Thickening of galactic discs through clustered star formation

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ABSTRACT

The building blocks of galaxies are star clusters. These form with low star formation efficiencies and, consequently, lose a large part of their stars that expand outwards once the residual gas is expelled by the action of the massive stars. Massive star clusters may thus add kinematically hot components to galactic field populations. This kinematical imprint on the stellar distribution function is estimated here by calculating the velocity distribution function for ensembles of star clusters distributed as power-law or log-normal initial cluster mass functions (ICMFs). The resulting stellar velocity distribution function is non-Gaussian and may be interpreted as being composed of multiple kinematical subpopulations.

The velocity dispersion of solar-neighbourhood stars increases more rapidly with stellar age than theoretical calculations of orbital diffusion predict. Interpreting this difference to arise from star formation characterized by larger cluster masses, rather than as yet unknown stellar-dynamical heating mechanisms, suggests that the star formation rate in the Milky Way disc has been quietening down, or at least shifting towards less massive star-forming units. Thin-disc stars with ages 3–7 Gyr may have formed from an ICMF extending to very rich Galactic clusters. Stars appear to be forming preferentially in modest embedded clusters during the past 3 Gyr.

Applying this approach to the ancient thick disc of the Milky Way, it follows that its large velocity dispersion may have been produced through a high star formation rate and thus an ICMF extending to massive embedded clusters (<10^5–6 M☉), even under the extreme assumption that early star formation occurred in a thin gas-rich disc. This enhanced star formation episode in an early thin Galactic disc could have been triggered by passing satellite galaxies, but direct satellite infall into the disc may not be required for disc heating.

Key words: stars: kinematics – Galaxy: evolution – Galaxy: formation – globular clusters: general – open clusters and associations: general – Galaxy: structure.

1 INTRODUCTION

Observations have shown that the Milky Way (MW) and other comparable disc galaxies are composed of a number of more-or-less discrete components. The broadest categories of these comprise the central bulge with a mass ≈10^10 M☉ and a characteristic radius of about 1 kpc, the Galactic spheroid (or stellar halo) with a mass ≈10^8 M☉ being mostly confined to within the solar radius and also containing globular clusters that add up to a mass of about 10^6–7 M☉, the embedded stellar and gaseous disc, and a hypothesized extensive dark matter halo surrounding the lot and extending to 20–200 kpc (see Gilmore, Wyse & Kuijken 1989 and Binney & Merrifield 1998, hereafter BM, for reviews). For the MW, the disc can be subdivided into at least two components, namely the thin disc with a mass of about M_{disc} = 5 × 10^{10} M☉, with exponential radial and vertical scalelengths of approximately h_R = 3.5 kpc and h_z = 250 pc, respectively, and the thick disc with roughly h_{thd, R} = 3.5 kpc and h_{thd, z} = 1000 pc. Near the Sun, the thick disc comprises about 6 per cent of the thin-disc mass (Robin et al. 1996; Buser, Rong & Karaali 1999; Chiba & Beers 2000; Vallenari, Bertelli & Schmidtobreick 2000; Kerber, Javiel & Santiago 2001; Reylé & Robin 2001), so that the thick-disc mass amounts to M_{thd} = (0.2–0.3) × M_{disc}. Mass-models of the MW, let alone of other disc galaxies, remain rather uncertain though (Dehnen & Binney 1998).

The structure of galaxies is linked to the physics of their formation, which is the topic of much ongoing research (e.g. Chiba & Beers 2000; Reylé & Robin 2001). Relevant to the long-term survival of thin discs is understanding the origin of the Galactic thick disc. This component is made up mostly of low-metallicity ([Fe/H] ≤ −0.4) stars that have a velocity dispersion perpendicular to the disc plane of σ_z,obs ≈ 40 pc Myr^{-1}, compared to the
significantly smaller $\sigma$, of the thin disc, which varies from about 2\r$-5$ pc Myr$^{-1}$ for the youngest stars to about 25 pc Myr$^{-1}$ for stars about 10 Gyr old (Fuchs et al. 2001). The classical work of Wielen (1977) has shown that this increase can be understood as a result of progressive heating of the thin disc population through a diffusive mechanism.

The heating agent remains elusive though. This is nicely evident in the work of Asiain, Figueras & Torra (1999), who find that spiral arms and a central Galactic bar alone cannot account for the diffusion, and, as shown by Fuchs et al. (2001), scattering off molecular clouds also cannot produce the necessary heating. Jenkins (1992) also shows that heating through spirals and molecular clouds, and adiabatic heating through mass growth of the Galactic disc, do not lead to the observed rise in velocity dispersion with stellar age. Even worse, assuming that orbital diffusion does operate from some yet to be discovered scattering agent(s), the large $\sigma$, for thick-disc stars cannot be obtained from an extension of the Wielen heating law. It follows that the thick disc must have formed under different conditions. This may be expected naturally, given that thick disc stars are not substantially younger than the old halo stars, thus having been born at the very beginning of the formation of the Galactic disc (e.g. Gilmore & Wyse 2001).

There are two broad classes of theories for the formation of a thick disc component. One class of models involves the settling of an initially hot protogalactic gas cloud. A thick disc may form as a result of dissipational settling to a thin disc (Burkert, Truran & Hensler 1992). According to the alternative hypothesis, the MW formed from many smaller components in a chaotic manner, leading first to the formation of the spheroidal components, and a few Gyr later, of the thin gaseous disc. Perturbation of the early thin stellar disc through continued accretion of dwarf galaxies may have lead to a thick disc component, a scenario that has the advantage of not producing a vertical metallicity gradient in the disc. $N$-body computations, however, may cast doubt on this scenario, because realistic dwarf galaxies that have densities comparable to the parent galaxy are likely to be destroyed before they venture close enough to the disc to cause significant vertical heating (Huang & Carlberg 1997; Sellwood, Nelson & Tremaine 1998; Velazquez & White 1999), but the situation is not clear since adequate computational resolution of gas-rich and star-forming galactic discs is at present not possible. The current state of understanding concerning the MW thick disc is reviewed by Norris (1999), who stresses that its origin remains unclear, and by Gilmore & Wyse (2001), who present the first results of an extensive observational UK–Australian collaboration towards casting light on this issue.

This paper addresses an additional mechanism that may be relevant to the thickness of discs, and which is motivated by recent progress on understanding star-cluster formation. Section 2 summarizes clustered star formation, and details the calculation of the stellar velocity distribution function. It also discusses known heating mechanisms active in disc galaxies that increase the velocity dispersion of stars with time. The large velocity dispersion of the thick disc is considered in Section 3 by studying the velocity field produced in a thin disc in which star formation is actively ongoing. The initial cluster mass function (ICMF) required to give the observed velocity dispersion is constrained. Similarly, the residuals of thin-disc age–velocity-dispersion data over current understanding of secular disc heating are analysed and linked to the star formation history in Section 4. Section 5 contains a discussion of the findings, and concluding remarks follow in Section 6.

