Rev. Mexicana Astron. Astrof., **21**, 314-316 (19

SUBJEANS CONDENSATIONS DUE TO A THERMAL INSTABILITY

Reuven Opher and Adriana Válio

Instituto Astronômico e Geofísico
Universidade de São Paulo, Brazil

RESUMEN. Las observaciones recientes muestran que las nubes moleculares no son homogéneas, sino que tienen condensaciones. Se observa que estas condensaciones están libres gravitacionalmente. ¿Cómo se forman estas condensaciones? Sugerimos explicar estas condensaciones como debidas a que la inestabilidad térmica ayuda a la gravedad. Se estudió una función de enfriamiento por gramo de la forma general $\Lambda \propto \rho \; T^{\beta}$, en donde ρ y T son la densidad y la temperatura. Estamos interesados en el valor máximo de β para la cual el colapso ocurre. Se estudiaron varios modelos. Nuestros resultados indican que los valores de β comparables con aquellos sugeridos por la literatura ($1 < \beta \lesssim 2$) son suficientes para provocar el colapso de masas inferiores a la masa de Jeans por medio de inestabilidad térmica, ayudada por gravedad y así se forman las condensaciones libres gravitacionalmente.

ABSTRACT: Recent observations show that molecular clouds are not homogeneous, but clumpy. Some clumps are observed to be gravitationally unbound. How did these clumps then form? We suggest explaining these condensation as due to thermal instability aiding gravity. The cooling function per gram studied is of the general form $\Lambda \propto \rho \; T^{\beta}$, where ρ and T are the density and temperature, respectively. We are interested in the maximum value of β for which collapse still occurs. Various models are studied. Our results indicate that β values comparable to those suggested in the literature ($1 < \beta \lesssim 2$) are sufficient to trigger the collapse of subjeans masses by thermal instability, when aided by gravity, and form the observed gravitationally unbound clumps.

Key words: HYDRODYNAMICS — INTERSTELLAR CLOUDS

I. INTRODUCTION

Small condensations (called "clumps") have been detected in molecular clouds by t observations of the molecular lines of CO, NH_3, H_2CO, HI and OH. The dimensions of these clumps range from hundredths to tenths of a parsec. The mean number density of the hydrogen molecule (the dominant molecule) is $10^4 - 10^7$ cm^{-3} in the clumps. The clumps have masses 1 - 10 $M_{\odot}$ and are subjeans (Heiles and Stevens 1986, Massi et al. 1988).

We find, in general, that the gas of a molecular cloud is thermally unstable, and that the thermal instability can sufficiently aid gravity to form subjeans clumps.

II. FORMATION OF CLUMPS

We studied three models. In the first two models we neglect the effect of a magnetic field and the basic equations are:

$$\frac{d\rho}{dt} + \rho\vec{\nabla}.\vec{V} = 0 \qquad (1)$$

$$\rho\,\frac{d\vec{V}}{dt} + \vec{\nabla}P + \rho\vec{\nabla}\phi = 0 \qquad (2)$$

$$\frac{dU}{dt} = - L + \frac{P}{\rho^2} \frac{d\rho}{dt} \quad (3)$$

$$\nabla^2\phi = 4\pi G \rho \quad (4)$$

where ϕ is the gravitational potential, U is the internal energy per gram and d/dt is the convective derivitive.

Eq. (3) for the molecular cloud can be written as

$$\frac{3}{2} \frac{dT}{dt} = - \frac{L}{N k_B} + \frac{T}{\rho} \frac{d\rho}{dt} \quad (5)$$

where $N = 1/\mu m_p$, μ is the mean molecular weight ($\mu = 2.3$) and m_p the proton mass. L is the cooling function per gram

$$L = \Lambda - \Gamma \quad (6)$$

where Λ (Γ) is the rate of energy loss (gain).

The gain function, Γ, is unknown. We assume, similar to recent analysis of the thermal instability by Gouveia Dal Pino and Opher (1989a, 1989b), that Γ is independent of the physical parameters of the cloud (i.e., Γ is constant). We have Γ constant, for example, if heating is due to cosmic rays. We also have Γ constant if heating is due to magnetohydrodynamic (MHD) waves and the perturbed region is opaque (i.e., the perturbed region absorbs all the incident energy of the MHD waves independent of the physical parameters of the region) (e.g. Gouveia Dal Pino and Opher 1989a, 1989b; Eilek and Caroff 1979). Large amplitude MHD Alfvēn waves have recently been discussed in relation with young stellar objects (Jatenco-Pereira and Opher 1989a), late-type stars (Jatenco-Pereira and Opher 1989b), and the sun (Jatenco-Pereira and Opher 1989c).

For the loss function, Λ, we use the general form

$$\Lambda = C \rho T^{\beta} \quad (7)$$

where ρ is the mass density. The value of the constant C used is $C = 3 \times 10^{16}$ erg s^{-1} g^{-2} cm^{-3} $K^{-\beta}$, estimated from Goldsmith and Langer (1978, table 4).

