THE FORMATION OF DISK GALAXIES

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1. INTRODUCTION

In this talk, I will discuss a few particular topics, rather than attempting a general review of the formation of disk galaxies. First recall the basic structure and kinematics of a disk galaxy like the Milky Way. The Table below lists the four main structural components as they are presently understood, and gives typical masses, and (if known) the characteristic rotational velocities (at the sun) and the radial velocity dispersion for each component. For more details, see Freeman (1987).

	Mass	$V_{rot}(R_\odot)$	$\sigma(R_\odot)$
Thin disk	6.10^{10} $M_\odot$	210 km s^{-1}	40 km s^{-1}
Thick disk	4.10^9	190	70
Metal weak halo	2.10^9	≈ 0	140
Bulge	5.10^9		
Dark halo	$\approx 10^{12}$		

Some comments: (1) The velocity dispersion of the galactic bulge is similar to that of the halo. There is no secure information yet about the rotation of the galactic bulge. However, the bulges of other spirals like the Milky Way are known to rotate (eg Kormendy and Illingworth 1982). (2) Bulges and thick disks appear to occur together (van der Kruit and Searle, 1981); many disk galaxies have neither a bulge or a thick disk, but those with bulges appear to have thick disks. (3) There is no rotationally intermediate population near the sun. The disk and thick disk rotate rapidly, with rotational velocities close to the circular velocity; the metal weak halo rotates very slowly.

The disk is close to rotational equilibrium, so its radial structure is determined largely by its total angular momentum J and its internal distribution of angular momentum M(h) (defined as the mass with

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specific angular momentum less than h). The angular momentum content of disk galaxies, and the way in which this angular momentum is acquired, are a very important part of the formation process and will be discussed in Section 2.

The metal weak halo is supported by its velocity dispersion. The bulge probably rotates but its main support is again from its velocity dispersion. The traditional view of the formation of these pressure supported components is that they formed before the disk, through the rapid collapse of part of the protocloud. An alternative view has evolved over the last decade, that the bulge and halo formed by mergers or by the accretion of satellites; see Toomre (1977), Searle and Zinn (1978), Silk and Norman (1981), Rodgers and Paltoglou (1984), Toomre (1987) and Quinn and Goodman (1986) for elements of this view. In Section 3, I will discuss how this picture for the formation of the bulge and halo fits qualitatively with the known properties of the Milky Way and other similar spirals.

2. THE ANGULAR MOMENTUM OF DISK GALAXIES

2.1 The Specific Angular Momentum

Most disk galaxies show the familiar exponential surface brightness distribution $I(R) = I_o \exp(-\alpha R)$ out to $R = 5\alpha^{-1}$ at least. From a recent survey by van der Kruit (1987), the scale length α^{-1} for disk galaxies lies between about 1 and 8 kpc. The scale surface brightness I_o for most galaxies has a typical mean value of about 21.7 B mag arcsec^{-2}, with a standard deviation of only 0.5 mag. This value of I_o corresponds to about 140 $L_\odot$ pc^{-2} or roughly 500 $M_\odot$ pc^{-2}. However there do exist disk galaxies (dwarfs and some larger low surface brightness systems) with significantly fainter values of I_o.

This small range of I_o observed for most disk systems has an immediate implication for the total angular momentum content of their disks, if we accept that a small range in the surface brightness I_o also means a small range in the corresponding characteristic surface density. The circular velocity in a disk galaxy is determined by the gradient of the potential of the luminous matter (dominated by the disk in a system like the Milky Way) and the dark halo. The rotation curves of such galaxies are flat except in the innermost parts. Several authors (eg Carignan and Freeman 1985; van Albada et al 1985; Kent 1987; Athanasssoula and Bosma, preprint) have attempted to decompose the observed rotation curves into the contributions from the luminous matter and the dark halo, and in most cases it turns out that these two contributions have very similar amplitudes: ie there is only one characteristic rotational velocity in a typical disk galaxy, although there are at least two components contributing to it (this is sometimes referred to as a conspiracy). The stars of the exponential disk move in roughly circular orbits in the combined potential of the disk and the dark halo: if there is only one characteristic velocity and the characteristic surface densities of disk galaxies are similar, then it follows directly (Freeman 1970) that

$$J_D/M_D \propto M_D{}^{3/4}$$

where M_D is the mass of the disk and J_D/M_D is the disk's specific angular momentum. The Tully-Fisher law also follows.