## 2 KINEMATICAL IMPLICATIONS OF CLUSTERED STAR FORMATION

Stars are essentially never observed to form in isolation, but rather in a spectrum of diversely rich clusters. As outlined in Kroupa (2001a) and Boily & Kroupa (2001), a star cluster forms stars over a time period $\tau_{\text{cl}} \approx 1-2$ Myr in a contracting gas-cloud. Because the collapse time of an individual protostar takes of the order of $0.1$ Myr $\ll \tau_{\text{cl}}$, each protostar decouples dynamically from the gas and has enough time to add to the growing star + gas system that is, consequently, approximately in virial equilibrium at any time, provided that the protocluster crossing time (equation 1 in Kroupa 2001a) is shorter than $\tau_{\text{cl}}$. This is true for cluster masses $M_{\text{cl}} \geq 500 M_{\odot}$ and cluster radii of 1 pc. In sufficiently rich clusters, O stars terminate star formation, and a large proportion of the cluster stars become unbound as a result of rapid expulsion of the remaining gas and the intrinsically low star formation efficiency, $\varepsilon = M_{\text{cl}}/(M_{\text{cl}} + M_{\text{gas}}) \approx 0.4$, where $M_{\text{cl}}$ and $M_{\text{gas}}$ are the masses in stars and gas, respectively, before gas-expulsion. Observations of very young clusters support this scenario. For example, the Orion nebula cluster is at most 2 Myr and probably only a few $10^6$ yr old, and already largely void of gas. Similarly, the massive 30 Doradus cluster in the Large Magellanic Cloud is not much older and has already removed its gas.

Direct computations of these processes using the Aarseth state-of-the-art direct $N$-body code are now available. Beginning with $N = 10^4$ stars in an Orion-nebula-cluster-like configuration, and assuming $\varepsilon = 0.33$ with the residual gas being blown out faster than the cluster’s dynamical time, Kroupa, Aarseth & Hurley (2001) find that about $2/3$ of the cluster stars are lost and form a rapidly expanding stellar association, while a Pleiades-like cluster condenses as a nucleus near the origin of the flow. The relative number of massive stars remaining in the core that forms the cluster, and those that are lost, depends on the initial concentration of the cluster prior to gas expulsion, and whether the massive stars form near the centre of the cluster. This scenario is supported by the fact that the velocity dispersion in the Orion nebula cluster is supervirial (e.g. Jones & Walker 1988), so that it is probably expanding now (Kroupa, Petr & McCaughrean 1999; Kroupa 2000; Kroupa et al. 2001). Especially striking in this context is the very recent measurement of the velocity dispersion of stars in the 30 Doradus cluster by Bosch et al. (2001), who find $\sigma = 35$ pc Myr$^{-1}$. This is too large for the cluster’s mass, and the authors attribute the surplus kinetic energy as being due to binary-star orbital motion and a binary proportion among the massive stars of 100 per cent. The notion raised here is that the velocity dispersion may also appear inflated due to recent gas blow-out. This notion that star clusters form as the nuclei of expanding OB associations is also (retrospectively) supported by the distribution of young stars around the 30 Doradus cluster, suggesting that it is the core of a stellar association (Seleznev 1997), and the likely association of the $\alpha$ Persei cluster with the Cas–Tau OB association noted by Brown (2001), and other moving groups with star clusters (Chereul, Crézé & Bienaymé 1998; Asiain et al. 1999). Furthermore, Williams & Hodge (2001) note that most of the young clusters in M31 are located within large OB associations.

The unbound population expands approximately with a one-dimensional velocity dispersion, $\sigma$, typical of the pre-gas-expulsion cluster + gas mixture. Neglecting factors of the order of one,

$$\sigma = \sigma_{0,\text{cl}} = \sqrt{\frac{GM_{\text{cl}}}{\epsilon R_{\text{cl}}}}$$  \hspace{1cm} (1)
where $G = 0.0045 \text{ pc}^3/(\text{M}_\odot \text{ Myr}^2)$ is the gravitational constant, and $R_0$ the characteristic embedded-cluster radius. It becomes immediately apparent that $\sigma_{0,\text{cl}} = 40 \text{ pc Myr}^{-1}$ (1 km s$^{-1} = 1$ pc Myr$^{-1}$) corresponds to

$$M_{\text{cl}} = 10^{5.5} \text{ M}_\odot \text{ pc}^{-1},$$

coming close to a typical globular cluster mass if $\epsilon R_0 = 0.3$ pc, which is typical for young embedded clusters that have characteristic radii $R_0 = 1$ pc ($R_0 = 1$ pc is assumed in what follows, unless stated otherwise; examples of results with $R_0 = 5$ pc are given in Fig. 8). Most of the variation of $\sigma$ stems from variations of the embedded cluster mass which spans many orders of magnitude, in contrast to the typical radii of modest embedded clusters and very young massive clusters, all of which are more concentrated than a few pc. For example, local modest embedded clusters have $R_0 \leq 1$ pc (Kaas & Bontemps 2001; Lada & Lada 1991), while the rich Orion nebula cluster has $R \approx 2$ pc (Hillenbrand & Hartmann 1998). Young massive clusters in external galaxies have $R \approx 2$–$5$ pc (e.g., R136 in the Large Magellanic Cloud, Massey & Hunter 1998; Sirianni et al. 2000) and in massively interacting gas-rich galaxies, the Antennae, the young massive clusters remain unresolved with $R \leq 5$ pc (Whitmore 2001). These clusters are, however, already devoid of their gas despite being less than a few Myr old, so they should have already expanded ($R > R_0$). This is also true for the somewhat older clusters in a sample of early-type galaxies compiled by Larsen et al. (2001) ($R \leq 4$ pc), and in M31 Williams & Hodge (2001) note cluster radii $R \leq 5$ pc for cluster ages between about 10 and 200 Myr.

Expansion also implies that the observed velocity dispersion in clusters is smaller than $\sigma_{0,\text{cl}}$. For example, Ho & Filippenko (1996) measure a line-of-sight velocity dispersion of about 11–16 pc Myr$^{-1}$ for two extragalactic young massive star clusters. These have inferred masses of about $10^4 \text{ M}_\odot$ and are $10$–$20$ Myr old. Smith & Gallagher (2001) find $13$ pc Myr$^{-1}$ for a young massive cluster (60 ± 20 Myr old) in M82, and deduce its mass to be about $10^6 \text{ M}_\odot$. If the present notion is correct and if $\epsilon = 0.3$, then the deduced cluster masses correspond to only about 30 per cent of their birth stellar masses ($M_{\text{cl}}$).

Star clusters with masses indicated in (2) are observed to form in profusion whenever gas-rich galaxies interact or are perturbed (see Lancer & Boily 2000 and Larsen 2001 for overviews). It is thus feasible that equation (2) may indicate that the thick disc resulted from massive clusters forming in a thin disc, rather than being produced through orbital scattering by a merging satellite galaxy. Perturbation of an early thin and gas-rich MW disc by a passing satellite may suffice to trigger the required star formation.

### 2.1 The velocity distribution function

To address the above question, the distribution function of stellar velocities resulting from a burst of star formation needs to be estimated. Attention is focused on velocities perpendicular to the Galactic disc, because motions in the plane are much more difficult to handle analytically since they depend on the evolving mass distribution throughout the entire MW. An extension to include the velocity ellipsoid would go beyond the scope of this scouting work, but will be addressed in future contributions.

