EVOLUTION OF THE GALACTIC HALO AND DISK

GERARD GILMORE
Institute of Astronomy
Madingley Road, Cambridge CB3 0HA, UK
(gil@mail.ast.cam.ac.uk)

Abstract.

Correlations between stellar kinematics and chemical abundances are fossil evidence for evolutionary connections between Galactic structural components. Extensive stellar surveys show that the only tolerably clear distinction between galactic components appears in the distributions of specific angular momentum. Here the stellar metal-poor halo and the metal-rich bulge are indistinguishable from each other, as are the thick disk and the old disk. Each pair is very distinct from the other. This leads to an evolutionary model in which the metal-poor stellar halo evolves into the inner bulge, while the thick disk is a precursor to the thin disk. These evolutionary sequences are distinct. The galaxy is made of two discrete "populations", one of low and one of high angular momentum. Some (minor?) complexity is added to this picture by the debris of late and continuing mergers, which will be especially important in the outer stellar halo.

1. Introduction

Early models of Galaxy formation and evolution envisaged an isolated set of gas clouds whose mutual tidal torques generated net angular momentum. These clouds cooled, coalesced, fragmented locally into stars (in some unspecified way), and collapsed to form stellar galaxies. This picture was essentially formulated by Stromberg (1934), expanded to include chemical evolution by Schmidt (1959) and van den Bergh (1962), extended and popularised by Eggen, Lynden-Bell and Sandage (1960), and further generalised to emphasise the possible importance of longer lived sub-structures by Searle (1977). Extensive discussions of these developments and the many later

P. C. van der Kruit and G. Gilmore (eds.), Stellar Populations, 99–107.
© 1995 IAU. Printed in the Netherlands.
https://doi.org/10.1017/S0074180900108460 Published online by Cambridge University Press

observationally-based attempts to clarify and verify their essential features may be found in Gilmore and Carswell (1987).

All these models are essentially monolithic, in that they assume the bulk of the present galactic baryonic mass was in place very early in Galactic evolution, and all are concerned primarily with the Galactic stellar halo, or Population II. The relationship between the stellar halo and the galactic disk and bulge remained problematic. In particular, the very large difference in specific angular momentum between the halo and the disks implied very different collapse factors, and possible time-scales, for formation of the halo and the disks. The halo is moreover only a tiny part of the whole Galaxy. Both the disks and the bulge are more massive, and more chemically evolved.

The timescale and collapse factor difficulties with these models began to be resolved with the discovery of massive dark halos, and the realisation that their presence changed substantially the expected evolution of a proto-galaxy, particularly for disk formation (White and Rees, 1977; Fall and Efstathiou, 1980). In currently popular models of galaxy formation, very different initial conditions are assumed than are relevant to the earlier models of galaxy evolution. It remains probable that a picture rather similar to that outlined by Eggen, Lynden-Bell and Sandage provides a valid description of the inner stellar halo of the Galaxy, so that present efforts in dating globular clusters and the oldest field stars remain focussed on such models. Current models of the whole of galaxy evolution suggest that very late mergers of what were really independent galaxies, not simply local subcondensations in the initial proto-galaxy, are the most important physical process affecting the formation and evolution of the outer stellar halo, the disk and perhaps the bulge. The most appropriate questions for current observational test based on field stars and chemical evolution are related to the rate, timescale and effect of such mergers, rather than to the details of the initial core about which the Galaxy later accreted. The essential physical point is that galaxies are not expected to be closed systems.

In this paper we consider observational methods to isolate representative properties of the stellar populations in the old disk, the thick disk, and the halo, and use these to address the evolutionary questions noted above. While the oral version of this talk additionally summarised current evolutionary models, in the interests of space we refer to a comprehensive recent review by Silk and Wyse (1993) and to papers in this volume by Wyse and by White, for such discussions, and references to the extensive relevant literature. Some other recent useful introductions to the literature include Gilmore, King and van der Kruit (1989), Gilmore, Wyse and Kuijken (1989), Humphreys (1993) and Majewski (1993).

The essential question of immediate interest is to determine the evolu-

https://doi.org/10.1017/S0074180900108460 Published online by Cambridge University Press

tionary relationship, if any, between the stellar populations in the different structural components of the Galaxy. We attempt this below, noting that present galaxy evolution models do not presume that there is a simple, or even a single, evolutionary path from monolithic initial conditions to a present-day Galaxy in which all stellar populations are inter-related. That is, we must allow for the possibility that the evolutionary sequence which led to today's Milky Way contains parallel paths as well as serial links.

