FORMATION OF GALAXY DISKS

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ABSTRACT. Galaxy disks are observed to be young, dynamically cold, and centrifugally supported. These properties suggest that they formed in a quiescent dynamical context, reached their current configuration while still gaseous, and have been relatively undisturbed since formation. This situation can be understood if disks grow by the cooling of a gaseous atmosphere within a quasi-equilibrium dark halo. A simple version of this model can be combined with results from numerical simulations of halo formation to provide quantitative explanations for the Tully-Fisher relation, for the typical sizes of disks, and for their star formation history. A viable model seems to require stellar winds and supernovae to heat the gaseous halos of spirals via a galactic fountain. Such models predict observable X-ray halos, and suggest that continued infall replenishes the gas consumed by star formation in late-type galaxies.

1. Clues to Disk Formation

1.1 THICKNESS AND COLDNESS

The primary defining characteristics of galaxy disks are their flatness and the fact that they are supported by rotation. Axis ratios in excess of 10:1 are normal, and rotation velocities greatly exceed the random motions of stars and gas both in our own and in other spirals (*e.g.* van der Kruit and Searle 1981; van der Kruit and Freeman 1986; Gilmore, Wyse and Kuijken 1989). Thus disks are thin and cold. Such structures can only be formed by dissipative processes. Disks must have been assembled and have come to equilibrium *before* their stars were formed. In the prestellar gas strong shocks could radiate the energy in random motions, and so allow the material to settle into the observed configuration. Once stellar, disks can tolerate changes in the galactic potential only if they are small or slow; too much disturbance leads to a thicker, hotter system. Thus the potential well of a spiral must be stable before the formation of the bulk of its disk stars, and most systems must experience only relatively weak perturbations subsequent to this epoch. Quinn (1987) found that the accretion of a satellite containing only 4% of the disk mass was sufficient to thicken a disk by a factor of two.

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1.2 STELLAR AGES AND STAR FORMATION RATES

The theoretical inference that galaxy disks are assembled before significant star formation is supported by observational evidence on the solar neighborhood. Carlberg *et al.* (1985) studied how abundance, velocity dispersion, and metallicity depend on age in Twarog's (1980) sample of nearby dwarfs. They concluded that the "local" star formation rate has been approximately constant over the entire lifetime of the system, and they favored a model in which much of the mass of the disk is added late by infall. An indication that local star formation began well after the initial collapse of the Galaxy comes from the work of Winget *et al.* (1987). These authors found a sharp faint-end cutoff in the luminosity function of white dwarfs, corresponding to an age since formation of 9 Gyrs. Thus formation of the local disk population appears to be a late and ongoing process. Although detailed age estimates are not available for other galaxies, the colours of many disks suggest that their present star formation rate would be sufficient to form all their stars in a Hubble time (*e.g.* Tinsley 1980), and direct estimates of star formation rates from $H\alpha$ fluxes lead to a very similar conclusion (Kennicutt 1983). These inferred rates seem to imply a "gas consumption problem": the remaining gas in many late-type systems appears sufficient to fuel the observed star formation for at most a few billion years. Although controversial, this state of affairs suggests that ongoing infall may be required to replenish the gas supply.

1.3 ANGULAR MOMENTUM

Further clues to the formation of disks come from theoretical arguments concerning the origin of their angular momentum. The only viable production mechanism appears to be that first suggested by Hoyle (1949). Neighboring irregularities exert tidal torques on the protogalactic material as it separates from the universal expansion and begins to recollapse. As a result the collapsing object gains spin angular momentum which is compensated by the orbital angular momentum of surrounding objects. N-body simulations of the growth of structure in an expanding universe show this process to be quite inefficient. The amount of angular momentum acquired by virialised objects varies considerably, but seems almost independent of mass or environment (Barnes and Efstathiou 1987). The denser regions of quasi-equilibrium lumps are found to have systematic streaming velocities proportional to the velocity required for centrifugal equilibrium but about an order of magnitude smaller. Thus the extensive numerical data of Frenk *et al.* (1988) give $V_r(r/GM)^{0.5} = 0.11$ as the median value of the ratio of these two velocities. Dissipative contraction by a substantial factor is thus necessary for the protodisk material to become centrifugally supported.

