STRUCTURE AND EVOLUTION OF THE MILKY WAY GALAXY

Gerard Gilmore
Institute of Astronomy, Cambridge

Rosemary F.G. Wyse
Department of Physics and Astronomy
The Johns Hopkins University

Abstract. The combination of chemical abundance, kinematic, and age data for stars near the sun provides important information about the early evolution of the Galaxy. We review available data, with some new analysis, to show that the sum of all available information strongly suggests that the extreme population II subdwarf system formed during a period of rapid collapse of the proto-Galaxy. This subdwarf system now forms a flattened, pressure-supported distribution, with axial ratio ~2:1. The thick disk formed subsequent to the subdwarf system. At least the metal-poor tail of the thick disk is comparable in age to the globular cluster system. The thick disk is probably kinematically discrete from the Galactic old disk, though the data remain inadequate for robust conclusions.

1 INTRODUCTION

One of the most important aspects of current non-stellar astrophysical research to which studies of variable stars contribute invaluable information is the study of the structure and evolution of the Milky Way Galaxy. In this paper we provide a brief overview of some active areas of Galactic research to which knowledge of the kinematics, chemical abundances, ages, and spatial distribution of pulsating variable stars make a fundamental contribution.

In principle, an understanding of the formation and early evolution of the Galaxy is a well-defined theoretical problem. All one requires is a detailed knowledge of the spectrum of perturbations in the early universe and their subsequent evolution; an understanding of the physics of star-formation in a variety of environments, with particular emphasis on a prediction of the distribution of orbital elements of those intermediate mass massive-star binaries which will evolve to supernovae; a description of the hydrodynamics of a proto-galaxy, particularly including the effects of a high supernova rate, the efficiency of mixing of the chemically enriched ejecta, and the incidence of thermal and gravitational instabilities; the growth and transport of angular momentum and their effect on the growth of a disk; and the effects of a time-dependant gravitational potential on the dynamics of any stars formed up to that time. In practise, there remain some limitations in our understanding of at least some of these physical processes. Hence,

https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

it is still useful on occasion to try to deduce the important physics involved in galaxy formation from observations of those old stars which were formed at the time of the formation of the Milky Way, and whose present properties contain some fossil record of the Galaxy's history.

We discuss some of this information here, with emphasis on results relevant to the evolution of all galaxies. In §2 we present evidence from stellar chemical abundance and kinematic data that the oldest stars in the Galaxy formed during a period of rapid collapse of the proto-Galaxy, while §3 summarises some recent results regarding the shape of the stellar distribution in the Galactic spheroid, and §4 discusses current data which suggest that the thick disk is an old, discrete component of the Galaxy.

2 THE TIMESCALES OF GALACTIC FORMATION

The kinematic properties of stars in the Galaxy are related, through the gravitational potential Φ, to their spatial distribution. The scale length of the spatial distribution is determined by the total energy of the stellar orbits, as well as by the gradient of the potential. The shape of the spatial distribution depends on the relative amounts of angular momentum (rotational), and pressure (stellar velocity anisotropy) balance to the potential gradients. The total orbital energy and angular momentum of the gas which will become a star depend on the maximum distance from the centre of the Galaxy which it ever reached, the angular momentum of its orbit at that time, the depth of the potential well (generated by both dark and luminous mass) through which it fell, the fraction of the total orbital energy which was dissipated before star formation, and the subsequent dynamical evolution of the stellar orbit. That is, the present kinematic properties of old stars in the solar neighbourhood are determined in part by the initial conditions in the proto-galaxy, and in part by the physics of galaxy formation. Hence, local kinematic studies can help to determine both the detailed physics of galaxy formation and the distribution of gravitating mass in the Galaxy.

The chemical abundance of the ISM at any time depends on the local history of formation and evolution of stars sufficiently massive to have created new chemical elements, and the mixing of local gas with more distant material. This more distant gas may or may not itself be enriched, so that the time-dependance of the chemical abundance of newly forming stars depends on both the local and the global star formation rates, the rate of infall of primordial gas, and the efficacy of mixing in the ISM. Thus, while the chemical abundance of newly formed stars is a timepiece, this chronometer need not be a smooth or even a single-valued function of chronological time.

Clearly, however, the distribution function of stellar kinematics, chemistry and age contains a wealth of information on the distribution of protogalactic gas, the dissipational and star-formation history of that gas, the subsequent dynamical history of the resulting stars, and the Galactic gravitational potential.

2.1 Kinematics and chemistry of old stars

The dynamics of any large stellar system are governed by the collisionless Boltzmann equation (CBE):

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + \frac{\partial \vec{x}}{\partial t}\cdot\frac{\partial f}{\partial \vec{x}} + \frac{\partial \vec{v}}{\partial t}\cdot\frac{\partial f}{\partial \vec{v}} = \frac{\partial f}{\partial t} + \vec{v}\,\frac{\partial f}{\partial \vec{x}} - \nabla\Phi\,\frac{\partial f}{\partial \vec{v}} = 0, \tag{1}$$

where f is the phase space density at the point $(\vec{x},\vec{v})$ in phase space (i.e. there are $f(\vec{x},\vec{v})d^3\vec{x}d^3\vec{v}$ stars in a volume of size $d^3\vec{x}$ centered on $\vec{x}$ with velocity in the volume of size $d^3\vec{v}$ about $\vec{v}$). The collisionless Boltzmann equation is satisfied by **any** stellar population. If there exist several identifiable populations in the system, the CBE is satisfied by each of them separately. This arises because stars do not interact except through long-range gravity forces, which are being described through a smooth background potential. Consequently, f does not have to describe the entire Galaxy; one can concentrate on any subsample of stars, and apply the collisionless Boltzmann equation to it.

If we have a steady-state tracer population, and a time-independent potential, as the large-scale field in the Milky Way presumably is, we can set

$$\partial f/\partial t = 0. \tag{2}$$

For present purposes, the Galaxy is adequately described as being rotationally symmetric, so that it is convenient to write out the collisionless Boltzmann equation in cylindrical polar coordinates (r,Φ,z) in which $z = 0$ is the disk plane of symmetry, with corresponding velocity components (v_r, v_Φ, v_z):

$$v_r\frac{\partial f}{\partial r} + v_z\frac{\partial f}{\partial z} + \left(K_r + \frac{v_\Phi^2}{r}\right)\frac{\partial f}{\partial v_r} - \frac{v_r v_\Phi}{r}\frac{\partial f}{\partial v_\Phi} + K_z\frac{\partial f}{\partial v_z} = 0 \tag{3}$$

where the accelerations $\dot{v}_r$, $\dot{v}_\Phi$, $\dot{v}_z$ have been equated to the forces that cause them, Φ-gradients in f and in the potential have been set to zero, and K_r and K_z are the components of the gravity force.

