THE DISK OF THE GALAXY

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ABSTRACT. In this review, I will concentrate on the observational aspects of the dynamical evolution of the disk population. First I will discuss some general properties of disks, such as their structure and kinematics and the thick disks. The next section is on the kinematical properties of the galactic disk near the sun, including some important new results on the age-velocity dispersion relation and the age-metallicity relation. Finally I will discuss some properties of the galactic thick disk. Two important questions, chemical gradients and dark matter in the disk, could not be included in this review.

1. The Structure and Kinematics of Disks

1.1. THE STRUCTURE OF DISKS

For a sample of edge-on galaxies, van der Kruit and Searle (1981,1982) showed that the light distribution has the form $L(R,z) = L_{\circ}e^{-R/h}\text{sech}^2(z/z_{\circ})$. The scale height $z_{\circ}$ is typically about 700 pc, and is independent of radius. This $L(R,z)$ brightness distribution is truncated at about 4 to 5 radial scalelengths. A surface density distribution of this form represents a locally isothermal sheet (ie the vertical velocity dispersion σ_z is independent of z) with ${\sigma_z}^2 = 2\pi G\rho_{\circ}{z_{\circ}}^2$. For $z \gg z_{\circ}$, $\text{sech}^2(z/z_{\circ}) \rightarrow \exp(-2z/z_{\circ})$.

Galactic dust is a problem in determining the form of L(R,z) near the plane of external galaxies. In our Galaxy, star counts towards the galactic poles (Gilmore and Reid 1983; Pritchet 1983) indicate that the z-distribution more nearly exponential, with a scaleheight of about 300 pc. The effects of dust in external galaxies can be greatly reduced by infrared observations, and 2.2μ surface photometry of edge-on galaxies also shows that the vertical surface brightness distribution in disks is nearly exponential (eg Wainscoat *et al.* 1989). Such a vertically exponential disk is not locally isothermal; the velocity dispersion increases by a factor $\sqrt{2}$ from its value at z = 0 to the asymptotic value at large z. New observations of the vertical velocity dispersion for K giants near the SGP (Flynn and Freeman, preprint) show that the old disk *is* indeed isothermal up to at least 450 pc above the plane. There is no inconsistency here; it just means that the colder young disk and the hotter old disk together produce the observed vertical exponential density distribution.

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1.2. THE VELOCITY DISPERSION OF DISKS

The vertical velocity dispersion of the constant scaleheight van der Kruit and Searle disks is given by hydrostatic equilibrium as $\sigma_z(R) \propto \exp(-R/2h)$. This is observed directly in a few face-on spirals (*e.g.* van der Kruit and Freeman 1986). Then, *if* the anisotropy σ_R/σ_z is approximately constant with radius, we would expect that $\sigma_R(R)$ is also $\propto \exp(-R/2h)$. In the Galaxy, σ_R would then rise to about 100 km s^{-1} near the center of the disk.

It is difficult to measure $\sigma_R(R)$ in the disks of external galaxies (see however Bottema 1988). In the Galaxy, $\sigma_R(R)$ can be measured directly, using velocities of individual stars. Lewis and Freeman (1989) measured velocities for about 600 K giants of the old disk, out to about 18 kpc from the galactic center. The variation of σ_R with R follows closely the expected exponential law given above; in the inner parts of the disk, σ_R is about 110 km s^{-1} and the stability parameter Q is roughly constant with radius, in the range 1.5 to 2. The kinematically determined scalelength $h = 4.4 \pm 0.3$ kpc, which is close to the mean scalelength determined directly from the distribution of various kinds of objects (de Vaucouleurs and Pence, 1978; van der Kruit, 1986; Habing 1988). From the above equations, it follows that the anisotropy σ_R/σ_z is indeed approximately constant with radius. This result means that the processes which heat the disk in the radial and vertical directions keep the ratio σ_R/σ_z approximately constant (≈ 2), despite the large variation in density and velocity dispersion over the observed range in radius. The reason for this is not yet fully understood: see Carlberg (1987), Wielen and Fuchs (1988).

To summarize: the kinematics of galactic disks show that σ_R and $\sigma_z \propto \exp(-R/2h)$, as expected. The disk heating processes lead to constant scaleheight with radius, and constant anisotropy σ_R/σ_z.