For a self-gravitating gas cloud the ratio of rotation speed to virial velocity dispersion increases as the square root of the contraction factor. Thus if the material in the solar neighborhood had started in a self-gravitating cloud of typical angular momentum, its initial virialised size would have been of order $(0.11)^{-2} \times 8\text{kpc} \sim 600\text{kpc}$! Its collapse time would have been of order $(0.11)^{-3} \times 10^8\text{yrs} \sim 10^{11}\text{yrs}$! This model clearly can't work. On the other hand, Fall and Efstathiou (1980) showed that the problem is avoided if contraction takes place within a gravitationally dominant dark halo. For an isothermal halo the ratio of rotation speed to circular velocity increases in proportion to the contraction factor. Hence, if our Galaxy has such a halo, local material must initially have virialised at about

$(0.11)^{-1} \times 8\text{kpc} \sim 70\text{kpc}$. The free fall time from this radius is roughly 10^9yrs. Notice that contraction factors estimated in this way are likely to be *underestimates*; they neglect the fact that the gas is likely to lose some of its angular momentum to outlying material as it settles to its final resting place in the disk.

1.4 MASSIVE HALOS AND COOLING FLOWS

Quite apart from the above theoretical argument in favor of massive halos surrounding spirals, there is, of course, abundant dynamical evidence for such extended mass distributions (*e.g.* Sancisi and van Albada 1987; Zaritsky *et al.* 1989). A simple model indicates the amount of dark matter required for the angular momentum argument of the last section to work. Consider an exponential disk, $\rho = \rho_0 \exp(-r/r_0)$ in equilibrium in an isothermal dark halo with circular speed, $V_c = (GM/r)^{0.5} = \text{const}$. If the gas was initially distributed in the same way as the dark matter and had a systematic rotation speed of $0.11V_c$, then one can calculate the radius, R, such that the mean specific angular momentum of the gas within R was equal to that of the final disk. This calculation gives $R \approx 23r_0$. For a typical halo the gas in the disk must have come from a volume at least this large. In real galaxies the inner regions seem to be marginally self-gravitating (*e.g.* Kent 1987). The ratio of halo mass to observed stellar mass must therefore exceed $RV_c^2/2.4r_0V_c^2 \sim 10$. Such large amounts of dark matter seem required by the kinematics both of our own Galaxy halo and of groups and clusters of galaxies. However, in the latter case the unseen material may not be attached to individual galaxies.

The picture of disk formation suggested by all the above arguments is one in which gas contracts dissipatively within a pre-existing and massive dark halo. This is the general galaxy formation picture first proposed by White and Rees (1978). When the dissipation timescale is long compared to the dynamical time of the halo, the gas is expected to contract quasistatically. The situation is then directly analogous to the cooling flows seen in many rich clusters of galaxies (Fabian, Nulsen and Canizares 1984). In such gaseous atmospheres a cooling time can be defined at each radius as the time required for the gas to radiate its thermal energy content. The cooling radius is then the point where the cooling time is equal to the age of the system. A large fraction of the gas initially within the cooling radius is expected to sink to the centre, and thus to be available for making a disk. For parameters appropriate to galaxy halos, the cooling radius can be comparable to the entire virialised region of the halo. In this case, substantial dissipation and disk formation may occur during the initial collapse of a halo (see the calculations of Katz and Gunn 1991). Gas accreted at later times (perhaps in the form of dwarf galaxies) may also be added almost immediately to the central system.

2. A Simple Model for Disk Formation

Let us assume that at the time of collapse gas makes up a fixed fraction, F, of the mass of every protogalaxy. Further let us assume that the dark matter forms an "isothermal" halo with $\rho \propto r^{-2}$. This is a good approximation to the kind of structure seen in numerical simulations (*e.g.* Frenk *et al.* 1988). When cooling is inefficient, gas shocks and comes to equilibrium with a density distribution which parallels that of the dark matter quite closely (Evrard 1990). Let us adopt this simple model for the *initial* virialised distribution of the gas. Its density and temperature are then related to the circular velocity of the halo through:

$$\rho_g = \frac{FV_c^2}{4\pi G r^2}; \quad T = 2 \times 10^6 \left(\frac{V_c}{250 \text{ km/s}}\right)^2 \,^\circ\text{K}. \tag{1}$$

The cooling time at each radius can be defined from these equations in the standard way to give

$$t_c(r) = 7 \times 10^8 F^{-1} \Lambda_{23}^{-1} \left(\frac{r}{100 \text{ kpc}}\right)^2 \text{yrs}. \tag{2}$$

The cooling function, $\Lambda_{23} = \Lambda(T)/(10^{-23} \text{ erg cm}^3\text{s}^{-1})$, is roughly unity for unenriched gas in the appropriate temperature range, but is about $10^4\ T^{-0.5}$ for gas with solar metallicity (Binney and Tremaine 1987 p.580). At some later epoch, equating the cooling time with the age of the system defines a cooling radius,

$$r_c(t) = 390 \left(\frac{F\Lambda_{23}t}{10^{10}\text{yrs}}\right)^{0.5} \text{kpc}. \tag{3}$$