In view of the intractability of the general problem of solving the CBE, one proceeds in general by taking velocity moments. Multiplying through by v_z and by v_r and integrating over all velocity space produces the Jeans' equations:

$$\nu K_z = \frac{\partial}{\partial z}\left[\nu\sigma_{zz}\right] + \frac{1}{r}\frac{\partial}{\partial r}\left[r\,\nu\sigma_{rz}\right] \tag{4}$$

$$\nu K_r = \frac{1}{r}\frac{\partial}{\partial r}\left[r\,\nu\sigma_{rr}\right] + \frac{\partial}{\partial z}\left[\nu\sigma_{rz}\right] - \frac{\nu\sigma_{\Phi\Phi}}{r} - \frac{\nu}{r}\langle v_\Phi\rangle^2, \tag{5}$$

where $\nu(r,z)$ is the space density of the stars, and $\vec{\sigma}(r,z)$ their velocity dispersion tensor (i.e. $\sigma_{ij} = \langle v_i v_j\rangle - \langle v_i\rangle\langle v_j\rangle$). Note that the velocity dispersions σ_{ij} are thus squared velocities, not r.m.s.

https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

values.

For present purposes, we rewrite the radial moment equation (5) in terms of observables in the Galactic plane (z = 0) to get:

$$v_c^2 - \langle v_\Phi \rangle^2 = \sigma_{\Phi\Phi} - \sigma_{rr} - \frac{r}{\nu}\frac{\partial(\nu\sigma_{rr})}{\partial r} - r\frac{\partial\sigma_{rz}}{\partial z} = \sigma_{rr}\left\{\frac{\sigma_{\Phi\Phi}}{\sigma_{rr}} - 1 - \frac{\partial \ln(\nu\sigma_{rr})}{\partial \ln r} - \frac{r}{\sigma_{rr}}\frac{\partial\sigma_{rz}}{\partial z}\right\} \tag{6}$$

In this relation v_c is the circular velocity (i.e. $v_c^2 = r(\partial\Phi/\partial r) = -rK_r$ where we adopt a locally flat rotation curve with $v_c = 220$ km·sec^{-1} here), $\langle v_\Phi \rangle$ is the mean rotation velocity of the relevant sample of tracer stars, which has velocity dispersions $\sqrt{\sigma_{rr}}$, $\sqrt{\sigma_{\Phi\Phi}}$, and $\sqrt{\sigma_{rz}}$ and radial spatial density distribution $\nu(r)$, remembering that r is the **planar** radial coordinate. The quantity $v_c - \langle v_\Phi \rangle \equiv v_a$ is usually called the asymmetric drift.

2.2 The asymmetric drift

Equation (6) relates measurable local moments of the stellar distribution function to global properties of the Galaxy. In order to understand its application, we discuss each term briefly.

$\sigma_{\Phi\Phi}/\sigma_{rr}$: The velocity dispersions at z = 0 of old disk stars are probably best estimated from the nearby, spectroscopically-selected K+M dwarfs with good parallax distances. These give $\sigma_{rr}:\sigma_{\Phi\Phi}:\sigma_{zz}$ = $39^2:23^2:20^2$ (Wielen 1974). For spectroscopically-selected low metallicity field stars the relevant values (Carney & Latham 1986) are $\sigma_{rr}:\sigma_{\Phi\Phi}:\sigma_{zz} = 128^2:96^2:93^2$. The first term in equation (6) then becomes $\sigma_{\Phi\Phi}/\sigma_{rr} = 0.35$ for the old disk, and $\sigma_{\Phi\Phi}/\sigma_{rr} = 0.56$ for the low-abundance field stars.

$\partial\ln(\nu\sigma_{rr})/\partial\ln r$: If one assumes that galactic disks have constant thickness independent of distance from the galactic centre, as suggested by photometric observations, and combines that assumption with the assumption that the shape of the velocity ellipsoid is independent of position, or more specifically that $\sigma_{rr} \propto \sigma_{zz}$, then

$$\partial\ln(\nu\sigma_{rr})/\partial\ln r = 2\ (\partial\ln\nu/\partial\ln r) = -2rh_r^{-1} \tag{7}$$

The derivation of equation (7) assumes a form for the velocity ellipsoid. For simplicity, we restrict discussion of spheroidal distributions to an isothermal spheroid, σ_{rr} = constant, so that

$$\partial\ln(\nu\sigma_{rr})/\partial\ln r = \partial\ln\nu/\partial\ln r \tag{8}$$

$(r/\sigma_{rr})(\partial\sigma_{rz}/\partial z)$: The term involving σ_{rz} describes the orientation of the velocity ellipsoid, and has no general analytic solution. It is discussed in detail in Kuijken & Gilmore (1989). Here we consider two limiting cases only. If the potential is that of an infinite constant

https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

surface density sheet the velocity ellipsoid will be diagonal in cylindrical-polar coordinates, and point always at the Galactic minor axis, so that $\sigma_{rz} \equiv 0$. This is the assumption most commonly adopted. An alternative idealisation is to assume that the potential is dominated by a spherical mass distribution, so that the velocity ellipsoid points always at the Galactic centre. In this case it is straightforward to show that, for the velocity ellipsoid parameters from Wielen noted above,

$$\sigma_{rz} = (3rz/\{4z^2+r^2\})\sigma_{zz}$$

so that

$$(r/\sigma_{rr})(\partial\sigma_{rz}/\partial z) \approx 3 \ (\sigma_{zz}/\sigma_{rr}). \tag{9}$$

For the velocity dispersions quoted above, equation (9) provides, for the old disk,

$$(r/\sigma_{rr})(\partial\sigma_{rz}/\partial \ ) \cong 0.75,$$

while for the spheroidal field stars the numerical value is 0.47. The true value for the σ_{rz} term is quite uncertain, though of large amplitude. Neglect of this term, as often done, is unjustified.

For an exponential disk of radial scale length h_r, and a sample of stars observed in the solar neighborhood, equation (6) therefore becomes

$$v^2 - \langle v_\Phi\rangle^2 = \sigma_{rr} \ (2\{d_*/h_r\} - 1.4) \tag{10}$$

where d_* is the distance of the sun from the Galactic centre (~7.8 kpc, Feast 1987). Alternatively, for a spheroid with a power-law density distribution with exponent γ, $\nu(r) \propto r^{-\gamma}$, we have