As an Ansatz, the distribution of stellar velocities in one dimension (perpendicular to the Galactic disc, $v_z$) in the cluster prior to gas expulsion is assumed to be Gaussian (i.e., a one-dimensional Schwarzschild distribution),

$$g(\sigma, v_z) = \frac{1}{\sqrt{2\pi} \sigma} e^{-\frac{(v_z - \bar{v}_z)^2}{2\sigma^2}},$$

$v_z$ being the centre-of-mass velocity of the cluster, and $\int_{-\infty}^{\infty} g(\sigma, v_z) = 1$. Gas expulsion leads to isotropic expansion, and the velocity dispersions in galactic radial and tangential directions can be linked to the $z$-component via the epicyclic approximation if sufficiently small compared to the circular velocity about the galaxy (Binney & Tremaine 1987, hereafter BT). Large expansion velocities would require detailed orbit integration in a self-consistent potential, which goes beyond the aim of the present study. After the gas is expelled from the cluster, the major part of the stellar population is assumed to expand freely, conserving this distribution but with a velocity dispersion somewhat reduced due to self-gravity, and leaving behind the nucleus that forms the bound cluster (Kroupa et al. 2001). The cluster fills its tidal radius and has a much smaller velocity dispersion than $\sigma_{0,\text{cl}}$, but analytical quantification is difficult since the processes operating in shaping the cluster are complex (three- and four-body encounters redistributing kinetic energy into potential energy, stellar evolution, and tidal field).

The stellar velocity distribution function after gas expulsion for an ensemble of coeval identical clusters with mass $M_{\text{cl}}$ becomes

$$\mathcal{V}(v_z, M_{\text{cl}}) = k \mathcal{E}(v_z, M_{\text{cl}}) + (1 - k) C(v_z),$$

where $k(\epsilon)$ is the fraction of stars expelled after the gas is thrown from each cluster. The distribution function of the expanding stars is

$$\mathcal{E}(v_z, M_{\text{cl}}) = g(\sigma_{\text{exp}}, v_z) = 0,$$

since the centre-of-mass of the ensemble is stationary, and where

$$\sigma_{\text{exp}, s}^2(M_{\text{cl}}) = \frac{G M_{\text{cl}}}{\epsilon R_0} \bar{s} + \sigma_{\text{c}}^2,$$

is the velocity variance of the freely expanding populations, with $\sigma_{\text{c}}$ being the cluster–cluster velocity dispersion resulting from a cluster centre-of-mass velocity distribution that is assumed to be Gaussian (equation 3). In the present thin MW disc, molecular clouds move relative to each other with a velocity dispersion of about $5$ pc Myr$^{-1}$ (e.g. Jog & Ostriker 1988), so that $\sigma_{\text{c}} = 5$ pc Myr$^{-1}$ is adopted in what follows. Gravitational retardation of the expanding population is approximated through the reduction factor, $\epsilon = 1 - \bar{s}$, which comes from the loss of kinetic energy, as the fraction $\kappa$ $M_{\text{cl}}$ of the cluster expands out of the cluster potential well to infinity ($\sigma_{\text{exp}, s} - \sigma_{\text{c}} = \sigma_{\text{exp}, s} - GM_{\text{cl}}/R_0$, where $\sigma_{\text{exp}, s}$ is the velocity variance in the cluster prior to gas expulsion; equation 1).

In what follows it is assumed that the clusters live short lives relative to the age of their galaxy due to evaporation through two-body relaxation; any remaining clusters contributing an insignificant amount of stars. The clusters ultimately leave an extremely long-lived cluster remnant consisting of a strongly hierarchical multiple star system (de la Fuente Marcos 1997, 1998). The velocity distribution function of stars remaining in the cluster remnants and in the resulting tidal tails and moving groups is summarized as

$$C(v_z) = g(\sigma_{\text{cl}, s}, v_z) = 0.$$  

The velocity variance of the stars that ultimately leak out of the bound clusters that form as the nuclei of the expanding associations

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is approximated here by
\[ \sigma_{cl}^2 = (2 \text{ pc Myr}^{-1})^2 + \sigma_{\text{irr}}^2, \]  
(8)
taking the velocity dispersion in the cluster remnant and of its
evaporated stars to be 2 pc Myr\(^{-1}\).

Note that \[ \int_0^\infty v_1^2 \xi(v_1) = 1, \] and \( \kappa = 1 - e \) with \( e = 0.33 \)
is adopted based on the results of Kroupa et al. (2001) and discussion
therein. The star formation efficiency, \( e \), may, at most, be a weak
function of \( M_{cl} \), possibly achieving 0.5 for massive clusters
(Matzner & McKee 2000; Tan & McKee 2001).

Each cluster contributes \( M_{cl} \xi(M_{cl}) \) stars to the field population,
where \( m_{av} = 0.4 M_\odot \) is assumed to be the invariant average stellar
mass (Kroupa 2001b and Reylé & Robin 2001 note possible evidence for
a weak dependency on metallicity). The total number
of stars that result from a burst of star formation is thus
\[ N = \frac{1}{m_{av}} \int_{M_{cl,min}}^{M_{cl,max}} M_{cl} \xi(M_{cl}) dM_{cl} = \frac{\eta M_{disc}}{m_{av}}, \]  
(9)
where \( \xi(M_{cl}) dM_{cl} \) is the number of clusters with masses in the
range \( M_{cl} \) to \( M_{cl} + dM_{cl} \), and \( \eta \) is the fraction of the total galactic
disc mass in this population of clusters.

The ICMF, \( \xi(M_{cl}) \), is extremely hard to infer from the observed
distribution of cluster luminosities, because young clusters rapidly
evolve dynamically as well as photometrically, and since the light
need not follow mass by virtue of mass segregation. Stellar-
dynamical evolution of young or forming clusters stands only at the
beginning stages (Kroupa 2000; Kroupa et al. 2001), while
significant uncertainties in stellar evolution continue to hamper the
interpretation of the stellar population in clusters, let alone of
integrated cluster luminosities and colours of unresolved clusters
(Santos & Frogel 1997). Some progress is evident though, and for
example Whitmore et al. (1999), Elmegreen et al. (2000) and Maoz
et al. (2001) report, for different star-forming systems, power-law
ICMFs,
\[ \xi_{P}(M_{cl}) = \xi_{P0} M_{cl}^{-\alpha}, \]  
(10)
with \( \alpha = 1.5-2.6 \). Old globular clusters, however, are typically
distributed normally in \( \log(M_{cl}) = I_{M_{cl}} \), which is also the
distribution of young clusters reported by Fritze-von Alvensleben
(2000) for the interacting Antennae galaxies,
\[ \xi_{G}(I_{M_{cl}}) = \frac{\xi_{G0}}{\sqrt{2\pi \sigma_{M_{cl}}}} e^{-\frac{(I_{M_{cl}}-\mu_{M_{cl}})^2}{2\sigma_{M_{cl}}^2}}, \]  
(11)
where \( \mu_{M_{cl}} \approx 5.5 \) is the mean log-mass, \( \sigma_{M_{cl}} \approx 0.5 \) is the standard
deviation in log-mass \( (M_{cl} \) in units of \( M_\odot \)), and \( \xi_{G}(I_{M_{cl}}) dI_{M_{cl}} \) is the
number of clusters with log-mass in the interval \( I_{M_{cl}} \) to
\( I_{M_{cl}} + dI_{M_{cl}} \).