1.3. THICK DISKS

Following the early work on the thick disk component of disk galaxies (Tsikoudi 1979, 1980; Burstein 1979), van der Kruit and Searle (1981,1982) showed that some edge-on galaxies with bulges have a *second* flattened component, the thick disk, in addition to the usual thin disk. Star counts by Gilmore and Reid (1983), confirmed by Yoshii *et al.* (1987), showed that the Galaxy also has a thick disk, with scale height of about 1000 pc and column density of order 10 percent of that of the thin disk.

The thick disk raises some interesting questions about its origin and its implications for galaxy formation:

- Are thick disks found only in galaxies with significant central bulges ? Some disk galaxies do not have thick disks (eg van der Kruit and Searle, 1981, 1982), so thick disk formation is not an essential part of the formation and evolution of disk galaxies.
- Are thick disks in rotational equilibrium, like thin disks (in which case they could have come from heated thin disks) or are they more slowly rotating (as if they were an intermediate population formed during the collapse) ?
- How old are the stars of the thick disk ? Did the thick disk form very early in the life of the parent galaxy (like the metal-weak halo) or later (like much of the thin disk) ?

Observations of stellar kinematics in the Galaxy are needed to understand the nature of the thick disk, because such measurements cannot be made yet for external galaxies. The next section is on the relationships between the kinematics of nearby stars (including thick disk stars) and their ages and metallicities. Here are two preliminary points about the thick disk near the sun, which will be useful in interpreting the kinematics of the nearby stars:

1. Yoss *et al.* (1987) showed that there is a population of G and K giants at the galactic poles in the metallicity range $-0.5 >$ [Fe/H] > -1 with a vertical velocity dispersion of about 40

km s^{-1} and therefore a scaleheight of about 1000 pc. This identifies the metallicity range in which most of the nearby thick disk stars are found.

2. Many stars in this metallicity range are included in the study of nearby high proper motion stars by Laird *et al.* (1988). These stars belong to a rapidly rotating population, with an asymmetric drift less than 50 km s^{-1}. From their color distribution, these stars appear to be as old as the disk globular clusters.

There will be more discussion of the galactic thick disk in §3.

2. The Nearby Disk

The chemical and kinematical properties of nearby disk stars depend on their age. The older disk stars have lower metallicities in the mean, which reflects the chemical evolution of the Galaxy, although the details are not fully understood. This age-metallicity relation (AMR) is usually presented as a fairly smooth relationship between the mean metallicity and the age (eg Strömgren 1987). The velocity dispersion σ of nearby stars increases with stellar age. This is believed to result from heating of the disk by interactions of disk stars with spiral arms, giant molecular clouds, and possibly massive black holes in the galactic halo. The age - velocity dispersion relation (AVR) is usually presented as a smooth increase of the velocity dispersion with stellar age: see Wielen (1977). However, for solar abundance stars, Strömgren's (1987) Table 1 shows that the velocity dispersion does not change much between ages of about 4 to 13 Gyr, which indicates that the dynamical heating may saturate at some level.

A new kinematically unbiased sample of nearby F stars (Edvardsson *et al.* 1991), with very precise ages, velocities and metallicities, shows that there is significant structure in the age - σ - [Fe/H] relations. See Nissen (1990) for a preliminary report. Here are some of the important results:

- The age - metallicity relation: Figure 1 shows that the AMR is broad. The younger stars (age < 3 Gyr) have higher mean metallicity and the older stars (age > 10 Gyr) have lower mean metallicity, as previously recognized. However, the stars with ages between 3 and 10 Gyr cover the entire [Fe/H] range from +0.2 to -0.6, with no obvious trend of metallicity with age.
- The age - velocity relation show three age zones:
  1. The youngest stars, with ages < 3 Gyr, have a low velocity dispersion, $\sigma_W = 10 \pm 1$ km s^{-1}.
  2. For ages between 3 and 10 Gyr, $\sigma_W = 19 \pm 2$ km s^{-1}, ***with no trend of velocity dispersion with age***. These stars have [Fe/H] in the range +0.2 to -0.6 and represent the old disk.
  3. The oldest stars, with ages > 10 Gyr, have $\sigma_W = 42 \pm 3$ km s^{-1}. These old stars have [Fe/H] values mostly below -0.5, so their velocity dispersion and metallicities indicate that they belong to the thick disk; this velocity dispersion corresponds to a scaleheight of about 1 kpc.