Fall (1983) presented an interesting plot of the specific angular momentum of disk and elliptical galaxies against their mass. The disk galaxies show a well defined J/M - M relation with a slope of 3/4, just as expected. His plot also shows the very important result, that the specific angular momenta of disk galaxies are about an order of magnitude larger than those of ellipticals at the same mass.

We should now look at the results on the angular momentum properties of galaxies from recent N-body cosmological simulations with different power spectra and Ω. The angular momenta of proto-objects grow through tidal interactions (Hoyle 1949, Peebles 1969). It turns out that the angular momentum properties of identifiable virialised systems from the simulations are in quantitative agreement with the observed angular momenta of galaxies, if we assume that the gas and dark matter are mixed together during this phase and are torqued up to similar J/M.

The parameter $\lambda = J|E|^{1/2}G^{-1}M^{-5/2}$ for such an identifiable system is a measure of the ratio of its rotational velocity to its virial velocity. (Here E is the energy of the system). For disk galaxies, $\lambda \approx 0.45$; for ellipticals, $\lambda \approx 0.05$. Cosmological simulations give $\lambda = 0.05 \pm 0.03$ (σ), with almost no dependence on the power spectrum, halo density, mass or local overdensity. If the gas and the dark matter have similar J/M, then these low values of λ suggest that the gas needs to become more bound, dissipating and conserving its angular momentum to form an equilibrium disk galaxy with $\lambda \approx 0.45$. Fall and Efstathiou (1980) gave a quantitative discussion of this process; see also Barnes (1987) and Blumental et al (1986) for discussion on the restructuring of the dark halo as the disk dissipates within it.

We can estimate the collapse factor for the disk. Take a truncated dark halo with density distribution $\rho(r) = V^2/4\pi G r^2$ for $r \le r_t$, and zero for $r > r_t$; here r_t is the truncation radius. Then the mass of the dark halo is $M_H = V^2 r_t/G$ and its energy is $E_H = -GM_H{}^2/2r_t$, so its specific angular momentum is

$$(J/M)_H = \sqrt{2}\lambda_H V r_t$$

The gas dissipates within the potential of this dark halo, and settles to centrifugal equilibrium as an exponential disk with a scale length α^{-1}. Its specific angular momentum is then

$$(J/M)_D = 2V\alpha^{-1}$$

Then, if $(J/M)_H = (J/M)_D$, the collapse factor $\alpha^{-1}r_t = \sqrt{2}\lambda_H{}^{-1} \approx 25$.

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This is similar to the collapse factor estimated by comparing the luminosity density of a galaxy on a scale of say 10 kpc with the luminosity density derived from the galaxy correlation function. This simple expression for the collapse factor ($\alpha^{-1} r_t = \sqrt{2}/\lambda_H$) is a good approximation to the more detailed calculations of the collapse factor as a function of λ made by Fall and Efstathiou (1980).

