ADVANCES IN COMPUTATIONAL ASTROPHYSICS: METHODS, TOOLS, AND OUTCOMES
ASP Conference Series, Vol. 453
R. Capuzzo-Dolcetta, M. Limongi & A. Tornambè, eds.

Spiral Structure Formation in Disk Galaxies

E. D'Onghia,[1,2] M. Vogelsberger,[2] and L. Hernquist[2]

[1]*Keck fellow*

[2]*Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138 USA*

Abstract. Spiral structure in galaxies was recognized as likely originating from the action of density waves propagating through a differentially rotating disk. However, the origin of these features remains controversial. Using very high resolution numerical simulations we show that spiral arms might be seeded by density inhomogeneities orbiting in the disk itself. These perturbations can be identified with fluctuations in the distribution of gas in the interstellar medium of galaxies, such as giant molecular clouds. Our simulations show that when sufficient numbers of these perturbers are present, they collectively amplify to yield large-scale spiral patterns that resemble the spiral arms in flocculent and intermediate late type spiral galaxies.

1. Introduction

The spiral structure in galaxies is a complex problem and after fifty years its formation has not yet been fully understood. Among the decades various theories have been proposed to explain how these patterns can be generated. A theory proposed by Lin & Shu (1964) suggests that the spiral structure in galaxies likely originated from the action of density waves propagating through a differentially rotating disk. In particular this theory proposes that the matter in the galaxy (stars and gas) can maintain a density wave through gravitational interaction in the presence of the differential rotation of the disk components. This density wave provides a spiral gravitational field which underlies the concentration of young stars and the gas. In this way an observable spiral is considered a wave pattern which either remains stationary or quasi-stationary in a frame of reference rotating around the center of the galaxy at a fixed angular speed and can be maintained over the whole disk. Note that this theory does not contain information on the sources of the initial stationary waves and more importantly predicts also that spiral arms are uniformally rotating patterns although the gas and stars in the disk rotate differentially (this comes because if the arms rotate differentially, as the observations indicate, the arms would wind up in a typical orbital period). The amount of winding of arms is small in the nearby galaxies, hence the density wave theory has to deduce that the spiral patterns have to rotate rigidly even if the material flowing through it rotated differentially. The theoretical emphasis since that time has been on finding driving mechanisms that can sustain the wave in spite of this damping. Indeed, whereas observations show that spiral arms might be density waves, subsequent N-body experiments performed later have to date not yielded long-lived spiral structure, as predicted by the stationary density wave theory. Indeed simulations of cold, shearing

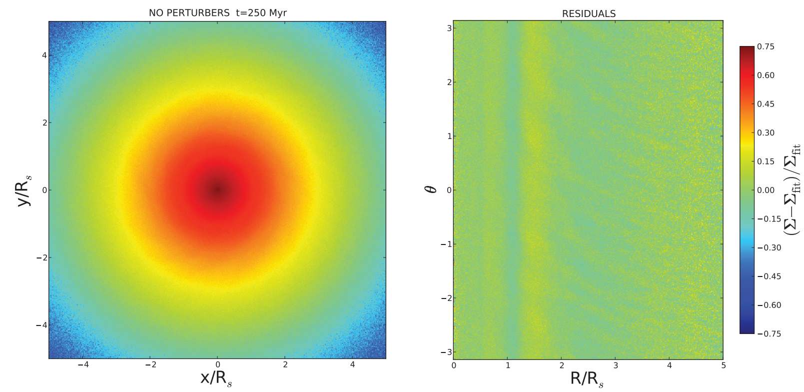

Figure 1. *Left Panel.* The outcome of an N-body experiment where a live disk of 100 million stars embedded in a dark Milky Way-sized halo is run unperturbed in isolation. *Right Panel*. The residuals of the stellar surface density are shown.

disks always exhibit recurrent transient spiral activity and this result has not changed in the last decades as numerical power increased.

An alternative analytic theory suggested that the spiral arms are stochastically produced by a gravitational response of a thin, differentially rotating and self-gravitating disk of stars to the presence of overdense material (interstellar material) orbiting within its plane (Julian & Toomre 1966). Similar studies of gravitational perturbations have considered pure gas disks (Goldreich & Lynden-Bell 1965). In particular the mechanism by which the spiral arms would be produced is termed *swing amplification* which results from the action of the gravity from any massive orbiting overdensity that evokes a strong wake in the stellar medium that shears past it in a differentially rotating disk (Julian & Toomre 1966). In this theory spiral arms are considered to be transients. Indeed Sellwood & Carlberg (1984) showed that infall of gas simulated by adding fresh particles on circular orbits, allows spiral patterns to reform.

Instead, we explore the idea that spiral arms are seeded by density inhomogeneities orbiting in the disk itself and we investigate the longevity of the arms. The galaxy in our study consists of a dark matter halo and a rotationally supported disk of stars. The total mass of the halo is $9.5\text{x}10^{11}\ h^{-1}\ M_{\odot}$ computed at a radius of 160 kpc. The stellar disk follows an exponential profile and consists of 100 million particles.

