THE STELLAR DISK–HALO CONNECTION

ROSEMARY F. G. WYSE
The Johns Hopkins University, Baltimore, MD 21218, USA

GERARD GILMORE
Institute of Astronomy, Cambridge CB3 0HA, England

ABSTRACT. The thick disk is the stellar disk-halo connection. At least near the solar circle, this component is on average as old as the system of disk globular clusters, or ~ 12 Gyr. This implies that it most probably formed early in the process of Galaxy formation, so that its properties – chemical abundances, stellar kinematics and spatial distribution – contain clues to the physics of these stages of Galaxy evolution. Its present-day importance for the interstellar disk-halo connection lies in the evolution of its constituent stars – gas loss through winds on the red giant and asymptotic giant branches, through planetary nebulae prior to white dwarf formation, and through supernovae. This gas loss results in mass injection, momentum injection and energy injection into the interstellar medium from a stellar population with a scale height of ~ 1kpc.

1. THE STELLAR THICK DISK

The canonical disk galaxy of the 1970s consisted of two stellar components, *viz.* a metal-poor, low-angular momentum, high velocity dispersion, extended spherical halo on the one hand, and a metal-rich, low dispersion, high-angular momentum thin disk on the other hand. The disk-halo connection was tenuous. Recent observations have revealed the existence of the thick stellar disk, which provides the stellar disk-halo interface, and whose importance lies in the clues it contains to the physics of Galaxy formation. The properties of the thick disk, as presently understood, are discussed below, in the context of the disk-halo transition.

2. KINEMATICS AND METALLICITY

The best available description of the properties of the stellar disk-halo connection is obtained by observations of stars which currently occupy the region a few kiloparsecs above the plane of the thin disk. This description can be derived from

H. Bloemen (ed.), The Interstellar Disk-Halo Connection in Galaxies, 97–108.

studies of nearby but high-velocity stars, or by study of distant stars currently *in situ* at the disk-halo interface.

2.1 Kinematically Selected Samples

Samples of nearby stars with high space motions provide an observationally convenient probe of the structure of the Galaxy far from the Galactic plane. The large proper-motion selected stellar samples of Sandage & Fouts (1987) and of Carney, Latham and collaborators have proved particularly valuable for studying the kinematics and chemical abundances expected a few kiloparsecs from the Sun. Figure 1, which shows the data of Laird, Carney & Latham (1988), illustrates the difference between the thick disk and the halo in terms of kinematics and metallicity. The mean value of the rotation velocity decreases from $\sim 160\,\mathrm{km\,s^{-1}}$ at $[\mathrm{Fe/H}] = -0.8$ (these values are evidently still poorly determined) to near zero at $[\mathrm{Fe/H}] = -1.5$, and shows no significant correlation at lower abundances. The broad distribution of properties of the different components of the galaxy is evident, illustrating the difficulties in distinguishing between continuous and discrete multi-component descriptions of the Galaxy.

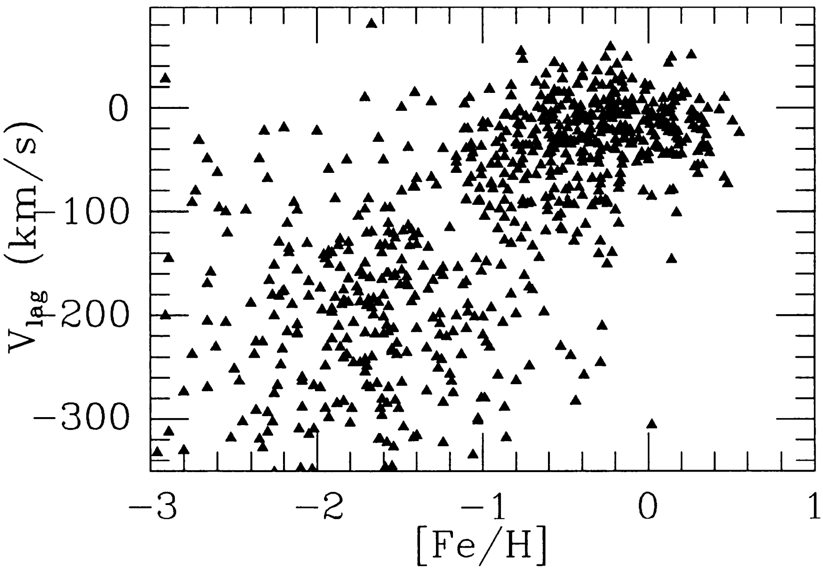

Figure 1. The relation between rotation velocity relative to the Sun, V_{lag}, and metallicity, for the sample of proper motion stars studied by Laird, Carney & Latham (1988).