2. Identification of Stellar Populations

Gravitational potentials do not respect stellar populations. All orbits will be found in some place in the Galaxy, such as the Solar Neighbourhood, which had initially and have retained, or which later acquired, the relevant orbital energy and angular momentum. This has two significant consequences: we must sift carefully through the contents of our neighbourhood to isolate representatives of stellar "populations" with some specific set of properties, and we must remember that large parts of allowed parameter space will not be sampled locally. We illustrate these factors by isolating the statistical properties of the Galactic thick disk from local data.

2.1. VERTICAL VELOCITY DISPERSION

The vertical velocity dispersion of K giants and FG dwarfs (and by implication, all stars) in the Solar Neighbourhood is correlated with chemical abundance. Bahcall, Flynn and Gould (1992) showed the vertical velocity dispersion of local K giants to increase systematically with decreasing metallicity, from $\sigma_W = 14$ km/s for stars with [Fe/H]> 0 ("young disk"), to $\sigma_W = 19$ km/s for stars with $0 >$[Fe/H]> -0.5 ("old disk"), to $\sigma_W = 46 \pm 2$ km/s for stars with $-0.5 >$[Fe/H]> -1.0("thick disk"). These vertical velocity dispersions correspond to exponential vertical scale heights of approximately 300 pc for the old disk and 1 kpc for the thick disk. Thus, to isolate a sample of stars with a substantial thick disk contribution one should look out of the Galactic Plane. This is nicely illustrated in Soubiran (1993), where she uses the disk's gravitational gradient as a thick disk selection filter.

The numerical preponderance of the old disk combined with the relatively small kinematic difference between the old disk and the thick disk is such that nowhere can one isolate a clean sample of either (or any) stellar population. Rather, statistical deconvolutions of composite distribution functions are the sharpest available tool. These analyses do of course benefit from sample selection which maximises the thick disk contribution to the sample, so that inevitably large samples of faint stars, thus on average far from the Plane, are required. Mixture estimation is an appropriate al-

https://doi.org/10.1017/S0074180900108460 Published online by Cambridge University Press

gorithm in such cases, and has been widely applied. Such an analysis was applied by Soubiran to deduce that the asymmetric drift of the thick disk is some 40 km/s behind that of the old disk. This provides an additional selection criterion.

2.2. ASYMMETRIC DRIFT

Noting that the relative fraction of thick disk to old disk stars is increased at distance of order 1-2 kpc from the Plane, and the distinction between the overlapping distribution functions of the disks is maximised in mean galactocentric rotation velocity, allows one to optimise a study. Ojha *et al.* have completed the most recent and extensive such survey, acquiring proper motions and photometry for a complete sample of stars in directions optimised to determine the rotation velocity of stars in the several galactic structural components as a function of distance from the Galactic Plane. Applying statistical deconvolution methods to their data, they show that the asymmetric drift of the thick disk is constant with distance, in the range $0 < z < 2000$ pc, at a value of ~ -50 km/s. There is no detectable gradient in this value with distance from the Plane, even though some earlier studies had suspected such a result. This result is particularly important, as it allows a reliable calculation of the angular momentum distributions of the several Galactic components, which in turn are an important clue as to their evolutionary relationships.

2.3. CHEMICAL ABUNDANCE DISTRIBUTIONS

Given the results above, we infer that a sample of stars with Galactocentric rotation in the range $V_{rot} < 100$ km/s is primarily associated withe the stellar halo, a sample with $100 < V_{rot} < 150$ km/s is primarily associated with the thick disk, especially if selected from stars distant from the Galactic Plane, while a sample of stars with $V_{rot} > 150$ km/s is predominantly old disk. Applying these expectations, we consider the distribution of chemical abundances as a function of V_{rot}. The most recent such results are provided by surveys by Norris (1994), by Schuster, Parrao and Contreras Martinez (1994), and by Gilmore, Wyse and Jones (1995), who also provide references to the extensive earlier surveys. These results show the thick disk to be predominant in the metallicity range from $-0.5 > \text{[Fe/H]} > -1.0$, but with suggestive evidence for a tail in the thick disk abundance distribution below [Fe/H]=-1, and for a tail in the stellar halo abundance distribution above [Fe/H]=-1. This leads to a separation between the stellar halo and the thick disk in plots of V_{rot} *vs* [Fe/H] which is not parallel to either axis.