In the absence of heat sources, all the gas within r_c should have sunk into the disk by time, t. Notice that the cooling radius is independent of circular velocity for unenriched gas, and is proportional to $V_c^{-0.5}$ for solar metallicity. For large galaxies it seems reasonable to identify the present value of r_c with the minimum radius, R, from which gas must come in order to account for the specific angular momentum of the disk. We saw above that R must exceed 23 times the exponential scale length, r_0, of the final disk. As an example, M31 has an exponential scale-length of 5 kpc (Kent 1987), suggesting $R \sim 115$ kpc and $F \sim 0.09$ for unenriched gas. This is roughly the fraction of the mass of rich clusters which is in gaseous form and so seems plausible *a priori*. For solar metallicity the greater efficiency of cooling requires either a low gas fraction or a cooling radius substantially greater than R. The latter might be appropriate if there is significant angular momentum loss from the gas to the dark halo during the cooling process.

The radius given by equation (3) is large and can enclose the entire virialised region of a galaxy halo. The extent of this latter region can be estimated from the requirement that the circular orbital time be everywhere less than the age of the system. For an isothermal halo this condition gives the bounding radius as

$$r_v(t) = V_c t/2\pi = 400 \left(\frac{t}{10^{10}\text{yrs}}\right) \left(\frac{V_c}{250 \text{ km/s}}\right) \text{kpc}. \tag{4}$$

For a galaxy like our own, all the gas in the virialised region can cool if $F\Lambda_{23} \sim 1$. In this case a quasistatic cooling flow does not form; rather, gas dissipates its energy and becomes available for disk and star formation as soon as it accretes onto the halo. The infalling gas may be very irregular in this situation (for example, in the form of gas clouds or dwarf galaxies) and the simple arguments given above are likely to underestimate substantially the contraction factor required to reach centrifugal equilibrium. This is because the gas tends to lose angular momentum to the dissipationless dark matter component as it settles towards the disk (*e.g.* Katz and Gunn 1991). Notice that for dwarf galaxies the gas supply will accretionregulated in this way even for relatively small values of $F\Lambda_{23}$.

The total amount of gas available for disk formation is clearly that within r_c when $r_c < r_v$, and that within r_v in the contrary case. This mass is therefore given by

$$M_g = 6 \times 10^{12} \left(\frac{F^3 \Lambda_{23} t}{10^{10} \mathrm{yrs}} \right)^{0.5} \left(\frac{V_c}{250 \text{ km/s}} \right)^2 \mathrm{M}_\odot; \quad r_c < r_v;$$

$$M_g = 6 \times 10^{12} \left(\frac{Ft}{10^{10} \mathrm{yrs}} \right) \left(\frac{V_c}{250 \text{ km/s}} \right)^3 \mathrm{M}_\odot; \quad r_c > r_v. \tag{5}$$

For $F \sim 0.1$, as seen in rich galaxy clusters, and for $\Lambda_{23} \sim 1$ (*i.e.* negligible cooling by heavy elements) the cooling radius is smaller than the virial radius for $V_c > 80$ km/s. The mass given by the first of equations (5) is then comparable to the observed disk mass of large galaxies like M31, but it substantially exceeds the observed disk mass of smaller systems like M33. If heavy element cooling is significant, too large a mass is obtained for all galaxies unless the gas fraction is very low. No parameter set can give disk masses which are correct on all scales because this model gives $M_g \propto V_c^2$, whereas $M \propto V_c^4$ is a better representation of the properties of observed disks.

This failure of the simplest cooling model was first noted by Cole and Kaiser (1989). It suggests that some process has been omitted which reduces the efficiency with which gas is able to accrete into a disk. Furthermore this process must be more effective in small galaxies than in large ones. An obvious candidate is feedback from the stars which do form, as first suggested by Larson (1974). Larson pointed out that the low metallicities of dwarf galaxies might reflect the fact that most of their protogalactic material had been blown away by supernovae. The same idea was used in the galaxy formation theory of White and Rees (1978) to prevent all the gas turning into stars in low mass systems long before hierarchical clustering built up objects as large as bright galaxies. Its application to the properties of dwarfs was investigated in considerable detail by Dekel and Silk (1986).