The other two velocity components show similar structure. See Freeman (1991) for a more detailed discussion of this age - velocity dispersion relation.

The Edvardsson *et al.* data suggest that:

- thin disk heating saturates after about 3 Gyr, at $\sigma_W \approx 20$ km s^{-1}, because the velocity dispersion does not increase between ages of 3 and 10 Gyr (see also Carlberg *et al.* 1985; Strömgren 1987, Table 1).
- The thick disk is very old, because the characteristic metallicity range and velocity dispersion of the thick disk are seen only among the stars older than 10 Gyr.
- the energy of the thick disk ($\sigma_W \approx 40$ km s^{-1}) does not come from the processes that heat the thin disk, which appear to saturate at about 20 km s^{-1}. Its velocity dispersion must come from some other kind of process.

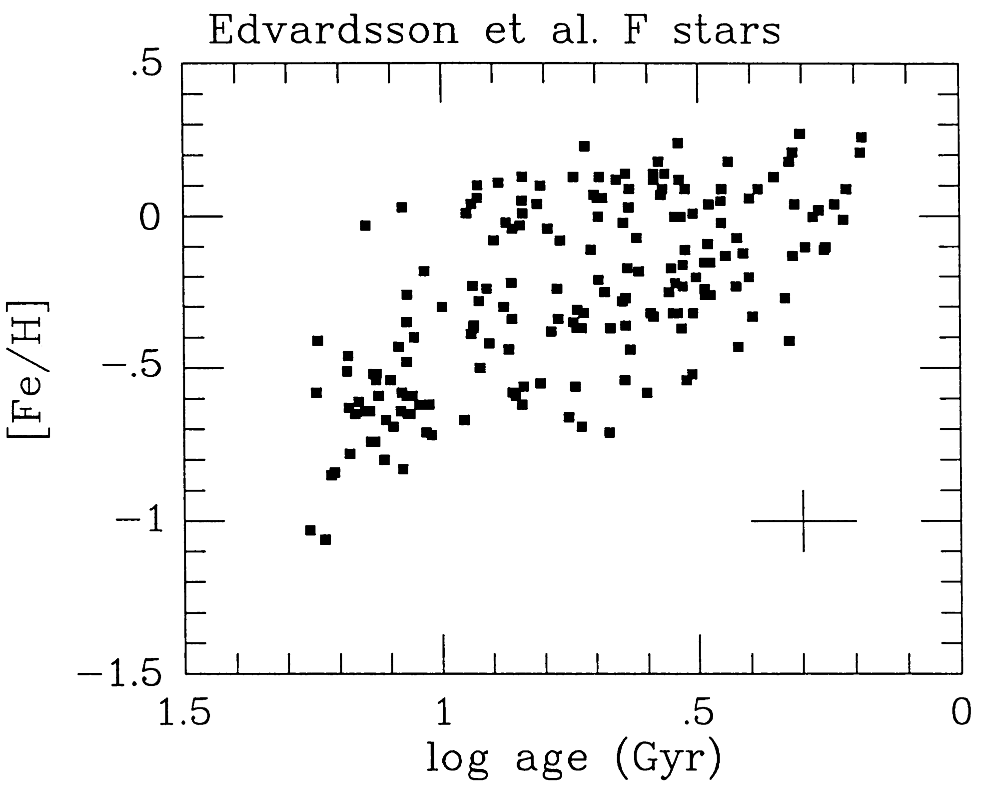

Figure 1:–The metallicity - age distribution for the Edvardsson *et al.* (1991) F stars. The error bars are shown in the lower right corner. Note the large spread in metallicity for stars with ages between about 3 and 10 Gyr.

This new F star sample shows that there is a homogeneous old disk population with stellar ages between about 3 and 10 Gyr, [Fe/H] between +0.2 and -0.6, and $\sigma_W \approx 20$ km s^{-1}. This old disk population shows no obvious internal correlations of velocity dispersion, abundance and age. The interesting point here is that the old disk near the sun is not just some mean point on the AVR and AMR, but is in fact a well defined and homogeneous population in which there is little evidence for dynamical and chemical evolution.

How do we reconcile the well-known correlations between age, velocity dispersion and metallicity with the picture given by the new F star data ?