A question of some interest is whether or not the appearance of Figure 1 is consistent with a continuous trend – indicative perhaps of significant star formation *during* the period when the protogalaxy was collapsing and spinning-up, or represents a superposition of relatively discrete sub-systems – indicative perhaps of the later merger of subsystems which retained a recognisable identity during the early stages of Galactic formation. Some suggestive rather than conclusive evidence in favour of the picture of discrete substructure in phase space comes from the existence of several apparently intermediate groups of tracers which are identifiably discrete using astrophysical criteria. These include the metal-rich RR Lyrae stars ($\Delta S \lesssim 3$, $V_{rot} \sim 110\,km\,s^{-1}$, Strugnell *et al.* 1986); c-type RR Lyrae stars ($V_{rot} \sim 100\,km\,s^{-1}$, Strugnell *et al.* 1986); long period variables with 150d $\lesssim$ Period $\lesssim$ 200d, ($V_{rot} \sim 115\,km\,s^{-1}$, Osvalds & Risley 1961); the metal rich (G-type) globular clusters ($[Fe/H] \gtrsim -1, V_{rot} \sim 100 - 200\,km\,s^{-1}$, Armandroff 1989); and the Arcturus moving group ($V_{rot} \sim 110\,km\,s^{-1}$, Eggen 1987). The field type-II Cepheids (Harris 1981) are another closely related tracer sample, but with less well-known kinematical properties at present.

2.2 Photometrically Selected Samples

Although solar-neighbourhood, proper-motion selected samples provide valuable clues to the earliest phases of Galaxy formation, the kinematic biases inherent in these samples require careful modelling. It is therefore desirable to have available an *in situ* sample, truly representative of the dominant stellar population. A variety of such studies exist or are in progress, and are summarised by Gilmore, Wyse & Kuijken (1989). The available data provide the following description of the thick stellar disk:

The thick disk has a scale-height of $\sim$ 1 kpc, at least at the solar radius, and of order 2% of local stars belong to this component (the other $\sim$ 98% being members of the thin disk, with the $r^{1/4}$ spheroid accounting for merely a fraction of a percent). The first evidence for the global applicability of these thick disk parameters (Gilmore & Reid 1983) is found in the analysis by Fenkart (1989 and refs therein) of the extensive star-count data set available from the Basel Halo Program, in many fields at both high and low Galactic latitudes.

The total luminosity of the thick disk can at present best be constrained either by analogy with external galaxies (van der Kruit 1987; Wyse & Gilmore 1988) or by theoretical considerations, such as the chemical evolution of the Galaxy (Gilmore & Wyse 1986). These imply that the thick disk dominates over the $r^{1/4}$ spheroid out to many kpc away from the plane, and probably has a total luminosity several times that of the metal-poor $r^{1/4}$ spheroid, or a few $\times 10^9 L_\odot$. 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.

The vertical velocity dispersion corresponding to a scale-height of $\sim$ 1 kpc, $\sim$ 45 $km\,s^{-1}$, has now been observed in many samples (Hartkopf & Yoss 1982; Sandage &

Fouts 1987; Carney, Latham & Laird 1989; Ratnatunga & Freeman 1985). Figure 2 shows the run of vertical velocity dispersion with height above the plane, from the photometrically-selected samples of Gilmore & Kuijken (Kuijken & Gilmore 1989) and of Gilmore & Wyse (in preparation). Typical thick disk stars appear to be on high-angular-momentum orbits (Sandage & Fouts 1987; Carney, Latham & Laird 1989; Ratnatunga & Freeman 1985), lagging behind the Sun by only $\sim 40\ \mathrm{km\,s^{-1}}$. 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 thick disk is probably also kinematically discrete from the Galactic old thin disk, though the data remain inadequate for robust conclusions (Norris 1987; Gilmore, Wyse & Kuijken 1989). Determination of the kinematic relationship between the thin and the thick disks is of interest primarily as a test of the dynamical history of high angular momentum material early in the evolution of the Galaxy, and thus is a topic of considerable current activity.

