Cloud Formation in a Galactic Fountain Resulting from Rayleigh-Taylor Instabilities

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Abstract. Intermediate and high velocity clouds are produced in a Galactic fountain as a result of Rayleigh-Taylor instabilities that grow at the interface separating the cool descending gas and the hot ascending gas within the fountain flow. It is proposed here that there is no need to introduce any initial perturbation to the system in order to trigger such instabilities. They will arise naturally as a result of the difference in the adiabatic parameters above and below the interface. A three-dimensional study of the unstable layer and the resulting cloud formation is presented.

1 Introduction

We have carried out three-dimensional hydrodynamical simulations of a Galactic fountain in a section of the Galaxy, having an area of 1 kpc^2 and a vertical extent ranging from -4 kpc to 4 kpc, using a grid resolution of 10 pc and have presented them in these proceedings (Avillez et al., 1997). The simulations show that as the hot intercloud medium enters the fountain it starts cooling and after some 200 Myr the lower halo is populated with intermediate velocity structures having sizes ranging from $\sim$ 20 to 100 pc. The descending gas, headed by a shock, sweeps up the ascending flow thereby heating it. In consequence the interface separating the descending fountain structure from the ascending flow becomes Rayleigh-Taylor unstable and breaks up into clouds. Several small clouds are observed which have previously been detached from the larger structures; however, as a result of grid resolution cloudlets with sizes smaller than 10 pc are not resolved. Here a three-dimensional hydrodynamical scheme is applied to a typical fountain structure in order to simulate the formation of the cloudlets; this scheme has been described in Avillez (1997) and uses an adapted mesh refinement algorithm of Berger & Collela (1989). Thermal conduction is not included but, cooling is allowed by approximating the cooling curve of Raymond, Cox & Smith (1976) but with Kahn's (1976) approximation in the range of temperatures $5 \times 10^5 - 5 \times 10^7$ K. Because magnetic fields are important, a minimum temperature in the gas is arranged so that the effects of magnetic pressure support are simulated.

2 Numerical Modelling

Rayleigh-Taylor instabilities that occur at the interface of two states in perfect but unstable equilibrium, with a sharp variation at the interface, have been carried out among others by Hachisu et al. (1990), and Jun et al. (1995). In their papers initial perturbations introduced at the interface are necessary to trigger the instabilities. Such an initial set-up introduces spurious effects that lead to non-linear growth of the instabilities. In consequence non-linear modes of the perturbation start dominating the flow prematurely. For the present study this picture must be modified because (a) there is a smooth variation at the interface between the two gases and (b) the refined grid itself introduces a type of smoothing at the interface. The modes of perturbation are grid resolution dependent; that is, the smallest wavelengths are of the order of the cell width, and as a result there is a maximum temperature for which the instability will occur in the descending cool sheet. No initial perturbations are introduced explicitly but numerical inhomogeneities in the medium may be responsible for triggering the instabilities.

2.1 Threshold Conditions for Rayleigh-Taylor Growth

Initially, the gas moves with velocities very small compared with the gas sound speed at the interface and so the effects of gas compressibility are negligible (Jun, Norman & Stone, 1995). Thus, the linear growth rate of the instability, σ_{RT}, is expected to be similar to that of an incompressible fluid, given by (Chandrasekhar, 1961)

$$\sigma_{\mathrm{RT}} = \left(\frac{2\pi g}{\lambda}\right)^{1/2} \left(\frac{\rho_+ - \rho_-}{\rho_+ + \rho_-}\right)^{1/2} \tag{1}$$

where λ is the wavelength of the perturbation at the interface between the two fluids, g is the gravitational acceleration, and ρ_+/ρ_- are the gas densities above/below the interface. For a numerical scheme with a grid resolution Δx, instabilities only develop if the growth time, τ_{RT} $(= 1/\sigma_{\mathrm{RT}})$ is shorter than the hydrodynamical time scale given by the Courant-Friedrich-Lewy condition (Richtmyer & Morton, 1967). This leads to an upper limit for the initial wavelengths given by

$$\lambda_{\text{in}} \leq 2\pi g \left(\frac{\rho_+ - \rho_-}{\rho_+ + \rho_-}\right) \left(\frac{\Delta x}{\max(c_s)}\right)^2 . \tag{2}$$

For $\rho_+ \gg \rho_-$, this inequality becomes

$$\lambda_{\text{in}} \leq 2\pi g \left(\frac{\Delta x}{\max(c_s)}\right)^2 . \tag{3}$$

The minimum wavelength must cover at least 4 grid cells ($\lambda \sim 4\Delta x$) and so the local sound speed at the interface must satisfy

$$\max(c_s) \leq \left(\frac{\pi}{2} g \Delta x\right)^{1/2} . \tag{4}$$

So, for the cool gas, the sound speed must be smaller than 22 km s^{-1} for the resolution considered in these calculations, which corresponds to a temperature of 3.5×10^4 K. Gas with temperatures above this value would not develop any instabilities.

