THE POLYTROPIC EQUATION OF STATE OF PRIMORDIAL GAS CLOUDS

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ABSTRACT

The polytropic equation of state (EOS) of primordial gas clouds with modest enrichment is computed, motivated by the recent observations of very Fe-deficient stars, [Fe/H] ~ 10^{-3.5} to 10^{-5}, such as HE 0107−5240 and CS 29498−043. These stars are overabundant, relative to Fe, in C and O. We assume that the observed abundances of species like C, O, Si, and Fe are representative of the gas from which the currently observed metal-deficient stars formed. Under this assumption, we find that this primordial metal abundance pattern has profound consequences for the thermal balance and chemical composition of the gas and hence for the EOS of the parental cloud. The polytropic EOS is soft for low, [O/H] < 10^{-3}, oxygen abundances but stiffens to a polytropic index \gamma larger than unity for [O/H] > 10^{-2} because of the large opacity in the CO and H2O cooling lines. It is further found that a regulating role is played by the presence and temperature of the dust, even when the overall carbon abundance is only [C/H] ~ 10^{-2}. When the dust is warmer than the gas, a region with \gamma \sim 1.2 results around a density of \sim 10^4 cm^{-3}. When the dust is colder than the gas, a region with \gamma \sim 0.8 is found for a density of \sim 10^6 cm^{-3}. Implications for the primordial initial mass function (IMF) as well as the IMF in starburst galaxies, for which the metallicity is supersolar, are explored and related to processes that influence the temperature of the ambient dust.

Subject headings: cosmology: theory — galaxies: starburst — ISM: clouds — ISM: molecules — molecular processes — radiative transfer

1. INTRODUCTION

A fundamental issue in the study of star formation is understanding the physical structure of molecular gas clouds from which stars are formed. Despite a wealth of observational data for the Milky Way (cf. Fuller & Myers 1992; Goodman et al. 1998), the nature of the equation of state (EOS) remains a major theoretical problem in understanding the stability and collapse of molecular clouds. The stiffness of the EOS can be largely responsible for the resulting density probability function of interstellar gas in the turbulent ISM. In particular, the value of the polytropic index \gamma strongly influences the mass distribution of density condensations as well as the amount of clump fragmentation (Vázquez-Semadeni et al. 1996; Li et al. 2003). In Spaans & Silk (2000) the properties of a polytropic EOS were investigated and it was found that the stiffness of the EOS depends strongly on the ambient metallicity.

Recent observations of metal-deficient stars such as HE 0107−5240 (Christlieb et al. 2004) and CS 29498−043 (Aoki et al. 2004) indicate that formation of (low mass) stars is possible in very low metallicity gas clouds. The formation of stars in low-metallicity environments (Abel et al. 2002) is important for the reionization of the universe and the early enrichment of the interstellar and intergalactic medium (Hirashita & Ferrara 2002). Even though more (but not many more) stars are known with very low Fe abundances (e.g., CS 22949−037; Aoki et al. 2004), we concentrate on the two stars mentioned above, since they appear to reflect the wide range in C, N, O, and \alpha element abundance patterns for Fe-deficient stars.

It is not generally known what influence the environment has on the shape of the initial mass function (IMF). The Hubble Space Telescope (HST) WFPC2 observations of the LMC by Gouliermis et al. (2005) indicate that local conditions seem to favor the formation of higher mass stars (top-heavy IMF) in associations and not in the background field. However, Meyer et al. (2005 and references therein) find that the IMF is not a strong function of environment or initial conditions. In any case, the numerical simulations of Li et al. (2003 and references therein) indicate that the value of the polytropic index strongly influences the spectrum of density condensations that is formed under the influence of gravity and turbulent driving. In particular, fragmentation is enhanced or inhibited when \gamma is smaller (0.7) or larger (1.1) than unity. In this context, we present computations of the polytropic EOS of primordial (low metallicity) gas clouds at high redshifts. We also comment on interstellar regions that have supersolar metallicities and are exposed to a warm (dusty) infrared background (e.g., starbursts).