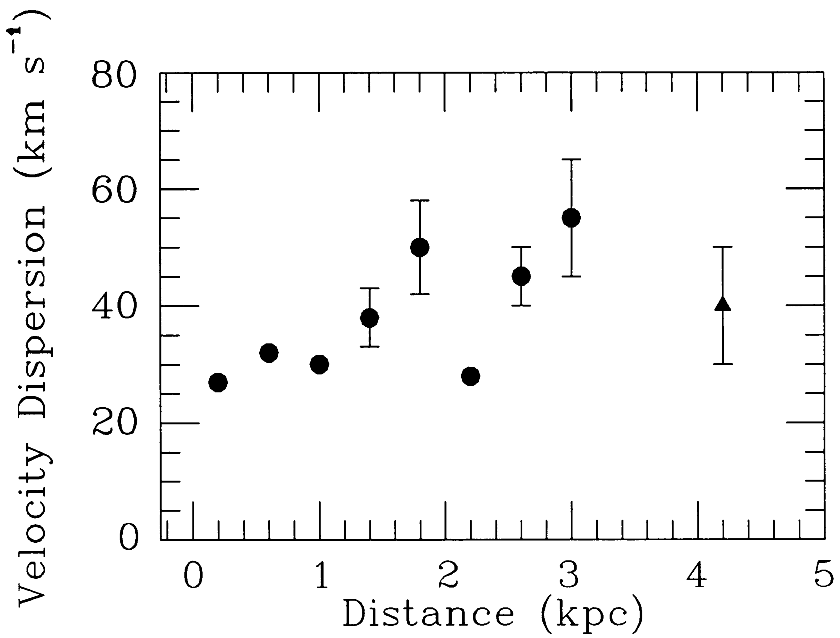

Figure 2. Vertical velocity dispersion for samples of stars *in situ* at height z above the plane of the Galaxy. Circles: some data from the ongoing Wyse/Gilmore survey; triangle Hartkopf & Yoss (1982).

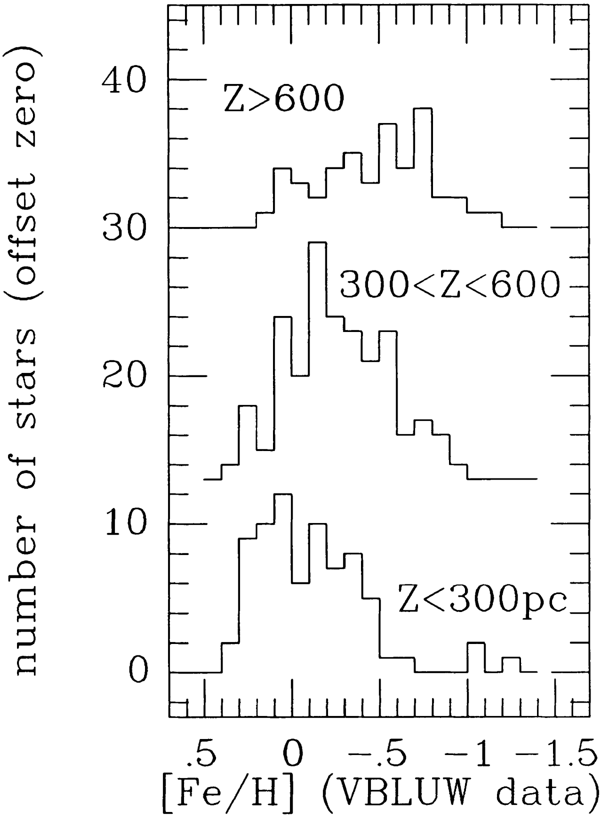

Figure 3. Metallicity distributions for F/G stars observed at different heights above the plane.

