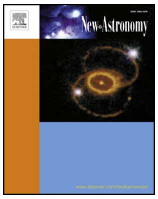
New Astronomy 66 (2019) 45–51

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast



Fragmentation of molecular cloud in a polytropic medium

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ARTICLE INFO

Keywords:
Interstellar medium
Fragmentation
Jeans mass

ABSTRACT

In search of the scenario of the star formation process, fragmentation of molecular clouds has been modelled under two different conditions. In the first case, thermal instability along with an equation of state with negative polytropic indices (n) has been considered which give rise to minimal fragment masses in the range $0.001M_{\odot}$ to $8.5\ M_{\odot}$ for $-10 < n < 0,\ n \neq -1$. In the second case, an opacity limited fragmentation along with positive polytropic indices is considered which lead to a wide range of minimal fragment masses resulting in field stars, massive stars, and star bursts. This might be due to the effect of opacity which is responsible for slow dissipation of heat in a compressed medium.

1. Introduction

The interstellar medium (ISM) is commonly known as a dilute mixture of charged particles, atoms, molecules and dust grains. The physics of the ISM plays a crucial role in many areas of astronomy. The fragmentation process of the molecular cloud as well as its structure and evolution is still considered to be a poorly understood problem in astrophysics. The thermal instability is the most commonly known physical process that helps us to understand the dynamics of the ISM. Thermal instability happens in a system when the rate at which energy is radiated predominates or underrates the acquisition of compressional energy when the system is someway under gravitational collapse. Thermal instability could occur in denser regions like molecular clouds and have actually been studied by various authors (de Jong et al., 1980; Gilden, 1984; Nejad-Asghar, 2011).

Molecular clouds (MCs) are characterized as parts of the ISM that are dense and cold enough to allow the formation and survival of molecules. Thus, the density is the primary characteristic of a MC. One particularly interesting characteristic in the context of fragmentation is that molecular clouds use to show supersonic velocity dispersions due to turbulent flows (Larson, 1981; Sabano and Tosa, 1985; Solomon et al., 1987).

The opacity limited fragmentation occurs when the optical depth across a fragment is unity i.e. most of the compressional energy remains within the system due to various optical properties of the particles in the system e.g. shape, porosity as well as the wavelength one is detecting. The most dominant sources of opacity in the present case are various properties of dust grains at low and high densities as well as molecular gas at high densities. The minimal fragment mass for gravitational collapse for a dark molecular gas cloud suggested by various authors is about $0.006M_{\odot}$ (Silk, 1977) and $0.007\ M_{\odot}$ (Low and Lynden-Bell, 1976). In implementing the condition that the rate at which the energy is radiated equals the rate of acquisition of compressional energy and the optical depth across a fragment of scale be unity of a volume element of the collapsing cloud in the temperature -density plane, Silk (1977) computed the adopted parameters of grain materials. Similar work regarding the thermal balance of heating and cooling of different substances along with opacity have been considered by Kanjilal and Basu (1992).

In the present work we have considered equation of state of a polytropic gas as $p = K\rho^{1+\frac{1}{n}}$ where, p and ρ are respectively the thermal pressure and gas density and n is the polytropic index. Applying this Eq. on a gas in thermal equilibrium we find in Section 4, a relationship between the minimal fragment mass and the minimal gas temperature, as well as the composition of dust, contained within the cloud, and n. Like the classical polytropes with positive indices the study of polytropes with negative indices is also practically important from the point of view that they can approximate either some models of interstellar gas clouds in the case of $n < -1$ (Shu et al., 1972; Viala, 1972; Toci and Galli, 2015) or in the case $-1 < n < 0$ (Chavanis, 2014) where thermally unstable gas phases of the interstellar medium have $\frac{\partial p}{\partial \rho} < 0$ (Viala and Horedt, 1974) and also in a shock compressed layer (Lou and Gao, 2006) as a result of explosive shocks at the central region of Galaxy (Kanjilal and Basu, 1991).