https://doi.org/10.1017/S0074180900108460 Published online by Cambridge University Press

3. Correlations between Chemical Abundance and Kinematics

The methodology by which one interprets joint kinematics and chemical abundance information is reviewed by Gilmore, Wyse and Kuijken (1989). Essential observational requirements are some roughly monotonic function of time, for which chemical abundance is appropriate, and some hopefully monotonic function of proto-Galactic collapse (or binding energy), for which stellar orbital eccentricity was adopted. The important point for the present to include in such a discussion is that current observational data do *not* support a simple evolutionary transition from the stellar halo into the (primordial) disk. The observational surveys which have established the details and the complexity of the relationship between stellar kinematics and stellar chemical abundance distributions have required massive efforts from many astronomers, and form the great achievement of recent Galactic structure studies. These efforts, in large part motivated by the early synthesis of Eggen, Lynden-Bell and Sandage, now allow us to extend that synthesis to the next stage of complexity.

The overlapping distribution functions in abundance with a relatively clear distinction in galactocentric velocity suggest specific angular momentum as a primary criterion. The current determinations of these distributions are shown in Fig. 1 (from Ibata and Gilmore, 1995).

4. Implications for Galactic Evolution

A correlation between stellar orbital eccentricity and metallicity has been interpreted for many years as a indication that there is an evolutionary sequence from radial stellar orbits populated by stars with low chemical abundances (the stellar halo population) to circular stellar orbits populated by stars with high chemical abundances (the disk stellar population). The stellar population of the bulge remains somewhat vaguely located in this sequence. The most recent determination of this relationship is presented by Twarog and Anthony-Twarog (1994), whose Fig. 10 allows a major advance in appreciation of Galactic evolution. There is increasing evidence, noted the discussion above, that stars exist locally with low abundances and low eccentricity (circular) orbits, sometimes called the "metal-weak thick disk". Even if there were no such stars, however, the angular momentum distributions would still force a re-interpretaion of the evolutionary links between the various components of the Galaxy. It is clear from Fig. 1 that the stars of the bulge, which have high chemical abundances, are on high eccentricity (radial) orbits. Thus such stars are fundamentally more closely related to the lower abundance stars of the stellar halo than are the stars of the disks, regardless of their abundances. Similarly, low abundance thick disk stars are more closely related to high abundance disk stars than to the

https://doi.org/10.1017/S0074180900108460 Published online by Cambridge University Press

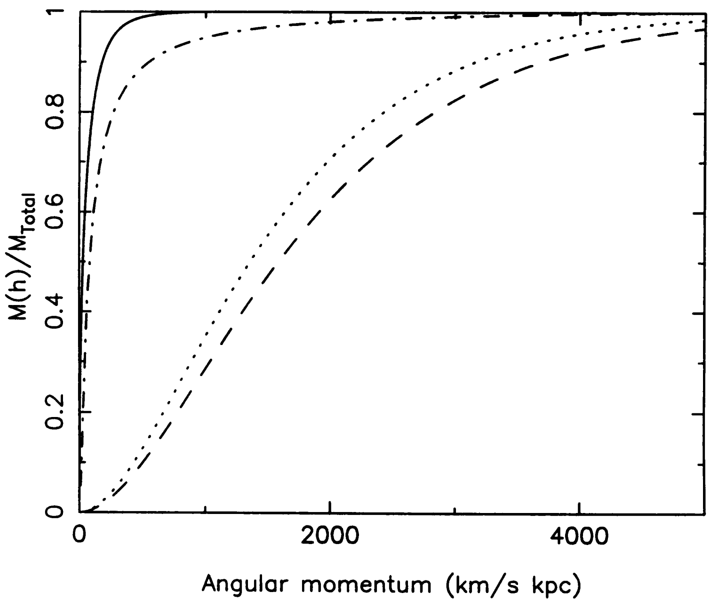

Figure 1. Angular momentum cumulative distribution functions for the stellar halo (dash-dot), the bulge (solid), the thick disk (dotted) and the old disk (dashes). The similarity between the halo and the bulge, and that between the two disks, as well as the differences between the two groups, are apparent, and indicate their evolutionary relationships.

stars of the stellar halo.