The rate at which the gaseous halo of a spiral is heated by ongoing star formation is plausibly proportional to the star formation rate. Since the proportionality constant must have the units of velocity squared, we can write

$$\dot{E}_* = \dot{M}_* V_0^2. \tag{6}$$

If only part of the available gas, M_g, is turned into stars, the remainder must be kept hot (or blown away) since it is not currently observed as cold gas. The rate at which this material is radiating energy is given by

$$\dot{E} = (\dot{M}_g - \dot{M}_*) V_c^2, \tag{7}$$

where the mass supply, $\dot{M}_g$, comes from cooling or accretion and is given by the derivative of the appropriate case of equations (5). If we suppose that star formation is self-regulating, we can equate (6) and (7) to obtain the star formation rate,

$$\dot{M}_* = \dot{M}_g / (1 + V_0^2 / V_c^2). \tag{8}$$

This model assumes that gas accumulates in a disk until star formation is sufficiently rapid for feedback to prevent any further increase in the gas supply. Heating may regulate star formation in a smooth way, or produce alternating active and quiescent periods. In either case, energetics arguments suggest that (8) should describe the mean star formation rate. Notice that star formation is suppressed by two powers of V_c/V_0 when this ratio is small, and that all the detailed physics of *how* star formation heats the halo gas is hidden in the single "constant", V_0. The integral of equation (10) immediately gives a formula for the stellar mass in a disk,

$$M_*(V_c, t) = M_g(V_c, t)/(1 + V_0^2/V_c^2), \tag{9}$$

where M_g is taken from equations (5). For plausible parameters, $F \sim 0.1$, $\Lambda_{23} \sim 1$, this equation gives reasonable disk masses over the entire range of V_c provided that $V_0 \sim 300$ km/s. This latter value is actually quite large and implies a heating efficiency almost an order of magnitude greater than that estimated by Dekel and Silk (1986). It is unclear whether this is plausible; very efficient conversion of supernova energy into mechanical heating of a wind is observed in some galaxies with high star formation rates (Armus, Heckman and Miley 1990), but in these systems the winds appear too energetic for the present purpose. Notice also that while star formation is occurring in the disk at radii of 5 - 10 kpc, the material which needs to be kept hot or reejected is typically at radii exceeding 100 kpc. This only seems plausible if the situation resembles the classic galactic fountain (*e.g.* Bregman 1980). Incoming gas is in the form of cool clouds, either because it accreted that way or because clumps formed from hotter gas by thermal instability. Outflowing gas, which may or may not leave the galaxy entirely, carries the supernova energy to large radii and deposits it in the cooler material there through a variety of thermal and hydrodynamical interactions.

3. Consequences of the Model

The above picture of disk formation by the gradual accretion of infalling material is an old one in many of its aspects (*cf.* for example, Gunn 1981). The main difference with earlier work is a more explicit consideration of the thermal evolution of the gas component. It is clear that gaseous atmospheres of the kind suggested may be detectable by their X-ray emission. In a simple one-phase model for a cooling flow the present temperature is given by (1) and the bolometric luminosity is of order,

$$L_x \sim \log(r_c/r_0)\dot{M}_g V_c^2 \sim 4 \times 10^{43} F^{3/2} \Lambda_{23}^{1/2} \left(\frac{V_c}{250 \text{ km/s}}\right)^4 \text{erg/s}, \tag{10}$$

and is distributed logarithmically in radius (*i.e.* surface brightness decreasing as r^{-2}) between the disk radius, r_0, and the cooling radius, r_c. Only the largest spiral halos are predicted to be hot enough to have been detectable with Einstein, and in fact only a very few spirals seem to have been examined for halo emission. Fabbiano and Trinchieri (1987) quote an upper limit for halo emission around NGC 4631, but this galaxy has $V_c \sim 140$ km/s so that the gas should have $kT \sim 0.06$ keV, too cool to be detected. An even lower temperature is predicted for NGC 4244, observed by Bregman and Glassgold (1982). The second galaxy studied by these authors, NGC 3628, has a predicted temperature ~0.15 keV, and so might give interesting constraints. Unfortunately, too few observational details are given for interpretation to be possible. Only the observations of M101 by McCammon and Sanders (1984) really constrain the model. This galaxy is not ideal because it is face-on and fills the IPC field of view; this makes it very difficult to establish the background level accurately. Nevertheless, their analysis suggests that the luminosity of equation (10) is less than about 10^{41} erg/s. For $V_c \sim 200$ km/s this implies $F_{23} < 0.04$, a very stringent constraint indeed.

