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GRAIN GROWTH IN COLLAPSING CLOUDS

S.C.F. Rossi, P. Benevides-Soares, B. Barbuy

Instituto Astronômico e Geofísico, USP, Brazil

RESUMEN. Se ha considerado un proceso de coagulación de granos en nubes colapsantes de diferentes metalicidades. Se aplicaron los cálculos al intervalo de densidades $n = 10^5$ to $10^{12}\,cm^{-3}$, forrespondiendo a la fase isotérmica de contracción de nubes. A lo largo de esta fase en el colapso, la temperatura es por lo tanto constante, en donde se alcanza $T \sim 10\,K$ para nubes de metalicidad solar y $T \sim 100$ K para nubes de baja metalicidad. El tamaño final del grano es mayor para las mayores metalicidades.

ABSTRACT. A process of grain coagulation in collapsing clouds of different metallicities is considered. The calculations are applied to the density range $n = 10^5$ to $10^{12}\,cm^{-3}$, corresponding to the isothermal phase of cloud contraction. Along this phase in the collapse, the temperature is thus a constant, where $T \sim 10$ K for solar-metallicity clouds, and $T \sim 100$ K for low metallicity clouds is reached. The final grain size is larger for the higher metallicities.

Key words: INTERSTELLAR-CLOUDS — INTERSTELLAR-GRAINS

I. Introduction

The presence of dust in contracting and fragmenting protostellar clouds is generally considered to be due to a previous enrichment of the interstellar medium as a result of grain formation in the envelopes of cool evolved stars (e.g., Gail et al., 1984). The high grain densities observed in clouds such as the dark globules (for a review on dark globules, see Leung, 1985; Benson and Myers, 1989, for example) might however be due to a process of grain growth in the collapsing cloud itself.

In the present work, a grain coagulation process is computed for contracting clouds where the parameters density and temperature are adopted from Yoshii and Sabano (1980) for the metallicities $z = Z/Z_{\odot} = 1, 10^{-1}, 10^{-2}, 10^{-3}$, and zero metallicities (where Z is the mass fraction of heavy elements), for clouds of initial mass of $10^6\,M_{\odot}$.

II. Fragmentation phases

Following the Jeans criterion, a cloud will fragment to smaller Jeans masses along its collapse, due to the increasingly higher densities and lower temperatures.

The illustration of a temperature versus density (n,T) diagram for a 3 $M_{\odot}$ solar metallicity cloud is given in figure 10 of Tohline (1982). The (n,T) diagram for a zero metallicity cloud of initial mass $10^5\,M_{\odot}$ is given in Villere and Bodenheimer (1987); in that work it can be seen that the tracks of the fragments and that of the parent cloud are similar in the (n,T) plane, in the density range $n = 10^5$ to $10^{12}\,cm^{-3}$.

Yoshii and Sabano (1980) give the evolution of clouds of different metallicities in the (n,T) plane, showing that clouds of metallicities $z = 1, 10^{-1}, 10^{-2}, 10^{-3}$ and 10^{-4} go through approximately isothermal phases, at temperatures $T \sim 10$, 20, 40, 100 and 10^4 K respectively, for the contraction in the density range 10^3 to $10^{11}\,cm^{-3}$. These physical conditions of contracting clouds are adopted for the present calculations of grain growth.

III. Grain growth in highly supersaturated vapours

Grain growth in collapsing clouds was already suggested by Burke and Silk (1976), Kolesnik (1978), Draine (1975). In the present work, a more detailed calculation of grain growth is done.

Although very little is known about saturation pressures of the significant vapour species at low temperatures, it is vey likely that most of the existing metals will be in conditions of supersaturation (S >> 1). Therefore, we expect that heterogeneous coagulation becomes an efficient process, provided that the ratio between the collision and collapse timescales is small.

The composition of grains will comprise all heavy elements present in the gaseous phase. Even volatile species, in the ordinary view, are able to condense. In other words, all the elements heavier than helium will be condensed in dust during the low temperature isothermal phase.

In this work, a solution of the kinetic theory for the growth of grains from highly supersaturated vapours is obtained. Small grain seeds are defined as monomers X_1 of mass m_1, radius r_1 and absolute density γ.

The coagulation occurs through the irreversible reactions:

$x_n + x_m \rightarrow x_{n+m}$ where n = 1, 2, ...