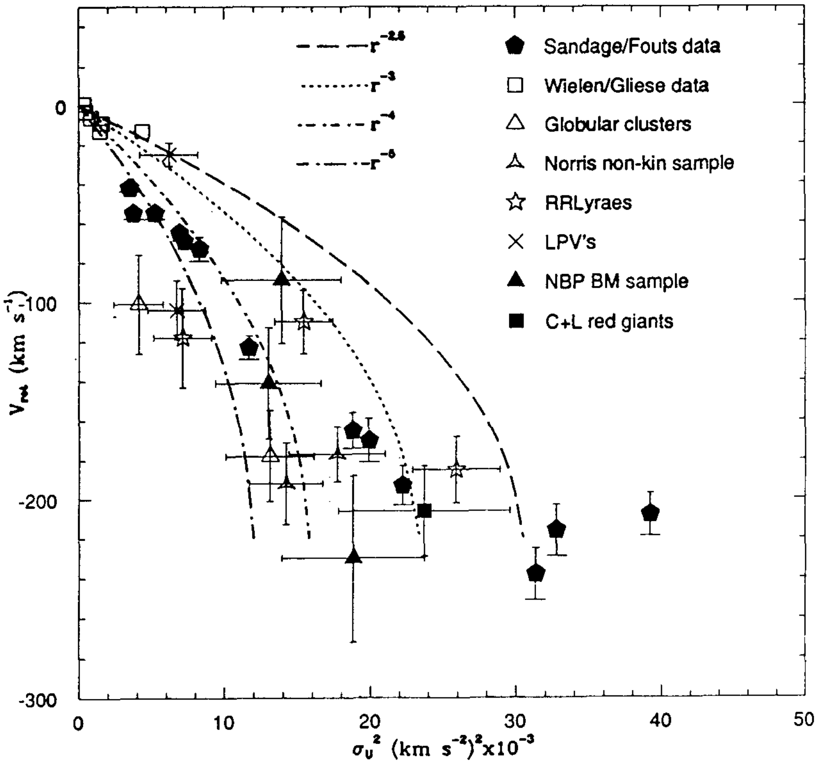
$$v_c^2 - \langle v_\Phi\rangle^2 = \sigma_{rr}(\gamma - 0.9) \tag{11}$$

Thus a stellar tracer population which belongs to an exponential distribution with scale length ~ 3.5 kpc (a plausible value for the Galactic old disk) will follow a similar asymmetric drift relation to that of a tracer population which is part of an isothermal distribution describing an r^{-4} spheroidal density distribution. It is also interesting to note that the largest allowed radial velocity dispersion, corresponding to zero net rotation, for such a stellar system is $\sim v_c/\sqrt{3}$, or ~130 km·sec^{-1}. For a tracer population with any smaller radial velocity dispersion, equation (6) describes the interplay between the pressure (velocity anisotropy) support and the angular momentum (rotation velocity) support to the spatial distribution. A stellar system with velocity dispersion larger than ~130 km·sec^{-1} has larger total energy and will form a more extended system. One might also assume it would have formed from less dissipated material, which is of course the clue to the physical significance of equation (6).

https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

The relevant observational data are shown in Figure 1, where the data points shown have been either collated from or calculated from data available in the identified references. It is apparent that all data for tracer samples with a Galactic rotation velocity greater than about 50 km·sec^{-1} are consistent with a single density distribution, with the marginally significant exception of the metal-rich globular cluster system, whose radial velocity dispersion is rather low. This datum is however somewhat more uncertain than most of the other data shown, due to distance and reddening uncertainties. Observational selection effects can have a very substantial effect on the appearance of the diagram, and have not been considered at all adequately. Obvious examples include explaining the apparent systematic difference in the

Figure 1. The relation between rotation velocity relative to the local standard of rest and the radial velocity dispersion for recently studied tracer samples. The model lines are for different solutions of equation (6). The data and models are described more fully in Gilmore et.al. (1989). The tendency for the data to cross the model lines at low V_{rot} indicates that the oldest stars in the Galaxy formed during a period of dissipational collapse.



https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

deduced radial velocity dispersion between spectroscopically- and kinematically-selected samples for the highest velocity stars, which are far from the regions of phase space expected to be affected strongly by the selection criteria, and allowing for the fact that stars on high angular momentum high energy orbits will always lie beyond the solar circle, and so will not be sampled in local surveys.

The mean density law consistent with the majority of the data with significant angular momentum corresponds to an isothermal spheroidal distribution with a power law with index ~ -4.5, or an exponential disk with scale length 3.1 kpc. The tendency for the tracer populations with the lowest mean rotational velocities to have larger radial velocity dispersions than consistent with this density profile is of considerable significance, if real. (We note that systematic distance uncertainties move the data roughly parallel to the body of the data with smaller σ_{rr}, so are unlikely to be relevant. With the exception of the data for the metal-poor RR Lyrae stars, however, there are very few stars in the bins with the highest values of σ_{rr}.) The stars with the highest radial velocity dispersions are also the most metal-poor (see below) and hence those which presumably formed first in the Galaxy. If they really do form a more extended spatial distribution than more metal-rich stars, then one may conclude that these stars formed earlier in the collapse of the proto-galaxy than more metal-rich stars, from less dissipated gas, and hence preserve a fossil record of the star-formation and dissipation history of the protogalaxy during the first condensation of the Galaxy from the expanding background. The validity of this conclusion rests almost entirely on the data for low metallicity RR Lyrae stars at present. Confidence in the distance scale and kinematics for these stars is clearly of considerable importance.

Although the asymmetric drift arguments above provide strong evidence that star formation continued **during** a period of dissipational collapse, there is no information in this relation regarding the **rate** of this collapse. For this one requires another clock.

2.3 Correlations between kinematics and chemistry

Stellar chemical abundance is a clock which measures age in units defined by the lifetimes of massive stars. Stellar orbital energy in the Galaxy is a measure of the amount by which the proto-Galactic gas had collapsed out of the background Hubble expansion and cooled, prior to star formation. Thus the existence of a correlation between stellar kinematics and [Fe/H] would allow one to relate the chemical evolutionary timescale to the dynamical timescale.

The existence or otherwise of an abundance gradient in the spheroid is often cited as an important diagnostic of the timescale of galaxy formation. In general this is **not** correct. The presence of an abundance gradient means that dissipation was an important process during formation of the stellar component of the spheroid, but does not necessarily define timescales. Imagine a cloud of gas orbiting in the proto-Galaxy. Star formation in this cloud is presumed to increase the

https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

chemical abundance with time, so that stars formed at later times are increasingly more metal rich than stars formed earlier. If the total orbital energy of the cloud is unchanging, all stars formed will have the same orbit as the cloud, there will be no correlation of abundance with orbital parameters. Only if the enriched gas is continually transferred onto lower energy orbits will an abundance gradient exist. In modern terminology, dissipationless collapse does not create abundance gradients; dissipation is essential.

The important parameter which must be added to this argument to determine timescales for the collapse is the timescale for loss by cooling of the dissipated energy. Idealised models of protogalaxies suggest this cooling timescale is less than a dynamical collapse time (see Gilmore et al. 1989 for a review). Thus dissipation will not necessarily slow a collapse significantly beyond a dynamical timescale. Thus, the existence of an abundance gradient determines whether or not dissipation was significant during star formation and collapse, but does not constrain the rate of the collapse.

The existence of a correlation between chemical abundance and kinematics in stars at present however requires not only that such a correlation was set up during the relevant epoch of star formation, but also that the stellar orbital energy has not been totally rearranged since star formation. That is, one expects a tight correlation between rotation velocity and stellar chemical abundance only if the star formation occurred during a dissipational collapse, and also if there has not been an efficient violent relaxation of the Galaxy since the metal-poor stellar tracer population formed. The fact that the velocity ellipsoid of metal-poor stars near the sun is anisotropic clearly shows that such violent relaxation has not been completely efficient (if it happened at all), so that at least some memory of conditions in the proto-Galaxy remains. Nevertheless, the existence or otherwise of a tight correlation between asymmetric drift and chemical abundance is not the clean test of the relative timescales of star formation and dissipation which it is often assumed to be.

