouš et al. (2013). We then can applied Dwek (1986) prescriptions to calculate the temperature distribution, $G(a, T_d)$, of dust grains. Figure 1 presents dust temperature distributions for different grain sizes in the case of graphite grains; small grains ($\lesssim 0.05$ μm) are more likely to undergo strong temperature fluctuations and therefore span a wide range of temperatures (from a few ~ 10 K to a few ~ 1000 K for grains with $a = 0.001$ μm, making them to strongly emit in all NIR, MIR and FIR wavelengths) due to their low heat capacity (which scales as $\sim a^3$) and small cross sections.

The infrared flux per unit wavelength, produced by a population of dust grains with the same chemical composition (in our case silicate or graphite), from a star cluster located at distance D_{SC}, can then be calculated as Dwek & Arendt (1992):

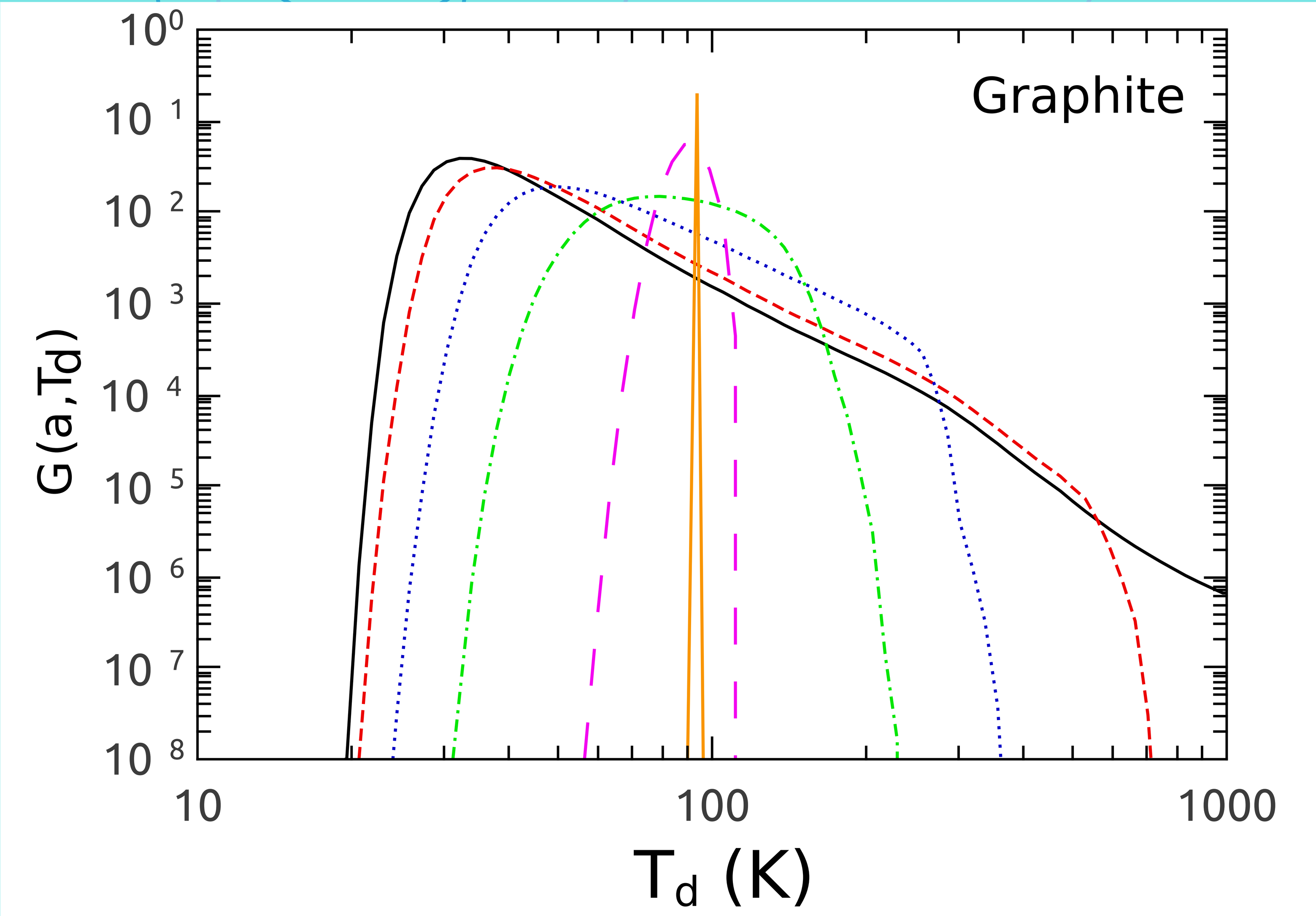

Figure 1: The figure displays the dust temperature distribution for different grain sizes for graphite grains. The solid, dashed, dotted, dashed-dotted, long-dashed and the delta-like curves correspond to sizes 0.001, 0.002, 0.01, 0.05, 0.1 and 0.5 μm, respectively.

