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BUILDING A VIRTUAL MILKY WAY

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RESUMEN

Las simulaciones numéricas han progresado con rapidez hasta convertirse en un apoyo poderoso para astronomía observacional. Este trabajo describe el modelado de una galaxia de la Vía Láctea utilizando uno de los códigos más recientes de la hidrodinámica, ENZO. Se trata de una de las simulaciones de mayor resolución a escala global que produce un medio interestelar de fases múltiples el cual, debido a su complejidad, normalmente está restringido a simulaciones a escala pequeña. Estudiamos la formación de estrellas a través de inestabilidades gravitacionales del disco galáctico y encontramos una buena concordancia con observaciones. La adición de retroalimentación suprime la formación de estrellas produciendo una fuente galáctica donde el gas es expulsado de la superficie del disco y gravitacionalmente es arrastrado de regreso hacia abajo.

ABSTRACT

Numerical simulations have rapidly progressed to be a powerful accompaniment to observational astronomy. This work describes the modeling of a Milky Way galaxy using one of the latest hydrodynamics codes, *Enzo*. It is one of the most highly resolved simulations on a global scale and produces a multiphase interstellar medium which, due to its complexity, is normally confined to small scale simulations. We study the formation of stars through gravitational instabilities in the galaxy disk and find good agreement with observations. The addition of feedback supresses star formation and produces a galactic fountain where gas is ejected from the disk's surface and is gravitionally drawn back down.

Key Words: **GALAXIES: EVOLUTION — GALAXIES: ISM — GALAXIES: SPIRAL — ISM: STRUCTURE — METHODS: NUMERICAL**

1. INTRODUCTION

Despite excellent observational data, it is extremely difficult to model the Milky Way. One of the key reasons for this is the complexity of star formation. Stars are born in a multiphase, turbulent gas where many forces are fighting for dominance. In summary, gravity tries to cause the gas to form dense molecular clouds, but it is hindered by rotational shear, thermal pressure, turbulence, magnetic fields and cosmic ray pressure all of which act to resist the collapse. As a result, simulations have often resorted to modeling either a small volume of the galaxy for which the majority of these competing forces can be included, or they model the entire galaxy but simplify the gas to an isothermal or fixed phase medium. Recent work that has allowed the possibility of a global galaxy model with a self consistent ISM has been either in two-dimensions (Wada & Norman 2001) or restricted to a box size of a few hundred parsecs across (Wada 2001).

In this research, we perform high resolution three-dimensional simulations of a global galaxy disk and attempt to retain the full thermal the structure of the ISM. We use an adaptive grid-based code, *Enzo* (Bryan & Norman 1997; O'Shea et al. 2004) which is well suited to modeling the multiphase medium, a traditionally difficult task. Gas cooling is allowed down to 300 K and stellar feedback from type II supernovae is included in one run. Our maximum resolution (smallest cell size) is ~ 50 pc for our main runs and ~ 25 pc for our high resolution run. The proof of any model of this sort is the comparison with real galaxies so we compare our results with a number of observations.

The purpose of such simulations are two-fold; we hope to gain a more complete understanding of how star formation operates in the galaxy, including the distribution of gas densities, pressures and temperatures in the ISM. A longer term goal is to apply this to cosmological simulations where a lack of understanding of the role of star formation and feedback in galaxies is often cited as a reason for poor agreement with observational data (Tasker & Bryan 2006b).

This work is described in detail in Tasker & Bryan (2006a).

2. INITIAL CONDITIONS

Our simulations start with an isothermal gas disk with a temperature of 10^4 K and a density profile

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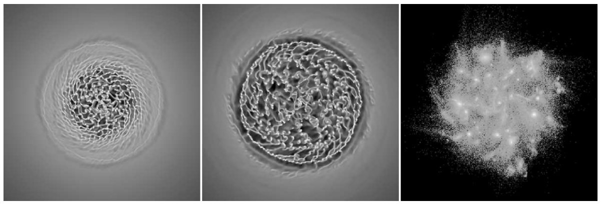

Fig. 1. The evolution of the disk as a function of time. Left image shows the projected gas density at 100 Myrs, middle shows the gas density at 150 Myrs and right is the stellar density after 330 Myrs. Image sizes are $\sim 22\,$kpc across.

given by $\rho(r,z) = \rho_0 e^{-r/r_0} \mathrm{sech}^2\left(\frac{1}{2}\frac{z}{z_0}\right)$, where we took typical Milky Way values of $r_0 = 3.5\,$kpc and $z_0 = 400\,$pc. Integrating the density gives a gas mass of $\mathrm{M_{gas}} = 1 \times 10^{10}\,\mathrm{M}_\odot$, which we note is low compared to the Milky Way disk which is roughly 4 times higher (e.g. Klypin et al. 2002).

