SPIRAL GALAXIES

https://doi.org/10.1017/S0074180900232087 Published online by Cambridge University Press

THE EVOLUTIONARY HISTORY OF THE MILKY WAY

K.C. FREEMAN
Mount Stromlo and Siding Spring Observatories
The Australian National University
Canberra, AUSTRALIA

Abstract. The accretion of small satellite galaxies appears to have been important in the formation of the metal-poor halo of the Galaxy. The disrupting Sgr dwarf galaxy and the recent discovery of a young, metal-poor component of the halo indicate that this is a continuing process. The evolution of the galactic disk, and some consequences of the bar-like nature of the galactic bulge are briefly discussed.

1. Introduction

The Milky Way is a large disk galaxy. Its main components are the rapidly rotating thin and thick disks, the very slowly rotating metal-poor halo, the bulge, and the dark corona. For the early evolutionary history, we must look to the kinematics and chemical properties of the old components that are well represented near the sun: these are the metal-poor halo and the thick disk. The thin disk gives information about the later evolutionary history. The bulge and the dark corona are less well understood and do not yet provide much useful insight.

The metal-poor halo is supported by its velocity dispersion. Eggen *et. al.* (1962: ELS) proposed that it formed before the disk, through the rapid collapse of part of the protogalaxy. This was based on evidence that the orbital and chemical properties of halo stars are correlated, with the most metal-poor stars having the largest orbital eccentricities, the largest range of velocities perpendicular to the galactic plane, and the lowest systemic rotation. Their galaxy formation picture suggests a dissipative time sequence of increasing chemical abundance, decreasing random velocities and increasing ordered rotation; the stellar abundances and kinematics are

R. Bender and R. L. Davies (eds.), New Light on Galaxy Evolution, 3–10.

https://doi.org/10.1017/S0074180900232087 Published online by Cambridge University Press

then measures of the time elapsed since the beginning of the collapse. The ELS picture was the standard galaxy formation picture during the 1960s and 1970s, but two aspects were contentious: (i) The timescale for the rapid collapse, required to produce the high observed orbital eccentricities of the halo stars, was given by ELS as 2×10^8 years. So any indication of Gyr age spreads among halo objects was taken as evidence against the ELS picture. (ii) the progressive chemical enrichment of the halo implies a correlation of kinematics and metallicity among the halo objects. As more data became available for halo stars and clusters, it became clear that this correlation is weak or absent.

During the 1970s, an alternative view of halo formation developed. To quote Toomre (1977): "It seems almost inconceivable that there wasn't a great deal of merging of sizeable bits and pieces (including quite a few lesser galaxies) early in the career of every major galaxy, no matter what it now looks like. The process would obviously have yielded halos from the stars already born, whereas any leftover gas would have settled quickly into new disks embedded within such piles of stars". This view fits well with the hierarchical galaxy formation picture that is now widely accepted. At about the same time, Searle and Zinn (1978: SZ) showed that the chemical and dynamical properties of the outer halo globular clusters are decoupled, and independently proposed that the halo formed by the accretion of small metal-poor fragments or satellites. If the halo formed from accreted fragments, then the kinematical and chemical properties of the halo objects depend on the orbital and chemical properties and structure of the infalling fragments. There would be no reason to expect a tight correlation of dynamical and chemical properties. After some controversy, this is the currently favored picture.

The galactic disk is believed to be easily heated by the accretion of small fragments. The Galaxy has a substantial thin disk, so most of these accretion events must have occurred early, while the disk was mainly gaseous and could resettle. However, recent unpublished work by several groups (Athanassoula, Barnes, Walker, White and their associates) on accretion of satellites by disk galaxies with live halos shows that disks are more robust than was previously believed.

2. The Metal-Poor Population: Halo and Thick Disk

This population is the source of the clues that led to the ELS and SZ pictures of galaxy formation. A comment: Metal-poor stars were long believed to be very old. In the SZ picture, age and abundance do not necessarily go together: *eg.* we see star-forming dwarf galaxies at the present time with [Fe/H] values as low as -2.

Beers and Sommer-Larsen (1995) compiled velocity and abundance data for 1936 metal-poor ([Fe/H] < -0.6) stars, selected by their chemical properties. Their analysis provides a useful summary of present views about the properties of the metal-poor halo and thick disk of our Galaxy.

