COMPUTATIONAL STUDIES OF CLOUDY GASEOUS GALACTIC DISKS

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ABSTRACT. Computational studies are carried out to address questions centered on the clumpy cloudy interstellar medium, giant molecular clouds, and star formation in galactic disks. In application to galactic spirals, gaseous self-gravity is found to act on the "large scale" to enhance the overall collective gravitational field driving the gaseous response and thus help maintain the global spiral structure. On "local scales," gaseous self-gravity is found to aid the formation and assembling of massive aggregations of clouds into giant cloud complexes, spurs, and feather-like features. Striking is the local raggedness and patchiness of the computed distribution of gas and young stellar associations. Local spurs, feathers, and secondary features continually break apart and reform as the loosely-associated aggregations and giant complexes of clouds continually disassemble and reassemble over time. Such transient features give rise to local disorder within the global spiral structure and blur the global coherence. Of paramount importance are the nonlinear effects and the dissipative character of the cold cloudy galactic gas component, which largely distinguish it from the stellar component. Without the presence of a cold and dissipative gaseous component, galactic disks would be hard pressed to produce and exhibit sharp, clear-cut spiral structures on global scales.

This work is divided into three stages: 1) 'formulation' of the physical problem in mathematical terms, 2) 'solution' of the mathematical model thus formulated, and 3) 'interpretation' of the results. In the 'formulation' stage the focus is on dominant physical mechanisms and dynamical processes. These are outlined in Table 1, with particular emphasis on the self-gravitational effects, dissipative effects, and collisional dynamics of cloudy gaseous galactic disks. In the 'solution' stage, an N-body, cloud-particle computational code is developed for the purpose of isolating the role of gaseous self gravity from the roles of other dominant physical mechanisms and dynamical processes, e.g. the interstellar medium's collisional dynamics and dissipative processes (Roberts and Hausman, 1984; Hausman and Roberts, 1984; Roberts, Adler, and Stewart, 1988). Self gravitational effects of the interstellar medium's gas clouds are included in this work by means of Fourier Transform techniques, adapted from those developed by Miller (1976), Miller and Smith (1979a, b), and Smith and Miller (1986).
TABLE I.
FORMULATION STAGE: PHYSICAL MECHANISMS AND DYNAMICAL PROCESSES

- Orbital Dynamics of Interstellar Gas Clouds. Finite Cloud Cross Sections; Representative Cloud Collisional Mean Free Paths.
- Inelastic, Energy Dissipating Cloud-Cloud Collisions.
- Supernova Explosions; Gas-Star Interactions. Replenishment of Random Kinetic Energy.
- Birth of Protostars. StellarAssociations.
- Time Delay before "Active Period" of Star Formation.
- "Refractory Period" for Gas Clouds Delaying their Participation in Subsequent Star Formation.

Figure 1 shows the results of one representative simulation in which the gas mass to stellar disk mass is 10%. Displayed in a photographic intensity map at one sample time epoch [ 800 Myr ] during the computations are the computed global distributions of the system of gas clouds, represented by patches, and the system of young to middle-aged stellar associations active (with supernova events) during the past 60 Myr, represented by white dots. Gaseous self-gravity is present, along with a prescribed spiral perturbation gravitational force field of magnitude adopted as 5% - 10% that of the central axisymmetric force field. The results show that both gas clouds and the stellar associations triggered from the clouds exhibit aggregations of giant complexes along the global, spiral-wave-arm structures. Stellar associations are strongly correlated with the gas, with few associations which are not adjacent to clouds. The important multifold role played by the gas is quite evident. On the "large scale," gaseous self-gravity acts to enhance the overall collective gravitational field driving the gaseous response and thus help maintain the global spiral structure. On "local scales," gaseous self-gravity aids the formation and assembling of massive aggregations of clouds into giant cloud complexes, spurs, and feather-like features. Such transient features give rise to local disorder within the global spiral structure and blur the global coherence (c.f., Roberts and Adler, 1988).
Figure 2 illustrates in further detail this multifold role of the gas. Four cases with different gas-to-stellar disk mass fractions are displayed, all at the same sample time epoch [800 Myr]. The gas mass fraction increases along the sequence of cases from upper left, to upper right, to lower left, to lower right. The case at upper left is one for which gaseous self gravity is fully excluded. At upper right is the case displayed in Figure 1 with 10% gas mass fraction. The cases at lower left and lower right have 15% and 20% gas mass fractions respectively. It is evident that the effects of gaseous self gravity become increasingly important as gas mass fraction increases. The global coherence of the computed spiral structure in the "outer" disk is particularly strong in the self gravity cases with 15% and 20% gas mass fractions. These cases exhibit gas cloud density distributions with peak-to-mean values across the outer-disk spiral arms typically in the range of 2.8 to 2.9. In contrast in the case with self gravity excluded [upper left], corresponding peak-to-mean values across the outer-disk spiral arms are typically only 2.3. Likewise, within the "inner" disk the global gas cloud distribution is locally quite ragged under the influence of gaseous self gravitational effects, with massive aggregations and large complexes of clouds appearing throughout the global spiral structure particularly in the cases with higher gas mass fraction.
Figure 3 displays the corresponding distributions of stellar associations computed at the same sample time epoch [800 Myr] in these four cases (upper left - self gravity excluded; upper right, to lower left, to lower right - 10%, 15%, and 20% gas mass fractions respectively). Note that the spiral structure is much more sharply defined by the system of young stellar associations (Figure 3) than by the system of gas clouds (Figure 2). This is presumably due to the collisional origin of many stellar associations (collision rate goes as the square of cloud number density) and the relatively short average delay time between star formation and supernova explosions (leading to strong correlations in the positions of successive generations of associations). Quite prominent in the "outer" disk is the global spiral arm structure exhibited by the distributions of stellar associations, particularly in those self gravitational cases for which the gas represents higher fraction of total galactic mass. Likewise, more striking in
the cases with higher gas mass fraction is the local raggedness and patchiness of the computed distribution of young stellar associations in the "inner" disk under the influence of the more pronounced gaseous self gravitational effects. Local spurs, feathers, and secondary features continually break apart and reform as the loosely-associated aggregations and giant complexes of stellar-association forming clouds continually disassemble and reassemble over time. It is evident that these continually-evolving, transient manifestations effectively perturb the global spiral structure on local scales in the "inner" disk.

