# The Structure and Evolution of the Galaxy

*By* K. C. Freeman
Mount Stromlo and Siding Spring Observatories
The Australian National University
Woden Post Office, ACT 2606, Canberra, Australia

## *Abstract*

The structure and evolution of the Galaxy is discussed, with particular emphasis on the properties of the old disk, the thick disk and the metal weak halo. The dynamics of satellite accretion may be fundamental to understanding the kinematics and structure of the thick disk and halo.

I very much regret that I did not know Strömgren well. I greatly admire his farsighted work on galactic evolution, and the work of those that follow him, and it is a pleasure to give a talk on the structure and evolution of the Galaxy at this meeting in his honor.

Our Galaxy has several major structural components, which I will discuss in turn. They include the thin disk (total mass of about $6.10^{10}$ $M_\odot$), the metal weak halo ($2.10^9$ $M_\odot$), and the thick disk ($4.10^9$ $M_\odot$). There is also the bulge ($5.10^9$ $M_\odot$) and the dark corona ($10^{12}$ $M_\odot$), which I will not discuss here. For recent reviews, see Frogel (1988), Wyse and Gilmore (1988), Strömgren (1987) and Freeman (1987).

## 1. *The Thin Disk*

Near the sun, the star formation rate in the disk has been approximately constant over the last 10 Gyr (Twarog 1980; Miller and Scalo 1979). The older stars, in the mean, have a higher velocity dispersion and a lower chemical abundance [Fe/H]. There are several versions of the age-velocity dispersion relation (AVR) and the age-metallicity relation (AMR): see Strömgren (1987) for recent estimates from evolved F stars. The work of Nissen *et al.* (1985) shows that the AMR has substantial intrinsic scatter; we will return to this subject later. The AVR (eg Wielen 1974) shows a fairly continuous increase of velocity dispersion $\sigma$ with age, which indicates that the disk is evolving dynamically. The dynamical heating process is not yet fully understood. It has been known for many years that an isotropic diffusion process reproduces the observed shape of the AVR and the observed ratio of the vertical component of the velocity dispersion to the planar component (see Fuchs and Wielen 1986). Two-body interactions between stars and giant molecular clouds (GMC's) have long been considered as the primary heating source (Spitzer and Schwarzschild 1951). Recent detailed studies (eg Lacey 1984) show that this mechanism alone is not fully successful in reproducing the shape and the amplitude of the velocity ellipsoid. However, the interaction of a disk of stars and GMC's will be more complex: spiral waves will increase the plane component of $\sigma$, and scattering by GMC's will deflect the stellar orbits out of the plane, increasing the vertical component of $\sigma$. Carlberg (1987) has shown that this process appears to work well in reproducing the shape of the velocity ellipsoid.

An interesting complication in the AVR arises from recent work by Knude *et al.* (1987). For disk stars, the equilibrium ratio of the azimuthal to the radial components of the velocity dispersion, $\sigma_V/\sigma_U$, is $[-B/\ (B-A)]^{1/2} \approx 0.7$, from epicyclic theory, where A and B are the Oort constants. We would expect this ratio to be established on a timescale of a few epicyclic periods, ie a few $\times\ 10^8$ yr. Knude *et al.* studied a sample of evolved F stars at the NGP, with known distances, ages and [Fe/H] between 0.2 and $-0.2$. Their data suggest that $\sigma_V/\sigma_U$ does not reach its equilibrium value for stars younger than about 4 Gyr. Why does it take so long? We can speculate that this effect is associated with the dissolution of aggregates along Lindblad dispersion orbits, for which phase mixing can take much longer than the expected few $\times\ 10^8$ yr.