In Section 2 we have developed the model of fragmentation governed by thermal instability. Here we have calculated the minimal fragments masses for gravitational collapse under the similar negative polytropes. Section 3 gives the initial values of the various parameters

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https://doi.org/10.1016/j.newast.2018.07.008
Received 30 April 2018; Received in revised form 14 July 2018; Accepted 25 July 2018
Available online 01 August 2018
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used in the model. Section 4 computes minimal fragment masses under various conditions for models with negative polytropic indices. Section 5 outlines opacity limited fragmentation. Section 6 includes discussion.

2. Model and basic equations

In the present model the gravitational collapse of molecular clouds have been considered in a low temperature range ($T < 50$ K). During the collapse it is thus necessary for the thermal energy generated during the collapse, to be dissipated in order to continue the collapse. Now at such low temperature range the particles, excited, must have low excitation potentials ($<$ 0.1 eV). In molecular clouds H atoms and heavy elements do not satisfy the condition. On the contrary rotational levels of molecular hydrogen (Hirasawa, 1969; Matsuda et al., 1969; Puy et al., 1999), carbon monoxide (Goldsmith, 2001) and similar molecules (Peebles and Dicke, 1968; Bally et al., 1987; Bally et al., 1988 generally in the submillimeter range) and dust grains (Silk, 1977 at high densities $\sim 10^{-18}$ g cm^{-3} by far-infrared) are excited which therefore act as the effective cooling elements in such cold molecular clouds (Section 3 for more details).

Thus we have considered here the thermal balance for most of the heating and cooling processes known to be important in the interstellar medium along with the polytropic equation of state with a negative index in the molecular gas clouds. The modified form of the equation of state for the ideal gas to express the thermal pressure is as follows:

$$p = \frac{R}{\mu_0}\rho T, \tag{1}$$

where R is the Universal gas constant, $\mu = \mu_0 m_H$, μ is the mean molecular weight and m_H is the mass of hydrogen and T denotes the gas temperature.

A polytropic equation of state is a special case of barytropic equation of state where p and ρ are related as

$$p = K\rho^{1+\frac{1}{n}}, \tag{2}$$

where K is a constant and n is the so-called polytropic index. The values of K are determined from the several initial conditions of temperatures and number densities e.g. $T = 10$ K, 20 K and number densities as 10^4 and 10^5 cm^{-3} respectively (Herbst and Klemperer, 1973; Goldsmith and Langer, 1978; Bally et al., 1987; 1988; Caselli et al., 1999). Then Eqs. (1) and (2) imply

$$\rho = \left(\frac{RT}{\mu_0 K}\right)^n. \tag{3}$$

We assume that Γ_c is the rate of heating due to cloud compression (Silk, 1977) and

$$\Gamma_c = \frac{\rho k T}{\mu}(16\pi G\rho)^{\frac{1}{2}}. \tag{4}$$

We also assume that Λ_g, Λ_{H_2} and Λ_{CO} are the rates of cooling due to grains (Silk, 1977), molecular hydrogen (Peebles and Dicke, 1968) and cooling due to excitation of rotational levels of CO (Oppenheimer and Dalgarno, 1975) respectively and

$$\Lambda_g = 3\sigma T_g^{4+\delta} q\frac{Z\rho}{\rho_g}, \tag{5}$$

where q, δ are grain parameters and T_g, ρ_g, Z are the grain temperature, grain density and fraction of grain by mass of the total density respectively (Section 3 for more detail).