2. MODEL DESCRIPTION

We assume that the observed abundances of species like C, O, Si, and Fe are representative of the gas from which the currently observed metal-deficient stars formed. We further employ a polytropic EOS, \( P \propto \rho^\gamma \), where \( \gamma \) is the polytropic index and \( \rho \) the mass density. We adopt a perfect gas equation of state, \( P \propto \rho T_g \), for the gas temperature \( T_g \), to write \gamma as

\[
\gamma = 1 + \frac{d \log T_g}{d \log \rho}.
\]

This last step is justified (Scalo & Biswas 2002; Vázquez-Semadeni et al. 1996) as long as the heating and cooling terms in the fluid energy equation can adjust to balance each other on a timescale shorter than the timescale of the gas dynamics (i.e., thermal equilibrium). It should be noted that because \gamma depends on the (logarithmic) derivative of the temperature with respect to density, it implicitly depends on radiative transfer effects and changes in chemical composition through derivatives of the heating and cooling functions (Spaans & Silk 2000). The model described in Spaans & Silk (2000) is used in this work, and the interested reader is referred to that paper for a detailed

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TABLE 1
PARAMETERS USED FOR MODELS

| Model       | C (Z_{\odot}) | O/C (O_{\odot}/C_{\odot}) | Z | Dust | Figure | Color |
|-------------|---------------|-----------------------------|---|------|--------|-------|
| 1           | …              | …                           | … | No   | 1–4    | Red   |
| 2           | 0.03           | 1/3                         | 10 | No   | 1      | Light blue |
| 3           | 0.03           | 1/3                         | 20 | No   | 1      | Blue  |
| 4           | 0.01           | 1/3                         | 10 | No   | 1      | Black |
| 5           | 0.01           | 1/3                         | 20 | No   | 1      | Green |
| 6           | 0.03           | 1                           | 10 | Yes  | 2      | Light blue |
| 7           | 0.03           | 1                           | 20 | Yes  | 2      | Blue  |
| 8           | 0.03           | 1                           | 20 | Yes  | 2      | Black |
| 9           | 0.03           | 0                           | 10 | No   | 3      | Green |
| 10          | 0.03           | 0                           | 20 | No   | 3      | Blue  |
| 11          | 0.03           | 0                           | 20 | No   | 3      | Green |
| 12          | 0.03           | 0                           | 20 | No   | 3      | Green |
| 13          | 3 \times 10^{-4}| 0                           | 0  | No   | 3      | Black |
| 14, starburst | 2              | 1                           | 0  | Yes  | 75 K   | Black |
| A, HE 0107–5240 | 0.03          | O at 0.0013 Z_{\odot}       | 10 | No   | 4      | Light blue |
| B1, CS 29498–043 | 0.1          | 3                           | 20 | Yes  | 4      | Blue  |
| B2, CS 29498–043 | 0.03        | 3                           | 0  | Yes  | 4      | Green |

NOTES.—All models use \( \Delta V_{\text{tot}} = 0.5 \text{ km s}^{-1} \), except for model 14, which uses \( \Delta V_{\text{tot}} = 3 \text{ km s}^{-1} \). The observed O and C abundances for the halo stars HE 0107–5240 and CS 29498–043 are adopted in models A, B1, and B2. For CS 29498–043 the two adopted C abundances are indicative of the observational uncertainties in carbon.

Solar relative abundances are assumed (Asplund et al. 2005; Jenkins 2004). The latter condition is replaced by the observed abundance pattern of metal-deficient stars for some of the primordial gas cloud models. We further adopt an MRN grain size distribution (Mathis et al. 1977) and assume that the dust abundance scales with the carbon abundance.

The velocity dispersion of microscopic turbulence is \( \Delta V_{\text{tur}} = 0.5 \text{ km s}^{-1} \) in the quiescent primordial gas, to which the purely thermal contribution is added (in the square) while the iterations on the thermal and chemical balance are performed. However, for the starburst model \( \Delta V_{\text{tur}} = 3 \text{ km s}^{-1} \) is adopted to take the larger input of kinetic energy (e.g., through supernovae) into account.