The disk sits in a dark matter profile which takes the form described by Navarro, Frenk, & White (1997) with a virial mass of $M_{200} = 10^{12}\,\mathrm{M}_\odot$ and a concentration of 12. Adding together the gaseous and dark matter components allows us to calculate the initial circular velocity of the disk using $V_{\rm circ}(R) = \sqrt{GM_{\rm tot}/R}$.

3. FORMATION OF THE INSTABILITIES

The initial evolution of our disk follows the formation of the gravitational instabilities, which start at the center where the dynamical time is the shortest ($t_{\rm dyn} \sim \rho^{-0.5}$). Figure 1 shows this evolution. The perturbations begin as a set of spiral density waves which form as the disk begins to collapse in the radial direction. The rotation of the disc initially supports these early pertubations against tangential collapse, but this soon follows, turning the spirals into dense knots of matter (left most image of Figure 1). The collapse moves outwards until all the gas that is gravitationally unstable has fragmented into knots which start to accrete and merge (middle image of Figure 1). Outside this region, there is still a significant density of gas, but this remains stable and does not fragement in the simulation. These cold collapsed knots are the sites of star formation (right-hand image in Figure 1) which is confined to the central 10 kpc of the disk, i.e. where it is gravitationally unstable.

The instabilty of the disk can be measured quantitatively with the Toomre stability parameter (Toomre 1964), defined as $Q = \kappa c_s/\pi G\Sigma_g$, where κ is the usual epicyclic frequency, c_s is the thermal sound speed as measured in the disk (about 2 $\mathrm{kms^{-1}}$ for our minimum temperature of 300 K), and Σ_g is the gas surface density. In his original paper, Toomre calculates that a thin disk becomes gravitationally unstable when $Q < 1$. For a thick disc, Goldreich & Lyden-Bell (1965) found a slightly lower value of $Q < 0.676$. Kennicutt (1989) measured this value observationally and found a higher value of $Q < 1.5$, although he used the thermal sound speed of the gas (at $6\,\mathrm{kms^{-1}}$), rather than the velocity dispersion. Our calculations are shown in Figure 2 where Q is plotted with the star formation rate as a function of radius for disk models with and without stellar feedback and one at a higher resolution. The star formation in all cases stops at roughly 7 kpc, corresponding to a $Q \sim 0.6$. This is in good agreement with the analytical studies of Goldreich & Lyden-Bell (1965) and, if we adopt an effective sound speed of $6\,\mathrm{kms^{-1}}$, our value increases by a factor of 3, bringing it into line with Kennicutt's value.

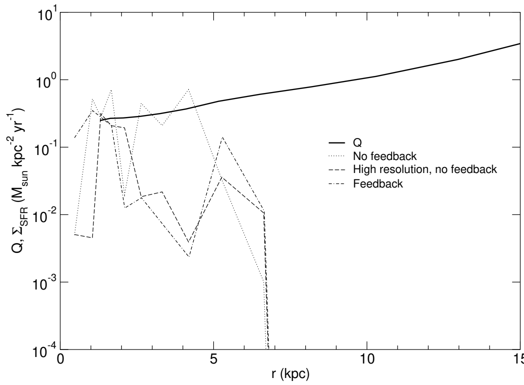

Fig. 2. The solid line shows the Q parameter shortly after the start of the simulation when the gas has reached its minimum temperature (300 K). Other lines show the instantaneous rate of star formation (averaged over 20 Myrs) for three varients of the galaxy disk.

4. STAR FORMATION PROPERTIES

Observational studies of the star formation in disk galaxies show a simple relation between the gas surface density and rate of star formation which increases as $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{1.5}$ (Kennicutt 1989). Our results for the simulations with and without feedback and the high resolution run are shown in Figure 3. The slope of all the runs is very similar to that observed, except that we persistantly produce a higher star formation rate which is unaffected by re solution. When we introduce feedback, the star formation is suppressed, but still results in an overestimate.

The most likely reason for this excess star production is that our simulations are still not at the

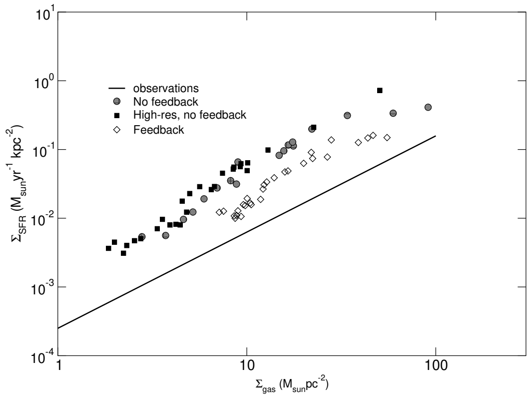

Fig. 3. The relationship between the gas surface density and the surface star formation rate averaged over the whole disk for the models listed above (global Schmidt law). Each point is at a different time in the same simulation. The solid line shows the best fit to the observations (Kennicutt 1989).