2. Results

We show the outcome of our N-body experiments: *i)* the case where the live stellar disk is embedded in a rigid dark Milky Way-sized halo potential and run in isolation without perturbers is shown in Figure 1; *ii)* the case where the live disk rotates with the addition of 1000 softened particles (with mass of the order of typical giant molecular clouds $9.5\text{x}10^{5}\ M_{\odot}$) which are distributed within the disk and assumed to be *corotating* on circular orbits with the disk (see Figure 2). The live disk is shown in all cases after 250 Myrs and is displayed face-on. Surprisingly we note that when the disk is perturbed

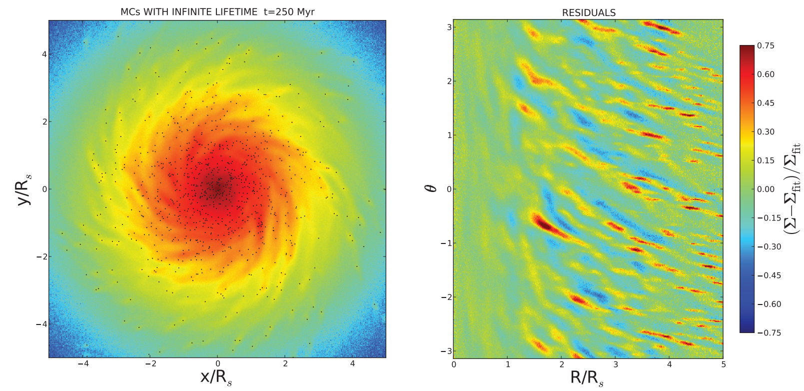

Figure 2. *Left Panel.* A live disk of 100 million stars embedded in a dark Milky Way-sized halo run in isolation with 1,000 softened particles (with mass of the order of typical giant molecular clouds 9.5x10^5 $M_\odot$) distributed within the disk and assumed to be *corotating* on circular orbits within the disk. *Right Panel*. The residuals are shown.

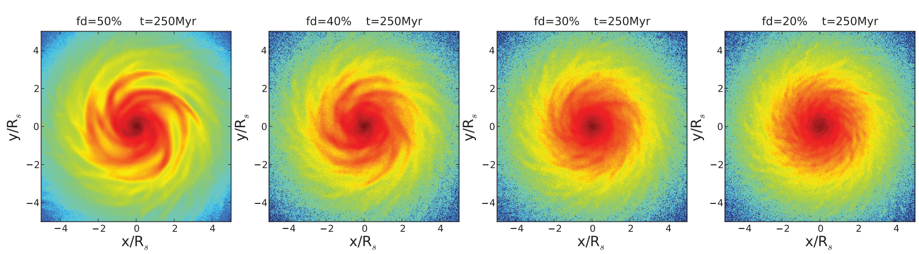

Figure 3. Disk galaxies displayed face-on for four different models. From the right to the left the contribution of the disk mass to the total mass distribution in the rotation curve of the galaxy measured at two scale lengths is increased from disk fraction of 20% (last right panel) to 50% at the left panel.

by the presence of inhomogeneities co-rotating with the stellar disk on circular orbits, the disk dynamically responds to the presence of these irritators by forming several segments which resemble multi-armed structures as shown in Figure 2. These features extend well beyond two scale lengths of the disk.

2.1. Disk fraction and number of arms

In the following experiment we changed the contribution of the disk to the total mass distribution in the rotation curve of the galaxy. We keep the total mass of the galaxy and the mass distribution of the dark halo as in the fiducial case (Figure 1-2) but we run experiments where we increase the disk mass to the total mass of the galaxy (dark matter plus stars) from a disk fraction of 20% to the following values: 30%, 40% and 50% at two scale lengths of the disk. First we run these models without perturbers orbiting within the disk and verify that the disks do not develop patterns. We introduced subsequently in the initial conditions the presence of 1000 overdensities corotating with the disk.

Figure 3 illustrates the outcome after one orbital period: models with a disk mass fraction of 20% of the total mass do show several spiral arms as is typical of the flocculent galaxies (last panel on the right). In particular the number of arms is reduced to four for disk mass fraction of 50% of the total at two disk scale lengths. Note that this model resembles the case of M101, a late intermediate spiral galaxy showing four arms without interacting with any close visible satellite galaxies.

3. Conclusion

We have examined the global dynamical response of self-gravitating disks to local perturbations from overdensities, e.g. identified as giant molecular clouds orbiting within the disks. From our N-body experiments we find that a *stochastic* distribution of overdensities such as giant molecular clouds orbiting within the disk of stars can generate a *global coherent* spiral pattern that extends up to 3-4 disk scale-lengths due to the swing amplification process. This process is triggered locally in the disk by the gravity excerted from the giant molecular cloud (the perturber) which evokes the formation of a wakelet in the surrounding medium that shears past it in a differential rotating disk and is amplified by the self-gravity of the stellar disk. However the arms formed in our simulations are not transients and do not fade away in a orbital period as predicted by the Julian & Toomre (1966) theory. The patterns appear to be long-lived, although they develop and self-maintain differently from the classical spiral density wave theory of Lin & Shu (1964). The properties and the longevity of the arms are currently under investigation and will be the subject of a forthcoming paper.

References

Goldreich, P. & Lynden-Bell, D. MNRAS, 1965, 130, 125
Julian, W.H. & Toomre, A. 1966, ApJ, 146, 810
Lin, C. C. & Shu, F. H. 1964, ApJ, 140, 646
Sellwood, J.A. & Carlberg, R. G. 1984, ApJ, 282, 61