This leads to a picture of Galactic evolution in which the primordial stellar halo evolves, roughly conserving angular momentum while self-enriching its chemical abundances and cooling into a steeper density distribution, into the Galactic bulge. In parallel, though probably somewhat later, in agreement with the greater collapse factor required to explain its high specific angular momentum, the primordial disk self-enriched, perhaps cooling and contracting somewhat, through what is now the thick disk into the old disk and the thin disk. An essential prediction of such a model is that the stars of the Galactic bulge are old. Observational tests here are complex, however, as the central regions of the Galaxy, where the Bulge is most visible, also host the central parts of every other Galactic component. A deconvolution process as complex as that outlined above to isolate the properties of the thick disk will be required.

Interaction between the low angular momentum stellar populations of the stellar halo and bulge, and the high angular momentum poulations of the disks may have been minimal. The Galaxy is best thought of as two discrete components, with very different and (almost) non-overlapping distributions of specific angular momentum, but which overlap in age, chemical

https://doi.org/10.1017/S0074180900108460 Published online by Cambridge University Press

abundance, and so on.

5. Late Mergers

The remaining substantive issues not addressed above are the role of late mergers, and why the thick disk is thick. It is possible that these two questions are one, as one consequence of a significant merger is a thickening of a stellar disk. Direct evidence for an ongoing merger event has been discovered recently in a study by Ibata, Gilmore and Irwin (1994). While investigating the kinematic structure of the Galactic bulge, they discovered a large phase-space structure consisting of > 100 K giant, M giant and carbon stars in three low Galactic latitude fields. The group has a velocity dispersion of < 10 kms^{-1}, and a mean heliocentric radial velocity of 140 kms^{-1}, that varies by less than 5 kms^{-1} over the $8°$ wide region of sky investigated kinematically. The colour–magnitude (CM) diagram of this region of sky was obtained from APM scans of UKST plates; over the expected Galactic CM signature an unexpected excess was revealed, in the form of a tight CM relation similar to that of the SMC. A giant branch, red horizontal clump and horizontal branch are clearly visible. Stars belonging to the low velocity dispersion group lie on the upper giant branch of the unexpected CM relation. From the magnitude of the horizontal branch, Ibata, Gilmore and Irwin find that the object is situated 15 ± 2 kpc from the Galactic centre; this value agrees well with that obtained by direct comparison to the CMD of the SMC. An isodensity map shows the object to be elongated (with axial ratio ≈ 3), spanning $> 10°$ on the sky in a direction perpendicular to the Galactic plane. It is a dwarf galaxy, the Sagittarius dwarf, probably the thrid most massive of the Galactic (former) satellites.

6. Conclusions

An interesting feature of the Sagittarius dwarf is that it contains 3 or 4 (the data remain inconclusive) globular clusters. This provides direct evidence that any interpretation of observational properties for stellar components, or even stellar populations, in the Galaxy needs to recognize that a Galaxy is not a closed system. It did not spring forth fully formed, or evolve as a single discrete monolith.

Nonetheless, present data are interpretable in terms of a Galaxy evolving in two more or less discrete parallel paths. Low angular momentum material formed the stellar halo, with chemically enriched debris cooling into the Galactic bulge. This sequence is consistent with that outlined by Eggen, Lynden-Bell and Sandage (1962). High angular momentum material evolved independently, forming the disk. The early disk either formed thick, or was thickened by the last major galactic merger, some 10Gyr ago. Later

https://doi.org/10.1017/S0074180900108460 Published online by Cambridge University Press

and continuing accretion and mergers confuse but do not obliterate the surviving evidence for this evolutionary path.