It is critical to investigate the nonlinear dynamical nature of the gas and the extent to which nonlinear effects of the gaseous component may dominate galactic disks. Figure 4 provides a perspective of the degree to which nonlinear gaseous effects may come into play in real galactic disks. Displayed are detailed characteristics of selected physical quantities at three sample epochs computed in the computa-
tional studies for the representative self gravitational case with 10% gas mass fraction (displayed in Figure 1 and the upper right panels of Figures 2 and 3). Plotted with respect to spiral phase around a representative annulus in the model galactic disk are: cloud number density, components of velocity perpendicular and parallel to spiral equipotential loci, computed velocity dispersion among gas clouds, and computed distribution of young stellar associations currently active in supernovae explosions (SN rate). The density distribution of the self-gravitating cloud system is strongly-peaked with peak-to-mean values in the range of 2.4. to 2.8 and arm-to-interarm contrasts typically 6:1, with arm thicknesses on the order of a kpc. The sharp deceleration, just preceding 180° spiral phase, reflected in the $u_\perp$ velocity component from supersonic to subsonic is a striking manifestation, in these self-gravitating computations, with much-more-gradual-characteristic-rise downstream. This characteristic skewness in the $u_\perp$ velocity component as well as the characteristic asymmetry in the parallel velocity component together delineate the galactic shock structure formed. Such skewness is less apparent in the density distribution, with the density rise occurring over the broad shock width of a number of collisional mean free paths (e.g., consistent with quasi-analytical calculations of star-gas density waves over an annulus [Lubow, Balbus, and Cowie, 1986]).

Figure 4.
Of paramount importance in these studies is the dissipative character of the cold cloudy component of the gaseous interstellar medium that largely distinguishes it from the stellar component (also see Kalnajs, 1972; Roberts and Shu, 1972; Lubow, 1986). First of all, it is the presence of this cold, cloudy component that makes possible an overall sufficiently-low velocity dispersion system to promote regimes of unstable, growing global spiral modes (Bertin, Lin, Lowe, and Thurstans, 1988). Secondly, in real galaxies it is likely to be the balance achieved between such moderately to rapidly growing global modes on the one hand and the dissipative nonlinear gaseous response on the other that allows the emergence of finely tuned, coherent grand designs of global spiral structures. Without the presence of a cold and dissipative gaseous component, real galactic disks may be hard pressed to produce and exhibit any such sharp, clear cut structures on global scales.

Roberts and Stewart (1987) have shown that the results of these computational simulations can be largely understood in terms of individual cloud-particle orbits. In particular, the upper panel in Figure 5 shows the computed radial position as a function of time for one sample cloud-particle in a stripped-down collisionless test case. The cloud-particle undergoes nonlinear epicyclic motion, characterized by repeatable sequences of radial oscillations. The spiral forcing modulates the epicyclic oscillations in a regular nonlinear manner, leading to "periodic trapping" of the cloud-

![Figure 5.](image-url)
particle in the arms. The lower panel shows the spiral phase of the cloud-particle versus time, where $180^\circ$ marks the location of the spiral potential minimum. Each continuous segment represents the motion of the cloud-particle around half the disk (through a full $360^\circ$ in spiral phase), from one interarm region to the next. The relative amount of time that the cloud-particle spends in any given interval of spiral phase is inversely proportional to the slope along each segment. Many of the segments exhibit "bumps" of retrograde motion where the cloud-particle temporarily becomes trapped and for a short time (about 50 Myr) moves backwards across the arm, before continuing in its forward motion. Such nonlinear trapping events cause the cloud-particle to spend a large fraction of its total orbital time within a spiral arm. It is evident that the strong global spiral response of the self-gravitating collective cloud system in the computational simulations can be largely attributed to this tendency of individual cloud-particles to become trapped and spend a large fraction of their time in the region of the spiral potential minima. On this basis, we speculate that the self-gravitating, dissipative (cold), "nonlinear" gaseous component in galaxies may play a critically important role in the nonlinear locking of two or more density wave modes together over significant epochs.

Effective synergism of the computational studies with corresponding high resolution observational studies should help determine to what degree these characteristics apply or do not apply in real galaxies and to what degree our current understanding requires further refinement. Such synergism is expected to have strong impact on our deeper understanding of the clumpy, cloudy interstellar medium, star formation, and the underlying dynamical processes.

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