$$f_\nu = \left(\frac{1.4 m_H Z_d N_H}{\langle m_d \rangle}\right) \Omega_{SC} A \int_{a_{min}}^{a_{max}} \int_0^\infty a^{2-\alpha} \pi Q_{abs}(\nu, a) B_\nu(T_d) G(a, T_d)\, \mathrm{d}T_d\, \mathrm{d}a \quad (1)$$

in units 10^{-26} erg s^{-1} cm^{-2} Hz^{-1} or mJy, taking into account the contribution from graphite and silicate grains. In the above equation, N_H is the hydrogen column density through the star cluster volume ($= 4/3 n R_{SC}$), a is the dust grain radius, $\rho_d = 4/3\pi\rho_{gr} \int_{a_{min}}^{a_{max}} a^3 \frac{\partial n_i}{\partial a}\, da$ is the size-averaged dust density, and $\Omega_{SC} = \pi(R_{SC}/D_{SC})^2$, is the solid angle subtended by the star cluster. Additionally, T_d is the dust temperature, $Q_{abs}(\lambda, a)$ is the dust absorption efficiency and $B_\nu(T_d)$ is the Planck function in terms of the frequency, ν. In these models the distance to the star cluster was set as $D_{SC} = 10$ Mpc.

Results

The outcomes from our reference model are displayed in Figure 2. In this case, the prevailing conditions inside the star cluster are: an average gas density $n \sim 10$ cm^{-3} and an average temperature $T \sim 1.35 \times 10^7$ K. From those conditions, we calculate the dust temperature distributions.

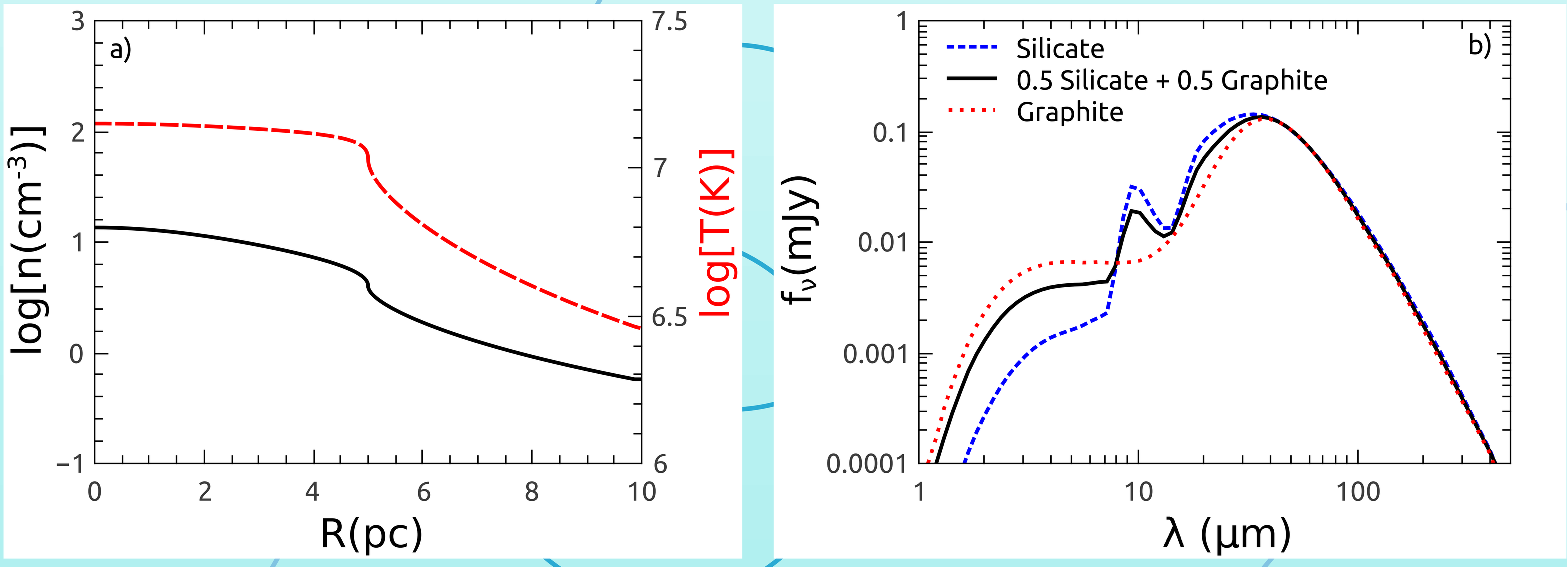

Figure 2: The Reference Model. Panels a) shows the gas density (black solid line, left axis) and temperature (red dashed line, right axis) radial profiles for our reference model. Panel b) presents the flux per unit frequency, f_ν. The blue dashed line depicts the contribution from graphite grains, the red dotted line the contribution from silicate grains while the solid line comprises both contributions.

The reference model *A* has been evaluated at four later times (models *A1*, *A2*, *A3* and *A4* evaluated at ~ 17000, 17500, 25000, and 33000 yr, respectively). Figure 3 shows evolving spectral energy distributions for models these models.