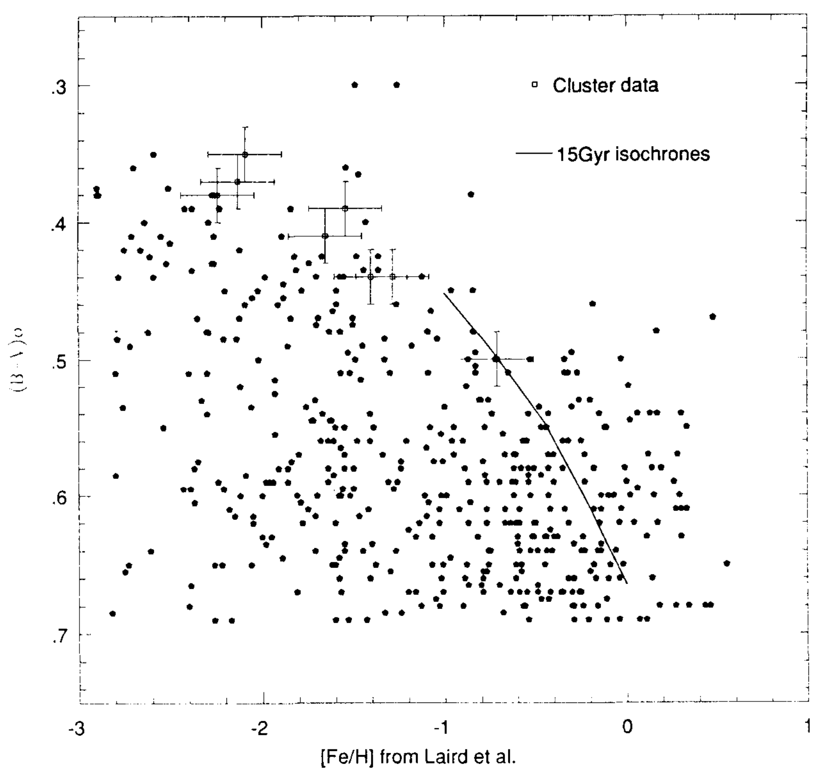
2.4 Correlations between abundances and ages

Calibration of the abundance enrichment rate onto a time scale which is calibrated independently of the collapse rate, i.e. in years, is necessary to provide direct evidence for the timescale of Galactic formation. In practise only stars near the main-sequence turnoff have surface gravities which change sufficiently rapidly and monotonically that reliable comparison with evolutionary tracks is possible, although some useful information on a combination of age and chemical abundance can be derived from the colour of field giant stars (e.g. Sandage 1987). For single stars near the turnoff the comparison of uvbyβ photometry with theoretical isochrones is by far the most reliable and precise age-dating technique available.

https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

If independent abundance estimates are available, then any photometric measure of the temperature of the hottest turn-off stars will measure the age of the **youngest** star in a tracer population. It is this method which is utilised to determine ages for globular clusters, where it also seems that all the member stars are coeval. A similar technique can be applied to field stars (cf. e.g. Gilmore & Wyse 1987), and is illustrated in Figure 2. The important conclusion from Figure 2 is that essentially all stars with [Fe/H] $\lesssim -0.8$ are, insofar as is measurable, the same age as the globular cluster system. More metal rich stars have a bluer turnoff, implying that **at least some** of these stars are younger. The **distribution** of ages is however unmeasurable from a turnoff colour. Some information on the age distribution for stars with [Fe/H] $\gtrsim -0.8$ is provided by studies of open clusters. These form a system with a very large scatter in the age-metallicity plane; clusters exist near the sun with solar abundance and an age of 12 Gyr (NGC 6791, Janes in

Figure 2. B-V vs [Fe/H] for stars observed by Laird et al. (1988; points) and turnoff colours for globular clusters with good CCD data. The solid line is a 15 Gyr oxygen enhanced isochrone scaled from those of Vandenberg & Bell (1985) to match 47 Tuc.



preparation) and with [Fe/H] $\sim$-0.5 but an age of only a few Gyr (e.g. Melotte 66). Thus any attempt to deduce an age for a stellar population from the turnoff colour of the bluest field stars with metallicity $\gtrsim$-0.8 dex (Norris & Green 1989) is fundamentally unreliable.

2.5 The timescales of galactic chemical evolution

In attempting to deduce the rate of star formation and dynamical evolution in a proto-galaxy, it is desirable to have available a clock whose rate can be calibrated, and which runs sufficiently fast to resolve the dynamical evolutionary timescales. Such a clock is provided by stellar evolution of high-mass stars, while the fossil record of the clock is observable in the chemical abundance enrichment patterns in long-lived low-mass stars. Fortunately, there exists a subset of common elements (most importantly oxygen) whose creation sites are restricted to very massive stars, and another subset (most importantly iron) which is also created in lower mass stars. Since the evolutionary timescales for high- and low-mass stars span the timescale range of interest in galaxy formation, the differential enrichment of oxygen and iron provides an ideal clock to calibrate the rate of star formation in the proto-Galaxy.

Oxygen to iron element ratios have been now been measured for a sufficient number of stars to define the systematic trends in the data. The important result for present purposes is that a significant change of slope occurs in the relationship between the element ratio [O/Fe] and [Fe/H] close to a metallicity where there also occurs a change in the stellar kinematics, that is at [Fe/H] $\sim$ -1. The [O/Fe] ratio is observed to be approximately constant, independent of [Fe/H] for the most metal-poor stars, -2.5 $\lesssim$ [Fe/H] $\lesssim$ -1, while [O/Fe] declines for the more metal-rich stars, [O/Fe] $\sim$ -½ [Fe/H]. Present data are summarised in Figure 3, in which all scatter is considered by the relevant observers to be consistent with observational error (Sneden et al. 1989).

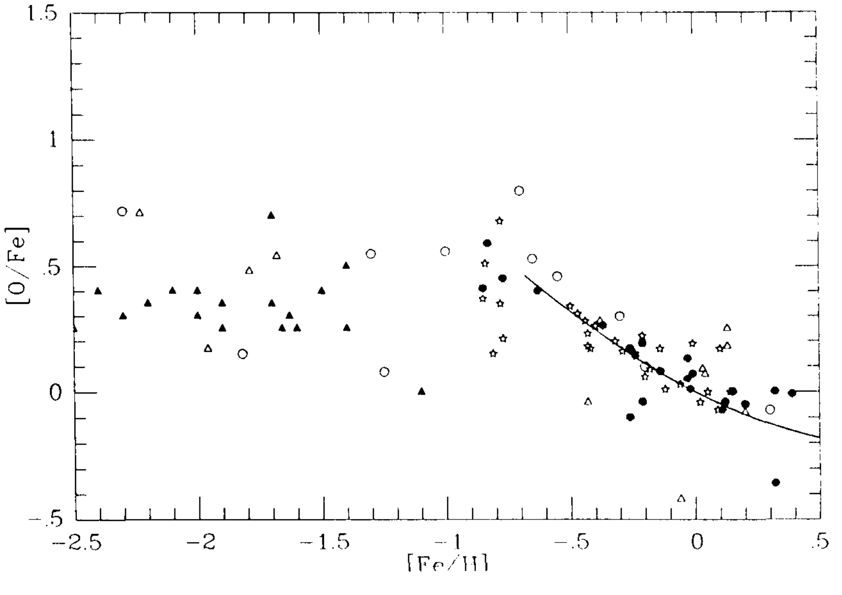
Assuming that [Fe/H] is a monotonically increasing function of time, this behavior can be explained if the oxygen and iron in the more metal poor stars have been produced in stars of the same lifetime, while for the more metal-rich stars, although the oxygen and iron continue to be produced together, an additional, longer timescale source now dominates the iron production. Such behaviour is in good agreement with supernova nucleosynthesis calculations, which show that oxygen is produced only in Type II supernovae by massive stars ($M \gtrsim 20\ M_{\odot}$), while iron has a contribution from both massive and low mass stars ($M \gtrsim 3\ M_{\odot}$, Type I supernovae) thereby having an enhanced production once the much more numerous, lower mass stars contribute to its nucleosynthetic yield (Tinsley 1979; Matteucci & Greggio 1986; Wyse & Gilmore 1988). This results in the ratio [O/Fe] decreasing systematically with increasing metallicity [Fe/H].