References

Bahcall, J.N., Flynn, C. and Gould, A., 1992, *Ap. J.* **389**, 234
Eggen, O.J., Lynden-Bell, D. and Sandage, A., 1962, *Ap. J.* **136**, 748
Fall, M. and Efstathiou, G., 1980, **M. N. R. A. S. 193**, 189
Gilmore, G. and Carswell, R.F. (eds.), 1987, *The Galaxy*, Reidel, Dordrecht
Gilmore, G., King, I.R. and van der Kruit, P.C., 1989, *The Milky Way as a Galaxy*, University Science Books
Gilmore, G., Wyse, R.F.G. and Kuijken, K., 1989, *Ann. Rev. Astron. Astroph* **27**, 555
Gilmore, G., Wyse, R.F.G. and Jones, J.B., 1995, *A. J.*, in press
Humphreys, R.M. (ed.), 1993, *The Minnesota Lectures on the Structure and Dynamics of the Milky Way*, A.S.P. Conf. Ser. vol. **39**
Ibata, R.A. and Gilmore, G., 1995, **M. N. R. A. S.**, submitted
Ibata, R.A., Gilmore,G. and Irwin, M., 1994, **Nature 370**, 194
Majewski, S.R. (ed.), 1993, *Galaxy Evolution: The Milky Way Perspective*, A.S.P. Conf. Ser. vol. **49**
Norris, J.E., 1994, preprint
Ojha, D.K., Bienayme. O., Robin, A.C. and Mohan, V., 1994, *A. & A.* **290**, 771
Schmidt, M., 1959, *Ap. J.* **129**, 243
Schuster, W.E., Parrao, L. and Contreras Martinez, M.E., 1994, *A. & A.*, in press
Searle, L., 1977, *The Evolution of Galaxies and Stellar Populations*, eds. B.M. Tinsley and R.B. Larson, Yale Univ. Press
Silk, J. and Wyse, R.F.G., 1993, *Physics Reports* **231**, 295
Soubiran, C., 1993, *A. & A.* **274**, 181
Stromberg, G., 1934, *Ap. J.* **79**, 460
Twarog, B.A. and Anthony-Twarog, B.J., 1994, *A. J.* **107**, 1371
van den Bergh, S., 1962, *A. J.* **67**, 480
White, S.D.M. and Rees, M.J., 1977, *M. N. R. A. S.* **181**, 37P

RENZINI: There are a few clusters in Baade's Window that (1) are as metal-rich as the Sun, and (2) HST C-M diagrams indicate that they are nearly as old as the halo globulars. Does that fit with your picture in which the Bulge does not exist, or was recently acquired?
GILMORE: It is an essential feature of the picture outlined here that at least some part of the Bulge is old, and that may be chemically evolved. A point I failed to make sufficiently clearly in the talk is that at least some, and possibly most, of what is now in the central parts of the Galaxy may be unrelated to the early evolution of the Galaxy. It may have been far away long ago.
PRYOR: Numerical simulations (Piateh and Pryor, AJ submitted) suggest that a dwarf spheroidal galaxy might survive a pericentre equal to the current distance of the Sagittarius dwarf. The models show that tidal destruction does not produce a lumpy distribution. The clearest signature of destruction is a strong velocity gradient. Since Sagittarius is more luminous than Fornax, but the same size, it seems premature to conclude it is being destroyed by tides. Does the kinematic data resolve this?
GILMORE: Present data do not adequately limit the true size of the Sagittarius dwarf. The central surface brightness is however some 4-5 magnitudes fainter than that of Fornax, and our calculations provide a tidal radius of 0.5 kpc, or about 10%

https://doi.org/10.1017/S0074180900108460 Published online by Cambridge University Press

of its size. Future kinematic observations and dynamical modelling are required to determine its fate and recent past orbit reliably.
PECKER: was happy to see you had found a "young galaxy" (or a candidate for that) in the vicinity of our own Galaxy. You insist upon the evolutionary pattern of galaxies (halo to bulge, not halo to disk). It sounds fine; it shows also that the ratio "halo:disk" is a measurement of evolutionary stage (age?) for all galaxies of the type studied. Is there any statistical evidence of a dependance of that with the distance (measured perhaps by the redshift?). At least all galaxies in our vicinity are not as old as our Galaxy is, as you have shown!
GILMORE: I suspect that parameters such as bulge:disk ratio, thick disk:thin disk ratio, and more generally the Hubble type, are set as much by the chance distribution of size and time of mergers and by the physics which sets up the initial conditions of lumpiness, angular momentum distributions, early star formation rate, and such like, as uniquely by time. Certainly the nearest few large spirals are all different in these parameters, while there is no reason to suspect their oldest stars differ substantially in age.

https://doi.org/10.1017/S0074180900108460 Published online by Cambridge University Press