1. The correlation of velocity dispersion with metallicity comes primarily from the young stars (ages $<$ 3 Gyr) of high [Fe/H] and the old (ages $>$ 10 Gyr) thick disk stars of lower [Fe/H]. There is no trend of velocity dispersion with metallicity for stars in the 3 to 10 Gyr (old disk) interval.

2. The AVR given by the new F star data, which suggest the thin disk - old disk - thick disk structure described above, is rather different from the usual smooth version of the solar neighborhood AVR. It seems likely that the high internal precision of the new F star ages (± 0.1 in log age) from Strömgren photometry reveals this structure. The ages used for the older AVR determinations come mostly from less direct methods (Ca II emission and mean main sequence lifetimes) which may have somewhat larger errors that smooth out the structure in the AVR.
3. The age - metallicity relation shown in Figure 1 is intrinsically quite broad, and shows little trend between ages of 3 and 10 Gyr. The trends usually associated with the AMR are again produced mainly by the presence of the relatively metal rich stars younger than 3 Gyr and the relatively metal poor (thick disk) stars older than 10 Gyr.

What does the breadth of the AMR imply about the chemical evolution of the thin disk ? We see from Figure 1 that the younger stars are metal rich and have a relatively small spread in metallicity. These young stars have a smaller velocity dispersion, so they come from a relatively small region of the Galaxy. The older stars of the thin disk (the 3 to 10 Gyr sample) have a larger velocity dispersion and include objects that were born anywhere in a broad annular region that extends right around the Galaxy; their metallicity distribution is an average over this annulus. It appears that (i) chemical enrichment is rather inhomogeneous, as Nissen *et al.* (1985) suggest, and (ii) the younger F stars in the solar neighborhood come from a region that just happens to have relatively high metallicity. The metallicity of the younger stars is not exceptionally high; the sample includes some much older stars with similarly high metallicities.

In summary, this new sample of F stars suggests that the well known trends of age, metallicity and velocity dispersion among disk stars are produced primarily by stars younger than 3 Gyr and older than 10 Gyr. Stars with ages between 3 and 10 Gyr come from a homogeneous old disk population which shows no such trends.

The F stars in the Edvardsson *et al.* sample were older than about 1 Gyr. Wilson (1990) has recently measured the kinematics and abundances for a sample of about 500 nearby K giants, which includes some younger objects. For solar neighborhood F stars with ages < 1 Gyr, the (U,V) velocity distribution is quite clumpy (Eggen, 1969); it is dominated by two major clumps which represent the Hyades and Sirius moving groups in the solar neighborhood. These groups are believed to come from dissolving giant molecular clouds or spiral arm segments. Unbound aggregates in the galactic disk dissolve along precessing ellipses (the Lindblad dispersion orbits). From the dispersion orbits for the Hyades and Sirius groups, Wilson calculated the expected radial velocities of stars on these dispersion orbits away from the solar neighborhood. He then tested this dispersion orbit picture by observing about 500 disk K giants out to about 1 kpc from the sun, in the predicted direction of the dispersion orbits ($l = 270 \pm 30°$). The ages of the Hyades and Sirius group stars are only a few galactic years so, from the discussion of the Edvardsson *et al.* F stars, we would expect to see evidence for their dispersion orbits only among the more metal rich stars. It turned out that the dispersion orbits are seen very clearly for stars with metallicities [Fe/H]$>$ -0.25, and not for more metal weak stars.

Wilson's sample covers the metallicity range $0.3 >$ [Fe/H]> -1. The distribution of stars with [Fe/H]> -0.25 is dominated by the groups. In the (V component of velocity) - metallicity plane shown in Figure 2, this population, which has an age of a few galactic years, is obviously unmixed. For the more metal weak stars, the populations are similar to those seen in the Edvardsson *et al.* sample. Stars with $-0.3 >$ [Fe/H]> -0.6 belong to the old disk, with velocity dispersion $\sigma_V = 27 \pm 1$ km s^{-1} and asymmetric drift 8 ± 2 km s^{-1}. The K giants with [Fe/H]< -0.6 belong to the thick disk, with $\sigma_V = 38 \pm 4$ km s^{-1} and asymmetric drift 27 ± 5 km s^{-1}.

