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THE VELOCITY DISPERSION OF THE GIANT MOLECULAR CLOUDS: A VISCOUS ORIGIN

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We propose the energy source and study the details of the acceleration mechanism for the random motion of the Giant Molecular Clouds (GMCs) in the Galaxy.

Introduction

The observations of interstellar cloud motion show that the cloud velocity dispersion is nearly constant, to within a factor of 2, for clouds covering at least three orders of magnitude in mass. For example, the GMCs with typical masses of ~ 5 x 10^5 $M_\odot$ have a one-dimensional, planar, cloud-cloud, random velocity dispersion of ~ 3-7 km s^{-1} (Clemens 1985; Stark 1984). The HI clouds, of ~ 400 $M_\odot$ each, on the other hand, have a typical one-dimensional velocity dispersion of ~ 6 km s^{-1} (Spitzer 1978). Clearly, the clouds are not in kinetic energy equipartition.

The spatial distribution of the GMCs in the galactic disk is not that of an isolated, 3-D system; rather, the GMCs exhibit a very thin disk (~ nearly a monolayer) distribution; with the ratio of the diameter of a typical GMC to the vertical scale-height of the GMC distribution being ~ 50 pc/150 pc = 0.3.

The supernova shocks, which can accelerate the low mass clouds, are extremely ineffective in accelerating the GMCs because of the much larger mass/area ratio for the GMCs.

The above points suggest that the GMCs do not constitute an isolated, 3-D system - rather, they indicate that the dynamics of the GMCs is mainly determined by the fact that they are located in a differentially rotating galactic disk, and that, as for particles in planetary rings, "viscosity" is the primary energy input.

Specifically, we propose that gravitational scattering of the massive clouds off each other in the differentially rotating galactic disk constitutes an effective gravitational viscosity; which causes an increase in the random kinetic energy of the GMCs at the expense of their ordered, rotational kinetic energy.

This mechanism is developed for the first time in this paper. In the problem of the planetary rings on the other hand, the gravitational interaction among the particles is negligible and in that case physical collisions account for the viscosity (see e.g., Goldreich and Tremaine, 1982).

Energy Input Due to the Gravitational Viscosity

We calculate the rate of increase, due to the gravitational viscosity, of the random kinetic energy of a test GMC with a non-zero initial random velocity. As long as this random velocity is much less than the rotational speed in the disk; the unperturbed motion in the galactic disk of such a test cloud is described by an epicycle, which can be represented as a coupled, two-dimensional harmonic oscillator.

Since an encounter between such a test cloud and a passing field cloud lasts for ~ an epicyclic time, one cannot evaluate the effects of the encounter under the impulse approximation. Instead, we treat the encounter between the test cloud and a field cloud in the sheared disk as a perturbed, coupled, two-dimensional harmonic oscillator problem, with the gravitational interaction between the two clouds being the time-dependent perturbation force. In order to obtain the change in the energy of the test cloud per encounter, one has to evaluate the change in the total energy of the epicyclic motion of the test cloud. A major portion of this paper deals with this calculation. Assuming the subsequent encounters to be independent, one can then obtain the net rate of increase of the random kinetic energy of the test cloud.

The Steady-State Cloud Velocity Dispersion

In a steady-state, the rate of energy input from the viscosity due to gravitational and physical interactions among the GMCs in the differentially rotating galactic disk equals the rate of energy loss due to the inelastic physical collisions among the GMCs; this yields the value for the steady-state cloud velocity dispersion.

The main functional dependence of the resulting steady-state cloud velocity dispersion is ~ $[(Gm/r)\ \kappa H]^{1/3}$; where m and r are the cloud mass and cloud radius respectively, κ is the epicyclic frequency and H is the total vertical scale-height of the gas distribution. Note that this result is independent of the cloud number density and it depends only weakly (through κ) on the galactocentric radial distance of a cloud. Also note that the cloud velocity dispersion is an increasing function of (m/r) - this point clearly underlines the gravitational viscous nature of the cloud acceleration mechanism considered in this paper.

For the typical GMCs, each of mass ~ $5 \times 10^5\ M_\odot$, and located between the galactocentric radii 4 to 9 kpc in the Galaxy; the resulting one-dimensional cloud velocity dispersion is ~ 4-6 km s^{-1}, in good agreement with the observed values of the same. The gravitational viscosity, therefore, provides the main energy input for the random motion of the GMCs in the Galaxy.

Discussion

In the viscous acceleration mechanism, the ultimate energy source is the rotational kinetic energy of the clouds in the disk. The fraction of the rotational kinetic energy lost in supporting inelastic cloud motions for ~ ten billion years is small ~ 0.1. Thus the rotational kinetic energy of the GMCs proves to be more than adequate for the long term support of their random motion.

As a result of the viscous interaction among the clouds, the clouds drift inwards with a local velocity of ~ 0.3 km s^{-1}, thus depleting gas within the region of $R \leq 3$ kpc in the Galaxy in ~ ten billion years. This is in rough agreement with the observed minimum or the "hole" in the galactic CO distribution. The detailed analysis for this will be presented in a subsequent paper.

Thus, the dynamics as well as the radial distribution in the Galaxy of the GMCs is determined by their gravitational viscous interaction, which operates because of their location in the differentially rotating galactic disk.

References

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