From equation (9),
\[ \xi_{P} = m_{av} N \left( 2 - \alpha \right) (M_{cl,max} - M_{cl,min})^{-\alpha}, \]  
(12)
and
\[ \xi_{G} = m_{av} N 10^{\left( \mu_{M_{cl}} - \mu_{M_{cl}} \right) \log_{10}(M_{cl})^2}, \]  
(13)
for integration over \( I_{M_{cl}} \) with \( I_{M_{cl,min}} = -\infty \) to \( I_{M_{cl,max}} = +\infty \),
remembering that \( 10^\phi = e^{\phi \ln 10}. \)

The distribution function of stellar velocities, \( D(v_z) \), which
results from the formation of an ensemble of star clusters, becomes
\[ D_P(v_z; M_{cl,max}, \alpha) = \frac{1}{m_{av}} \int_{M_{cl,min}}^{M_{cl,max}} M_{cl} \xi_p(M_{cl}) \sqrt{2\pi \sigma_{v_z}} e^{-\frac{v_z^2}{2\sigma_{v_z}^2}} dM_{cl}, \]  
(14)
and
\[ D_G(v_z; I_{M_{cl}}, \sigma_{M_{cl}}) = \frac{1}{m_{av}} \int_{I_{M_{cl}}}^{I_{M_{cl}}} 10^{\left( \mu_{M_{cl}} - \mu_{M_{cl}} \right) \log_{10}(M_{cl})} \sqrt{2\pi \sigma_{v_z}} e^{-\frac{v_z^2}{2\sigma_{v_z}^2}} dM_{cl}, \]  
(15)
with
\[ N = \int_{-\infty}^{\infty} D_{P_{G}}(v_z) dv_z. \]  
(16)

Equations (14) and (15) are solved by numerically integrating
\( dD_P(v_z)/dM_{cl} \) and \( dD_G(v_z)/dI_{M_{cl}} \) [initial condition \( D_{P_{G}}(v_z) = 0 \)
for \( M_{cl} = M_{cl,min} = 10 M_\odot \) or \( I_{M_{cl}} = I_{M_{cl,min}} = 1 \)] using a fifth-
order Runge–Kutta method with step-size adaptation (Press et al.
1994) for \( 1 \times 10^5 \) velocity bins ranging from \( v_z = -500 \text{ pc Myr}^{-1} \)
to \( v_z = +500 \text{ pc Myr}^{-1} \), \( 500 \text{ pc Myr}^{-1} \) being taken as the escape
velocity from the solar neighbourhood (e.g. BT). The mass interval
used for the log-normal ICDF, \( I_{M_{cl,min}} = 1, I_{M_{cl,max}} = 7 \) covers
the mass range of known star clusters, but implies that the
distribution \( D_G \) needs to be scaled numerically to \( N \), since
analytical integration cannot determine the correct constant \( \xi_{G0} \).

Note that the finite escape velocity from the galaxy implies
\( \int_{-\infty}^{\infty} D_{P_{G}}(v_z) dv_z < N \) by a negligible amount for ensembles of
clusters ranging up to \( M_{cl} = 10^3 M_\odot \). Note also that \( I_{M_{cl,max}} = 7 \) is
consistent with the allowed central number density for the Orion
nebula cluster (Kroupa 2000).

Results for the power-law ICDF with \( \alpha = 1.5 \) are plotted in Fig. 1.
Fig. 2. As Fig. 1, but assuming that the ICMF is a Gaussian in \( \log_{10}M_\text{cl} = \log_{10}M_\text{cl} \) with dispersion \( \sigma_{\text{IMF}} = 0.5 \) and mean \( \overline{M}_\text{cl} \) shown next to the curves (mass in M•). For the four models (equations 17 and 19); \( \sigma_0 = 99.4 \) pc Myr\(^{-1} \) with \( \phi = 0.33 \) (\( \overline{M}_\text{cl} = 5.5 \)), \( \sigma_0 = 37.5 \) pc Myr\(^{-1} \) with \( \phi = 0.33 \) (\( \overline{M}_\text{cl} = 4.5 \)), and \( \sigma_0 = 12.9 \) pc Myr\(^{-1} \) with \( \phi = 0.21 \) (\( \overline{M}_\text{cl} = 3.5 \)).

For Gaussian ICMFs the results are plotted in Fig. 2. In general, the resulting velocity distribution, \( D_{\text{PortG}} \), is distinctly non-Gaussian. Note the wings of high-velocity stars, which become more dominant with increasing \( M_{\text{Lmax}} \) and \( \overline{M}_\text{cl} \). The peak at \( v_z = 0 \) comes from the contribution of \( M_{\text{cl}} \approx 2000 M_\odot \) clusters, and because \( \kappa < 1 \) in equation (4). A cluster–cluster velocity dispersion, \( \sigma_v > 5 \) pc Myr\(^{-1} \), broadens this peak, but here interest is with the extreme case, namely the kinematical implications of cluster formation in a thin gaseous disc.

2.2 The velocity dispersion and population fraction

Given \( ^0D_{\text{PortG}} = D_{\text{PortG}} \), the variance of the velocities obtains from

\[
\sigma_n^2 = \frac{1}{N} \int_{v_n} v_z^2 \left[ \phi D_{\text{PortG}}(v_z) \right] \ dv_z,
\]

where \( n = 0, 1, 2, 3 \) are iterations. Equation (17) is integrated numerically. The entire distribution is used to compute the dispersion \( \sigma_n \). An observer would instead try to isolate distinct subpopulations from the distributions evident in Fig. 1 or Fig. 2, given their non-Gaussian form (e.g. Reid, Hawley & Gizis 1995; Gilmore & Wyse 2001). This is modelled here by replacing, in the first iteration, the central, low-velocity peak in \( ^0D_{\text{PortG}} \) by a Gaussian with dispersion \( \sigma_v, \) i.e., \( ^1D_{\text{PortG}} = \phi(\sigma_v, 0) \) for those \( v_z \), near zero for which \( ^0D_{\text{PortG}} \approx \mathcal{G} \), but \( ^1D_{\text{PortG}} = ^0D_{\text{PortG}} \) otherwise. This is repeated three times (see Fig. 3), until most of the central maximum is removed, yielding the improved estimate for the velocity dispersion

\[
\sigma_n = \sigma_v.
\]

Figs 4 and 5 show \( \sigma_n \) as a function of ICMF parameters.

An additional constraint is the relative number of stars in the peak and the whole population,

\[
\phi = \frac{N - 3N}{N},
\]

where \( ^0N = \frac{N}{N} \) (equation 16 with \( D_{\text{PortG}} = ^0D_{\text{PortG}} \)), and \( ^0N = \int v_z^0 D_{\text{PortG}}(v_z) \ dv_z \). The fraction of the population in the wings of the velocity distribution is thus \( 1 - \phi \), which is plotted in Fig. 6 for three values of \( \alpha \) and \( \sigma_{\text{IMF}} \). Admissible models for the thick disc must not have too many stars in the peak, so \( 1 - \phi \geq 0.6 \) is imposed, in addition to the constraint on \( \sigma_r \) (Section 3). Note that if the total thick disc mass amounts to a fraction \( \eta \) of the mass of the Galactic disc, then the observer will identify a fraction \( \eta(1 - \phi) \) of the Galactic disc as being the actual thick disc, whereas \( \phi \eta \) is the fraction of the thick disc 'hiding' (subject to adiabatic heating not taken into account here but in Section 2.3) as a thin disc component, but with the same chemical and age distribution as the observationally identified thick disc. Observations suggest

\[
\eta = \eta(1 - \phi) = 0.2 \pm 0.3
\]

(Section 1) so that \( \eta \leq 0.3 - 0.5 \). In fact, 'thin-disc' stars with [Fe/H] \( \leq -0.4 \) may simply be the low-velocity \( \phi \)-peak of the thick-disc population.

2.3 Adiabatic heating

If the disc surface mass density, \( \Sigma \), of a galaxy accumulates over time through infall, the velocity dispersion of already existing stars increases adiabatically, leading to an apparent heating of the disc.
Figure 4. Dependence of the velocity dispersion $\sigma_v$ (equation 18) on the maximum cluster mass, $M_{c,\text{max}}$, for a power-law ICMF for three different values of the power-law index $\alpha$ (line-types indicated in lower panel; $lM_{c,\text{max}} = \log \text{to} M_{c,\text{max}}$). The dotted line is the dependence of $\sigma_{0,cl}$ on $M_{c,\text{max}}$ (eq. 1 in Griffiths et al. 2001), and $\sigma_{0,cl}$ properties, so that the heating agent is still not fully accounted for.