2.2 Evolution of the Unstable Interface

The results presented in this section refer to an HI cloud having a LSR speed of -25 km s^{-1}, and a density of 10^{-24} g cm^{-3}. The falling sheet headed by a shock sweeps up the ascending flow which rises with a speed ~ 60 km s^{-1}. The shocked gas is heated to temperatures of $\sim 10^5$ K. Figure 1 (a-d) shows the evolution of a section of the descending sheet with a width of 100 pc and with a grid resolution of 0.25 pc. Both the shocked and cooled layers are shown in Figure 1-a. Small amplitude perturbations at the interface separating both fluids are observed. The width of the shocked layer is approximately 10 pc - a value in accordance with the predictions of Kahn (1981). The other gray scale images show the evolution of the interface until some clouds start detaching from the descending layer. As the instabilities set in, smaller structures appear first, because the growth rate is larger for smaller wavelengths. At later stages fingers expand and interact with their neighbouring fingers introducing turbulence in the flow (Figure 1-b). As a consequence, non-linear effects are originated by these interactions which, in addition to larger wavelengths dominating the flow at later stages, give the appearance shown in Figures1 (c-d). The cool gas, as it expands in finger-like structures, leaves behind empty spaces that are filled with the hot ascending flow. No mixing occurs between the gases apart from numerical mixing. As the fingers stretch and break up, filaments and cloudlets of cool gas with sizes of several parsecs detach from them as shown in Figure (1-d).

3 Summary

It has been shown here that hydrodynamic simulations of the Rayleigh-Taylor unstable layer in a fountain do not require any initial perturbation to trigger the growth of the instabilities. Furthermore, refinement recalculations show the formation of clouds having sizes of the order of several parsecs; these clouds were missing in the previous simulations carried out using coarser grids.

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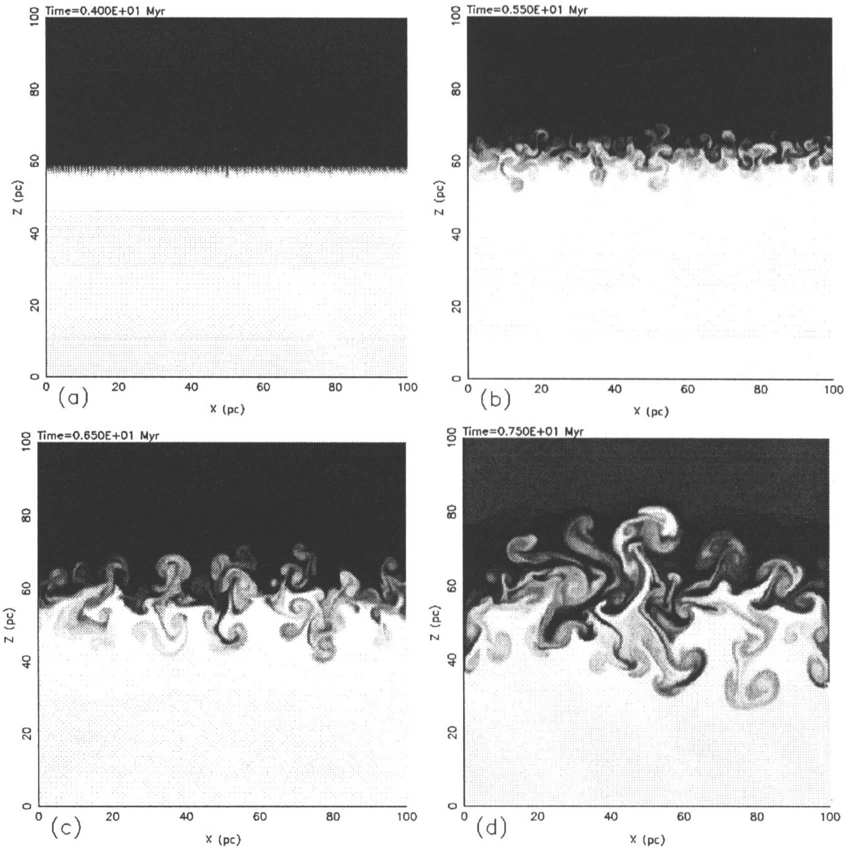

Fig. 1. Evolution of the descending cool layer over the Galactic disk at (a) 4 Myr, (b) 5.5 Myr, (c) 6.5 Myr and (d) 7.5 Myr after start of calculations.

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