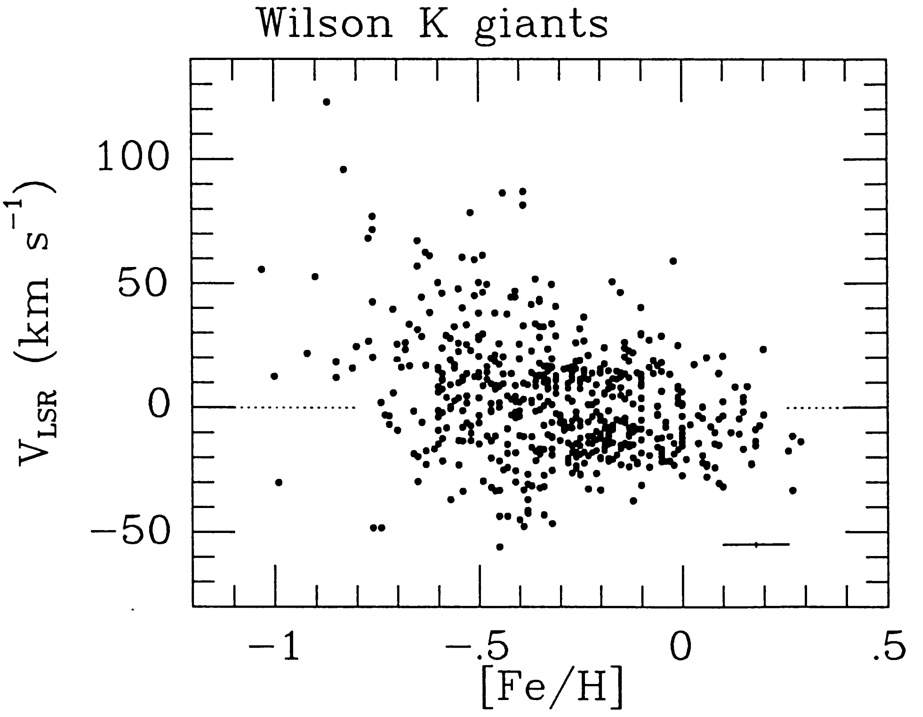

Figure 2:–The metallicity - velocity relation for Wilson's K giants. V_{LSR} is the V-component of the stellar velocity relative to the local standard of rest. (Here V is positive towards $l = 270°$). For [Fe/H] > -0.25, the distribution is dominated by the two velocity clumps which correspond to the young Hyades and Sirius moving groups. These stars are obviously unmixed dynamically. Stars with $-0.3 >$ [Fe/H] > -0.6 belong to the old disk. Stars with [Fe/H] < -0.6 are predominantly thick disk objects, with a larger velocity dispersion and asymmetric drift. Error bars are shown in the lower right-hand corner.

3. The Galactic Thick Disk

In this section, I return to the questions of the age and rotation of thick disks, which can be measured only for the galactic thick disk; even there the situation is not entirely clear. I also discuss the discreteness of the thick disk, and then the recently discovered metal-weak extension of the galactic thick disk, which may have some interesting implications for the early history of the Galaxy.

3.1. THE ROTATION AND AGE OF THE THICK DISK.

The kinematical properties of the galactic thick disk can be measured from observations of stars with metallicities between about −0.6 and −1.0. For these stars, the vertical velocity dispersion is about 40 km s^{-1} and their scaleheight is therefore about 1 kpc. In the solar neighborhood, there are many estimates of the mean rotation of the thick disk: see Sandage and Fouts (1987), Norris (1987), Laird *et al.* (1988), among others. There are also several studies of the kinematics of the thick disk *in situ*: *e.g.* Yoss *et al.* (1987), Friel (1988), Ratnatunga and Freeman (1989), and Armandroff (1989). The solar neighborhood and the *in situ* data give similar results for the velocity dispersion and asymmetric drift of the thick disk. The radial component of its velocity dispersion is about 65 km s^{-1} and the asymmetric drift is about 30 km s^{-1} relative to the LSR. The thick disk is clearly a rapidly rotating population.

Most recent work indicates that the thick disk near the sun is very old, *i.e.* at least as old as the disk globular clusters. See for example the work of Edvardsson *et al.* discussed above and also Nissen (1990) for the nearby F stars, Rose and Agostinho (1991) for more distant F stars, and Gilmore *et al.* (1989) and Carney *et al.* (1989) for age estimates from nearby high proper motion stars. For an alternative view, see Norris and Green (1989).

