A Model for the Declining Rotation Curves of Cluster Spirals

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ABSTRACT

Numerical studies have shown that mean tidal fields in clusters of galaxies can cause a significant increase in the planar velocity dispersions of stars and gas clouds in the disks of spiral galaxies. Since the perturbations caused by cluster tidal fields are generally weak and fairly symmetric, the stellar distributions of galaxies would not necessarily show obvious signs of tidal disturbance.

In this paper it is shown that the increased non-circular velocities of stars can result in a symmetric decline (at large radii) of the rotation curves of the perturbed spiral galaxies. This decline results from the well known phenomenon of the "asymmetric drift" of a high velocity dispersion stellar population.

This suggests that the observations of the declining rotation curves of spiral galaxies in clusters do not necessarily imply that their dark matter halos have been tidally truncated as is generally assumed.

Subject headings: galaxies: clustering — galaxies: dynamics and kinematics — galaxies: internal motions — galaxies: structure

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1. Introduction

In a series of papers Rubin and co-workers (Burstein, Rubin, Ford & Whitmore 1986; and Rubin, Whitmore & Ford 1988) showed that cluster spiral galaxies have optical (Hα) rotation curves which are different from those of field spirals. The major difference is that a large fraction of cluster spirals have rotation curves that begin to decline within their optical disks. They also found that galaxies closer to the center of the cluster have more rapidly declining rotation curves than the galaxies in the cluster periphery (Whitmore, Forbes, & Rubin 1988, however see Distefano et. al. 1990).

The observations of declining rotation curves have not been corroborated by HI studies (Guhathakurta et. al. 1987) largely because HI rotation curves do not extend out to sufficiently large radii. This is because a large fraction of spiral galaxies in the central regions of clusters are also HI-deficient.

Two dimensional Fabry-Perot (Hα) spectroscopy (Amram et. al. 1992) of cluster spirals indicate the presence of highly disturbed velocity fields and asymmetric rotation curves. However, these authors find no obvious correlation between the shapes of the rotation curves of galaxies and their distances from the cluster center.

Rubin and co-workers attribute the decline of rotation curves to the stripping of the dark matter halos of these spiral galaxies by the tidal fields in clusters. While this is a distinct possibility, it is shown in this paper that the cluster environment affects not just the masses of these galaxies but also their internal velocities and consqeuently the shapes of their rotation curves.

A numerical study of the effects of the mean tidal field of a cluster of galaxies on a disk galaxy travelling through the cluster (Valluri 1993, hereafter Paper 1) showed that the major effect of the tidal encounter was an increase in the planar random velocities of stars and gas in the disks of these galaxies. Some of the important features of the model and the results are discussed in § 2.1.

In the present paper the consequences of the tidal interaction on the rotation curves of model galaxies are explored (§ 2.2). It is shown that the rotation curves of galaxies travelling fairly close to the core of the cluster are likely to show a significant decline even within their optical extents.

In § 3 it is shown that the decline in the rotation curves arises out of the increase in the planar random velocities of stars. Some consequences of these results are discussed (§ 4).

2. Interaction with the Mean Cluster Field

2.1. The Model

In Paper 1 the dynamical evolution of a disk galaxy travelling through the cluster for the first time on a bound orbit with constant angular momentum was modeled numerically in the restricted 3-body framework. The study showed that tidal fields can dramatically increase the velocity dispersions of gas clouds and stars and also disturb the axisymmetry of their disks.

The orbits of test particles were evolved in the combined fields of the disk galaxy and the cluster potentials. The cluster was modeled by a spherically symmetric modified Hubble potential, sometimes called the analytic King potential (see Binney and Tremaine 1987, hereafter BT). The cluster potential is parameterized by a core radius a and a velocity dispersion σ_{cl}. A canonical value of 1000 km s^{-1} was chosen for σ_{cl}. Two values of the core radius a were used: 250 kpc and 100 kpc. The first value, estimated for a large sample of clusters, is obtained from their optical and X-ray luminosity distributions (Bahcall 1975), while the second value is obtained from gravitational lensing studies (Tyson, Valdes, & Wenk 1990).