No freezeout of molecules is assumed. The latter assumption is justified because our dust is generally warmer than 20 K. The total extinction through the starburst region containing the model cloud is 100 mag (Spaans & Silk 2000). The results of Le Bourlot et al. (1999) are used for the collisional excitation of H\(_2\) by H, He, and H\(_2\), for which nonlinear thermodynamic equilibrium level populations and quantum-mechanical cross sections are computed. For HD cooling, the results of Flower et al. (1999) are used. Both H\(_2\) and HD line emission are optically thin. For completeness we have also included H\(_2\) formation heating with equal contributions from the binding energy (4.93 eV) to translational, rotational, and (statistically distributed) vibrational degrees of freedom (Sternberg & Dalgarno 1989; Meijerink & Spaans 2005).

The computed values of \( \gamma \) depend sensitively on a number of effects: (1) line trapping, (2) metallicity, (3) H\(_2\)O heating and cooling, and (4) microturbulence versus a large velocity gradient (LVG) velocity field. In particular, (4) is important in the context of collapsing molecular cloud cores. Note that a LVG

The description of the various heating and cooling terms that influence the polytropic index. The (updated) two-dimensional numerical radiative transfer code of Spaans (1996) with the detailed chemical treatment of Spaans & van Dishoeck (1997) and its extensions to lower metallicities by Norman & Spaans (1997) and Spaans & Norman (1997) is used in this work. With the work of Scalco (1998) and Le Bourlot et al. (1999) it is possible to extend the Spaans & Silk (2000) model to metallicities much smaller than 1% of solar, for which H\(_2\) and hydrogen deuteride (HD) completely dominate the cooling of the gas. The main features of the model are summarized below.

We consider self-gravitating spherical clouds, and therefore we adopt a singular isothermal sphere (Neufeld et al. 1995), for which the total hydrogen number density \( n_\text{H} \) scales with column density \( N_\text{H} \) per unit of velocity as

\[
N_\text{H} = 7.2 \times 10^{19} n_\text{H}^{0.5} \text{ cm}^{-2} (\text{km s}^{-1})^{-1}.
\]

We include number densities, \( n_\text{H} = n(\text{H}) + 2n(\text{H}_2) \), up to \( 2 \times 10^7 \text{ cm}^{-3} \) and metallicities as low as \( 3 \times 10^{-4} \) and 0 in solar units. Furthermore, dust temperatures between 10 and 100 K can be treated, and the latest chemical reaction rates have been used in the computations (Le Teuff et al. 2000). Care has been taken to check the convergence of the chemical equilibrium calculations for oxygen over carbon (O/C) ratios that significantly differ from solar. In general, the thermal and chemical balance was solved iteratively with a convergence criterion of 0.1% for the chemical abundances and level populations.

The computed grid is accurate enough to do linear interpolations between the log of any two adjacent values. Extrapolation of the values of \( \gamma \) to densities lower than \( 10^2 \text{ cm}^{-3} \) (say to 1 cm\(^{-3}\)) is reliable because the slopes are modest. Note that softening of the EOS due to gas cooling on cold dust can be important and flips over to gas heating when the dust is warm.

We have used a cosmic-ray heating rate for the low-metallicity models that is given by a cosmic-ray ionization rate of \( \dot{\zeta} \), with \( \zeta = 3 \times 10^{-17} \text{ s}^{-1} \). This means that cosmic-ray heating is provided by a background star formation rate of the order of 1 \( M_\odot \) yr\(^{-1}\). However, the zero-metallicity polytropic index is only weakly dependent on temperature between 100 and 2000 K so that the actual value of the cosmic-ray heating rate, as long as it is proportional to density, does not matter much for the low-metallicity case (Scalo & Biswas 2002). For starburst environments, we assume a cosmic-ray ionization rate of 30 \( \text{C} \).
approximation suppresses line trapping somewhat and yields a relatively softer EOS (see Spaans & Silk 2000). Also, H$_2$O heating, for which absorption of infrared photons and collisional de-excitation causes heating (Takahashi et al. 1983), plays a smaller role for a LVG model unless $A_T > 20$ mag.