- in the abundance range [Fe/H]$= -0.6$ to -1.0, we see the rapidly rotating thick disk population. Its mean rotation $V_{\rm rot} = 190$ km s^{-1} and its (U, V, W) velocity dispersion components (in the usual sense) are $\sigma = (63, 42, 38)$ km s^{-1}. Compare this with $V_{\rm rot} = 210$ km s^{-1} and $\sigma \approx (40, 30, 20)$ km s^{-1} for the old thin disk. These parameters for the thick disk agree well with other estimates from the solar neighborhood and *in situ*. From these parameters, the inferred scale length h_R and scale height h_z of the thick disk are 4.7 kpc (similar to the thin disk) and 1 kpc (300 pc for the thin disk) respectively.

- for [Fe/H] < -1.0, we see two components:
  (1) the hot halo with $V_{\rm rot} \approx 0$ and $\sigma \approx (150, 100, 100)$ km s^{-1}, indicating radially elongated orbits. Its density is about 0.1 to 0.2 percent of the thin disk density near the sun. This halo shows no dependence of kinematics on abundance. The halo does show an apparent age gradient: the globular clusters and BHB stars (Zinn 1980, Preston *et. al.* 1991) indicate that the outer regions of the halo are younger by a few Gyr in the mean.
  (2) the thick disk, persisting on to [Fe/H] ≈ -2. In the abundance range [Fe/H]$= -1.0$ to -1.5, about 60% of the stars near the sun belong kinematically to this metal-poor tail of the thick disk. (For [Fe/H] < -1.6, the fraction is about 30%). Is this metal-poor thick disk the heated remnant of early disk star formation ? Or is it the debris of accreted metal-poor satellites whose orbits have been more or less circularized by dynamical friction (*eg.* Quinn *et. al.* 1993) ? In any case the discovery of this metal-poor thick disk population is a significant development (Norris *et. al.* 1985; Morrison *et. al.* 1990), and it now seems clear that low metallicity does not necessarily identify a star as extremely old, nor as a member of the metal-poor halo.

Near the galactic plane, the mean rotation $V_{\rm rot} \approx 0$ for the metal-poor halo, but is probably retrograde at larger heights z from the plane. From proper motions of faint stars towards the NGP, Majewski (1992) finds retrograde rotation $V_{\rm rot} \approx -55 \pm 16$ km s^{-1} for a wide range of z. Beers and Sommer-Larsen (1995) come to a similar conclusion for $z > 2$ kpc, as do Carney *et. al.* (1995) for stars with maximum orbital heights $z_{\rm max} > 5$ kpc. The presence of this slowly rotating or retrograde halo population in an otherwise rapidly rotating Galaxy requires some explanation. It is usually interpreted now in terms of the accretion of small fragments during or after the dissipative settling of the disk.

The distribution of RR Lyrae stars (Hartwick 1987, Layden 1995) and the BHB stars (Kinman *et. al.* 1994) indicate that the metal-poor halo itself may have two components, one of which is quite flattened. For example, the BHB stars appear to show a spherical component with density distribution $\propto r^{-3.5}$ and local density of 6 stars kpc^{-3}, and a flatter component with a scale height of about 2 kpc and local density of 24 stars kpc^{-3}.

2.1. STELLAR ORBITS IN THE OUTER HALO

Sommer-Larsen *et. al.* (1994) compiled radial velocities for halo BHB stars with galactocentric distances R_G between 5 and 55 kpc, and estimated the run of the radial and tangential components $\sigma_r, \sigma_t(R_G)$ of the velocity dispersion. The velocity ellipsoid in the halo is radially anisotropic near the sun but becomes tangentially anisotropic for $R_G > 15$ kpc. This would not be expected in a monolithic collapse picture but is qualitatively consistent with a halo built up by accretion.