$$\Lambda_{H_2} = 2 \times 8.05 \times 10^{-7} T^3 \rho y, \tag{6}$$

for $\rho \geq 10^{-20}$ g cm^{-3} where y is the relative abundance of molecular hydrogen compared to atomic hydrogen and the adopted value of $y = 0.2$ (Kanjilal and Basu, 1992). Further following Oppenheimer and Dalgarno (1975) we have, for the rate of cooling due to CO as,

$$\Lambda_{CO} = 7 \times 10^{-26} T^{\frac{1}{2}}\left[1 - \frac{5.3}{T}\exp\left(-\frac{T}{20}\right)\right]\exp\left(-\frac{5.3}{T}\right) n_{CO} n_{H_2}, \tag{7}$$

where n_{CO} and n_{H_2} are the number densities of CO and H_2 molecules respectively. We assume that the abundance of CO relative to hydrogen as $n_{CO}/2n_{H_2} = 7.3 \times 10^{-5}$ (Mortan, 1974), which corresponds to the depleted value of carbon abundance. We know that $n_H m_H = \rho$ and $n_H = 2n_{H_2}$. Then $n_{H_2} = \rho/(2 \times 1.67 \times 10^{-24})$. $n_{CO} = 7.3\rho/(1.67 \times 10^{-19})$ and $n_{CO} n_{H_2} = 7.3\rho^2 /\{2 \times (1.67)^2 \times 10^{-43}\}$ (Mortan, 1974). Then the condition of thermal balance reduces to

$$\Lambda_g + \Lambda_{H_2} + \Lambda_{CO} = \Gamma_c. \tag{8}$$

Jeans mass for gravitational collapse at density ρ and temperature T, is given by

$$m_J = \rho^{-\frac{1}{2}}\left(\frac{\pi k T}{\mu G}\right)^{\frac{3}{2}}, \tag{9}$$

where G is the gravitational constant. The minimal fragment mass is equivalent to the instant mass m_J.

3. Dust species and the initial values of the parameters

During the gravitational collapse of a low temperature molecular cloud one should consider the most important coolants and opacity sources over the appropriate ranges of densities and column densities due to molecules as well as dust grains. At densities $\rho \geq 10^{-18}$ g cm^{-3} and at optical depths $\tau \geq 100$ the effective cooling in the far-infrared is due to thermal emission by dust grains. In particular in a cold, dense cloud if the dust particles are spheroidal in shape (which is the most general assumption) the rate of cooling follows Eq. (5) where q and δ are grain parameters associated with Planck's mean absorption coefficient (Silk, 1977). As q and δ are high the rate of cooling increases. These parameters were obtained by Gilman (1974) by fitting data for various types of grains e.g. *Graphite*, the *Olivine* and *Graphite − coreandicemantles*.

Here we have also used three types of dust grain materials, the *Graphite*, the *Olivine*, and the *Graphite core and ice mantle* since they are the most efficient coolants and their adopted parameter values (Silk, 1977) are given in Table 1.

Bally et al. (1987, 1988) have delineated the central region of Galaxy especially the molecular gas in Sgr A and Sgr B2 complexes. They found several molecular transitions in ^{13}CO J = 1 - 0 (110.201 GHz) range. Also transitions from $J \rightarrow J-2$ rotational levels of molecular hydrogen are frequent in nearly isothermal contraction of cold dense molecular clouds (Yoshii and Saioo, 1986) until the density is so high that the radiation is trapped within the cloud due to self-absorption of the H_2 molecule. Hence we have considered CO and H_2 also as other cooling agents (Eqs. (6) and (7) respectively).

Now the ratio of dust to gas mass in the diffuse ISM of Milky way is around 1: 100 (Bohlin et al., 1978; Klapdor-Kleingrothaus, 2000) but within molecular clouds that ratio primarily depends on the evolutionary stage of the cloud. The ratio only increases significantly when a protostar evolves an accretion disk. These disks compress the matter immensely and separate the gas and dust particles by transporting the gas onto the protostar while the dust remains within the disk. The dust

Table 1
Parameters of dust grains used (Silk, 1977) in the study.

Type of grain	δ	*logq*	ρ_g (g cm^{-3})
Graphite	2.03	− 1.87	2.25
Olivine	1.96	− 3.17	3.5
Graphite *core and ice mantle*	1.05	− 0.30	1.0

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