We now turn to the vertical structure of the thin disk. Optical observations of other galaxies suggested that the vertical density distribution of the disk follows the $\mathrm{sech}^2(z/z_o)$ law, where z is the height above the plane, and $z_o$ is a scalelength which is independent of radius (see van der Kruit and Searle 1981a). This form is dynamically simple; it represents an isothermal sheet. Dust in the galactic plane prevents a definitive test of this law at optical wavelengths for other spiral galaxies. For our Galaxy, star counts (Pritchet 1983) suggest that the vertical density distribution is closer to exponential. Recently Wainscoat *et al.* (1989) have made infrared observations of the edge-on spiral IC 2531, which is structurally fairly similar to our Galaxy. In the K-band, the dust absorption is low, and they find that the vertical structure of this galaxy is very well represented by a simple exponential distribution. This light distribution has now been found by Wainscoat (unpublished) for several other edge-on spirals. This is interesting, because the vertical density profile of the disk represents the sum of components of different age and vertical velocity dispersion, which add together to give the observed exponential light distribution. It means that the star formation rate and the disk heating rate are coupled in a similar way in all these galaxies. This becomes particularly interesting if the mean age of the disk changes with radius, because the coupling is then able to maintain this vertical structure.

As mentioned earlier, the equilibrium value of the ratio $\sigma_V/\sigma_U$ for disk stars is determined from epicyclic theory by the local Oort constants. There is no such constraint on the ratio $\sigma_W/\sigma_U$, where $\sigma_W$ is the vertical velocity dispersion: $\sigma_W$ depends on the local disk heating. However, there is evidence now that $\sigma_W/\sigma_U$ is constant between about 2 kpc and 18 kpc from the galactic center. The argument depends partly on two well observed properties of other disk galaxies: (i) the disks have an exponential radial surface brightness profile $\mu(R) \propto \exp(-R/h_R)$, where $h_R$ is the radial scalelength, and (ii) the vertical scaleheight of the disk is independent of radius (see van der Kruit and Searle 1982). We assume that the mass to light ratio of the luminous matter in the disks is independent of radius, and that most of the mass of the disk is in old stars with velocity dispersion $(\sigma_U,\sigma_V,\sigma_W)$. From the vertical equilibrium of the disk, it then follows that

$$\sigma_W \propto \exp(-R/2h_R) \tag{1}$$

and this has been observed directly in some face-on galaxies (eg van der Kruit and Freeman 1986). Recently Lewis and Freeman (1989) measured the radial component $\sigma_U(R)$ for the old disk of our Galaxy, for $2 < R < 18$ kpc. They found that $\sigma_U$ also follows the law

$$\sigma_U \propto \exp(-R/2h) \tag{2}$$

where $h \approx$ the photometrically determined radial scalelength $h_R$ of the Galaxy. It follows that the ratio $\sigma_W/\sigma_U$ is approximately constant (at about 0.5) over most of the galactic disk. This provides another strong constraint on the theory of disk heating.

Finally, we should consider another problem which will hopefully soon be resolved: the local matter density $\varrho_o$ and the surface density $\Sigma$ of the galactic disk, as determined from the vertical distribution and kinematics of tracer populations (eg F stars, K dwarfs, K giants: see Oort 1965). At this time, the best estimates (Bahcall 1984) are $\varrho_o \approx 0.20\ M_\odot\ pc^{-3}$ (which is about twice the density of known matter near the sun) and $\Sigma \approx 70\ M_\odot\ pc^{-2}$. These estimates are far from definitive, because of deficiences in the tracer samples. Several groups, including a Danish group, are working on this problem with samples that are much better understood, and we should expect results soon. This work is important not only for the problem of local dark matter in the disk but also for understanding the radial equilibrium of the galactic disk. For example, if it turns out that $\Sigma \approx 80\ M_\odot\ pc^{-2}$, then the bulge and the disk together provide most of the local radial gravitational force. On the other hand, if $\Sigma \approx 50\ M_\odot\ pc^{-2}$, then the dark corona dominates the radial forcefield near the sun. Evidence from other galaxies suggests that the disk and bulge probably dominate at locations corresponding to the position of the sun (about $2h_R$ from the galactic center) but this is still contentious (see van Albada and Sansici 1986).