The mean metallicity of thick disk stars, which dominate 1 – 2 kpc above the Galactic plane, is about one-quarter of the solar metallicity (Gilmore & Wyse 1985) *i.e.* [Fe/H] ~ -0.7 dex. Their abundance distribution is important in understanding the chemical evolution of the solar neighbourhood, which requires knowledge of the abundance distribution for long-lived stars in a *representative* volume of the Galaxy. The large scale-height and low local normalisation of the thick disk meant that these stars were not found in the earlier small surveys of stars in the solar neighbourhood, even though they contribute significantly to the abundance distribution in a column through the Galactic disk, and may provide an elegant solution to the G-dwarf problem (Gilmore & Wyse 1986).[♠] Figure 3 shows the

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[♠] The 'G-dwarf problem' is the observed paucity of metal-poor G-dwarfs in the solar-neighbourhood, relative to the predictions of the most naive model of chemical evolution (van den Bergh 1958; Pagel & Patchett 1975) Since late G-dwarfs live for a data of Trefzger *et al.* (1990) for their sample of G-type stars selected from the Basel photographic RGU survey in three fields *viz.* the SGP, SA 94 and SA 107. Thus their sample is selected on a purely photometric basis, with metallicities and gravities estimated *via* Walraven VBLUW photometry. Their data are displayed in three bins of distance above the Galactic plane (the sample is complete only to $z = 600$pc). As is clear from the Figure, the data are better characterized not by a steady decrease in mean metallicity with increasing height above the plane, but rather by increasing dominance of a peak with mean metallicity [Fe/H]~ -0.7 dex, the thick disk. Similar results are apparent from the studies by Gilmore & Wyse (1985); Friel (1987); Sandage & Fouts (1987); Laird, Carney & Latham (1988).

3. FORMATION OF THE THICK DISK

Possible formation mechanisms for the thick disk include:

♡ A slow, pressure-supported collapse phase following formation of the extreme Population II system, similar to the sequence of events in Larson's (1976) hydrodynamical models of disk galaxy formation. The thick disk is then simply part of the thin disk, since the physics of formation is the same, but the oldest part. It should be remembered that Larson's models represent state-of-the-art for the 1970s rather than the 1990s. More numerically sophisticated analyses are required – and are being developed – to treat such parameters as viscosity, which Larson found to be a crucial parameter determining the final morphology of the galaxy, before one could confidently compare such models with observation.

♡ Violent dynamical heating of the thin disk by *(a)* satellite accretion (*c.f.* Hernquist & Quinn 1990), or by *(b)* violent relaxation of the non-spherical Galactic potential (Jones & Wyse 1983). The thick disk is then some part of the once-thin disk. For satellite accretion models the range of ages of the stars in the thick disk is determined by the epoch(s?) of satellite accretion, while the structural parameters of the thick disk (both radial profile and vertical profile) are determined by the details of the initial orbits of the satellites. Simulations of satellite accretion that contain all the known important physical effects have yet to be completed (Quinn 1990). In case *(b)* the present thick disk obviously consists of the oldest once-thin-disk stars, and the structural paremeters may be expected to be more uniform.

♡ An extended period of enhanced kinematic diffusion of stars formed in the thin disk to higher-energy orbits. The details of the heating process will determine the

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Hubble time all late G-dwarfs ever born should still be around today. They thus can form a convenient tracer of the time-integrated chemical abundance distribution, provided only that one determines abundances for an unbiassed subset of them within a suitably large volume. This volume must include the G-dwarfs in the thick disk.

properties of stars in the thick disk. As yet there is no identified heating mechanism that can produce the required vertical structure.

♡ A rapid increase in the dissipation and star-formation rates due to enhanced cooling once the metallicity is above ~ −1 dex (*c.f.* Wyse & Gilmore 1988).

The importance of the thick disk in terms of the disk-halo transition clearly differs among these models; discrimination amongst these several types of model is possible from appropriate age, metallicity, and kinematic data.

4. THE AGE OF THE THICK DISK

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 $uvby\beta$ photometry with theoretical isochrones is by far the most reliable and precise age-dating technique available. 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 (*c.f. e.g.* Gilmore & Wyse 1987), and is illustrated in Figure 4. This figure shows the colour-metallicity data for the high proper-motion stars studied by Laird, Carney, & Latham (1988), as well as the turn-off points of all those globular clusters with recent CCD photometry, and a representative isochrone for old metal-rich stars (VandenBerg & Bell 1985).