3.2. THE DISCRETENESS OF THE THICK DISK.

Is the thick disk a separate component of the Galaxy, or just the higher energy, metal weaker tail of the old disk. This problem has been widely and inconclusively discussed (see Freeman 1987; Gilmore *et al.* 1989). It remains important because it has obvious implications about galaxy formation and the origin of the thick disk. For example, did the stars of the thick disk form during galactic collapse, before thin disk star formation had started ? Or did the thick disk form after thin disk formation was already under way ?

In the second category of formation pictures, we can consider some specific possibilities:

1. The stars that we now recognize as members of the thick disk were the first stars to form in the early thin disk, and have therefore suffered the most heating by the same processes that continue to heat the thin disk to the present time. This picture, in which the thick disk is not a discrete component, now seems unlikely from the discussion in §2, which indicates that the heating of the thin disk saturates when σ_W reaches about 20 km s^{-1}. (We recall that $\sigma_W \approx 40$ km s^{-1} for the thick disk).
2. The stars that are now in the thick disk formed early in the life of the disk, and were heated by some short-lived phenomenon, such as a transient bar or strong spiral structure in the early disk, or by an early epoch of satellite accretion (see Freeman 1990 for more discussion of this possibility). In this case, the thick disk would be a discrete component, with some interesting information content about the early Galaxy.

We do not not yet understand how the thick disk fits into the galaxy formation picture. However thick disks are clearly not an essential feature of the formation and subsequent evolution of disk galaxies, because many disk galaxies do not have thick disks.

3.3. THE METAL-WEAK THICK DISK.

Norris *et al.* (1985) showed that a significant fraction of spectroscopically selected metal weak stars near the sun have kinematics like the thick disk, although their metallicities are in the range usually associated with the slowly rotating metal-weak halo of the Galaxy ([Fe/H]< -1). Morrison *et al.* (1990) then investigated the kinematics of spectroscopically selected G and K giants near the sun and also in a more distant field at about the same galactocentric radius. Their most metal weak stars, with [Fe/H]< -1.6, clearly belong to the slowly rotating halo.

Stars in the metallicity range −1.0 to −1.6 and with $|z| > 1$ kpc are also slowly rotating. However, in the same metallicity range, the stars near the galactic plane with $|z| < 1$ kpc include a rapidly rotating disk component with an asymmetric drift of 50 ± 15 km s^{-1} and velocity dispersion $\sigma_W = 40 \pm 13$ km s^{-1}; its density is comparable to that of the metal weak halo. This confirms the result by Norris *et al.* that the thick disk extends in metallicity to [Fe/H] ≈ -1.6.

The metal weak extension of the thick disk is not so evident in the RR Lyrae stars, although it is clearly seen among the G and K giants. The implications of this observation are not clear. One possibility is that the metal weak thick disk may be somewhat younger than the rest of the thick disk. For example, the metal weak thick disk stars may be the debris of younger metal weak satellites accreted towards the end of the satellite accretion phase. We note that the entire mass of the metal weak extension of the thick disk is only of order 10^8 $M_\odot$.

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References

Armandroff, T. 1989. Astron.J., **97**, 375.
Bottema, R. 1988. Astron.Astrophys., **197**, 105.
Burstein, D. 1979. Astrophys.J., **234**, 829.
Carlberg, R. 1987. Astrophys.J., **322**, 59.
Carlberg, R., Dawson, P., Hsu, T., VandenBerg, D. 1985. Astrophys.J., **294**, 674.
Carney, B., Latham, D., Laird, J. 1989. Astron.J., **97**, 423.
de Vaucouleurs, G., Pence, W. 1978. Astron.J., **83**, 1163.
Edvardsson, B., Gustafsson, B., Lambert, D., Nissen, P., Tomkin, J., Andersen, J. 1991. In preparation.
Eggen, O.J. 1969. Astrophys.J., **155**, 701.
Freeman, K.C. 1987. Ann.Rev.Astron.Astrophys., **25**, 603.
Freeman, K.C. 1990. In *Dynamics and Interactions of Galaxies*, ed R. Wielen, (Springer), p. 36.
Freeman, K.C. 1991. In *Dynamics of Disk Galaxies*, ed B. Sundelius, (University of Goteborg), in press.
Friel, E.D. 1988. Astron.J., **95**, 1727.
Gilmore, G., Reid, N. 1983. Mon.Not.R.Astron.Soc., **202**, 1025.
Gilmore, G., Wyse, R., Kuijken, K., 1989. Ann.Rev.Astron.Astrophys., **27**, 555.
Habing, H. 1988. Astron.Astrophys., **200**, 40
Laird, J., Carney, B., Latham, D. 1988. Astron.J., **95**, 1843.
Lewis, J.R., Freeman, K.C. 1989. Astron.J., **97**, 139.
Morrison, H.L., Flynn, C., Freeman, K.C. 1990. Astron.J., **100**, 1191.
Nissen, P. 1990. In *Elements and the Cosmos*, ed R. Terlevich, (Cambridge: Cambridge University Press).
Nissen, P., Edvardsson, B., Gustafsson, B. 1985. In *Production and Distribution of C,N,O Elements*, ed I. Danziger *et al.* , (ESO), p. 131.
Norris, J.E. 1987. Astrophys.J., **314**, L39.
Norris, J.E., Bessell, M.F., Pickles, A. 1985. Astrophys.J.Suppl., **58**, 463.
Norris, J.E., Green, E.M. 1989. Astrophys.J., **337**, 272.