The very wide CO lines observed in molecular clouds correspond to velocities approaching the virial equilibrium value of the cloud, $\Delta V \approx (2 G M/R)^{1/2}$, where ΔV is the FWHM of the CO line and M and R are the cloud's mass and radius respectively (Shu et al. 1987). The velocity width, ΔV, can be due to turbulence or MHD (e.g. Alfvēn) waves. Using the word "turbulence"for both possibilities, the first model studied is a turbulent pressure gradient balancing gravity in the equilibrium state

$$\nabla P_T \simeq - \rho_o \nabla \phi_o \quad (8)$$

The time development of a perturbation is treated similar to the recent analysis of Gouveia Dal Pino and Opher (1989a, 1989b) and de Araujo and Opher (1988, 1989).

Studying a cloud of density $n_{H_2} = 10^3$ cm^{-3} with an equilibrium temperature $T_o = 30$ K, we find for $M/M_J < 0.1$ and a small initial density perturbation (< 10%) that the critical value of β in Eq. (7) is $\beta_{crit} \simeq 1$ (where β_{crit} is the maximum value of β for which collapse occurs). This is in agreement with the results of Gilden (1984) who showed for $M << M_J$ that $\beta_{crit} \simeq 1$.

We find for $M/M_J \gtrsim 0.1$ that β_{crit} rapidly rises as a function M/M_J and $\beta_{crit} = 2$ when M/M_J is still less than unity. Thus subjeans masses (i.e., $M/M_J < 1$) can collapse for β in Eq. (7) in the range $1 < \beta \lesssim 2$. These values of β are in agreement with recently estimated values of β for the cooling function Eq. (7) of a molecular gas: Hollenbach and Mc Kee (1979) obtain $\beta = 1.5$; Falgorone and Puget (1985) obtain 1.8; and Arquilla and Goldsmith (1985) obtain 1.3. Silk (1985) obtains $\beta = 1.4$ for a molecular hydrogen number density 10^2 cm^{-3}, and $\beta = 2.0$ for a density 10^3 cm^{-3}.

Besides the above model, we also studied models where gravity is balanced by a density gradient and a one dimensional collapse model such as occurs when a cloud is in a strong magnetic field. Similar results were obtained for these other two models as was obtained for the first model discussed above.

Summarizing, we find for the various models studied:

a) β_{crit} increases with increasing M;

b) β_{crit} is approximately independent of the cloud's initial temperature and molecular hydrogen abundance;

c) β_{crit} increases for nonlinear (> 10%) initial perturbations; and

d) β values comparable with those suggested in the literature ($1 < \beta \lesssim 2$) are sufficient to cause the collapse of subjeans masses and explain the subjeans clumps observed.

ACKNOWLEDGEMENTS

One of the authors (R.O.) would like to thank the Brazilian agency CNPq for partial support. The other author (A.V.) would like to thank: a) the Brazilian agencies FAPESP and CNPq for support; b) A.J.R. Silva for help with the calculations and useful suggestions; and c) E.M. Gouveia Dal Pino and J.C.N. Araujo for fuitful discussions.

REFERENCES

Arquilla, R., and Goldsmith, P.F. 1985, Ap. J., 297, 436
de Araujo, J.C.N., and Opher, R. 1988, M.N.R.A.S., 23, 923
de Araujo, J.C.N., and Opher, R. 1989, M.N.R.A.S., 239, 371
Eilek, J., and Caroff, L.J. 1979, Ap. J., 233, 463
Falgarone, E., and Puget, J.L. 1985, Ast. and Ap., 142, 157
Gilden, D.L. 1984, Ap. J., 283, 679
Goldsmith, P.F., and Langer, W.D. 1978, Ap. J., 222, 881
Gouveia Dal Pino, E.M., and Opher, R. 1989a, Ap. J., 342, 689
Gouveia Dal Pino, E.M., and Opher, R. 1989b, M.N.R.A.S., (in press)
Heiles, C., and Stevens, M. 1986, Ap. J., 301, 331
Hollenbach, D., and Mc Kee, C.F. 1979, Ap. J. Suppl., 41, 555
Jatenco-Pereira, V., and Opher, R. 1989a, M.N.R.A.S., 236, 1
Jatenco-Pereira, V., and Opher, R. 1989b, Astr. and Ap., 209, 327
Jatenco-Pereira, V., and Opher, R. 1989c, Ap. J. (September)
Massi, M., Churchwell, E., and Felli, M. 1988, Astr. and Ap., 194, 116
Shu, F.H., Adams, F.C., and Lizano, S. 1987, Ann. Rev. Astr. and Ap., 25,23
Silk, J. 1985, Ap. J., 292, L71

Reuven Opher and Adriana Válio: Instituto Astronômico e Geofísico, Universidade de São Paulo, Caixa Postal 30627, CEP 01051, São Paulo, SP, Brazil