## 2. *The Metal Weak Halo*

The metal weak halo is a slowly rotating component. The kinematics of nearby stars show a fairly abrupt transition at [Fe/H] $\approx -1$, from the rapidly rotating disk (and thick disk: see belov) to the slowly rotating ($V_{rot} \approx 0$) metal weak halo (eg Norris 1986). The halo shows little direct evidence for an abundance gradient or for any dependence of mean rotational velocity on [Fe/H].

At the time of the Eggen, Lynden-Bell and Sandage (1962) paper on the relationship between the abundance and kinematics of halo stars, the metal weak stars ([Fe/H] $< -1$) were kinematically selected and had orbital eccentricities $e > 0.4$; ie they were kinematically members of the spheroidal halo. More recent work on non-kinematically selected samples of metal weak stars shows that about 20 % of stars with [Fe/H] $< -1.2$ have $e < 0.4$ (Norris *et al.* 1985); their mean rotation is high ($V_{rot} \approx 180$ kms$^{-1}$) and their vertical velocity dispersion $\sigma_W \approx 45$ km s$^{-1}$. These kinematical parameters for the metal weak stars with $e < 0.4$ are very similar to those of the thick disk, and it seems that they form a metal weak tail of the thick disk.

The globular clusters of the Galaxy fall into two components (Zinn, 1985): clusters more metal rich than [Fe/H] $\approx -0.8$ belong to a rapidly rotating disklike system with kinematical properties that are again very similar to those of the thick disk (Armandroff 1989), while the more metal poor clusters belong to the slowly rotating halo. The halo clusters show no abundance gradient. However, the second parameter effect (the anomalous distribution of stars along the horizontal branch) increases with increasing galactocentric distance, and suggests that the outer halo clusters formed later and over a longer period (Zinn 1980). It is not clear yet whether the disk clusters and the halo clusters have similar ages.

The formation of globular clusters is not well understood. Fall and Rees (1985) proposed that clusters form by fragmentation of the collapsing protogalaxy. Thermal instability of the low abundance gas leads to a two-phase medium, the two phases having temperatures of about $10^6$ K (the virial temperature) and $10^4$ K (H-recombination) with a density contrast of about 400. The critical mass for gravitational instability of the low temperature phase is about $10^6$ $M_\odot$. Searle and Zinn (1978) suggested that the clusters form in small disklike satellite galaxies which are then accreted by the Galaxy. (We note that globular clusters are forming now in some disklike galaxies, like the LMC, SMC and M33, although not at this time in our Galaxy.) Mass loss from these small satellites helps to explain the observed abundance distribution of the galactic globular clusters.

In the Searle-Zinn picture, the globular clusters form in metal weak satellites such as dwarf irregulars or nucleated dwarf ellipticals, which are then accreted. The globular clusters are dense and can survive the accretion event. However, most of the accreted satellite is disrupted and becomes part of the field halo. We might then expect to see some moving stellar groups in the halo, and there is some limited evidence that such groups do exist (eg Eggen 1979). In this picture for the formation of the metal weak halo, the halo comes from these pre-formed weak satellites, so the kinematics of the halo then depends on the dynamics of sinking and merging satellites. This picture does offer a natural explanation for the striking kinematical discontinuity between the rapidly rotating disk(s) and the non-rotating halo.

Recently Quinn and Goodman (1986) have studied the dynamics of satellites sinking into a parent disk galaxy. Here are their main conclusions:

1) Satellites with masses of a few percent of the parent mass and with orbits that come within about 8 of the parent's scale lengths 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 scalelengths, then the satellite survives. 3) If the orbital inclination of the satellite is less than about 60° to the plane of the parent, then the satellite orbit is dragged down into the plane and then decays radially. 4) The orbit energy goes into heating the parent disk, radially and in z. It follows that, if satellite accretion produced the metal halo, then this accretion must have occurred while the disk was mainly gaseous, to allow the disk to settle down again and form the presently observed thin disk. The heating of the stellar component of the early partly stellar disk could produce the thick disk. In this picture, the thick disk should be very old, ie older than most disk stars.