Pritchet, C. 1983. Astron.J., **88**, 1476.
Ratnatunga, K., Freeman, K.C. 1989. Astrophys.J., **339**, 126.
Rose, J., Agostinho, R. 1991. Astron.J., **101**, 950.
Sandage, A., Fouts, G. 1987. Astron.J., **92**, 74.
Strömgren, B. 1987. In *The Galaxy*, ed G. Gilmore and R. Carswell, (Dordrecht: Reidel), p. 229.
Tsikoudi, V. 1979. Astrophys.J., **234**, 842.
Tsikoudi, V. 1980. Astrophys.J.Suppl., **43**, 365.
van der Kruit, P.C. 1986. Astron.Astrophys., **157**, 230.
van der Kruit, P.C., Freeman, K.C. 1986. Astrophys.J., **303**, 556.
van der Kruit, P.C., Searle L. 1981. Astron.Astrophys., **95**, 105, 116.
van der Kruit, P.C., Searle L. 1982. Astron.Astrophys., **110**, 61, 79.
Wainscoat, R., Freeman, K.C.,, Hyland, A.R. 1989. Astrophys.J., **337**, 163.
Wielen, R. 1977. Astron.Astrophys., **60**, 263.
Wielen, R., Fuchs, B. 1988. In *The Outer Galaxy*, ed L. Blitz and F. Lockman, (Springer), p. 100.
Wilson, G.A. 1990. Thesis, Australian National University.
Yoshii, Y., Ishida, K., Stobie, R.S. 1987. Astron.J., **93**, 323.
Yoss, K., Neese, C., Hartkopf, W. 1987. Astron.J., **94**, 1600.

Discussion

Ellis: You commented that thick disks are not universal and therefore that they are not an essential feature of galaxy evolution. If, however, mergers are a common feature of galaxy evolution, then one would expect at least a major subset (say 50 percent) of luminous disk galaxies to have thick disks. Can you rule this out ?
Freeman: No, not at this stage. However, if mergers are a common feature of galaxy evolution, then the present frequency of thick disks would depend on the evolutionary phase at which the merging occurred. For example, if almost all the merging occurred while the fragments were almost entirely gaseous, then stellar thick disks need not be very common now. Conversely, it appears that thick disks typically contribute less than 10 percent of the light of the thin disk in large spirals; this means that there cannot have been much merger activity after the first one or two Gyr of star formation had taken place in the thin disk. Quinn, Hernquist and Fullagar (preprint) show that any such post-thin-disk accretion is limited to a few percent of the mass of the thin disk.
Carney: In a binary system, tidal effects act to turn eccentric orbits into circular ones, with close pairs affected most strongly. Thus the period at which the break between circular and eccentric orbits occurs is a chronometer. In the Hyades, this is 5.7 days, and in M67 it is 10.5 days. The survey of proper motion stars which Dave Latham, John Laird and I have been studying shows the transition at about 20 days in the halo and roughly the same for the thick disk stars. So star formation in both started at about the same time. But who knows where ?
Carney: Do you have an idea of the thick disk's scale length ?
Freeman: No; at this time there are arguments for the thick disk having a longer scale length than the thin disk, and also for a shorter scale length.

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