We assume a microturbulent velocity field for all simulations. For optically thin (e.g., low metallicity) line emission the velocity field plays no role. We ignore time-dependent effects (Bromm & Loeb 2003). UV illumination from the outside, not included here, will create a warm photodissociation region (PDR) in which the cooling is dominated by [C ii] and [O i] fine-structure emission and the polytropic index varies between 0.5 and 1.0 for C$^+$ and between 0.6 and 1.2 for O-dominated emission.

3. MODEL RESULTS

In order to assess the impact of elemental abundances that strongly deviate from solar, a grid was run with the parameters listed in Table 1. The figure number and color coding of each model are listed. The primordial model 1 is used as a baseline to assess the impact of C, O, and dust on the polytropic EOS. Redshifts of 10 and 20 are considered for the high-redshift universe, and the temperature of the dust, if any is present, is taken to be equal to that of the cosmic microwave background (CMB). Overall, the grid covers the two Fe-deficient stars, through models A, B1, and B2, and a range in carbon that limits, through model 13, to the zero-metallicity primordial cooling curve. Furthermore, various oxygen models are explored to show the large impact that O has on the EOS, i.e., models 10–12 for no O and models 2–9 for solar and supersolar O/C ratios. The latter are relevant because observations of CS 29498–043 (Aoki et al. 2004) indicate that the O/C ratio can also be enhanced relative to the solar ratio. Finally, model 14 is a starburst environment in which O/C is solar, but the overall metallicity is supersolar by a factor of 2.

It is straightforward to identify a number of trends in the models. We first note that in all models with a nonzero oxygen abundance, part of the gas cooling is provided by the [O i] 63 $\mu$m line. This line can go into absorption against the warm CMB below a gas kinetic temperature of $\sim 80$ K. Collisional de-excitation of excited [O i] then leads to heating and a change in the polytropic index with the CMB temperature, e.g., in models 2–5, even when no dust is present. The same effect occurs for absorption of the CMB by water, i.e., H$_2$O collisional de-excitation heating. From Figures 1–4 one also sees the following: (1) Carbon alone, even at 3% of solar, is not able to significantly stiffen ($\gamma > 1$) the EOS (Fig. 3). (2) Oxygen needs to be present at no less than 1% of the solar level to boost the opacity in the CO and H$_2$O lines at densities around $3 \times (10^3 - 10^4)$ cm$^{-3}$ (see Fig. 1) and yield values of $\gamma$ larger than unity. Note in this that the total abundance of oxygen (rather than carbon) sets a limit to the maximum amount of gas-phase CO when [O/H] $< 1/2$[C/H]. (3) The model parental cloud of HE 0107-5240 is characterized by a soft EOS, while that of CS 29498–043 has a stiff EOS (see Fig. 4). (4) An overabundance (relative to solar) of oxygen leads to a significantly stiffer EOS (Fig. 2), even when the overall metallicity is only of the order of 3% of solar. That is, if the O/C ratio is enhanced by a factor of 3 compared to its solar value, then the EOS stiffens to values of $\gamma$ in the 1.2 range at around $n_H \sim 10^4$ cm$^{-3}$.

(5) This effect is further enhanced (also Fig. 2) when the temperature of the dust is high, because of the CMB at $z = 10$–20, and allows H$_2$O (collisional de-excitation) heating to dominate the thermal budget and cause the gas heating to attain an $n_H^2$ density dependence. (6) At densities around $10^6$ cm$^{-3}$, the polytropic index dips below unity if the dust temperature, $T_d$, is lower than the gas temperature. This results in $\gamma \sim 0.8$ for models with dust at $z = 0$. If the dust grains are warm, then dust-grain heating
causes the EOS to stiffen further and $\gamma \approx 1.1$ beyond the H$_2$O opacity peak. Recall in this case that gas-dust heating or cooling scales as $(T_g - T_d)n_H^3/\rho$ (7) The starburst (Fig. 4) has the stiffest EOS because of its high absolute metallicity and warm $(T_d = 75 \, \text{K})$ dust. (8) The temperature of the dust, if present, plays an important regulating role (see Fig. 2).