The disk galaxy was modeled by a 3-component potential with a disk, a halo and a spheroidal bulge (Miyamoto, Satoh, & Ohsahi 1980) which provides a fairly good fit to the rotation curve of our Galaxy. The potential suggested by them is,

$$\Phi_g = -\sum_i^3 \frac{GM_i}{\left[R^2 + (a_i + \sqrt{z^2 + b_i^2})^2\right]^{1/2}}, \tag{1}$$

where M_i are the masses of the three components and a_i and b_i are scale lengths. This model has a very high total mass of $9.1 \times 10^{11} M_\odot$ with $M_1 = 0.195 \times 10^{11} M_\odot$, $M_2 = 1.74 \times 10^{11} M_\odot$, $M_3 = 7.35 \times 10^{11} M_\odot$. The scale lengths are $a_1 = 0.0$, $a_2 = 6.2$kpc, $a_3 = 0.0$, b_1=0.47 kpc, b_2= 0.15 kpc, and $b_3 = 31.2$ kpc.

Particles in the disk were originally on predominantly circular orbits with small initial random velocities in the radial and vertical directions. Initial velocity dispersions ranged from 5 km s^{-1} to 40 km s^{-1} representing the range of dispersions covered by disk particles from gas clouds to late type stars.

The galaxies were on fairly radial orbits in the cluster with a typical impact parameter of $\sim$ 200 kpc and were studied for at least two encounters with the cluster center.

In Paper 1 it was shown that the tidal field is purely compressive in the core of the cluster. When a disk galaxy is inclined at an arbitrary angle to the plane of the orbit, the tidal field caused a non-axisymmetric compression of the particle distribution in the plane of the disk.

A second major consequence of the tidal interaction was that the planar random velocities of particles increased significantly during the tidal encounter. The radial velocity dispersion ($\overline{v_R^2}$) which was initially independent of radius ($= 10 \ \mathrm{km\,s^{-1}}$) was found to evolve to a power law distribution in radius (R). At different times in the encounter the exponent (n) ranged between 1.5 and 4.0. This power law dependence was found to hold for a variety of parameters: different cluster potentials, galaxy potentials and galaxy orbits. In most cases, however, the value of the power n is between 1.8-2.3. Since the tidal force on a particle in the galaxy increases linearly with its radius from the center, the change in velocity dispersion is expected to increase as a square of the radius so these values are understandable. For the discussion in §3 this power law velocity dispersion is used.

2.2. Tidal Effects on Simulated Rotation Curves

In this section a study is made of the time evolution of the rotation curves of two particular model disk galaxies on nearly radial orbits through a cluster.

The rotation curves were obtained by placing 'slits' across two orthogonal axes of the model galaxies. Mean square velocities normal to a 'slit' was calculated by averaging over particles that lie in grid cells within the 'slit' located at different distances along the slit from the center of the disk. Two arbitrary, orthogonal slits were selected since the tidal field rapidly distorts the circular disk to a non-axisymmetric one (Paper 1). In such cases the asymmetry in the velocity field in the disk was evident from the differences in the rotation curves obtained along the two axes.

Figures 1 & 2 show the time evolution of the rotation curve of a disk galaxy in a cluster. The cluster potentials used in the two cases had different core radii, $a = 250$ kpc (Fig. 1) and $a = 100$ kpc (Fig. 2). During the first encounter (left hand columns in each figure; top to bottom) the tidal perturbation causes an asymmetric change in the rotation curves along the two axes. The rising rotation curves are seen because the disk undergoes an oval compression in the plane of the disk when it is inclined at an angle to its orbital plane in the cluster (see Paper 1). During the second encounter (right hand columns top to bottom) the rotation curves in both cases begin to fall at large radii. The effects are significantly stronger in Figure 2 indicating that a more centrally concentrated cluster mass distribution will result in a more severe perturbation to the galaxy. Thus galaxies in cD clusters are likely to show stronger signs of perturbation by the mean tidal field.

Since these simulations were done in the restricted 3-body framework the galaxy's potential was unchanged throughout the encounter and are entirely due to tidal effects on the internal dynamics of the galaxies. These declining rotation curves are likely to be the most easily observable signature of the tidal interaction.

3. An Analytic Model

The rotation curves of spirals are important indicators of the distribution of mass within them. The circular velocity of a particle in a potential is given by

$$v_c^2(R) = R(\frac{\partial \Phi_g}{\partial R})|_{z=0}. \tag{2}$$

If the mass distribution in a disk is assumed to be spherically symmetric the radial dependence of the integrated mass is given by

$$M(R) = 2.3265 \times 10^5 R v_c^2(R) \mathrm{M}_\odot \,, \tag{3}$$

where v_c is in km s^{-1} and R is in kpc (Burstein & Rubin 1985).