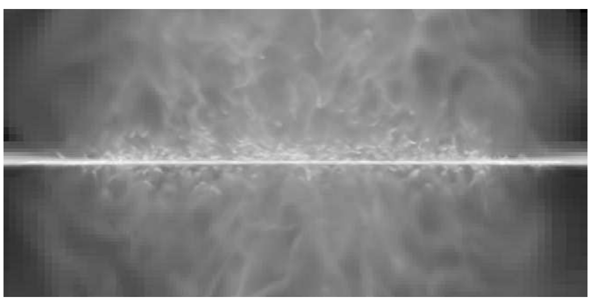

Fig. 4. Edge-on view of the gas density in the disk with feedback. Image is ~ 22 kpc across and ~ 10 kpc high.

level of modeling the structure and physics in the giant molecular clouds. If these clouds are allowed to exist undisrupted in our simulation for too long, then the final fraction of gas converted into stars is likely to be abnormally high.

5. THE INTERSTELLAR MEDIUM

As we can see from Figure 3, the introduction of feedback acts to lower the star formation rate. The introduction of energy from supernovae destroys the star-forming knots and also ejects gas from the disk's surface, causing it to rise up in large streamers of hot gas as shown in Figure 4. This gas cools rapidly and falls back towards the plane in a galactic fountain.

Figure 5 shows contour plots of the density versus temperature for the simulations with and without feedback. Traditionally, the ISM has been considered a three-phase medium (McKee & Ostriker 1977; Norman & Ikeuchi 1989), but the contour plots

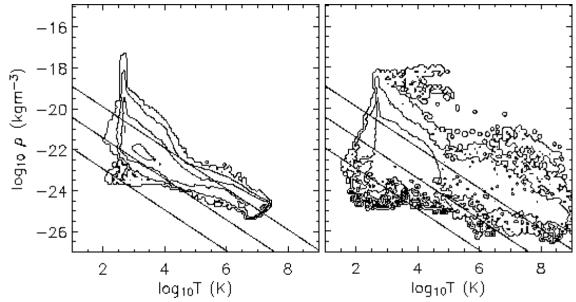

Fig. 5. 2D contour plots of the volume for the run without feedback (left) and with feedback at 566 Myrs.

clearly show this to be an over simplification. There is some evidence for a three-phase structure in the plots, but there are no sharp divisions here, rather a wide distribution of densities, temperatures and pressures. This is far more marked in the feedback run where the width of the distribution function increases significantly. The diagonal lines mark constant pressure and we see that the disk is in rough pressure equilibrium, but at any point there is a range of pressures.

6. CONCLUSIONS

Our simulations reproduce many of the observed features of galaxies, in particular the Toomre criterion for instability, the gradient of the Schmidt law, the galactic fountain and the multiphase ISM. However, we still have too high a star formation rate, implying that further feedback from sources such as photoionisation might be required to match observations.

REFERENCES

Bryan, G. L. & Norman, M. L. 1997, ASP Conf. Ser. 123: Computational Astrophysics, ed. D. A. Clarke & M. J. West (San Francisco: ASP), 363
Goldreich, P., & Lynden-Bell, D. 1965, MNRAS, 130, 97
Kennicutt, R. C. 1989, ApJ, 344, 685
Klypin, A., Zhao, H., & Somerville, R. S. 2002, ApJ, 573, 597
McKee, C. F., & Ostriker, J. P. 1977, ApJ, 218, 148
Navarro, J., Frenk, C., & White, S. D. M. 1997, ApJ,
Norman, C. A., & Ikeuchi, S. 1989, ApJ, 345, 372
O'Shea, B. W., Bryan, G., Bordner, J., Norman, M. L., Abel, T., Harkness, R., & Kritsuk, A. 2004, astro-ph/0403044
Norman, M. L. 1992, ApJS, 80, 753
Tasker, E. J., & Bryan, G. L. 2006a, ApJ, 641, 878
Tasker, E. J., & Bryan, G. L. 2006b, ApJ, 642, L5
Toomre, A. 1964, ApJ, 139, 1217
Wada, K. 2001, ApJ, 559, L41
Wada, K., & Norman, C. A. 2001, ApJ, 547, 172