Ensk: (1992) finds that adiabatic heating helps to explain the empirical Wielen disc heating in association with scattering on molecular clouds and spiral arms. The required cloud heating, however, remains incompatible with the observed molecular cloud properties, so that the heating agent is still not fully accounted for.

If the time evolution of the infall rate is $\dot{\rho}(t) = d\Sigma/dt$ and outflow can be neglected, then

$$\Sigma(t) = \int_0^{\rho_0} \dot{\rho}(t') dt' + \int_{\rho_0}^{\rho(t)} \dot{\rho}(t') dt';$$

with $\Sigma_{\text{now}} = \Sigma(t_{\text{now}})$ and $\Sigma_0 = \Sigma(0) = \eta \Sigma_{\text{now}}$ (equations 9 and 20), $t_0 = 4$ Gyr being the time when the thick disc material with surface mass density $\Sigma_0$ had accumulated (e.g. fig. 10.19 in BM; fig. 2 in Griffiths et al. 2001), and $t_{\text{now}} \approx 15$ Gyr being the present time. The dependence on Galactocentric distance, $R_g$, is dropped for conciseness, since the focus here is on the one sample available, namely near the Sun. Any infall history $\dot{\rho}(t)$ can be envisaged. Here, only a constant accretion rate on to the thin disc, $\dot{\rho}(t) = \dot{\rho}_0 = \Sigma_0(t_{\text{now}} - t_0)$, is considered to obtain insights into possible implications.

For highly flattened systems and using Jeans’s equations in the appropriate limit, $\Sigma = -1/(2\pi G \rho_0 \sigma_z^2)$ (Section 4.2 in BM), with the surface density $\Sigma = \int_0^\infty \rho(z') dz'$, $\rho(z)$ being the mass density at radial distance $R_g$ from the Galactic Centre and height $z$ above the disc plane. Assuming that the vertical structure of the MW at any $R_g$ is isothermal [$\sigma_z = \text{constant with } \rho(z) = \rho_0 \text{sech}^2(z/2\sigma_0)$], it follows that $\Sigma = (\sigma_z^2/2\sigma_0^4 \pi G) \text{tan}h(z/2\sigma_0)$. It can thus be assumed that as the mass of the disc builds up, $\sigma_z$ of existing stars increases following $\sigma_z^2 \propto \Sigma$ (see also Section 11.3.2 in BM). This implies that

$$\sigma_z^2(\Delta t) = \sigma_{z,\text{now}}^2 \left[ \eta + (1 - \eta) \frac{\Delta t}{\Delta t_{\text{now}}} \right],$$

where $\Delta t = t - t_0$ and $\Delta t_{\text{now}} = t_{\text{now}} - t_0$. The velocity ellipsoid of existing stars, defined by the velocity dispersions in galactic radial, azimuthal and vertical directions, distorts and rotates as a consequence of differential rotation and disc heating. However, the correction terms to $\sigma_z$ are negligible for the present treatment (equation 23 in Jenkins 1992).

Assuming that the ‘thick disc’ accumulated within a few Gyr and formed 30 per cent of the mass now in the MW disc ($\eta = 0.3$), $\sigma_{z,0} \approx 22$ pc Myr$^{-1}$ at formation ($\Delta t = 0$) follows from the presently observed value $\sigma_{z,\text{now}} \approx 40$ pc Myr$^{-1}$. Similarly, for the old thin disc $\sigma_{z,\text{obs}} \approx 25$ pc Myr$^{-1}$ (Fuchs et al. 2001), so that $\sigma_{z,0} \approx 14$ pc Myr$^{-1}$ at star formation from equation (22), while the observation of young stars suggest $\sigma_{z,0} \approx 2-5$ pc Myr$^{-1}$ (Asai et al. 1999; Fig. 7).

This thus demonstrates that if the Galactic disc accumulated mass at a uniform rate over its history, then the required heating of the thin disc is reduced, as already shown by Jenkins (1992). Nevertheless, as is evident in Fig. 7, additional heating is required to increase the velocity dispersion within $\approx 3$ Gyr to match the constraints of the Heidelberg group (Jahreiss, Fuchs & Wielen 1999; Fuchs et al. 2001). Jenkins (1992) shows that molecular clouds and spiral heating cannot account for this ‘minimal’ heating (minimal because adiabatic heating is taken into account),
although the possible short-lived nature of molecular clouds are not taken into account. If these are short-lived, with lifetimes \( \approx 10^6 - 10^7 \) yr, then an additional heating source may be active through the acceleration of young stars as they transgress time-varying cloud potentials. Asiain et al. (1999) note that different young moving groups appear to experience different heating histories if in fact their observed velocity dispersion is assumed to result from the same diffusive mechanism of Wielen (1977). Alternatively, they suggest that the diffusion constants differ between associations (‘episodic diffusion’).

On the other hand, according to the line of argument followed here, individual star-forming events produce associations that expand as a result of gas loss at different rates, and thus with different velocity dispersions depending on the particular star clusters sampled from the ICMF. Expansion thus depends on the density of the star formation episode. The history of \( \sigma_{\text{vel,obs}}(t) \) plotted in Fig. 7 may therefore be a mixture of adiabatic heating, heating from spiral arms and molecular clouds, and fluctuations of the velocity dispersion due to clustered star formation. It will not be easy to disentangle all these effects, given that the history of clustered star formation is not known, but an exemplary attempt is made in Section 4. There the approach is to adopt the age–velocity-dispersion data and Jenkins’s model, and to constrain the ICMFs that are required to give the unaccounted-for, or ‘abnormal’, velocity dispersions.

\[ 1 - \phi \text{, (equation 19)} \text{ on the maximum cluster mass, } M_{\text{cl,max}} \text{, for a power-law ICMF for three different values of the power-law index } \alpha \text{ (upper panel, as in Fig. 4), and on the average log-mass, } \ln M_{\text{cl}} = \hat{M}_{\text{cl}} \text{, for three different values of the standard deviation in log-mass, } \sigma_{\text{std,cl}} \text{, for a log-normal ICMF (lower panel, as in Fig. 5). The region between the horizontal dotted lines approximately constitutes the range of acceptable thick-disc models } (1 - \phi > 0.6) \text{, provided that the constraint on } \sigma_{\text{vel,obs}} \text{ is fulfilled (Fig. 8 below).}

Figure 6. Dependence of the fraction of stars in the wing component only, \( 1 - \phi \), in the thick disc only, \( \alpha = 2.3 \) (equation 19) on the maximum cluster mass, \( M_{\text{cl,max}} \), for a power-law ICMF for three different values of the power-law index \( \alpha \) (upper panel, as in Fig. 4), and on the average log-mass, \( \ln M_{\text{cl}} = \hat{M}_{\text{cl}} \), for three different values of the standard deviation in log-mass, \( \sigma_{\text{std,cl}} \), for a log-normal ICMF (lower panel, as in Fig. 5). The region between the horizontal dotted lines approximately constitutes the range of acceptable thick-disc models \( (1 - \phi > 0.6) \), provided that the constraint on \( \sigma_{\text{vel,obs}} \) is fulfilled (Fig. 8 below).