https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

If the arguments above contained the whole story over the history of star formation in the Galaxy, then it would have to be mere coincidence that the change in the predominant production mechanism of iron occurred close to a metallicity, or epoch, at which the stellar kinematics change from those of a pressure-supported system, which formed stars rapidly, to those of an angular momentum-supported system. Rather, the coincidence of the value of [Fe/H] at which the Galaxy changed from a pressure-supported system to an angular momentum-supported system, with the value of [Fe/H] at which the interstellar medium became diluted by the products of long-lived stars, provides a diagnostic of the relative star-formation and dissipation rates in the proto-Galaxy.

When sufficient data and reliable massive-star evolutionary models all the way through the supernova explosion, with corresponding elemental yields, become available it will be possible to quantify these arguments (subject to the assumption of a constant stellar IMF) and provide a real timescale (in years) for the periods of proto-galactic evolution which were dominated by collapse (possibly non-dissipational) on a dynamical timescale, and that period when angular momentum transport (in dissipational collapse) became an important physical process, and angular momentum support became the dominant dynamical process.

Figure 3. A compilation of oxygen to iron element ratio measurements from the literature. This figure is adapted from Wyse and Gilmore (1988). The smooth curve through the data for [Fe/H] $\gtrsim$ -1 shows the prediction of a simple model with constant supernova rates in the ratio 1.5:1.0 for Type I:Type II, resulting in twice as much oxygen as iron being produced per unit time.



https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

One conclusion which is relatively independent of the details of elemental synthesis follows from the fact that features in both the stellar abundance and kinematics occur more or less together, at [Fe/H] $\lesssim$ -1. As the elemental yields are a fairly slow function of progenitor mass, and hence lifetime, one does not expect discontinuities in element ratios to occur in a situation where the star formation proceeds at a reasonably constant rate. A discontinuity in kinematic properties implies that the ratio of the dissipation rate to the star formation rate also changes rapidly. A possible explanation is that at metallicities [Fe/H] $\gtrsim$ -1.5 the efficiency with which a gas cloud cools from $\sim 10^6$ K (a typical galactic virial temperature) increases markedly, due to a transition of the dominant cooling mechanism from free-free radiation, independent of metallicity, to line radiation, proportional to the number density of metals. Thus a rapid increase in the dissipation rate and collapse to a disk-like angular-momentum supported structure is not implausible at a metallicity of $\sim$ -1 dex. It is not crucial for these arguments that the breaks in kinematics and element ratios occur at **exactly** the same metallicity.

In terms of models of the early chemical evolution of the Galaxy, one must explain the fact that [O/Fe] is approximately constant, at three times the solar value, for [Fe/H] $\lesssim$ -1, while decreasing smoothly for [Fe/H] greater than this value, together with the fact that the mass of stars with [Fe/H] $\lesssim$ -1 is only a few percent of the total stellar mass of the Galaxy, as discussed in detail in §4 below. Clearly, the approximate constancy of the [O/Fe] ratio independently of the [Fe/H] ratio at low metallicities requires that essentially **all** the stars with [Fe/H] $\lesssim$ -1 formed on a timescale less than that on which a significant number of low mass (Type I) supernovae exploded. This timescale is rather difficult to estimate precisely, due to uncertainties in the mechanism of Type I supernovae and the fraction of all stars formed which are in binaries of the type that may be expected to be precursors (cf. Iben 1986); the lowest mass, and hence most numerous, progenitors of CO white dwarfs have main-sequence masses and lifetimes of $\sim 5\ M_\odot$ and $\sim 2.5 \times 10^8$ yr respectively. Thus a reasonable estimate for the characteristic time after which one expects dominance of iron from Type I supernovae is $\lesssim 10^9$ yr (but bearing in mind that some Type I systems may take a Hubble time to evolve). This general argument appears to be the strongest direct evidence for a rapid formation timescale for the Extreme Population II stars in the Galaxy.

3 THE SPATIAL STRUCTURE OF THE MILKY WAY GALAXY

Pulsating variable stars have traditionally been the most commonly applied and most reliable tracer of the spatial structure of the Milky Way Galaxy. One example of this type of analysis which is of considerable current interest involves comparison of the shape of the extreme Population II stellar system with the shape expected from dynamical analysis of the kinematics of local metal-poor stars. The shape of the non-thin disk stars is important for its implications for the early stages of galaxy collapse and star formation, the interpretation of the kinematics of high-velocity stars, and the shape

https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

of the underlying dark matter that generates the gravitational potential in which these stars move.

3.1 The shape of the metal-poor spheroid

The high-velocity, metal-poor field stars in the solar neighborhood have an anisotropic velocity-dispersion tensor, with $\sigma_r^2 : \sigma_\theta^2 : \sigma_\phi^2 \sim 2 : 1 : 1$. Since the velocity-dispersion tensor behaves as an anisotropic stress tensor in the equations governing stellar dynamics, one may expect this anisotropic 'pressure' to result in an anisotropic shape, i.e. a flattened metal-poor spheroid (see §2 above for the relevant equations). Binney & May (1986) investigated this idea in more detail, and concluded that in the locally non-spherical potential felt by the subdwarfs, due to the presence of the disk, the observed velocity dispersion anisotropy implies a substantially flattened spheroid, with shape $\sim$ E7 or axis ratio $\sim$1:4.