In the accretion picture, the shape of the halo and the shape of the velocity ellipsoid $\sigma(R_G)$ reflect the properties of the fragments and their trajectories. The dominant processes leading to the breakup of fragments are dynamical friction and tidal destruction, which depends on the mean density $\bar{\rho}$ of the fragment. For example, the mean galactic density ρ_G within R_G is $2\,[R_G(\mathrm{kpc})]^{-2}\ M_\odot\ \mathrm{pc}^{-3}$, so $\rho_G\,(10\ \mathrm{kpc}) \approx 0.02\ M_\odot\ \mathrm{pc}^{-3}$. We would then expect a typical fragment like a dIrr or dSph galaxy with $\bar{\rho} \approx 0.02$ to $0.05\ M_\odot\ \mathrm{pc}^{-3}$ to break up near the solar radius. More substantial lumps like the Dra and UMi dSph galaxies with $\bar{\rho} \sim 1\ M_\odot\ \mathrm{pc}^{-3}$ would survive in to smaller R_G. In this way, the kinematical properties of the halo can provide useful constraints on the properties of the small scale fluctuations represented by the fragments. High resolution simulations of galaxy formation from fluctuation spectra would be very interesting, to see if the radial variation of the halo shape and the shape of the velocity ellipsoid can be understood.

3. Direct Evidence for Past and Ongoing Accretion

The positions and kinematics of various dwarf spheroidal galaxies and younger globular clusters define galactic streams (Lynden-Bell and Lynden-Bell 1995, Majewski 1994) which are candidates for the debris of disrupted fragments. Similarly, the stellar moving groups in the halo (*eg.* Eggen 1979, Majewski *et. al.* 1994) may come from disrupted fragments or globular clusters. The Sagittarius dwarf (Ibata *et. al.* 1994) is an example of a large dSph galaxy which is now tidally disrupting. This dwarf contains a significant intermediate age population, as well as an underlying old population.

The four globular clusters associated with the Sgr dwarf include both old and younger clusters (Da Costa and Armandroff 1995), so it will contribute both old and younger clusters to the galactic globular cluster system.

Rodgers *et. al.* (1981) and Lance (1988) discuss the young metal-rich main sequence A stars found up to 11 kpc from the galactic plane. This is an unusual population: at the SGP its velocity dispersion $\sigma_W = 62$ km s^{-1}, while similar stars near $l = \pm 90°, b = -45°$ have a line of sight velocity dispersion of 40 km s^{-1} and $V_{\rm rot} = 210$ km s^{-1}. They argue that the formation of these stars is associated with the accretion of somewhat metal-poor gas, perhaps from a dwarf galaxy (or a high velocity cloud).

Preston *et. al.* (1994) discovered a population of blue metal-poor (BMP) main sequence stars near the solar circle. These stars have [Fe/H] < -1 and are bluer (*ie.* younger) than the old turnoff stars of the halo. The kinematics of the BMP stars are particularly interesting. Their velocity dispersion is about 90 km s^{-1} and isotropic, and their $V_{\rm rot} = 128 \pm 30$ km s^{-1}. (For an old halo sample with similar abundances, we would expect a lower $V_{\rm rot} \approx 55$ km s^{-1}). These early-type metal-poor stars appear to be kinematically intermediate between the rapidly rotating disk and the slowly rotating halo. What are they ? Their ages are > 3 Gyr and their abundances have [Fe/H] < -1. Where would such stars form ? Preston *et. al.* note that nearby satellites like the Carina dSph galaxy have major intermediate-age metal-poor components, and suggest that the galactic BMP stars may come from similar accreted dwarf galaxies, with the BMP stars representing the blue tips of the accreted populations. They estimate that the accreted population contributes about 10% of the local halo density, consistent with a similar limit by Unavane *et. al.* (1995) on the density of accreted objects, with a total accreted mass of about $10^8\ M_\odot$ (*ie.* several dSph galaxies).

4. The Disk of the Galaxy

Like the disks of most other spirals, the old disk of the Galaxy appears to have settled to a double exponential distribution: $\rho(R,z) \propto \exp(-R/h_R - z/h_z)$. The reason is not fully understood, but the radial structure may have to do with the dynamics of star-forming viscous disks which settle to an exponential in R if the star formation and viscous timescales are comparable but longer than the dynamical timescale (*eg.* Lin and Pringle 1987). For exponential disks in which the anisotropy σ_z/σ_R is constant with R, we would expect $\sigma_R \propto \exp(-R/2h_R)$. This is seen in our Galaxy (Lewis and Freeman 1989) and is common in others (*eg.* Bottema 1993). In our Galaxy, the velocity dispersion in the inner disk is almost as high as it is in the bulge (about 110 km s^{-1}); the source of the heating (spiral waves, bar heating, scattering by giant molecular clouds) is not well understood.