Figure 7. The most reliable age–velocity-dispersion data are shown as solid symbols (from fig. 1 in Fuchs et al. 2001). The short-dashed and long-dashed lines are equation (22) with \( \sigma_{\text{vel,obs}} = 25 \) and \( 17 \text{ pc Myr}^{-1} \), respectively, assuming that over the past \( \Delta t = 11 \text{ Gyr} \) a fraction \( 1 - \eta = 0.7 \) of the MW disc assembled through infall. The solid curve is Jenkins’s (1992) model, scaled to fit the data near \( \Delta t = 0 \) (his fig. 9), young stars having \( \sigma_{\text{vel}} = 2 - 5 \text{ pc Myr}^{-1} \). (Asiain et al. 1999) It takes into account heating through molecular clouds, spiral-wave heating and adiabatic heating through an accreting disc, and thus incorporates all known secular heating mechanisms. The dotted symbols indicate unpublished observational data of Quillen & Garnett (2000, QG), and Stroemgren’s (1987, SB7) data (see Section 5.2.1 for more details).

### 3 THE POSSIBLE ORIGIN OF THE THICK DISC

Given that clustered star formation is likely to leave a kinematical imprint along the lines of Section 2.1, the following question can now be addressed: Since, so far, no satisfying origin for the thick disc velocity dispersion, \( \sigma_{\text{vel,obs}} \approx 40 \text{ pc Myr}^{-1} \), has been found, may it conceivably be associated with vigorous star formation during the brief initial assembly of the thin disc? Observations tell us that violent molecular-cloud dynamics is associated with vigorous star formation, the units of which are star clusters. The maximum cluster mass appears to correlate with the star formation rate via the pressure in the clouds, which in turn is increased when gas clouds are compressed or collide in perturbed and interacting systems (Elmegreen et al. 2000; Larsen 2001). So maybe the typical \( M_{\text{cl}} \) was large when the thick disc formed?

Assuming that the velocity dispersion of the thick disc has not changed since its formation, the solution for ICMF parameters can be sought which bring \( \sigma_{\text{vel}} \) into agreement with \( \sigma_{\text{vel,obs}} \) at the (arbitrary) 30 per cent level. The solutions are displayed as thin dotted open squares in Fig. 8. The thick open squares in Fig. 8 show the solution space for the ICMF's leading to \( \sigma_{\text{vel}} \) within 30 per cent of \( 22 \text{ pc Myr}^{-1} \), which is the correct value to fit if the thick disc was adiabatically heated due to a linear growth of the MW disc mass (Section 2.3). The latter solution space is shifted uniformly to smaller cluster masses by about a factor of 5–10. If clusters form with \( R_0 = 5 \text{ pc} \) rather than \( R_0 = 1 \text{ pc} \) (equations 2 and 6), then the corresponding solution spaces are shifted to larger masses, as is
solutions in Fig. 8. Upper panel: Solutions in \( M_{cl,\text{max}} = \log_{10} M_{cl,\text{max}}, \alpha \) space for star formation occurring in clusters distributed as power-law mass functions. The solution space indicated as thin dotted squares \((R_0 = 1\, \text{pc})\) and thin dotted circles \((R_0 = 5\, \text{pc})\) leads to a velocity dispersion, \( \sigma \), within 30 per cent of the observed velocity dispersion of the thick Galactic disc, \( \sigma_{\text{obs}} = 40\, \text{pc}\, \text{Myr}^{-1} \) \((0.7\sigma_{\text{obs}} \leq \sigma \leq 1.3\sigma_{\text{obs}})\), whereas thick squares \((R_0 = 1\, \text{pc})\) and solid circles \((R_0 = 5\, \text{pc})\) delineate the solution space leading to an initial thick-disc velocity dispersion lying in the 30 per cent interval around 22\, \text{pc}\, \text{Myr}^{-1} \((15.3 \leq \sigma \leq 28.5\, \text{pc}\, \text{Myr}^{-1})\), this being the dispersion corrected for adiabatic heating due to linear growth of the Galactic disc mass after the thick disc formed. All solutions fulfil 1 - \( \phi \geq 0.6 \). Lower panel: As upper panel, but solutions in \( \langle M_{cl} \rangle = \langle M_{\text{cl}} \rangle, \sigma_{\text{cl},\text{max}} \rangle \) space for star formation occurring in clusters distributed as log-normal mass functions. The thick cross locates the ICMF typically inferred for young cluster populations (Sections 2.1).

evident in Fig. 8 as the solid and dotted circles for fitting to the 30 per cent interval around 22 and 40 \( \text{pc}\, \text{Myr}^{-1} \), respectively.

4 THE THIN DISC HISTORY

Returning to the discussion at the end of Section 2.3, the solid curve in Fig. 7 shows the most detailed available model, \( \sigma_{\text{mod}},(t) \), by Jenkins (1992) for disc heating through spiral arms, molecular clouds and the growth of mass of the MW disc. As stated in the introduction, the model cannot account for \( \sigma_{\text{obs}}(t) \), but it does not take into account possible short lifetimes of the molecular clouds (Section 2.3).

A bold step is now taken as an example of how the star formation history of the MW disc may be constrained using the approach discussed here. The residual deviations from the model, \( \sigma_{\text{c,diff}}^2(t) = \sigma_{\text{c,obs}}^2(t) - \sigma_{\text{c,mod}}^2(t) \), are plotted in the lower panel of Fig. 9. The deviations, equation (23), show an interesting feature in the age interval 1–4 Gyr and possibly in the age interval 5–7 Gyr. The former possibly correlates with the burst of star formation, deduced by Rocha-Pinto et al. (2000) to be at the 99 per cent level over a constant star formation rate using chromospheric age estimation, if the data sets have a relative systematic age difference of about 1 Gyr. This is not entirely unrealistic, given that the age estimators are indirect (Fuchs et al. 2001). Hernandez, Valls-Gabaud & Gilmore (2000) also find significant evidence for an increasing star formation rate with increasing age (\( \leq 3\, \text{Gyr} \)) using an advanced Bayesian analysis technique to study the distribution of Hipparcos stars in the colour–magnitude diagram. The possible rise in \( \sigma_{\text{obs}}(t) \) near 7 Gyr also yields an increased star formation rate at \( t \geq 7\, \text{Gyr} \) when compared to slightly younger ages, but the significance of this feature is not very high.

Assuming, for the purpose of illustration, a power-law ICMF with \( \alpha = 1.9 \), the upper panel of Fig. 9 plots the maximum cluster mass, \( M_{cl,\text{max}} \), involved in the star formation activity and giving rise to

\[
\sigma_{\text{c,diff}}^2 = \sigma_{\text{c,diff}}^2 + \sigma_{0c}^2, \tag{24}
\]

with \( \sigma_{0c} = 4\, \text{pc}\, \text{Myr}^{-1} \) here; \( \sigma_{\text{c,diff}}^2 \) is the correct quantity to fit with \( M_{cl,\text{max}} \), since equation (23) only accounts for the increase of the velocity dispersion over the current \( (\Delta t = 0) \) underlying quiescent star formation activity typified by modest embedded clusters, leading to \( \sigma_{0c} \approx 4\, \text{pc}\, \text{Myr}^{-1} \).

The analysis above serves to illustrate that clustered star...
formation probably leaves an imprint in the stellar distribution function. Taking Jenkins's (1992) model to be a correct description of the secular increase of $\sigma_z$, the above analysis suggests that the star formation rate in the MW may have been quietening down, i.e., that the star formation rate has been declining, and/or that the IC MF may have been changing towards smaller cluster masses.