The kinematic data of Ratnatunga & Freeman (1985; 1988) for distant metal-poor K giants can also most easily be explained by allowing these stars to form a flattened distribution. The most important feature of the data is the fact that the line-of-sight velocity dispersion in the SGP does not increase with distance despite the increasing contribution of the radial (relative to the Galactic centre) component of the velocity dispersion (σ_r) to the observed stellar radial (relative to the sun) speed. The assumption behind the expectation of a rising line-of-sight dispersion with distance is that the distant metal-poor K giants trace the same population as the local metal-poor K giants, the high ΔS RR Lyraes, and the local subdwarfs, and hence should have the same radially-biased velocity-dispersion tensor. To model this, one can depress the observed velocity dispersion at large distances by allowing suitable discontinuities in the stellar distribution function; essentially we are assuming that all stars beyond a given galactocentric radius are on circular orbits. This approach allows a fit which retains a spherical spatial structure for these stars (Sommer-Larsen 1987; Sommer-Larsen & Christensen 1989; Dejonghe & de Zeeuw 1988). Alternatively, adopting a global form of the distribution function in either a spherical (White 1985,1989) or in an oblate (Levison and Richstone 1986) potential requires a flattened spatial distribution for the spheroid stars, again with axis ratio $\sim$1:4 .

In the light of this kinematic and dynamical evidence, it is mildly puzzling that direct star-count studies suggest the subdwarf stellar system is approximately round (Freeman 1987). The most-quoted evidence for a spherical distribution of field spheroid stars comes from the modelling by Bahcall & Soneira (1980, 1984) (hereafter BS) of the faint star counts of Koo & Kron (1982) in two fields; BS conclude that the axis ratio of the spheroid stars is $c/a = 0.80^{+0.20}_{-0.05}$. Their technique is based on the fact that fields in the $l = 90°, 270°$ plane are at equal galactocentric distances if at equal distances from the solar neighborhood (i.e. us) and hence a spherical distribution of stars will contribute equally to all fields in this plane. Thus if one compares magnitude-limited samples in fields at high and low Galactic latitude

https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

one should obtain equal numbers of spheroid stars in the two fields. A flattened distribution of stars will yield lower counts in the higher-latitude field.

BS complicate their analysis somewhat by adopting different color-magnitude relations for the two fields, and thus they do not predict equal numbers of stars for a spherical distribution; they are forced to do this to obtain an acceptable fit for their model in each of the two fields, due to a combination of inadequacies in the model, such as lack of the thick disk component, and in the data, discussed below. There is no physical basis for such a variation of color-magnitude relation (metallicity gradients are not relevant since the fields are supposed to be at the same galactocentric distance) and it is a potential source of uncertainty. Adoption of a metal-poor color-magnitude relation has the effect of assigning a low intrinsic luminosity to stars of a given color. Hence, in an apparent-magnitude limited sample one will be comparing lower luminosity, less distant stars in the 'metal-poor' field with higher luminosity, more distant stars in the other field. The predictions of relative star-counts are therefore sensitive to the shape of the subdwarf luminosity function as well as to the shape and density profile of the stellar tracer population, so that it is possible to produce predictions for the ratio of counts that can exceed unity in a spherical distribution, as BS derived.

A new study of this problem, utilising a larger dataset and using a more general model-Galaxy program which requires internally consistent properties for a given stellar population in different fields, and which allows the inclusion of a thick disk is described by Wyse & Gilmore (1989). Following BS they counted stars blueward of a colour limit ($B-V = 0.6$) chosen to minimise contamination of the tracer sample by nearby old disk stars, with the precise value of this limit not being critical. The two fields used were ($l = 0°$, $b = 90°$; area surveyed = 0.75 square degrees) and ($l = 272°, b = -44°$; area surveyed = 0.75 square degrees). The observed ratio of blue stars in the two fields was 0.59. This disagrees strongly with Koo & Kron's counts in two fields at similar Galactic latitudes but at much fainter magnitudes, which yield a ratio of 1.09 for blue stars with $20 \lesssim V \lesssim 22$; the more recent calibration of the same data by Koo, Kron & Cudworth (1986) gives 1.3 (note that these numbers are based on a somewhat uncertain color cut, but this should not matter provided one is blue enough to have isolated the metal-poor spheroid stars). We suspect that this apparent disagreement reflects the uncertainty in the Koo and Kron counts, due to the difficulty of reliable star-galaxy discrimination at faint magnitudes. This suspicion is based on the results of the Koo, Kron & Cudworth (1986) 'subdwarf' category counts for their north Galactic pole field, together with predictions from the WG model and from the BS model, each model with an assumed spheroid axis ratio of 0.8. There is an obvious disagreement between the data and the models; the data fail to increase towards fainter magnitudes, contrary to both of the models, and contrary to intuition.

https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

The BS model predictions (their Table 3) combined with our low value of the relative observed counts would imply that the spheroid had an axis ratio $c/a \lesssim 0.5$. When one considers the presence of the thick disk, and also models the observed **total** counts as well as their ratio, the best estimate for the axis ratio of the metal-poor subdwarf stellar population within a few kpc of the sun is $c/a \sim 0.6$.

One can also utilise direct counts of other spheroid tracers, such as RR Lyrae stars, to derive the density profile of spheroid light. Early work based on RR Lyrae stars in the Palomar-Groningen and Lick surveys, which were towards the Galactic center (Kinman, Wirtanen & Janes 1966; Oort & Plaut 1975) concluded that these stars were distributed in a nearly spherical system. These results have now been superseded by better photometric data (Wesselink et al. 1987); the more modern analysis finds in contrast that the RR Lyrae stars towards the Galactic center have a rather flattened distribution, with axis ratio $\lesssim 0.6$, in excellent agreement with the star-count result above. A possible complication in this picture is due to the work of Hartwick (1987), who suggests that the RR Lyraes form a two-component system, with the more metal-rich stars being part of the thick disk. However, Hartwick analysed the available data for **metal-poor** RR Lyrae stars separately, and concluded that the axis ratio of the RR Lyrae system varies with galactocentric radius, being flattened (axis ratio $c/a \sim 0.6$ and scale height $\sim$1.5 kpc, i.e. rather similar to the parameters of the more metal-rich thick disk RR Lyraes) interior to the solar circle. At very large Galactocentric distances the RR Lyrae data somewhat favour a more spherical distribution.

Hartwick finds a similar two-component structure for the metal-poor ([Fe/H] < -1) globular clusters from the distribution of their projected positions on the sky; this should not be confused with the two well-established distinct components in the globular cluster system (Zinn 1985; Thomas 1988) one metal-rich and one metal-poor. However, the small number of clusters involved gives this small statistical weight. The kinematics of the metal-poor globular cluster system was found by Frenk & White (1980) to consist of negligible net rotation and isotropic velocity-dispersion tensor. These properties would suggest a spherical spatial distribution, given a spherical potential, and a flattened distribution given a flattened potential. However, Norris (1986) found there to be no statistically significant difference between the 'isotropic' velocity-dispersion tensor of the globular clusters and the markedly **anisotropic** velocity dispersions of the local subdwarfs, while Thomas (1988) has shown that one cannot in general draw **any** strong conclusions about the kinematics of the globular cluster system, due to the effects of distance errors. While it is interesting that the kinematic parameters derived for the globular clusters are so similar to those of the field stars, there is no compelling theoretical or observational evidence that the globular cluster system is intimately related to the field star system, so such similarities should not be over-interpreted.

In summary, the available evidence on the shape of the metal-poor field stars which make up the Galactic spheroid suggests that these stars form a rather non-spherical system, whose flattening may vary with radius, but is $c/a \sim 0.5$ within a few kpc of the sun, and within a few kpc of the Galactic centre.