4. DISCUSSION

In commenting on our results, we wish to distinguish slightly enriched, $Z/Z_\odot \sim 10^{-2}$, primordial gas that leads to Fe-deficient stars (models 2–12, A, B1, and B2) from almost zero metallicity, $Z/Z_\odot \sim 10^{-4}$, primordial gas associated with Population III star-forming regions (models 1 and 13). As Figures 1–4 show, these two metallicity regimes exhibit quite different behaviors as far as the polytropic index is concerned.

We point out that all the models presented in this work are computed for a microturbulent velocity field with $\Delta V_{\text{tur}} = 0.5 \, \text{km s}^{-1}$ (or $3 \, \text{km s}^{-1}$ for the starburst model 14) and a thermal velocity contribution that is determined by the thermal and chemical balance of the medium. However, if large velocity gradients are present, then optical depth effects, particularly line trapping in H$_2$O and CO transitions, are more modest and $\gamma$ decreases (Spaans & Silk 2000).

Also, adiabatic (compressional) heating has a density dependence of $\Gamma_A \propto n_H^{1.5}$, in between cosmic-ray ionization, $n_H^{1.0}$, and gas-dust or H$_2$O, $n_H^{2.0}$, collisional heating. Compressional work is not relevant to model clouds that can be described by singular isothermal spheres; however, in a collapsing medium it must play a role. Our heating terms bracket adiabatic heating when dust is present and/or $Z \geq 10^{-3} \, Z_\odot$. For $Z/Z_\odot \leq 3 \times 10^{-4}$, we expect $\gamma$ to attain a slightly larger asymptotic value of 1.0–1.3 for $n_H \geq 10^6 \, \text{cm}^{-3}$ (Scalo & Biswas 2002; Schneider et al. 2002). At smaller densities the higher resulting temperatures, $T_g \sim 200–800 \, \text{K}$ (Abel et al. 2000), prevent $\gamma$ from increasing significantly under the $\Gamma_A$ term, because excited atomic (e.g., O, Si) and molecular (e.g., CO, H$_2$O) states with progressively higher critical densities become accessible already at a metallicity of $10^{-4} \, Z_\odot$. These higher critical densities ensure that the subthermal $n_H^3$ density dependence is maintained for larger gas densities.

4.1. Fe-deficient Stars

In Spaans & Silk (2000) it is argued that a defining criterion for low or high mass star formation to prevail, i.e., whether fragmentation can proceed to small enough mass scales to cause a flattening in the IMF below about 0.3 $M_\odot$ (Scalo 1998), is whether the EOS has a polytropic index $\gamma_c$ that is smaller or larger than about unity, respectively. Above this canonical value of $\gamma_c = 2(1 - 1/\nu)$, where $\nu$ is the number of dimensions in which cloud contraction occurs, sheets ($\nu = 2$) are able to stop fragmentation and start gravitational contraction because the Jeans mass does not decrease any further. In the present discussion, the thermal Jeans mass, $M_J \propto \rho^{-5/3}$, as well as its generalizations to turbulent and magnetic media, plays a secondary role.

If the elemental abundance pattern that is observed for HE 0107–5240 is typical for the parental cloud in which this star formed, then low mass star formation is the dominating mode. This is consistent with the modest, 0.7 $M_\odot$, mass of HE 0107–5240. Furthermore, for a solar O/C ratio, a carbon abundance of less than 3% of solar still results in an EOS for which $\gamma$ does not become significantly larger than unity even for warm dust grains. This would imply that the IMF would not be top-heavy at high redshift once metal enrichment sets in. Such an IMF would not be desirable for scenarios in which the bulk of the reionization is caused by stars. We also checked that the abundance pattern observed in HE 0107–5240 provides sufficient levels of carbon to ensure that the cooling time is less than the free-fall time (Bromm & Loeb 2003).

However, if the abundance pattern of CS 29498–043 is typical, then we would expect that oxygen is relatively overabundant and that the EOS is stiff, particularly when the ambient dust is warm. This would cause a shallow IMF at high redshift and a continuation of the formation of high-mass stars. Such an IMF would yield a larger number of ionizing photons per unit of mass.