There is a problem in understanding the shape of the metal weak halo. For metal weak stars, the velocity dispersion in the direction of the SGP is constant, at about 75 km $s^{-1}$, out to distances of about 25 kpc. At lower latitudes, the observed velocity dispersion is in the range 120 to 140 km $s^{-1}$ (Ratnatunga and Freeman 1989). Dynamical models (eg White 1989) then indicate that the halo must be significantly flattened ($c/a \approx 0.5$). On the other hand, most direct indicators (star counts, distributions of RR Lyrae stars and BHB stars and globular clusters) suggest that the halo is nearly spherical (see Freeman 1987 for references). Recent developments, which show that the metal weak halo is not just a simple nonrotating system, may give some insight into this problem.

Hartwick (1986) investigated the galactic distribution of RR Lyrae stars with $[Fe/H] < -1$. To represent their distribution, he found that two components were needed (i) an inner ($R \lesssim 8$ kpc) flattened component, with $c/a \approx 0.6$, and (ii) a spherical outer component. By analogy with the halo globular clusters, he argued that both components are slowly rotating, so the inner component is flattened by its anisotropic velocity distribution. Sommer-Larsen (1986) compared the kinematics of nearby non-kinematically selected metal weak stars in the abundance ranges $-1.2$ to $-1.5$ and $\lesssim -1.5$. Both subsamples have similar values of $\sigma_U$ and $\sigma_V$ and are slowly rotating. However the values of $\sigma_W$ are very different: 59 km $s^{-1}$ for the metal richer subsample and 102 km $s^{-1}$ for the metal poorer stars. Again, this indicates that the metal richer halo stars form a flatter subsystem. These observations suggest that the local kinematics are perhaps dominated by the flatter component, while the star count data on the shape of the halo come mainly from the more spherical component.

However, the situation is not yet satisfactory: the anisotropy ($\sigma_U/\sigma_W > 1$) appears to persist to large values of R,z ($\approx$ 25 kpc), which would not be expected if the spherical component dominates at large distances.

How do these observations fit into the Searle-Zinn/Quinn-Goodman accretion picture? Here are a few comments: 1) Larger satellites are (now) more metal rich and are denser (see Dekel and Silk 1986). They will survive orbit decay (against tidal disruption) to smaller galactocentric radii, and their orbits at destruction will have lower inclinations and their debris will have lower $\sigma_W$. The debris from these larger satellites would contribute to an inner, flatter, metal richer population within the metal weak halo. 2) The disk globular clusters are metal rich ([Fe/H] $\gtrsim -0.8$). The absence of metal weak *disk* clusters suggests, in the accretion picture, that the metal weak clusters formed in fragile satellites (which could not survive orbit decay), rather than in larger more robust satellites. Nucleated dwarf ellipticals would seem to be attractive candidates for the formation sites of metal weak clusters: their dense nuclei would survive the accretion event, as present day globular clusters, while the fragile envelope would be disrupted to become part of the metal weak field halo. 3) The second parameter effect (the outer clusters formed later and over a longer period of time than the inner clusters) is also readily understood in the accretion picture. The theory shows that the outer clusters survive longer and have a larger spread in survival time.

## 3. *The Thick Disk*

The vertical density distribution of pure disk galaxies has the sech$^2$ or exponential form described above. The disks of galaxies with small bulges show extra light in a thick disk distribution for z $\gtrsim$ 1 kpc, in excess of that expected from the thin disk alone. This thick disk was first observed photometrically in other galaxies by Burstein (1979), and then in more detail by van der Kruit and Searle (1981b), and was identified in our Galaxy from star counts by Gilmore and Reid (1983). We will see that this thick disk is kinematically quite distinct from the metal weak halo (which would make a negligible contribution to the surface brightness of our Galaxy if it were seen edge-on from outside).