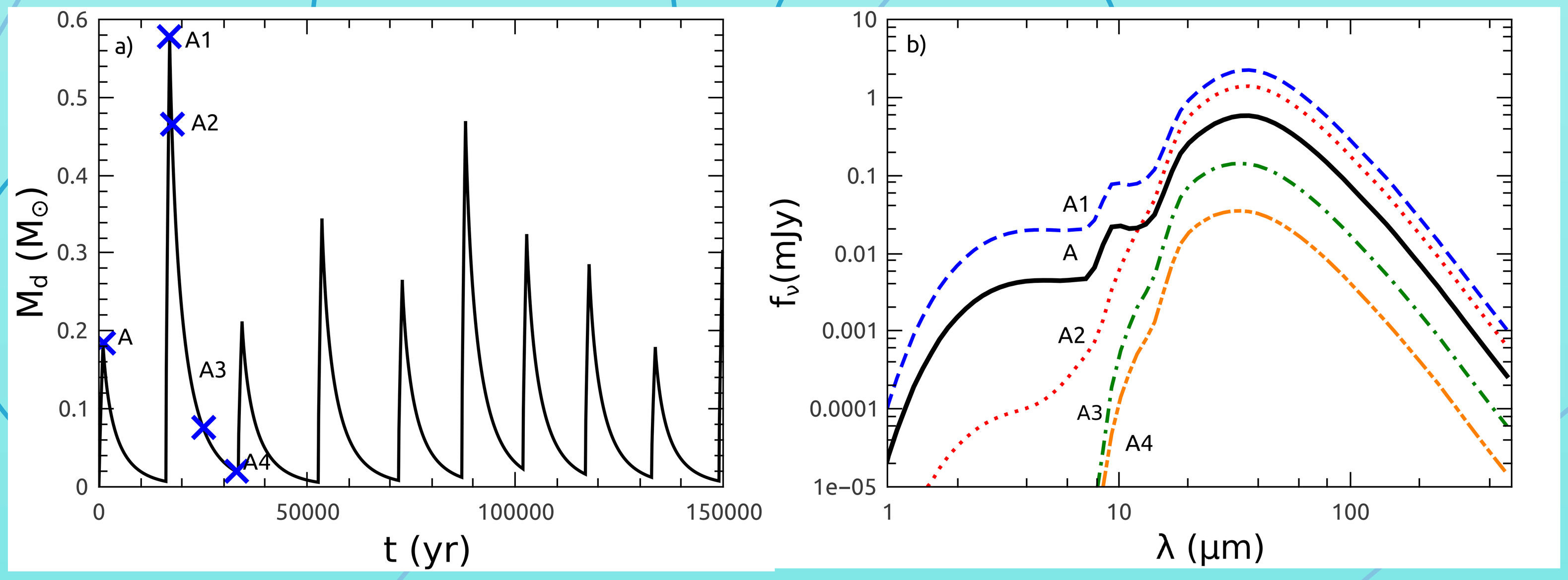

Figure 3: Panel a) shows the evolution during 9 injection events taking into account both dust sputtering and their exit out of the cluster as a wind. The times at which models *A1-A4* were evaluated are marked with crosses. Panel b) presents the values of the fluxes per unit frequency, f_ν, for each evolved models, respectively. Solid, dashed, dotted, dashed-dotted and dashed-double-dotted lines depict the SEDs for models *A*, *A1*, *A2*, *A3* and *A4*, respectively. Note that the strong emission present during dust injection rapidly vanishes when dust injection has ceased.The mean interval between supernova explosions and the standard deviation for $\Delta\tau_{SN}$ were taken to be ~ 17000 yr and 10% of the mean value, respectively, for a 10^5 M$_\odot$.

Conclusions

Motivated by the abundant evidence for core-collapse supernovae as major dust producers, and the large SN rate expected in young massive star clusters, here the frequent injection of dust grains into the plasma interior of super star clusters has been studied. Thus super star clusters become ideal laboratories to study dust grains which are heated by means of random gas-grain collisions. Then the hydrodynamic star cluster wind model has been combined with the stochastic dust injection, heating and cooling models to calculate the expected spectral energy distributions from super stellar clusters.

The evolution of the grain size distribution has been followed, what changes drastically the resultant spectrum. The exit of dust grains as they stream out, coupled to the gas, to compose the star cluster wind has also been considered. For the latter, a finite difference method was employed.

In this scenario, a certain mass of silicate and graphite dust, and an initial grain size distribution is injected into the intracluster medium. On top of this, the stellar winds are steady but the rate of supernova makes the dust injection an stochastic process. Therefore, dust is injected into the medium stochastically, and then heated and eroded before the next injection episode.

When dust injection is not taking place (models *A2-A4*), the dust size distribution rapidly evolves and greatly departs from the injection dust size distribution as a consequence of the short timescale for thermal sputtering. This is reflected in a lack of small grains and therefore, the NIR excesses noted in models *A* and *A1* (evaluated just before the end of the first and second dust injection episodes, respectively) rapidly vanish. Further description of the models is already published in Martínez-González et al. (ApJ, 2016, 816:39).

References

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