The free fall time from a radius r_t is $\sqrt{\pi}/(\alpha V \lambda)$: for the Galaxy, with $V = 220$ km s^{-1} and $\alpha^{-1} = 4$ kpc, $r_t = 100$ kpc for $\lambda = 0.05$, and the free fall time τ_{ff} is about 5.10^8 y. (This is all subject to the assumption that $(J/M)_D = (J/M)_H$, which may be correct if the gas and the dark matter have similar spatial distributions through to virialisation. Dissipative simulations should show whether this is correct.) For a typical L^* galaxy, with $V \approx 250$ km s^{-1} and $\alpha^{-1} \approx 6$ kpc.$(H_o/50)^{-1}$, $2\tau_{ff}H_o \approx 0.14(\lambda_H/0.06)^{-1}$. The epoch of collapse to the disk $(t_{coll}) \gtrsim 2\tau_{ff}$, depending on the rate of dissipation. The corresponding redshift z_{coll} is then $(1+z_{coll}) = (3H_o t_{coll}/2)^{-2/3} < 3(\lambda_H/0.06)^{2/3}$ for $\Omega=1$. The corresponding result for $\Omega = 0$ is $(1+z_{coll}) \lesssim 7(\lambda_H/0.06)$. We note that the large spread in λ_H observed in the simulations implies a significant spread in z_{coll}. The observed numbers of damped Ly-α systems (Wolfe et al, 1986) give a lower limit of $(1+z_{coll}) \gtrsim 3$. See also Baron and White (preprint).

Cosmological simulations, such as Zurek et al (preprint) and the Barnes and Efstathiou (1987) white noise models, show a relation between the specific angular momenta of identifiable virialised systems and their masses, which has the same slope (3/4) as the observed relation for disk systems. To compare the absolute J/M values for the two relations, we need an estimate of the ratio of the masses of the dark halo and the disk. This ratio is $M_H/M_D = \alpha r_t (V_H/V_D)^2$, where V_H and V_D are the contributions of the halo and disk to the rotation curve. As already mentioned, observations show that $V_H \approx V_D$, and the collapse factor $\alpha r_t \approx \sqrt{2}/\lambda$, so $M_H/M_D \approx \sqrt{2}/\lambda_H$, where λ_H is again the λ-value for the identifiable virialised system. With this normalisation, it turns out that the slopes and the absolute values of the J/M - M relation from the simulations are very similar to those for the real galaxies. This is encouraging support for the picture of tidal acquisition of angular momentum and the subsequent dissipation of the gas, in the potential of the halo, to form the disk.

I am very grateful to Michael Fall for some of the arguments used in this section.

2.2 The Internal Angular Momentum Distribution M(h)

So far we have discussed the total angular momentum content of disk galaxies. The internal angular momentum distribution M(h) is also interesting, because it is closely associated with the structure of the disk, and we have already seen that the disks of disk galaxies are structurally similar. If the dark halo dominates the radial potential gradient of a disk galaxy, then M(h) directly determines the radial surface density distribution $\mu(R)$ of the equilibrium disk. If the disk itself dominates the potential gradient, then M(h) does not uniquely determine $\mu(R)$: for example, the exponential disk and the disk with $\mu(R) \propto (1-R^2)^{1/2}$ have almost identical M(h) distributions, after appropriate scaling. The truth is probably somewhere between these two extremes: the disk dominates for $R < 2\alpha^{-1}$ and the dark halo dominates in the outer parts. Observationally, the M(h) function for disk systems has a well-defined form. van der Kruit (1987) has shown that the M(h) function, for an exponential disk (truncated at $4.5\alpha^{-1}$) in a realistic disk + halo potential, is very similar to the M(h) distribution for a uniform density, uniformly rotating sphere. It seems clear that this particular form of M(h) is closely associated with the exponential nature of the disks.

The origin of this form of the M(h) distribution, and therefore the origin of the exponential disk, is a fundamental problem and is not yet understood. Is it established by tidal torques before galaxy formation, or by internal torques during virialisation, or by internal transport of angular momentum after the disk has begun to form (see Barnes and Efstathiou 1987; Zurek et al, preprint; Ryden and Gunn 1987; Lin and Pringle 1987 for different aspects of this problem).