The important conclusion from Figure 4 is that essentially all of the stars with [Fe/H] $\lesssim -0.8$ are, insofar as is measurable, the same age as the globular cluster system. Stars more metal rich than ~ −0.8 dex 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. Stromgren photometry has been obtained by Nissen *et al.* (1990) for a photometrically-selected sample of evolved (turnoff) F/G stars, from which metallicities and ages can be derived. Their results support the conclusions from Figure 4, and further show that there is little spread in ages of stars more metal-poor than ≈ −0.5 dex, the scatter being 2–3 Gyr. Thus, stars of metallicity typical of the thick disk are as old as the (younger) disk globular clusters *i.e.* ~ 12 Gyr.

The distinct age and metallicity of the thick disk are severe constraints on the formation mechanism of the thick disk. In particular, they argue against kinematic diffusion of thin disk stars, and against recent satellite accretion causing heating of the thin disk, without considerable *post hoc* fine-tuning.

The absence of a younger turnoff shows that no substantial continuing star formation has taken place in the spheroid – though note the existence of some apparently young high latitude metal-rich A stars whose place of formation remains

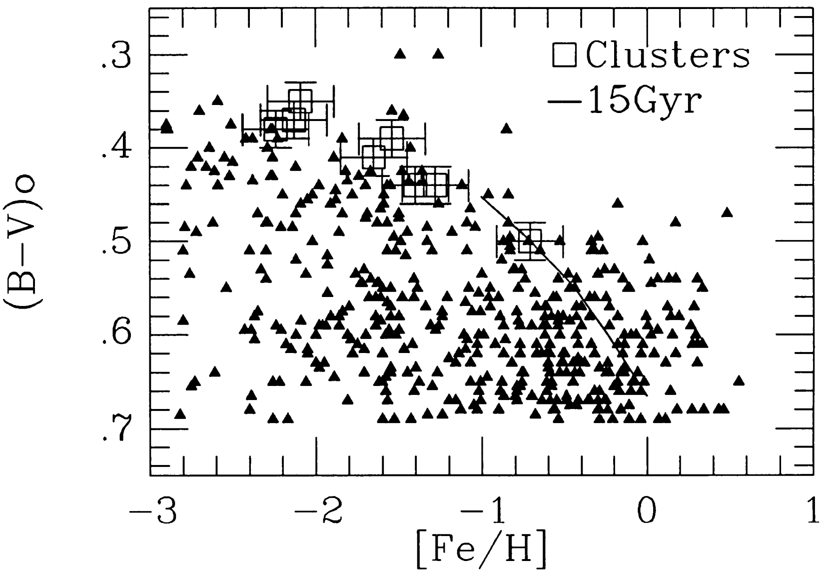

Figure 4. The B−V *vs* [Fe/H] relation for all stars observed by Laird, Carney, & Latham (1988; points), and for those globular clusters with recent turnoff colours from CCD photometry (Stetson & Harris 1988; boxes). The photometric data are corrected for interstellar reddening. The solid line is a 15Gyr isochrone calculated with oxygen-enhanced element ratios, and scaled in B−V to match the turnoff colour of 47Tuc. The blue edge of the stars with [Fe/H] $\lesssim -0.7$ is adequately defined by the isochrone and by the globular cluster data, showing that effectively all stars more metal poor than ~ -0.7 dex are as old as the globular clusters. At higher abundances the trend for the data to move to the blue of the isochrone shows that at least some stars are younger than the globular clusters.

an extremely important mystery (Lance 1988) and some distant B stars which cannot have travelled from the thin disk in their main sequence lifetimes (Keenan *et al.* 1986: Conlon *et al.* 1988).

5. CHEMICAL ELEMENT RATIOS

In attempting to deduce the rate of star formation and dynamical evolution in a proto-galaxy, it is desirable to have available a clock which is able to resolve 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 (Type II supernovae), and another subset (most importantly iron) which is also created during the evolution of lower mass stars (Type I supernovae). Since the evolutionary timescales for high– and low–mass stars span the timescale range of interest in galaxy formation, the differential enrichment of elements such as oxygen and iron provides an ideal clock to calibrate the rate of star formation in the proto-Galaxy.