Stars of the galactic thick disk have now been identified *in situ* in several fields (see Freeman 1987 for references). The mean abundance of the thick disk stars is about $-0.7$, with a dispersion of about 0.3. The vertical velocity dispersion $\sigma_W$ is about 40 kms$^{-1}$, and its scaleheight is about 1 kpc. In [Fe/H] and $\sigma_W$, the thick disk is intermediate between the thin disk and the metal weak halo, and in this sense it is an intermediate population. However, its rotation is almost as rapid as that of the thin disk: the asymmetric drift is in the range 30 to 50 kms$^{-1}$, so the thick disk is close to centrifugal equilibrium, with somewhat more internal energy than the thin disk. This intermediate population was of particular interest to Strömgren; it holds many clues to the formation of the Galaxy, as he saw long ago.

The vertical structure, kinematics and chemical properties of the thick disk are fairly similar to those of the Zinn/Armandroff population of disk globular clusters. It may be that the stellar thick disk, as defined by stars with [Fe/H] $\approx -0.7$, is a little younger: see Schuster and Nissen (1987) and Norris and Green (1989). However, Nissen *et al.* (1985) have shown that the age-metallicity relation for nearby stars has a large intrinsic spread, and in particular that there are very old stars (ages $\gtrsim$ 12 Gyr) at all abundances in the range $0 >$ [Fe/H] $> -1$. If accretion is important in forming the thick disk, we would expect that the stars of the thick disk are as old or older than the oldest stars of the thin disk, and it would be very interesting to know whether this is true.

There is some evidence that the galactic thick disk may not extend much beyond about 10 kpc from the galactic center. Ratnatunga and Freeman (1989) found thick disk stars *in situ* out to galactocentric distances r of about 10 kpc in their survey at $l = 270°$, $b = 39°$. Friel's (1988) survey at $l = 194°$, $b = -49°$ showed no stars with thick disk kinematics, although many thick disk stars were discovered in her survey at $l = 36°$, $b = 55°$. Armandoff's (1989) compilation of disk globular clusters has no clusters with $r \gtrsim 8$ kpc. This apparent limited extent of the thick disk has a direct and interesting implication for the epoch of satellite accretion, if the thick disk was indeed formed by heating of the stellar component of the early thin disk by accretion of satellites. It suggests that, by the end of the epoch of accretion, star formation in the early thin disk had not progressed much beyond about 10 kpc.

There is some controversy now about the nature of the thick disk: is it a discrete component, or is it just the high energy, low abundance tail of the thin disk (see Freeman 1987 for references). My view is that it is probably discrete. We know that not all disk galaxies have thick disks; there is an apparent association of bulges and thick disks, which suggests that the thick disk does not come from the normal secular evolution of the thin disk. Also, the velocity dispersion – abundance relation as given by Strömgren (1987) shows an abrupt rise in $\sigma_W$ at [Fe/H] $\approx -0.7$, from values of about 20 to 25 km s$^{-1}$ (which we would associate with the old thin disk) to about 40 kms$^{-1}$ (which is the characteristic thick disk value). This is a serious question, because the thick disk surely provides some of the potentially most useful clues to understanding the early formation events of our Galaxy, and it is important that we establish observationally whether or not it is a discrete component. This will probably be settled by careful derivation of the local AVR and AMR, to which Strömgren's large F-star program is very well suited.

