CLOUD-CLOUD COLLISIONS AND FRAGMENTATION

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ABSTRACT. Supersonic head-on collisions between quiescent clouds produce flattened sheets of shocked gas. We derive the condition which the cooling law must satisfy if this sheet is to fragment into protostellar condensations (*i.e.* gravitationally unstable lumps). If this condition is not satisfied, colliding clouds are likely to be disrupted and dispersed. We show that under the conditions obtaining in GMCs, most cloud-cloud collisions probably do not result in fragmentation.

1. Virial equilibrium

Consider first a single quiescent cloud of mass M_0, dimension L_0, density of hydrogen nuclei in all forms n_0 ($\equiv n_{HI} + 2n_{H_2} + \cdots$) and sound speed a_0. Virial equilibrium requires

$$a_0 \sim (GM_0/L_0)^{1/2} . \tag{1}$$

If m is the mass associated with one hydrogen nucleus ($m \simeq 2.4 \times 10^{-24}$ gm for population I composition), then

$$M_0 \sim L_0^3 n_0 m; \tag{2}$$

$$a_0 \sim L_0 (Gn_0 m)^{1/2} . \tag{3}$$

2. Thermal equilibrium

We shall assume that the cloud is optically thin to heating and cooling radiation, so that the heating rate per unit volume can be approximated by

$$\Gamma \sim \Gamma_r (n/n_r) , \tag{4}$$

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and — at least over a limited range — the cooling rate per unit volume can be approximated by

$$\Lambda \sim \Gamma_r \, (n/n_r)^2 \, (a/a_r)^\alpha \,. \tag{5}$$

n_r and a_r are simply reference values for the physical parameters n and a. The constant Γ_r is the same for both Γ and Λ because we want the reference state (n_r, a_r) to be a state of thermal equilibrium. $\Lambda \propto a^\alpha$ is roughly equivalent to $\Lambda \propto T^{\alpha/2}$. Typically $\alpha \sim 3$.

Equating equations (4) and (5) gives the thermal equilibrium condition:

$$(a/a_r) \sim (n/n_r)^{-1/\alpha} \,. \tag{6}$$

3. Reference values for physical parameters.

For the purposes of illustration we adopt $n_r = 100\,\mathrm{cm}^{-3}$ and $a_r = 0.5\,\mathrm{kms}^{-1}$. Equations (2) and (3) then give $L_r \sim 4$ pc and $M_r \sim 200 M_\odot$.

Combining equations (2), (3) and (6), we find that quiescent clouds (i.e. clouds in virial and thermal equilibrium) have,

$$(n_0/n_r) \sim (M_0/M_r)^{-2\alpha/(6+\alpha)} \,; \tag{7}$$

$$(a_0/a_r) \sim (M_0/M_r)^{2/(6+\alpha)} \,; \tag{8}$$

$$(L_0/L_r) \sim (M_0/M_r)^{(2+\alpha)/(6+\alpha)} \,. \tag{9}$$

In other words, a more massive cloud has to be hotter and more diffuse if it is to be in virial *and* thermal equilibrium.

Coincidentally (since we are here assuming only thermal pressure support), equations (7) to (9) with $\alpha \sim 3$ are compatible with Larson's relations, *viz.* $n \propto M^{-6/9}$, $a \propto M^{2/9}$ and $L \propto M^{5/9}$.

4. General cooling time-scale.

We shall adopt $\Gamma_r = 5 \times 10^{-27}\,\mathrm{erg\,cm^{-3}\,s^{-1}}$. This corresponds to a primary ionization rate of $\zeta \sim 10^{-17}\,\mathrm{s}^{-1}$. The cooling time-scale is then given by

$$t^{\mathrm{cool}} \sim \rho a^2/\Lambda \sim t_r^{\mathrm{cool}} \, (n/n_r)^{-1} \, (a/a_r)^{2-\alpha} \,, \tag{10}$$

$$t_r^{\mathrm{cool}} \sim n_r m a_r^2/\Gamma_r \sim 4\,\mathrm{Myr}. \tag{11}$$

5. Collision and expansion time-scales.

Now consider two identical clouds involved in a head-on collision at relative speed $2v_0 = 2\mathcal{M}a_0$, where $\mathcal{M}$ is the Mach number. Assuming a strong shock ($\mathcal{M} >> 1$), we know that the density and sound-speed immediately following the shock are $n_i \sim 4n_0$ and $a_i \sim \mathcal{M}a_0 = v_0$. It follows that the collision time-scale and the time-scale on which the flattened sheet expands sideways in the absence of post-shock cooling are roughly equal:

$$t^{\rm coll} \sim t^{\rm exp} \sim L_0/\mathcal{M}a_0 \sim t_r^{\rm exp}\mathcal{M}^{-1}\left(M_0/M_r\right)^{\alpha/(6+\alpha)}; \qquad (12)$$

$$t_r^{\rm exp} \sim L_r/a_r \sim 8\,{\rm Myr}. \qquad (13)$$

6. Post-shock cooling time-scale.

Since we expect $\alpha < 4$, and since the post-shock cooling regime will be approximately isobaric, cooling will be slowest at high temperatures and the cooling time-scale should be evaluated for the immediate post-shock density and sound-speed, *viz.*

$$t_i^{\rm cool} \sim t_r^{\rm cool}\left(n_i/n_r\right)^{-1}\left(a_i/a_r\right)^{(2-\alpha)} \sim t_r^{\rm cool}\mathcal{M}^{(2-\alpha)}\left(M_0/M_r\right)^{4/(6+\alpha)}. \qquad (14)$$

7. Fragmentation condition.

The flattened sheet can only fragment if it does not expand sideways significantly before it cools, *i.e.* if $t_i^{\rm cool} << t^{\rm exp}$ or

$$\mathcal{M}^{(\alpha-3)}\left(M_0/M_r\right)^{(\alpha-4)/(6+\alpha)} >> G^{1/2}\left(n_r m\right)^{3/2} a_r^2\,\Gamma_r^{-1} \qquad (15)$$

Putting $\alpha = 3 + \epsilon$ ($\epsilon << 1$), and substituting for the reference parameters, this reduces to

$$\mathcal{M}^{\epsilon}\left(M_0/M_r\right)^{-1/9} >> 0.5. \qquad (16)$$

Since the Mach number $\mathcal{M}$ is unlikely to exceed 10, this inequality can only be satisfied if the clouds are very small and dense $M_0 << M_r$.

8. Conclusion.

Unless the interstellar gas can cool much faster than we have assumed, the majority of cloud-cloud collisions result in disruption and dispersal of the clouds involved. Cloud coalescence is unlikely. Specifically, efficient fragmentation requires that the cooling law of equation (5) has $\alpha \geq 4$ and/or $\Gamma_r \geq 10^{-26}{\rm erg cm^{-3} s^{-1}}$ (corresponding to $\zeta \geq 2. \times 10^{-17}{\rm s^{-1}}$).