Element ratios have been now been measured for a sufficient number of stars to define the systematic trends in the data (Wheeler, Sneden & Truran 1989; Nissen 1990). A significant change of slope occurs in the relationship between the element ratios [O/Fe] and [Fe/H] close to the iron abundance where there also occurs a change in the stellar kinematics, that is at [Fe/H] ~ -1. The 'alpha' elements, so-called since their synthesis involves the addition of a helium nucleus to an extant nucleus, are believed to have similar stellar nucleosynthesis sites to those of oxygen, and so may be expected to show the same elemental ratio patterns. However, as emphasised by Lambert (1989), and most recently confirmed by Nissen (1990), magnesium shows a further break, in that the trend of [Mg/Fe] with [Fe/H] changes slope at [Fe/H] ~ -0.5. It should be remembered that the two values of [Fe/H] where the element ratios show breaks essentially bracket the thick disk – which is kinematically distinct certainly from the $r^{1/4}$ spheroid, and most probably from the thin disk. Indeed, Nissen's results mean that the thick disk may be defined equivalently in terms of [Mg/Fe], or in terms of of [Fe/H], or of kinematics.

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. 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 ~ -1 dex. It is not crucial for these arguments that the breaks in kinematics and element ratios occur at *exactly* the same metallicity.

As mentioned above, the breaks are generally explained by appeal to the onset of an additional source of one element, while keeping the sources of the other element constant. For example, the break in [O/Fe] at [Fe/H] ~ -1 can be understood by postulating that the stars more metal-rich than this formed subsequently to the explosion of a significant number of low mass and long-lived supernova progenitors (Type I). 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 (*c.f.* Iben 1986); the lowest mass, and hence most numerous, progenitors of CO white dwarfs have main-sequence masses and lifetimes of $\sim 5\mathcal{M}_\odot$ 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 will 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.

The second break, seen in [Mg/Fe] but not in [O/Fe], means that we do not understand the nucleosynthetic sites of these elements, since this is not predicted by present models (Wheeler, Sneden & Truran 1989).

The inhomogeneity and temporal variability of the star-formation process in the Galaxy is constrained by the important fact that there is apparently *no intrinsic scatter* in the value of the ratio [Mg/Fe] at a given [Fe/H]; all the scatter found is consistent with observational uncertainties. This lack of scatter contrasts with the recently-established but large (factor of several) intrinsic scatter in the [Fe/H]-age relationship for thin disk stars ([Fe/H] $\gtrsim -0.6$; Nissen *et al.* in preparation). Consistency between these observations suggests that the different elements are synthesised in the same enrichment 'event', but that enriched material can be transported a significant distance.

6. THE PRESENT EVOLUTION OF THE THICK DISK

Assuming that the age of the thick disk stars reflects the formation epoch of the thick disk leads to the conclusion that the thick disk is a fossil of the interstellar disk-halo connection during the early evolution of the Galaxy. The importance of the thick disk at the present epoch for the interstellar medium lies in the later stages of stellar evolution of its constituent stars. The mass loss from these stars provides a source of unenriched material from quiescent stellar winds and a source of enriched material from more violent events such as planetary nebula formation and Type I supernovae. The momentum and energy injection into the interstellar medium can also be significant, contributing to the existence of a tenuous, warm gaseous component above the plane, remembering that the sources are distributed vertically with a scale-height of $\gtrsim 1$ kpc (*c.f.* Heiles 1987, who first discussed the importance of Type I supernovae to the energy balance of the interstellar medium above the plane, but without taking account of the thick disk).

7. CONCLUSIONS

Metallicity may be used with reasonable confidence to distinguish the stellar populations in the Galaxy : [Fe/H]$= -1$ is a definable metal-rich end of the 'halo', while [Fe/H] $= -0.5$ is the metal-poor end of the thin disk. The stars with metallicity between these two limits belong to the stellar disk-halo connection, the thick disk. This population was first identified by star counts, and thus was originally characterized in terms of its vertical structure, but can be equivalently defined by kinematics – σ_W or V_{rot} – or by chemical abundances – [Fe/H] or [Mg/Fe] – and possibly also by age.

The thick disk stars are old, and hence provide a fossil record of the interstellar medium in the early galaxy, mapping its enrichment and mixing history. They are now relevant as a source of new interstellar gas, and as a source of energy and of momentum, at high vertical distance.

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