Clearly more X-ray data on spirals should be obtained with ROSAT. If massive edge-on systems ($V_c > 250$ km/s) are indeed found to have bolometric luminosities below 10^{41} erg/s, the whole framework I have constructed appears to be in critical trouble. It would then be very instructive to try and understand why the gas fraction in spiral halos appears so much smaller than that in rich clusters of galaxies. A possibility might be that almost all the incoming gas is cool, clumpy, and is never heated up to the virial temperature, while the outgoing hot phase is too sparse to radiate effectively. Begelman and Fabian (1990) discuss a mechanism by which cooling radiation could emerge at relatively low energies when two such components are coupled. It is clear that the feed-back processes I invoke above would imply a situation which is significantly more complex than that assumed in deriving equations (1) and (10). As a result the spectrum and the surface brightness distribution implied by the model are quite uncertain. Nevertheless, the bolometric luminosity comes from gross energetic arguments, and so it is difficult to see how it could be far in error.

A second observational argument against a simple one-phase cooling model is the fact that it produces pressures incompatible with those observed in galaxy disks. The similarity solutions of Bertschinger (1989) show that in such a model the pressure at 5% of the cooling radius is smaller than that predicted by equations (1) by a factor of 6. Using $V_c = 220$ km/s and $r = 8$ kpc, this gives the pressure in the solar neighbourhood as $n_H T = 9 \times 10^5 F$, which is to be compared with typical observational estimates of about 3×10^3 (*e.g.* Knapp 1990). These values cannot be reconciled for acceptable F. It is perhaps possible that the galactic fountain substantially reduces the density gradient within the cooling radius, thereby reducing the overpressure on the disk. The pressure predicted *at* the cooling radius is easily found from (1) and (3) to be $n_H T = 370/\Lambda_{23}$, independent of F. Thus only about one or two orders of magnitude increase in pressure are possible between the cooling radius and the local disk. A detailed model is needed to determine if this is plausible.

My galactic fountain hypothesis requires that material from the disk of a bright spiral be ejected to at least 100 kpc in order to heat the gaseous halo at those radii. Some products of stellar nucleosynthesis are therefore expected to end up well outside the luminous galaxy. In this context it is interesting that spectroscopic studies of galaxies projected within a few arcseconds of a quasar have almost always been able to find an object at the same redshift as any MgII absorption system with $z \sim 0.5$ (Bergeron 1987). These galaxies are inferred to have relatively high star formation rates and their angular separation from the quasar is typically about 3 times their Holmberg radius. These observations seem to confirm that metals are ejected to large radii in actively star-forming systems. The high metallicity of the intergalactic medium in galaxy clusters also appears to require that very large amounts of metals were ejected from the cluster galaxies during their star formation phase (*e.g.* Sarazin 1986).

According to the current model, disk formation is an ongoing process. Equations (5) and (9) imply that the stellar mass of a disk increases as $t^{0.5}$, and thus that the star formation rate declines as $t^{-0.5}$. Furthermore, gaseous infall should be continuing at a rate comparable to or larger than the present star formation rate, perhaps 10 $M_\odot$/yr in a giant spiral. However, it is not clear whether this material is being added in a gentle rain or in relatively large clouds, perhaps even dwarf galaxies. While the prediction of gently declining star formation agrees well with the observational data cited in Section 1, the amount of infall required is larger than most observational estimates (*e.g.* from high velocity clouds in our own Galaxy - the review of van Woerden, Schwarz and Hulsbosch (1985) gives ~ 1 $M_\odot$/yr with considerable uncertainty). If the incoming material is lumpy, individual lumps cannot contain more than a few percent of the disk mass, otherwise their perturbing effects will cause an excessive thickening of the stellar disk (Quinn 1987; Ostriker 1990).

Finally, my simple model predicts the star formation history and stellar mass of a disk (and hence its luminosity) to depend on the single parameter, V_c. As a result, the Tully-Fisher relation $L \propto V_c^4$ is "predicted" with negligible scatter. In this picture the intrinsic scatter in the Tully-Fisher relation must reflect fluctuations in the detailed formation and enrichment history of galactic halos and in the many assumptions which define the efficiency parameter, V_0, of equation (6). However properties of a disk such as its size depend in addition on the specific angular momentum of its halo; N-body work suggests that this will scatter around its mean value by at least a factor of two. Thus the model predicts that the Tully-Fisher relation should be tighter than the relations linking disk size with luminosity or circular velocity. This does indeed seem to be the case.

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Frank Bash incites people to drink a toast to the organisers, while Hans Olofsson is already enjoying the wine.