5 DISCUSSION

The analysis presented in this contribution serves to demonstrate that the kinematics of stars in the MW disc and other galaxies may be influenced by stellar birth in clusters. However, the application to specific kinematical abnormalities in the thin disc, and to the thick disc, is to be viewed as suggestive rather than definitive.

5.1 The model

The model set-up in Section 2.1 is simple, but sufficient for this first exploration of how the kinematically hot component emerging from a cluster-forming event may affect the stellar distribution function in a galaxy.

The model (equation 4) neglects possible variations of the star formation efficiency with cluster mass and the possible variation of the gas-expulsion time-scale, which may be much longer than the dynamical time of embedded massive clusters (Tan & McKee 2001). If this is so, then the stellar cluster reacts adiabatically to gas removal, and the final velocity dispersion in the cluster will be reduced by a factor $e$ (Mathieu 1983). The velocity distribution function of escaping stars is, in this case, much more difficult to estimate. It nevertheless remains a function of $M_{cl}$, so that the essence of the argument here remains valid, although the detailed solutions evident in Figs 8 and 9 would change somewhat towards larger cluster masses. Furthermore, the present models do not take into account the fact that the star clusters, which form as nuclei of the expanding stellar associations, continue to add to the thick disc by ejecting high-velocity stars due to three- and four-body encounters. This is evident for massive young clusters (figs 2 and 3 in Kroupa 2001c) as well as clusters that typically form the Galactic field population (Kroupa 1998). While such events are rare, the implication is that the hot disc component should have a complex metallicity and age structure. A next stage in this project is to assemble synthetic disc populations using high-precision direct N-body calculations of cluster ensembles.

This model predicts a complex velocity field in galaxies that are actively forming star clusters. In the MW this is evident through expanding OB associations, and the empirical finding that the velocity dispersions of these differ (Asiain et al. 1999). OB associations are most probably only the central regions of the expansive flow, because massive stars either form centrally concentrated, or they sink to the centres of their embedded cluster essentially on a dynamical time-scale. If a young cluster can approximately establish energy equipartition between the stars before gas expulsion, then the massive subpopulation will have a significantly smaller velocity dispersion than the low-mass members. Furthermore, an expanding association ‘loses’ its fast-moving stars early. An observer with a limited survey volume therefore underestimates the velocity dispersion.

The exploratory analysis presented here neglects the other velocity components. The focus is entirely on the component perpendicular to the Galactic disc, easing the analysis. However, according to the notion presented here, the birth of a star cluster leads to an initially isotropically expanding stellar population. The velocity ellipsoid, given by the ratio of the velocity dispersion perpendicular to the disc ($\sigma_W = \sigma_z$), towards the Galactic Centre ($\sigma_L$) and in the direction of the motion of the local standard of rest ($\sigma_0$), is thus initially spherical. Stars expelled from their cluster towards the Galactic Centre accelerate and overtake the other stars, while stars leaving the cluster in the opposite direction are decelerated by the Galactic potential and fall behind. The velocity ellipsoid is thus distorted due to the differential rotation, and it will be an interesting problem to investigate if the observed velocity ellipsoid is consistent with the present notion. For the thin disc Fuchs et al. (2001) give $\sigma_U : \sigma_V : \sigma_W = 3.5 : 1.5 : 1$, independent of age, while Chiba & Beers (2000) find for the thick disc $\sigma_U : \sigma_V : \sigma_W = 1.31 : 1.43 : 1$. Such differences may partially be due to secular heating mechanisms such as scattering off molecular clouds and spiral arms that decrease $\sigma_U/\sigma_V$ (Gerssen, Kuijken & Merrifield 2000). This is more efficient for the colder thin-disc population. Adiabatic heating due to the growth of the MW disc also evolves the velocity ellipsoid, and a passing satellite galaxy induces a radial compression of the gaseous disc, which can lead to enhanced star formation and an increased radial velocity dispersion owing to star formation in the radially infalling gas and the formation of a bar. A full model of the velocity ellipsoid is thus highly non-trivial, and subject to the details of the satellite orbit and the evolution of the Galaxy.

5.2 The thin disc

The literature contains various estimates of age–velocity-dispersion data, and contradictory claims have been made. It is thus useful to cast an independent eye at the situation (Section 5.2.1). The star formation history of the thin disc is also briefly discussed in Section 5.2.2.

5.2.1 Data

The most reliable age–velocity-dispersion data come from the (distance-limited) solar-neighbourhood sample contained in the fourth version of the catalogue of nearby stars originally compiled at the Astronomisches Rechen-Institut (ARI) in Heidelberg by the late Gliese, and continued by Jahreiss (CNS4) (e.g. Jahreiss et al. 1999; Fuchs et al. 2001). This sample has been yielding consistent results over the past 2–3 decades (e.g. Wielen 1977) despite significant improvements such as the inclusion of Hipparcos data for the majority of the stars. The data are shown in Fig. 7.

Since theoretical work has not been able to explain the strong apparent heating of stars with age, the data set has been questioned by a variety of researchers. For example, BM point to the work of Stroemgren (1987). Stroemgren used a preliminary version of the Edvardsson et al. (1993) catalogue to select a sample of stars with $-0.15 \leq [\text{Fe/H}] \leq +0.15$, and found essentially no increase in $\sigma$ for ages older than about 4 Gyr, in stark contrast to the results based on the CNS4 data, suggesting that this metal-rich thin-disc subpopulation was not subject to the heating mechanism advocated by Wielen and co-workers at the ARI. From Fig. 7 it in fact follows that the best available theoretical work is in next to excellent agreement with these data. Such a situation may arise if the local stellar sample is contaminated by thick-disc stars, but this would require some thick-disc stars to be mis-classified as being significantly younger than the thick-disc bulk. Alternatively, the metal-rich thin-disc population may have been born in modest embedded clusters, leading to no kinematical abnormality. Modern data should be used to verify if metal-rich and metal-poor thin-disc
populations do indeed follow different age–velocity-dispersion relations.

An additional age–velocity-dispersion data set that is not consistent with the CNS4 data has been submitted for publication by Quillen & Garnett (2000). Again, this data set, which is a re-analysis of the Edvardsson et al. (1993) data, is in perfect agreement with Jenkins’s model and with the data of Stroemgren (1987), but also shows the kinematical peculiarity in the age-interval 1–3 Gyr evident in the CNS4 data (Fig. 7).

While the Stroemgren (1987) data are interesting, no follow-up work has appeared in a refereed journal. Also, the Quillen & Garnett (2000) paper will not be published (Quillen, private communication), and Fuchs et al. (2001) demonstrate that their own analysis of the Edvardsson et al. (1993) data yields essentially the same results as they obtain from the CNS4 (fig. 2 in Fuchs et al. 2001). Furthermore, the large velocity dispersions of the older CNS4 thin-disc stars are verified by independent work. Notably, Reid et al. (1995, their table 6) also find $\sigma \approx 25$ pc Myr$^{-1}$ for stars with $8 < M_V < 15$. Such a large $\sigma$ is also obtained for stars within the very immediate solar neighbourhood with distances less than 5.2 pc (Kroupa, Tout & Gilmore 1993). Finally, Binney, Dehnen & Bertelli (2000) find, from a statistical analysis of their own new sample of kinematical data, essentially the same age–velocity-dispersion relation as advocated by Fuchs et al. (2001, their fig. 4).

The above discussion serves to demonstrate that some uncertainties remain in the definition of the age–velocity-dispersion data, but that the evidence lies in favour of the results obtained from the CNS4 (e.g. Fuchs et al. 2001), i.e., that stars have velocity dispersions that increase more steeply with age than theory can account for.