The grains of equal size i and density ρ_d have an average "mutual" velocity of thermal origin given by

$$v_{ii}^{th} \propto (T/r_1^3 \rho_d)^{1/2} i^{-1/2}$$

Besides this thermal velocity, turbulent velocity fields in the gas will be of a major importance in the grain growth process. For the turbulent regime, the results by Völk et al. (1980) are adopted; for similar particles, the following analytical expression can be given

$$v_{ii}^{tb} \propto (\rho_d r_1)^{1/2} \alpha^{1/2} (k \delta^3)^{1/2} (T/\rho)^{1/4} i^{1/6}$$

where ρ is the mass density and T is the temperature; the dimensionless quantities α, k and δ represent the spectral index of the assumed power law spectrum for the turbulent velocity, the ratio between the Jeans length and the maximum length scale of turbulence, and the ratio between the turbulent and thermal velocities of the gas, respectively.

The rate of the coagulation reactions between grains of equal size, where evaporation of monomers is neglected, is

$$I_{ii} = s_{ii} v_{ii} A_{ii} c_i^2$$

where A_{ii} = grain cross section, which is proportional to $(r_1 i^{1/3})^2$, c_i = number density, s_{ii} = sticking coefficient, $v_{ii} = \max(v_{ii}(\text{thermal}), v_{ii}(\text{turbulent}))$.

Let C be the total grain density and γ the absolute number density. The average grain size $\underline{m}$ is defined by

$$m = \langle i \rangle = \gamma/c$$

and the average grain radius is

$$r = r_1 m^{1/3}$$

Introducing the timescales for thermal and turbulent collisions, the variation of the average size of grains in a contracting cloud volume, can be written as

$$(dm/dt)^{th} \propto (\tau_c^{th})^{-1} T^{1/2} \rho m^{1/6}$$

$$(dm/dt)^{tb} \propto (\tau^{tb})^{-1} T^{1/4} \rho^{3/4} m^{5/6}$$

IV. Application to models of contracting clouds

A dependence of the temperature of the isothermal phase as a function of cloud metallicity, as given in Silk (1977) is assumed, as follows

$$\log T = 1 - 1/3 \log Z$$

Besides the temperature, other characteristic values for the cloud parameters adopted are

$\rho_o = 10^{-22}$ g cm^{-3} (initial density)

$\mu = 2$

For the grain seeds, we adopted:

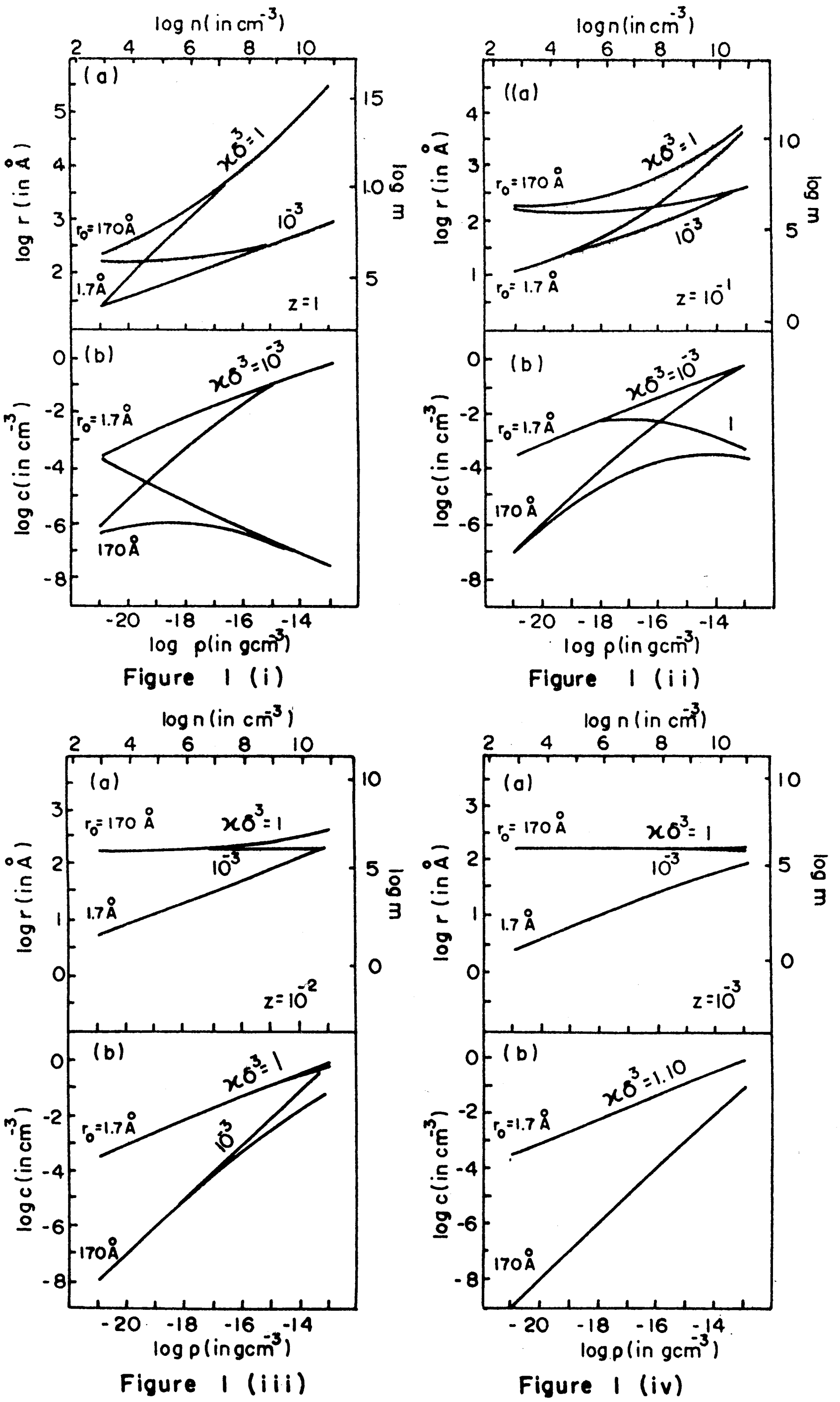

Figure 1 - (a) Grain size, (b) grain concentration, as a function of cloud density, for: (i) z = 1, (ii) z = 0.1, (iii) z = 10^{-2}, (iv) z = 10^{-3}

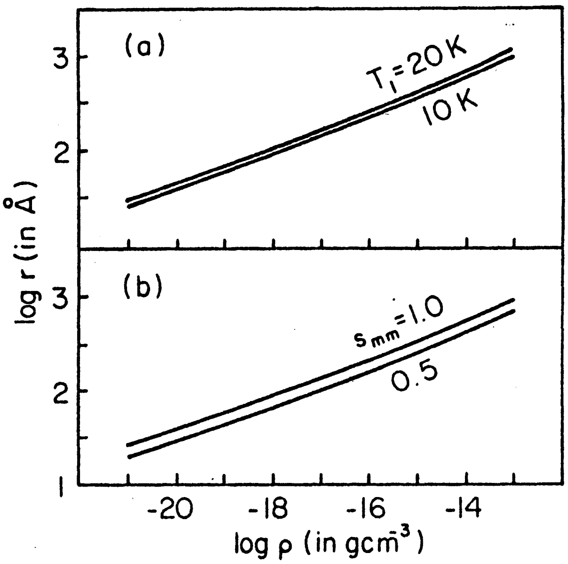

Figure 2 - Grain size versus cloud density, for the parameters z = 1, r_o = 1.7 A, k δ^3 = 10^{-3}, showing the effect of variations in (a) isothermal temperature, (b) sticking coefficient

r_o = 1.8 10^{-8} cm (monomer radius)

ρ_d = 1.6 g cm^{-3} (bulk density)

s_{mm} = 1 (sticking coefficient)

and the following dimensionless parameters are varied:

$z = Z/Z_o = 10^{-3}, 10^{-2}, 10^{-1}, 1$ (metallicity)

$\alpha = (2/3)^{1/2}$ (spectral index of a Kolmogorov spectrum)

k δ^3 = 10^{-3}, 1 (turbulence length scale and velocity)

m_o = 1, 10^6 (initial average grain size, corresponding to initial grain radii of 1.7 A and 170 A respectively)

The metallicity range represents values characteristic of population I to popula - tion II stars. Lower z's lead to (n,T) diagrams which depart considerably from an isotherm (Villere and Bodenheimer, 1987).

The turbulence parameters, which appear in the combined variable kδ^3, are not well known. The value of 10^{-3} is characteristic of a cloud where the turbulence scale is comparable to its dimensions, and where the turbulent velocity is about 10% of the thermal velocity. The value equal to 1 corresponds to a situation where either the turbulence scale is smaller by a factor of 10^3 or the turbulent velocity is higher by a factor of 10.

The results showing the grain growth as a function of initial grain size, along (n,T) values of a contracting cloud, are presented in figures 1 (i), (ii), (iii), (iv) and 2.

V. Conclusions and discussion

It has been shown that coagulation processes are very efficient at the low temperatures of the isothermal phase of contracting clouds. We point out that this may introduce a more efficient grain cooling than previously considered. In that case, the fragmentation of clouds is affected in a different way, and calculations on that problem will be of great interest.

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S.C.F. Rossi, P. Benevides-Soares, B. Barbuy: Universidade de São Paulo, Instituto Astronômico e Geofísico, Departamento de Astronomia, C.P. 30627, São Paulo 01051, Brazil