The real picture is far more complex and a complete determination of the dynamical structure of the disk requires the measurement of not only the rotation velocities but also the planar and vertical velocity dispersions (Antonuccio-Delogu 1991). Such measurements are, however, very difficult except possibly in a few nearby galaxies.

In the following section the stellar dynamic equations of a disk galaxy are used to show that changes in the planar velocity dispersions of stars can affect their observed rotation curves.

In the model described in the last section and Paper 1 the galaxy potential is not permitted to change during the encounter and hence tidal stripping of the galaxy's dark halo is not the cause for the decline at large radii. An alternative explanation is sought for the decline in the rotation curves seen in Figures 1 & 2. It is shown below that the non-circular motions induced in stellar disks by the tidal fields in clusters can produce systematic changes to their rotation curves even when there has been no change in their potentials.

3.1. The Jeans Equation and Asymmetric Drift

The first and second moments of the collisionless Boltzmann equation for a stellar disk give a set of equations called the Jeans equations (BT). Assuming that the potential and particle distribution are axisymmetric and system is in a steady state the radial component of the Jeans equation in cylindrical coordinates is,

$$\frac{\partial(\rho\overline{v_R^2})}{\partial R} + \frac{\partial(\rho\overline{v_R v_z})}{\partial z} + \rho\left(\frac{\overline{v_R^2} - \overline{v_\varphi^2}}{R} + \frac{\partial\Phi_g}{\partial R}\right) = 0\ , \tag{4}$$

where ρ is the space density of the disk v_R, v_φ and v_z are the three components of the particle velocities.

The radial and azimuthal velocity dispersions are defined as

$$\sigma_R^2 = \overline{(v_R - \overline{v_R})^2} = \overline{v_R^2} - \overline{v_R}^2 = \overline{v_R^2}\,; \qquad \sigma_\varphi^2 = \overline{(v_\varphi - \overline{v_\varphi})^2} = \overline{v_\varphi^2} - \overline{v_\varphi}^2. \tag{5}$$

$\overline{v_R} = 0$ if there is no mean radial streaming motion. The quantity $\overline{v_\varphi}^2$ is the square of the mean tangential velocity and is the observable quantity.

To evaluate equation (4) at $z = 0$ we use the fact that the density distribution is symmetric in z. Substituting $\partial\Phi_g/\partial R$ with the circular velocity (eq. [2]) in the radial equation (4) we get

$$\sigma_\varphi^2 - \overline{v_R^2} - \frac{R}{\rho}\frac{\partial(\rho\overline{v_R^2})}{\partial R} - R\frac{\partial(\overline{v_R v_z})}{\partial z} = v_c^2 - \overline{v}_\varphi{}^2\ . \tag{6}$$

The mean tangential velocity, $\overline{v}_\varphi{}^2$ is given by,

$$\overline{v}_\varphi{}^2 = v_c^2 + \overline{v_R^2}\left[1 - \frac{\sigma_\varphi^2}{\overline{v_R^2}} + \frac{R}{\rho\overline{v_R^2}}\frac{\partial(\rho\overline{v_R^2})}{\partial R} + \frac{R}{\overline{v_R^2}}\frac{\partial(\overline{v_R v_z})}{\partial z}\right]. \tag{7}$$

The last term in equation (7) depends on the orientation angle of the velocity ellipsoid. If the discussion is restricted primarily to the motion in the $z = 0$ plane and it is assumed that the velocity ellipsoid is always parallel to this plane, then the last term drops out of the equation. The density ρ of the disk and may be obtained from the potential via the Poisson equation. For the Miyamoto-Nagai potential the density ρ at large R falls as $\sim 1/R^3$. In the simulations the ratio $(\sigma_\varphi^2/\overline{v_R^2}) \sim 0.5$ at all times. The above equation at large R therefore becomes,

$$\overline{v}_\varphi{}^2 \sim v_c^2 + \overline{v_R^2}\Big[1 - 0.5 + (n - 3)\Big] \tag{8}$$

Thus for values of $n \lesssim 2.5$ the rotation curve drops below the circular rotation speed for large radii but will rise steadily for values larger than this. It has been noticed that if the tidal perturbation is large enough to make n larger than 2.5 the simulated disk looks obviously perturbed and the features on the rotation curves can be clearly identified as being due to tidal interaction.

The steady-state Jeans equation is not strictly applicable for the situation discussed in the last section since the system is undergoing tidal perturbation. It however simplifies the analysis and provides an insight into the behavior of rotation curves.