¿From the white dwarf luminosity function and nucleochronology, the age of the galactic disk near the sun is about 10×10^9 years. The disk shows dynamical evolution. This is well seen in the sample of F stars by Edvardsson *et. al.* (1993), with accurate ages, velocities and abundances (see also Freeman 1991). Important results from this study include:

- the run of stellar velocity against age shows the appearance of the old hotter thick disk at an age of about 12×10^9 years, and also the secular heating of the disk, particularly for stars younger than about 3 Gyr.
- the [Fe/H] – age plane shows a large spread of abundance among the disk stars of a given age. This indicates inhomogeneous enrichment; the amplitude of the scatter is comparable to that seen among the HII regions in the disks of other galaxies (*eg.* Zaritsky 1992).

5. More on the Thick Disk

For our Galaxy, the mass of the thick disk is about 10% of the thin disk mass. However, the thick disk is not an essential feature of galaxy formation and evolution: many disk galaxies, particularly those with weaker bulges, do not show thick disks. Gilmore *et. al.* (1995) studied galactic thick disk stars up to about 3 kpc from the galactic plane, and found no abundance gradient. This argues against dissipational settling as the formation process. Quinn *et. al.* (1993) made simulations of satellite accretion by disk galaxies, and showed how the disk is heated and the debris of the satellite is dispersed throughout the disk. The dynamical properties of the heated disk near the solar radius ($\sigma, V_{\rm rot}, h_R, h_z$) are very similar to those observed for the galactic thick disk. We note again that the heating must have occurred early in the life of the galactic disk, while the disk was still mainly gaseous and could resettle to a thin disk after the accretion events.

6. The Galactic Bulge

de Vaucouleurs (1964) pointed out that our Galaxy has an inner bar structure, and classified it as SAB(rs)bc. The evidence for an inner bar/bulge is now strong, and includes:

- the asymmetry in l of the DIRBE galactic light distribution and the brightness of bulge IRAS sources, Mira variables and clump giants,
- the $l-$velocity distribution of molecular gas, and
- the large optical depth (3×10^{-6}) to microlensing in bulge fields.

See Gerhard (1995) for references. The effects of this bar/bulge on the evolution of the Galaxy need to be fully considered, and include:

- bar-driven gas infall and chemical enrichment of the inner bulge (note that only the inner parts of the bulge are metal-rich),

https://doi.org/10.1017/S0074180900232087 Published online by Cambridge University Press

- effects on the chemical evolution of the disk via bar-induced gas flows,
- the dynamical heating of the inner stellar disk by the bar.

Bars can form from disks via dynamical instabilities. This makes sense in the galactic context: we note that (i) the scale height of the DIRBE bar/bulge is about 300 pc, similar to that of the old disk, and (ii) the chemical abundance of the bulge at about 1 kpc from the plane is similar to that of the thick disk. The stars of the bar/bulge are mostly old, but this does not mean that the *structure* of the bar/bulge is so old: it may well be relatively recent. Bars can self-destruct by developing a central mass of only a few percent (*eg.* Norman *et. al.* 1995). This will naturally happen if gas is present. The central mass destroys the bar-forming orbits, and the bar rapidly dissolves to a more axisymmetric structure. So it is possible that our galactic bar/bulge may be relatively young and impermanent if current ideas on the dynamics of bars are correct.