3.THE FORMATION OF THE BULGE AND THE HALO

The bulge and metal weak halo are not in centrifugal equilibrium, so angular momentum considerations are less important for determining their structure. Since the famous paper by Eggen et al (1962), it has been widely accepted that these pressure-supported components formed through rapid collapse of part of the protocloud, before the formation of the galactic disk. More recently (beginning with Toomre, 1977), an alternative view has emerged, in which the bulge and halo form through mergers and the accretion of satellite systems; these events may occur both before and after the disk matter has settled into centrifugal equilibrium. For example, the disk may form by dissipational collapse within its dark halo, as discussed by Fall and Efstathiou (1980), while the metal weak halo forms from the debris of small satellites accreted during and after the collapse of the disk. See Freeman (1987) for details and references. In this section, I will discuss how the properties of the bulge and halo fit qualitatively into this picture, without attempting to give a balanced account of the relative merits of the monolithic collapse and accretion pictures.

3.1 The accretion of satellites

Quinn and Goodman (1986) have recently made a study of the dynamics of satellites interacting though dynamical friction with the disk of the parent galaxy. Here are some of their results, which we will use in the following discussion:

(1) Satellites with masses of a few percent of the parent disk's mass, and with orbits that come within about 8 scale lengths of the disk center, are captured by dynamical friction in a few dynamical times (somewhat longer for satellites in retrograde orbits).

(2) If the orbits do not come within about 8 scale lengths of the disk center, the satellite survives.

(3) If the orbital inclination of the satellite is less than about 60° to the disk plane, the orbit is dragged down into the plane and then decays radially.

(4) The orbital energy of the satellite goes into heating the parent disk, in R and z. Therefore, if many such accretion events did occur, they must have taken place while the disk was mainly gaseous, to allow the disk to settle down again. The heating of the early partly stellar disk by accretion events is one way to produce a thick disk component.

3.2 The metal-weak halo

In the solar neighborhood, stars with [Fe/H] $\gtrsim -1$ belong to the rapidly rotating disk and thick disk. At [Fe/H] ≈ -1, there is an abrupt discontinuity in rotational velocity: the metal-weaker stars belong to the slowly rotating halo, and there is no rotationally intermediate population. The local density of this metal weak halo is 0.1 to 0.2 percent of the disk. Its density distribution goes approximately as $r^{-3.5}$, its surface density follows the $R^{1/4}$ law with an effective radius of about 2.7 kpc, and its total mass is about 2.10^{9} $M_{\odot}$. The metal weak halo shows no clear abundance gradient or change in rotational velocity with abundance. For references, see Freeman (1987).

The abrupt discontinuity in rotation between the halo and the disks suggests that they do not have a common origin, and thus favors an accretion picture for halo formation over the monolithic collapse.

Although the metal weak halo is in the mean slowly rotating, this does not mean that all metal weak stars are in highly elongated orbits. Recent work by Norris et al (1985) on spectroscopically selected metal weak stars showed that about 25 percent of stars with [Fe/H] < -1.2 have orbital eccentricities less than 0.4. The rotational velocity and velocity dispersion of these low eccenticity metal weak stars are similar to those of the thick disk. In the accretion picture, these stars would be interpreted as the debris of metal weak satellites whose orbits have been dragged down into the galactic plane, and partly circularised, before becoming tidally disrupted.

3.3 The globular cluster system

The galactic globular cluster system shows two components (Zinn, 1985): the metal weak clusters ([Fe/H] < - 0.8 form a slowly rotating spherical halo component, and the clusters with [Fe/H] > - 0.8 lie in a

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more rapidly rotating flattened disk component. The halo clusters show no abundance gradient: however the second parameter effect (an anomalous distribution of stars along the horizontal branch at a given metallicity) increases with galactocentric radius, which suggests that the outer halo clusters formed later and over a longer period. The globular clusters are the oldest known objects in the galaxy, and therefore their formation is particularly interesting. Several formation mechanisms for globular clusters have been proposed.

Searle and Zinn (1978) suggested that the clusters form in small disklike satellite galaxies which are then accreted by the Galaxy. Mass loss from these satellites helps to explain the observed distribution of [Fe/H] for the globular clusters. The second parameter effect fits qualitatively into this picture: star formation can continue longer in the outermost satellites, because their survival time against dynamical friction is longer and has a larger spread.