With the assumptions above equation (7) is used to determine the resultant mean tangential velocity for the galaxy. In Figure 3 the unperturbed circular velocity (obtained from eq. [2]) is plotted along with the perturbed rotation curves for disks with power law velocity dispersions $\overline{v_R^2} \propto R^n$ with $n = 1.8$ and $n = 2.2$. Figure 3 shows that a power law radial velocity dispersion results in a decrease in the mean tangential velocity at large radii.

There are a couple of ways in which this result may be understood (see Woltjer 1965, Chandrasekar 1942). In equation (4) the quantity $(\rho\overline{v_R^2}/R)$ can be thought of as contributing a radial 'pressure' which adds to the centrifugal force in balancing the inward gravitational force. If this radial pressure is increased the particles need less rotation velocity to balance the same gravitational force.

Therefore stellar populations with high random motions and high density gradients will have lower rotation velocities around the center. Alternatively, stars with large radial motions will have highly elliptical orbits. Near its apocenter a star on an elliptical orbit will have a tangential velocity that is smaller than that of a star on a circular orbit at the same radius. At its pericenter the reverse will be true. At a particular point there are likely to be more stars at the apocenters of their orbits than at their pericenters especially if the density of stars decreases with increasing radius. Thus the square of their mean tangential velocity is less than the circular velocity. In the very central region of the disk the number of stars at the pericenters of their orbits is much larger than those at the apocenters. This is because the random velocities of stars are smaller at small radii resulting in fewer elliptical orbits which lie entirely within the region.

If the radial velocity dispersion increases too rapidly ($n > 2.5$) (or density increases with radius) the radial pressure will act inwards and the stars will need to rotate faster to balance gravity. Both these situations are physically unlikely to occur.

Thus it is argued that since the declining rotation curves seen in Figures 2 & 3 do not reflect a change in the galaxy's potential they must arises from the large non-circular velocities in the disk.

4. Discussion

The Tully-Fisher (Tully & Fisher 1977) relation between the maximum rotation velocities of spirals and their absolute magnitudes provides one of the most important tertiary distance indicators for extragalactic astronomy. It is therefore important to understand how the rotation curves of galaxies and consequently the Tully-Fisher relation may be affected by environmental factors.

Djorgovski, de Carvalho & Han (1989) find tentative evidence that the Tully-Fisher relation may be affected by the cluster environment at a few percent level. The deviation from the relationship for field galaxies increases towards the centers of the observed clusters.

Rubin et al. (1988) found that the Tully-Fisher relation for their sample of cluster spirals showed a small deviation particularly at the low luminosity end.

Restricted 3-body simulations carried out on different kinds of galaxy potentials failed to show any significant effect of the cluster tidal field on the peak rotation velocities of these galaxies. This suggests that the "asymmetric-drift" phenomenon is unlikely to affect the Tully-Fisher relation.

Rubin et al. (1988) and Whitmore et al. (1988) suggested that the tidal stripping of the dark matter halos of cluster galaxies by tidal fields alters their mass distributions and this causes the decline in the rotation curves within the optical radius of these galaxies. While the possibility of tidal stripping is very high in clusters, Merritt (1984) has shown that typical tidal radii are about ~ 30 kpc. It is possible that tidal stripping will therefore have little effect especially on the optical rotation curves of the galaxies. If the observed differences between the Tully-Fisher relations for galaxies is substantiated by further observations it would imply that the tidal forces have in fact altered the potentials of these galaxies more severly than predicted theoretically.

5. Conclusions

It is well known that large non-circular motions resulting from tidal interactions can cause irregular features in rotation curves of spiral galaxies in pairs or compact groups (e.g., Rubin, Hunter & Ford, 1990).

In this paper it has been shown that large increases in the velocity dispersions of stars in the outer regions of spiral galaxies can arise from their interaction with the mean cluster tidal field. Also, the rotation curves of these galaxies begin to decline at large

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Figure Captions

Figure 1— Rotation curves for a disk galaxy inclined to the orbital plane, seen at different stages of its passage through the cluster: r is the distance of the galaxy from the cluster center in Mpc and T is the time in units of 10^9 yrs from the beginning of the simulation. The cluster has a core radius of 250 kpc. The symbols (·) and (+) represent the rotation curves seen through the two orthogonal slits.

Figure 2— Same as Fig. 1 for a cluster with a core radius of 100 kpc.

Figure 3— Theoretical rotation curves plotted for the 3-component potential when there are no non-circular velocities (solid line); the broken lines show the rotation curves with a power law velocity dispersion, $\overline{v_R^2} \propto R^n$, with the n values as indicated.