References

Beers, T., Sommer-Larsen, J. 1995. Astrophys.J.Suppl., 96, 175.
Bottema, R. 1993. Astron.Astrophys., , 275, 16.
Carney, B. *et. al.* 1995. Personal communication.
Da Costa, G., Armandroff, T. 1995. Astron.J., 109, 2533.
de Vaucouleurs, G. 1964. In "The Galaxy and the Magellanic Clouds" (Austr. Acad. Sci), ed. F. Kerr and A. Rodgers, p 195.
Edvardsson, B. *et. al.* 1993. Astron.Astrophys., 275, 101.
Eggen, O.J., Lynden-Bell, D., Sandage, A. 1962. Astrophys.J., 136, 748.
Eggen, O.J. 1979. Astrophys.J., 229, 158.
Freeman, K. 1991. In "Dynamics of Disc Galaxies" (Göteborg), ed B. Sundelius, p 15.
Gerhard, O. 1995. In "Unsolved Problems of the Milky Way" (Kluwer), ed L. Blitz, in press.
Gilmore, G., Wyse, R., Jones, B. 1985. Astron.J., 109, 1095.
Hartwick, F.D.A. 1986. in "The Galaxy" (NATO), ed G. Gilmore, R. Carswell, p 281.
Ibata, R., Gilmore, G., Irwin, M. 1994. Nature, 370, 194.
Kinman, T, Suntzeff, N., Kraft, R. 1994. Preprint.
Lance, C. 1988. Astrophys.J., 334, 927.
Layden, A. 1995. Preprint.
Lewis, J., Freeman, K. 1989. Astron.J., 97, 139.
Lin, D., Pringle, J. 1987. Astrophys.J., 320, L87.
Lynden-Bell, D., Lynden-Bell, R. 1995. Mon.Not.R.Astron.Soc., 275, 429.
Majewski, S. 1992. Astrophys.J.Suppl., 78 87.
Majewski, S. 1994. Astrophys.J., 431, L17.
Majewski, S., Munn, J., Hawley, S. 1994. Astrophys.J., 427, L37.
Morrison, H.L., Flynn, C., Freeman, K.C. 1990. Astron.J., 100, 1191.
Norman, C., Sellwood, J., Hasan, H. 1995. Preprint.
Norris, J., Bessell, M., Pickles, A. 1985. Astrophys.J.Suppl., 58, 463.
Preston, G., Shectman, S., Beers, T. 1991. Astrophys.J., 375, 121.
Preston, G., Beers, T., Shectman, S. 1994. Astron.J., 108, 538.
Quinn, P., Hernquist, L., Fullagar, D. 1993. Astrophys.J., 403, 74.
Rodgers, A., Harding, P., Sadler, E. 1981. Astrophys.J., 244, 912.
Searle, L., Zinn, R. 1978. Astrophys.J., 225, 357.
Sommer-Larsen, J., Flynn, C., Christensen, P.R. 1994, preprint.

https://doi.org/10.1017/S0074180900232087 Published online by Cambridge University Press

Toomre, A. 1977. In "The Evolution of Galaxies and Stellar Populations" (Yale University Observatory), ed B. Tinsley and R. Larson, p 420.
Unavane, M., Wyse, R., Gilmore, G. 1995. Preprint.
Zaritsky, D. 1992. Astrophys.J., 390, L73.
Zinn, R. 1980. Astrophys.J., 241, 602.

Discussion

Gerhard: In the dynamical simulations, the bending instability taking disk stars out of the plane often occurs shortly after the bar instability in the disk. If the latter is caused by gas infall and cooling of the disk, one would then expect significant star formation to occur shortly before the bulge.

Minniti: From all that stellar evidence, can you tell what kind of satellites were accreted to form the halo ?

Freeman: The total mass of all fragments accreted into the halo should not exceed about $1 \times 10^9\ M_\odot$ (the mass of the metal-poor halo). There should be many of them (because the rotation of the halo is low) and their masses should be relatively low (because the chemical abundance of the halo is low). The presence of the BMP stars suggests that accretion of several dSph galaxies with intermediate-age populations has also occurred more recently. And we see the Sgr dSph now in the process of being accreted.

Rix: You mentioned repeatedly the "intermediate age" populations of dSph galaxies. Has there been any progress in understanding how the galaxies managed to hold (or re-acquire) gas for a second star formation episode ?

Freeman: It will be interesting to learn if the dwarf irregular galaxies in the Local Group have had similar distinct episodes of star formation.

Harris: The supposed age gradient in the galactic halo might really be a result of an increased *range* in ages among the outer halo objects. Some new HST photometry of the outermost halo globular clusters ($R_G = 100$ kpc) shows that one or two of them are just as old as the inner halo.

Kormendy: If you plot the density profile of the bulge and halo as a function of radius, is there a clearcut transition or break between them ? Do you think that the bulge and halo are physically related ? If there is a transition between bulge and halo, at what radius does it occur ?

Freeman: The structure of the inner halo is not yet well enough known to make the test with the density profile that you suggest. I think the bulge and halo are probably not physically related, because the kinematics of the bulge (rotation at about 100 km s^{-1}) and the halo (low rotation, even in the inner parts) are so different.