4 THE THICK DISK

Confirmation that the Intermediate Population II stellar system defined at the Vatican Conference is indeed characterised by a vertical scale height of $\sim$1 to 1.5 kpc, a vertical velocity dispersion of $\sim$45 $km \cdot sec^{-1}$, a typical stellar chemical abundance of $\sim$-0.75 dex, and a mean asymmetric drift of $\sim$30 to 50 $km \cdot sec^{-1}$ has been provided by a very large number of photometric and spectroscopic surveys in the last few years (cf. Gilmore & Reid 1983, Freeman 1987). The detailed values of the descriptive parameters remain poorly determined however, primarily because the offset in the mean values characterising the thick disk distribution function over age, metallicity, and kinematics from those characterising the oldest thin disk stars is much less than the dispersions in these quantities. Reliable determination of the parameters of the distribution function is important since it may allow a discrimination between the several currently viable models of the formation of the thick disk.

Possible formation mechanisms for the thick disk include:
1) A slow pressure-supported collapse phase following formation of the extreme Population II system;
2) Violent dynamical heating of the early thin disk by, for example, satellite accretion or violent relaxion of the Galactic potential;
3) Accretion of the thick disk material directly;
4) A period of enhanced kinematic diffusion of stars formed in the thin disk to high energy orbits. This might be due perhaps to a transient bar, or to a large population of high velocity black holes in the Galactic halo.

Discrimination amongst these several types of model is possible from appropriate age-abundance data. The first type of model noted above will lead to an old system, with an abundance gradient. The second will have a small internal age range, but is unlikely to have an extant abundance gradient (modulo the details of the merger process). The third has a wide variety of allowed combinations of age and abundance, while the fourth will have a range of ages, but a kinematic discontinuity between the old disk and the thick disk. In view of this possibility to determine the evolutionary history of the thick disk, an extensive debate is underway to determine a reliable description of the kinematic, abundance and age structure of the thick disk. This is well reviewed in Sandage (1987) and Norris (1987).

Here we summarise the data on the determination of the age range of thick disk stars, and discuss the difficult question of the kinematic relationship between the thick disk and the old disk near the sun.

https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

4.1 The age of the thick disk near the sun

An age determination for samples of thick disk stars is an extremely difficult observational problem. In part this is due to the usual difficulty in assigning a reliable age to anything in astronomy, but in this case the situation is complicated by the point noted above that there is no obvious **a priori** way to define a sample of purely 'thick disk' stars. Any sample selected by abundance, kinematics, or chemistry will inevitably include old disk and/or extreme population II stars in addition to the thick disk. Thus determination of the age of the **youngest** or the **oldest** star in a sample, while tractable, is not an obviously clever way to answer the question of interest. Some information may be derived from Figure 2, in §2.5 above. It is evident from this figure that the age of the oldest stars with $[Fe/H] \lesssim -0.8$ is comparable with that of the globular cluster system. This abundance range probably is dominated by thick disk stars for $-1 \lesssim [Fe/H] \lesssim -0.8$, suggesting that the most metal-poor thick disk stars are among the oldest in the Galaxy. More metal-rich thick disk stars may or may not be the same age. It is impossible to tell from comparison with diagrams like Figure 2, as some old disk stars will contaminate the sample. This point is worth emphasising, as it removes the rigorous basis for the conclusion of Norris & Green (1989) that the thick disk is several Gyr younger than the subdwarfs near the sun. Their conclusion **may** be correct, but it cannot be derived reliably from photometric data alone. This point is discussed in more detail by Sandage (1989).

However, the horizontal branch, as studied by Norris & Green (1989), does provide important information on the age of the thick disk stars. The observational evidence that metal-rich RR Lyrae stars form a thick disk system (e.g. Hartwick 1987) is an important clue. The **youngest** dated population of RR Lyrae stars is that in NGC 121, which has an age of ~12 Gyr. Thus, if the small ΔS RR Lyrae stars do indeed belong to the thick disk, 12 Gyr is a lower limit on the age of at least some of the thick disk. Further studies of these stars is of considerable interest.

Similarly, while the relationship of the globular clusters to field stars is very non-obvious, **if** the disk globular cluster system studied so well by Zinn and collaborators (cf. Armandroff 1989 for the most recent analysis) is indeed part of the thick disk, then the antiquity of the thick disk is reliably established. All these arguments however leave open the possibility of a large age **range** in the thick disk. There is no reliable information yet available on this point.

4.2 Is the thick disk kinematically discrete?

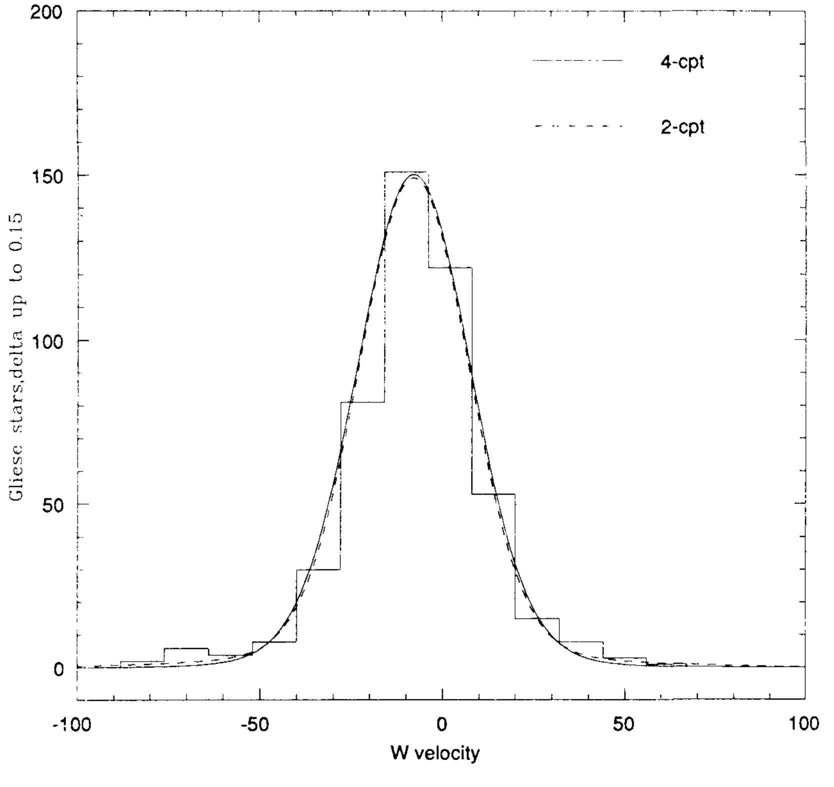
The velocity ellipsoid for the extreme population II subdwarf system is reliably determined to be $\sigma_{rr}:\sigma_{\phi\phi}:\sigma_{zz} = 128^2:96^2:93^2$ (Carney & Latham 1986). The vertical velocity dispersion of the thick disk is ~ 45 km$\cdot$sec^{-1} (cf. Figure 12a of Gilmore & Wyse 1987). The number of stars with abundances and kinematics such that they might plausibly be assigned to either the low velocity tail of the extreme population II or to the high velocity tail of the thick disk (i.e. those

https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

stars with [Fe/H] ~ -1) is very small (cf. Carney, Latham, & Laird 1989; Paper VIII in their current series). Thus the thick disk is apparently kinematically discrete from the subdwarf system to an adequate approximation. This means simply that the rate of dissipation in the vertical direction was relatively high, compared to the star formation rate, as the proto-disk collapsed.