Rodgers and Paltoglou (1984) made rotation solutions for globular clusters in several intervals of [Fe/H]. For most intervals of [Fe/H] below about - 0.8, the rotational velocity was in the range 40 to 100 km s^{-1}. However, the 30 clusters with -1.3 > [Fe/H] > - 1.7 have an apparent retrograde rotational velocity of - 70 km s^{-1}. The authors noted that globular cluster formation is still occurring now in the Magellanic Clouds, so the disks of such galaxies clearly provide a suitable environment for globular cluster formation. They suggested that the retrograde clusters may have come from a common (and therefore fairly large) parent satellite which was accreted by the Galaxy.

In these accretion pictures, the globular clusters form in satellites, which may be like the Magellanic Clouds or smaller dwarfs of lower abundance. The nuclei of accreted nucleated dwarf ellipticals may also be the source of some of the galactic globular clusters. The globular cluster objects survive the accretion event, more or less intact, because they are relatively dense. The remainder of the accreted satellite becomes part of the field halo of the Galaxy: ie the metal weak halo comes from the debris of pre-formed metal weak satellites. Zinn's (1985) work showed that the disk clusters have [Fe/H] > - 0.8. If the accretion picture is correct, then the absence of metal weak clusters in the disk suggests that these clusters formed in either (1) satellites with orbital inclinations greater than about 60°, such that their orbits are not dragged down into the galactic plane, or (2) relatively fragile satellites, such as the low density nucleated dwarfs (which could not survive orbit decay).

The accretion picture naturally explains the sharp kinematical discontinuity between the disk and the metal weak halo. Some of the coherently moving debris may appear as moving stellar groups in the halo; there is evidence for such halo groups (Eggen, 1979).

Alternatively, Fall and Rees (1985) proposed that clusters form by fragmentation of the collapsing protogalaxy. Thermal instability in the low abundance gas ([Fe/H] < -2) leads to a two phase medium with temperatures of 10^6 K (the virial temperature) and 10^4 K (H-recombination), with a density contrast of about 400. The critical mass for gravitational instability is then about 10^6 $M_\odot$.

3.4 The two-component metal weak halo

Recent work suggests that the metal weak halo may itself be a two component system. Hartwick (preprint) studied the galactic distribution of RR Lyrae stars with [Fe/H] < -1. He found two components: a flattened inner component (R < 8 kpc) with an axial ratio of about 0.6, and a spherical outer component. By comparison with the globular clusters, he inferred that both components are slowly rotating. Therefore the flat component is flatter because its vertical velocity dispersion is smaller. Sommer-Larsen (1986) compared the kinematics of nearby metal weak stars in two abundance intervals: -1.2 > [Fe/H] > -1.5, and [Fe/H] < -1.5. Both groups are slowly rotating and pressure supported. However the first group has a much smaller vertical velocity dispersion σ_z and is therefore more flattened. It is not yet clear whether the two components are characterised by location or abundance or both. Qualitatively, the existence of the two components can readily be understood in the accretion picture. The more massive dwarf galaxies at the present time are more metal rich and have a higher density; see Dekel and Silk (1985) for a summary. If this were also true for satellite systems at the accretion phase, then the more massive satellites would survive their orbit decay (against tidal disruption) further in towards the center of the parent galaxy. Their orbits at the time of disruption would have lower mean inclinations and their debris would therefore have a lower σ_z. In this way, satellite accretion could build up a metal weak halo which, in the inner parts, was somewhat flatter and more metal rich than in the outer parts.

3.5 The bulge

Here are some observed properties of bulges that are relevant to our discussion. For references, see Freeman (1987).