In this context, it should be mentioned that theoretical models for supernova yields of very massive, 20–130 $M_\odot$, primordial stars are capable of reproducing the C and O abundances but at the expense of the r- and s-process elements (Umeda & Nomoto 2003). An alternative would be that massive stars with $M < 8 \, M_\odot$, i.e., stars that do not go supernova, evolve rapidly enough to provide He-burning elements without the usual supernova dust production (J. W. Pel 2004, private communication). The latter scenario is interesting in that one would have a stiff EOS around $10^5$ cm$^{-3}$ but without the ability of cool silicate dust at $Z < 10^{-4}$ to soften $\gamma$ around $10^6$ cm$^{-3}$. Evidence is mounting that many carbon-enriched, metal-deficient stars are in binaries, in which they may have picked up enriched ejecta of an intermediate-mass companion (cf. Lucatello et al. 2005). The observed stellar abundance pattern is then still indicative of the elemental interstellar gas composition at early times.

4.2. Primordial Limit

In the limit of very low metallicity, $Z/Z_\odot < 3 \times 10^{-4}$ or less, the work of Schneider et al. (2002, 2003) and Bromm et al. (2001) suggests that a metallicity of $\sim 10^{-4}$ $Z_\odot$ at a density of $\sim 10^{12}$ cm$^{-3}$ leads to efficient cooling and causes a softening of the EOS that gives rise to fragmentation and the formation of clumps with masses $< 1 \, M_\odot$. We would like to stress that the polytropic index $\gamma$ is already less than unity at much smaller, $n_H < 10^6$ cm$^{-3}$, densities (Scalo & Biswas 2002) as shown by models 1 and 13. While in the density regime around $10^{12}$ cm$^{-3}$, individual clumps are no longer able to separate and accretion/coagulation dominates, at low densities the higher fragment mass ($M_J \propto \rho^{-5/3}$) may still lead to low-mass fragmentation (e.g., through disk formation) because the medium is very unstable to (turbulent) compression when $\gamma \approx 0.7$ (Li et al. 2003). In this
A similar scenario may apply to starburst galaxies. The supersolar abundances (Barthel 2005), high gas temperatures and high densities in those regions imply large amounts of H2O. Also, the dust (set here at 75 K) is warm because of the intense UV radiation field, which facilitates (1) H2O heating around 10^4 cm^{-3} and (2) gas-dust heating around 10^5 cm^{-3}. Note that H2O collisional de-excitation dominates the heating for supersolar oxygen abundances. In fact, an EOS as stiff as in Spaans & Silk (2000) for dust of 100 K is obtained in this work.

The resulting IMF, as also argued in Spaans & Silk (2000) for solar abundances, would be top-heavy and the overabundance of UV-luminous massive stars would continue the starburst cycle through radiative feedback. It is interesting to note that the starburst model (14) attains a value of \( \gamma \approx 1.4 \) at \( n_1 \approx 10^8 \text{ cm}^{-3} \). This is somewhat larger than the canonical value of \( \gamma_c = 4/3 \) for spherical \((\nu = 3)\) clouds.

5. FUTURE WORK

There are a number of issues that should be addressed in the future. (1) Observations of water lines with the Herschel instrument on the Herschel Space Observatory should be performed to determine the H2O level populations and substantiate our claim of a polytropic index \( \gamma > 1 \) in starburst galaxies. (2) Numerical simulations with density and metallicity-dependent values of \( \gamma \), i.e., a pointwise polytropic EOS, should be performed for collapsing gas clouds to assess the relative impacts of magnetic fields, turbulence, and the EOS on gravitational collapse and the shape of the IMF (cf. Klessen et al. 2005; Li et al. 2003). (3) The difference in influence of an external far-UV (O and B stars, Population III objects) or X-ray (QSos, miniquasars) radiation field on the EOS of molecular clouds should be studied (Meijerink & Spaans 2005).

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In a medium with carbon and oxygen in atomic form, fine-structure cooling would, in fact, lower \( \gamma \) to below 0.6 at densities below 10^6 cm^{-3}.