5.2.2 On its history

It is notable that the suggestive finding in Section 4 that the star formation rate may have declined in the last few Gyr is similar to the conclusion of Fuchs et al. (2001) based on the cumulative star formation rate as traced by a sample of G and K solar-neighbourhood dwarfs with measured chromospheric emission fluxes (their fig. 5). According to these data, the MW thin disc transformed into a quiescent star formation mode about 3 Gyr ago. Hernandez et al. (2000) also find a decreasing star formation rate during the past 3 Gyr (Section 4). Given the good empirical correlation between the mass of the most massive cluster formed and the star formation rate documented by Larsen (2001) for a sample of 22 galaxies, it would thus not be surprising to find that the star formation history of the MW disc is reflected in variations of the ICMF, as suggested in the upper panel of Fig. 9.

Janes & Phelps (1994) indeed find an old cluster population of Galactic clusters that have a vertical scaleheight of about 300 pc similar to old thin-disc stars, and may thus have been heated from $\sigma_{z0} = 5$ pc Myr$^{-1}$ to about 15 pc Myr$^{-1}$ as described by Jenkins’s model (Fig. 7), although cluster-survival during scattering events is controversial, and it may be necessary to allow $\sigma_{z0} > 5$ pc Myr$^{-1}$ during the starburst that formed this cluster population. These clusters are confined to Galactocentric radii $\gtrapprox 7.5$ kpc being qualitatively consistent with the present MW-disc perturbation hypothesis. Janes & Phelps identify this cluster population with a starburst about 5–7 Gyr ago, which corresponds to the maximum in the ICMF at about that time as inferred here (Fig. 9).

5.3 The thick disc

The thick-disc ICMF constrained in Section 3 implies that star clusters may have formed with masses extending to $10^3–6 \times 10^5 M_\odot$. Some of these may have survived to the present day. If it is correct that thick-disc star formation occurred in a thin gaseous disc, as assumed in Section 3 ($\sigma_{z0} = 5$ pc Myr$^{-1}$), then the surviving population of clusters ought to now have a vertical velocity dispersion of about 20 pc Myr$^{-1}$, according to Jenkins’s model (Fig. 7).

The extreme assumption $\sigma_{z0} = 5$ pc Myr$^{-1}$ was made merely to study if the hot kinematical stellar component emerging from star-cluster birth can give rise to the thick-disc kinematics for plausible ICMFs. Here the view is that a quiescent thin gas-rich MW disc may have assembled early on, the MW then essentially being a low surface brightness disc galaxy. A perturbation by a passing satellite galaxy may have induced significant star formation, leading to the thick-disc component.

However, it may well be that the thick disc formed with a cluster–cluster velocity dispersion $\sigma_{z0} \approx 22$ pc Myr$^{-1}$ due to the probably turbulent and chaotic conditions, leading to the assembly of the thin disc, later being heated adiabatically to 40 pc Myr$^{-1}$. In this alternative and maybe more plausible scenario, the resulting ICMF solutions would be only slightly shifted to lower cluster masses (Fig. 8). Fossils of this vigorous star formation event with $\sigma_{z0} \approx 22$ pc Myr$^{-1}$ may be the metal-rich MW globular cluster system which has a density distribution very similar to the stellar thick disc (e.g. BM).

According to Minniti (1996) and Forbes, Brodie & Larsen (2001), a large fraction of these metal-rich globular clusters may rather belong to a bulge population, so that a definitive identification of metal-rich globular clusters as being the fossils of the thick-disc star formation events cannot be made. Any such population of clusters is likely to have suffered some orbital decay towards the MW disc through non-isotropic dynamical friction on the disc (Binney 1977), implying that the original thickness of the metal-rich globular cluster disc population may have been larger than the present value, possibly compromising its association with the stellar thick disc.

6 CONCLUSIONS

The age–velocity-dispersion relation for the MW is addressed by considering the effects that star-cluster formation may have on the velocity field of stars.

Star clusters form with star formation efficiencies $\epsilon < 0.4$, and they are probably near global gravitational equilibrium just before the remaining gas is expelled. Observational evidence suggests that gas expulsion is rapid, so that the majority of stars expand outwards with a velocity dispersion that is related to the velocity dispersion prior to gas expulsion.

This scenario implies that the distribution function of stars in galaxies should reflect these events. Peculiar kinematical features, such as enhanced velocity dispersions for stars of particular ages, may thus be the result of specific star formation events, or bursts, that produced star clusters with masses larger than those typical under more quiescent star-forming conditions. An empirical correlation between cluster mass and star formation rate is established by Larsen (2001).

The calculations presented here show that the velocity distribution function of stars emerging from a star formation event is distinctively non-Gaussian with a low-dispersion $\phi$-peak and broad wings (Figs 1 and 2). It is noteworthy that Reid et al. (1995) find that the velocity distribution of solar-neighbourhood stars shows structure reminiscent of the present models. Ancient thin-disc stars
with overlapping metallicities to those of thick-disc stars may, according to this interpretation, be the kinematically cold $\phi$-peak of the star formation burst that formed the thick disc.

Examples of star formation bursts leading to abnormal kinematical signatures may be the Galactic thick disc, and possible star formation bursts about 1–3 and 5–7 Gyr ago evident in the age–velocity-dispersion data for the solar neighbourhood. These kinematical ‘abnormalities’ are analysed here by calculating the velocity distribution function assuming stars form in ensembles of star clusters distributed either as power-law or as log-normal initial mass functions (ICMFs). The allowed ICMFs are constrained (Figs 8 and 9). The results are plausible when compared to direct surveys of the ICMF (Section 2.1). The putative star formation burst 5–7 Gyr ago may be associated with the population of old (and thus initially relatively massive) Galactic clusters identified by Janes & Phelps (1994).

Satellite infall or perturbation may still be responsible for a burst of star formation that allows more massive clusters to form, but, as shown here, heating of galactic discs may not require direct satellite infall into the disc. It is thus interesting that Rocha-Pinto et al. (2000) find possible correlations between their star formation history and the orbit of the Magellanic Clouds, which in turn can be correlated with the above-mentioned age–velocity-dispersion abnormalities (Fig. 9). Schwarzkopf & Dettmar (2000, 2001) find that perturbed disc galaxies are significantly thicker than isolated disc galaxies. However, the present notion does not exclude that disc thickening can also be induced through satellites or high-velocity clouds hitting discs directly.

The notion raised here readily carries over to populating the Galactic spheroid through forming star clusters, only the most massive of which survived to become the present-day globulars. It also carries over to properties of the distribution function of moving groups associated with the formation of individual distant globular clusters in the out-reaches of the Galactic halo.

The concept introduced here relies on the unbound star-cluster population expanding with a velocity that depends on the cluster configuration before gas expulsion (equation 4). This can be tested with high-precision astrometry. A perfect test-bed is the Large Magellanic Cloud, which is forming star clusters profusely, probably as a result of being tidally perturbed (van der Marel 2000). Hence, stars in a cluster should have associated with it an overall velocity dispersion characteristic of the conditions before gas expulsion. Evidence for this is emerging (Section 2). If an empirical upper limit on the velocity dispersion of expanding associations independent of $M_{\ast}$ for some value larger than $M_{\ast,crit}$ can be found, then this would serve as an important constraint on the star formation efficiency and gas-expulsion time-scale for clusters more massive than $M_{\ast,crit}$. It will also be necessary to quantify the evolution of the velocity ellipsoid ($\sigma_U : \sigma_V : \sigma_W$) as an improved test of the model against available observational constraints.

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Thickening of galactic discs

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