(1) Many disk galaxies do not have bulges. (2) Galaxies with bulges usually have thick disks also. (3) In M31 and the Galaxy, the surface brightness distribution of the bulge follows the $R^{1/4}$ law, with the same effective radius as the halo cluster population. This suggests a dynamical association of the bulge (which is relatively metal rich) and the metal weak halo. (4) On the other hand, the surface photometry of the edge on galaxy NGC 891 (which has a small bulge and is similar to the Galaxy) is nicely represented by the sum of a thin disk and a thick disk. This suggests that the bulge may just be the inner region of the thick disk. (5) Although little is known about the rotation of the Galactic bulge, other bulges rotate rapidly enough to be flattened by rotation. This goes against the association of the bulge and the metal weak halo; however we do not yet know much about the rotation of the inner parts of the metal weak halo, in the same region of the galaxy as the bulge. (6) From their location in the (V/σ - ε) plane, bulges appear to be closely isotropic in (R,z): (Binney, 1982). In this sense,

the bulges are very different from the disks, which have an anisotropy $\sigma_R/\sigma_z \approx 2$ even into their central regions.

The bulges presumably formed by dissipative collapse or by mergers. Some bulges are likely merger products. An example is the edge on SO galaxy IC 4767 (Whitmore and Bell, preprint). Its rapidly rotating bulge shows an extreme peanut- or X-shaped structure which has been nicely modelled by a merger with a satellite on a low inclination orbit (Hernquist and Quinn, in preparation). This galaxy is the extreme example of a sequence of peanut- and box-shaped bulges, which includes the bulges of well-known galaxies like NGC 4565 and the Milky Way. See also Binney and Petrou (1985) for models of peanut bulges.

Work by Jarvis and Freeman (1985) and Rowley (preprint) gives some idea of the present dynamical state of bulges. For the large spheroidal bulges, eg the Sombrero galaxy and NGC 7814, rotating King models are a good fit to the observed distribution of light, rotation and velocity dispersion. The smaller peanut-shaped bulges rotate cylindrically. A distribution function which confines the stars to a region near the direct circular orbit line in the (energy-J_z) plane represents the observed structure and kinematics of these bulges very well. Such a distribution function could result from dissipation of a collapsing system, or from mergers, as in the example of IC 4767 mentioned above. Both kinds of distribution function are isotropic: $\sigma_R = \sigma_z$.

If the bulges of spirals like the Galaxy were produced by mergers, then the merging satellites may have had the following general properties: (1) They were dense enough to survive tidal disruption until they reached the center of the parent galaxy. This is reasonable for the larger disklike satellites, because the mean densities of most disk systems brighter than $M_B \approx -16$ are similar. (2) Bulges are not predominantly metal weak, so the satellites were large enough to have a high enough [Fe/H] value, and survived long enough before the merger to have attained this level of [Fe/H] through chemical evolution. However, the enhanced star formation associated with the merger events is also likely to contribute to the metallicity of the bulges and to their metallicity gradients. (3) The satellites did not live too long before merging, because the galactic disk itself must have been young enough to recover from the merger event(s).

Here are four comments on mergers and bulge formation: (1) Dynamical friction on larger satellites by the dark halo may help to extend the pre-merger timescale, by dragging larger satellites slowly inwards until the dynamical friction by the disk becomes effective. (2) The thick disk may be produced in these early mergers by the heating of the stellar component of the early thin disk; this could explain the observed association of bulges and thick disks. (3) In the inner parts of disk galaxies with bulges, the rotation curves are usually flat, so the peak contributions to the rotation curves from the disk and the bulge are similar. If the bulges form by mergers, then the tidal destruction of bulge-forming satellites, together with the similar characteristic densities of most disk systems, may couple together the dynamics of the inner disk and the virialised bulge, as required. **(4)** In some SO galaxies with prominent bulges, the bulge light is dominated by A and F stars (eg NGC 5102); extensive star formation has been going on recently throughout these bulges, and it may be that they have formed relatively recently. It is possible that some SO systems, which often have large bulges and not very prominent disks, may come from mergers which occurred so late in the life of a disk galaxy that there was not enough gas remaining to re-form a significant disk population.

I am grateful to S.M. Fall and P. Quinn for many helpful discussions.

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