## References

Armandroff, T. 1989. *Astron. J.,* **97**, 375.
Bahcall, J. 1984. *Astrophys. J.,* **287**, 926.
Burstein, D. 1979. *Astrophys. J.,* **234**, 829.
Carlberg, R. 1987. *Astrophys. J.,* **322**, 59.
Dekel, A., Silk, J. 1986. *Astrophys. J.,* **303**, 39.
Eggen, O. 1979. *Astrophys. J.,* **229**, 158.
Eggen, O., Lynden-Bell, D., Sandage, A. 1962. *Astrophys. J.,* **136**, 748.
Fall, S. M., Rees, M. 1985. *Astrophys. J.,* **298**, 18.
Freeman, K. 1987. *Ann. Rev. Astron. Astrophys.,* **25**, 603.
Friel, E. 1988. *Astron. J.,* **95**, 1727.
Frogel, J. 1988. *Ann. Rev. Astron. Astrophys.,* **26**, 51.
Fuchs, B., Wielen, R. 1986. In *The Galaxy,* ed. Gilmore, G., Carswell, R. (Dordrecht: Reidel), p. 375.
Gilmore, G., Reid, N. 1983. *M.N.R.A.S.,* **202**, 1025.
Hartwick, F. D. A., 1986. In *The Galaxy,* ed. Gilmore, G., Carswell, R. (Dordrecht: Reidel), p. 281.
Knude, J., Schnedler Nielsen, H., Winther, M. 1987. *Astron. Astrophys.,* **179**, 115.
Lacey, C. 1984. *M.N.R.A.S.,* **208**, 687.
Lewis, J., Freeman, K. 1989. *Astron. J.,* **97**, 139.
Miller, G., Scalo, J. 1979. *Astrophys. J. Suppl.,* **41**, 513.
Nissen, P.E., Edvardsson, B., Gustafsson, B. 1985. In *ESO Workshop on Production and Distribution of C,N,O Elements,* ed. Danziger, I., Matteucci, K., Kjär, K (Garching: ESO), p. 131.
Norris, J. 1986. *Astrophys. J. Suppl.,* **61**, 667.
Norris, J., Bessell, M., Pickles, A. 1985. *Astrophys. J. Suppl.* **58**, 463.
Norris, J., Green, E. 1989. *Astrophys. J.,* **337**, 272.
Oort, J. 1965. In *Galactic Structure (Stars and Stellar Systems* Vol 5), ed. Blaauw, A., Schmidt, M. (Chicago: Univ. Chicago Press), p. 455.
Pritchet, C. 1983. *Astron. J.,* **88**, 1476.
Quinn, P., Goodman, J. 1986. *Astrophys. J.,* **309**, 472.
Ratnatunga, K., Freeman, K. 1989. *Astrophys. J.,* **339**, 126.
Schuster, W., Nissen, P.E. 1987. In *Stellar Evolution and Dynamics in the Outer Halo of the Galaxy,* ed. Azzopardi, M., Matteucci, F. (Garching: ESO), p. 141.
Searle, L., Zinn, R. 1978. *Astrophys. J.,* **225**, 357.
Sommer-Larsen, J. 1986. Licentiate thesis, Copenhagen University.
Spitzer, L., Schwarzschild, M. 1951. *Astrophys. J.,* **114**, 385.
Strömgren, B. 1987. In *The Galaxy,* ed. Gilmore, G., Carswell, R. (Dordrecht: Reidel), p. 229.
Twarog, B. 1980. Astrophys. J. Suppl., **44**, 1.
van Albada, T., Sansici, R. 1986. *Phil. Trans. Roy. Soc. Lond.,* **A 320**, 447.
van der Kruit, P., Freeman, K. 1986. *Astrophys. J.,* **303**, 556.
van der Kruit, P., Searle, L. 1981a. *Astron. Astrophys.,* **95**, 105.
van der Kruit, P., Searle, L. 1981b. *Astron. Astrophys.,* **95**, 116.
van der Kruit, P., Searle, L. 1982. *Astron. Astrophys.,* **110**, 61.
Wainscoat, R., Freeman, K., Hyland, A. R. 1989. *Astrophys. J.,* **337**, 163.
White, S. 1989. *M.N.R.A.S.,* **237**, 51P.
Wielen, R. 1974. in *Highlights of Astronomy,* ed. Contopoulos, G. (Dordrecht: Reidel), **3**, 395.
Wyse, R., Gilmore, G. 1988. *Astron. J.,* **95**, 1404.
Zinn, R. 1980. *Astrophys. J.,* **241**, 602.
Zinn, R. 1985. *Astrophys. J.,* **293**, 424.