The relationship of the thick disk to the high velocity tail of the old disk is more problematic, and has been discussed extensively by Sandage (1987) and Norris (1987). To oversimplify the point at issue, is there a continuous relationship of vertical velocity dispersion with metallicity extending all the way to the ~45 km·sec^{-1} vertical velocity dispersion of the thick disk (Norris 1987, Figure 7), or does the old

Figure 4. The distribution of vertical (W) velocities of stars in the Gliese catalogue, excluding stars with $\delta_{0.6} > 0.15$. The two lines illustrate models with a kinematically discrete thick disk (dashed lines) and with a continuous kinematic relationship between the old disk and the thick disk (solid line). Distinction between these models on the basis of these data is clearly not possible.



https://doi.org/10.1017/S0252921100011465 Published online by Cambridge University Press

disk velocity dispersion become asymptotically constant at the value of $\sim 22\ \mathrm{km \cdot sec^{-1}}$ appropriate for spectroscopically selected samples of old dwarfs near the sun (Fuchs & Wielen 1987; Sandage 1987)? The difficulty in deciding this question is illustrated in Figure 4. This shows the vertical velocity distribution of those stars in the Gliese catalogue with photometric abundance parameter $\delta_{0.6} < 0.15$ (this abundance range was chosen so as to exclude high velocity subdwarfs). The two models overlaying the data histogram are a two-component model, with discrete old disk and thick disk, and the four-component approximation to a continuous relation between the old disk and the thick disk fitted by Norris. The two models are clearly both an excellent description of the data, and are equally clearly indistinguishable.

It is evident from Figure 4 that available **local** data are incapable of determining if the old disk and the thick disk are kinematically discrete. Resolution of this uncertainty, with its important implications for the formation history of the Galaxy, must await completion of the several extant **in situ** surveys of the stellar distribution several kpc from the Galactic plane. The available data marginally favour a model in which the thick disk is a kinematically discrete component of the Galaxy, but the issue remains to be decided by observational test.

ACKNOWLEDGEMENT

RFGW acknowledges partial support from the NSF, through grant AST-88-07799.

REFERENCES

Armandroff, T. (1989). A.J., in press.
Bahcall, J.N. & Soneira, R.M. (1980). Ap.J.Suppl., 44, 73.
Bahcall, J.N. & Soneira, R.M. (1984). Ap.J.Suppl., 55, 67.
Binney, J. & May, A. (1986). M.N.R.A.S., 218, 743.
Carney, B. & Latham, D.W. (1986). A.J., 92, 60.
Dejonghe, H. & de Zeeuw, P.T. (1988). Ap.J., 329, 720.
Feast, M. (1987). In The Galaxy, eds. G. Gilmore & B. Carswell, p. 1. Dordrecht: Reidel.
Freeman, K.C. (1987). Ann. Rev. Astron. Astrophys., 25, 603.
Fuchs, B. & Wielen, R. (1987). In The Galaxy, eds. G. Gilmore & B. Carswell, p. 375. Dordrecht: Reidel.
Gilmore, G. & Reid, I.N., (1983). M.N.R.A.S., 202, 1025.
Gilmore, G. & Wyse, R.F.G. (1986). A.J., 91, 855.
Gilmore, G. & Wyse, R.F.G. (1987). In The Galaxy, eds. G. Gilmore & B. Carswell, p. 247. Dordrecht: Reidel.
Gilmore, G., Wyse, R.F.G., & Kuijken, K. (1989). Ann. Rev. Astr. Astrophys., 27, in press.
Hartwick, F.D.A. (1987). In The Galaxy, eds. G. Gilmore & B. Carswell, p. 281. Dordrecht: Reidel.
Frenk, C.S. & White, S.D.M. (1980). M.N.R.A.S., 193, 295.

Iben, I. (1986). In Cosmogonical Processes, eds W.D. Arnett, C.J. Hansen, J.W. Truran & S. Tsuruta, p. 155. Utrecht: VNU Science Press.
Kinman, T.D., Wirtanen, C.A. & Janes, K.A. (1966). Ap.J.Suppl.,13, 379.
Koo, D.C. & Kron R.G. (1982). Astron. & Astrophys.,105, 107.
Koo, D.C., Kron, R.G. & Cudworth, K. (1986). P.A.S.P.,98, 285.
Kuijken, K. & Gilmore, G. (1989). M.N.R.A.S., in press.
Laird, J.B., Carney. B.W., & Latham, D.W. (1988). A.J.,95, 1843.
Levison, H.F. & Richstone, D.O. (1986). Ap.J.,308, 627.
Matteucci, F. & Greggio, L. (1986). Astron. & Astrophys.,154, 279.
Norris, J. (1986). Ap.J.Suppl.,61, 667.
Norris, J. (1987). In The Galaxy, eds. G. Gilmore & B. Carswell, p. 297. Dordrecht: Reidel.
Norris, J., & Green, E.M. (1988). Preprint.
Oort, J.H. & Plaut, L. (1975). Astron. & Astrophys.,41, 71.
O'Connell, D.J.K. (1965). Stellar Populations. Amsterdam: North Holland.
Ratnatunga, K.U. & Freeman, K.C. (1985). Ap.J.,291, 260.
Ratnatunga, K.U. & Freeman, K.C. (1988). Ap.J., in press.
Sandage, A. (1987). In The Galaxy, eds. G. Gilmore & B. Carswell, p. 321. Dordrecht: Reidel.
Sandage, A. (1989). In The Calibration of Stellar Ages, in press. Middletown, CN: Van Vleck Observatory.
Sneden, C., Wheeler, J.C. & Truran, J. (1989). Ann. Rev. Astr. Astrophys.,27, in press.
Sommer-Larsen, J. (1987). M.N.R.A.S.,227, 21P.
Sommer-Larsen, J. & Christensen, P.R. (1989). Preprint.
Thomas, P. (1988). Preprint.
Tinsley, B.M. (1979). Ap.J.,229, 1046.
Vandenbergh, D., & Bell, R.A. (1985). Ap.J.Suppl.,58, 711.
Wesselink, T.H., Le Poole, R.S. & Lub J. (1987). In Stellar Evolution and Dynamics in the Outer Halo of the Galaxy, eds. M. Azzopardi & F. Matteucci, p. 185. Garching: ESO.
White, S.D.M. (1985). Ap.J.,294, L99.
White, S.D.M (1989). Preprint.
Wielen, R. (1974). In Highlights of Astronomy, Vol. 3, ed. G. Contopoulos, p 395. Dordrecht: Reidel.
Wyse, R.F.G. & Gilmore,G. (1988). A.J.,95, 1404.
Zinn, R. (1985). Ap.J.,293, 424.