EARLY-TYPE STARS

K.C. FREEMAN
Mount Stromlo and Siding Spring Observatories
The Australian National University
Canberra, AUSTRALIA
(kcf@merlin.anu.edu.au)

Abstract. Away from the young disk, several classes of early type stars are found. They include *(i)* the old, metal-poor blue horizontal branch stars of the halo and the metal-poor tail of the thick disk; *(ii)* metal-rich young A stars in a rapidly rotating subsystem but with a much higher velocity dispersion than the A stars of the young disk, and *(iii)* a newly discovered class of metal-poor young main sequence A stars in a subsystem of intermediate galactic rotation ($V_{rot} \approx 120$ km s^{-1}). The existence and kinematics of these various classes of early type stars provide insight into the formation of the metal-poor stellar halo of the Galaxy and into the continuing accretion events suffered by our Galaxy.

1. Introduction

In this review, I will discuss some of the classes of early type stars inhabiting regions of the Galaxy which are usually associated with the older populations. I will not be able to discuss:

- The early type stars of the young disk;
- The apparently normal OB stars seen up to about 20 kpc from the galactic plane which are believed to have formed *in situ*, possibly through galactic fountains or associated with high velocity clouds;
- Other very young stars apparently ejected from the galactic plane by binary destruction or binary interactions within star clusters and associations;
- The RR Lyrae stars, which are an important metal-poor population tracer and a very large subject in themselves;

P. C. van der Kruit and G. Gilmore (eds.), Stellar Populations, 119–127.

- Other highly evolved early type stars such as the white dwarfs, subdwarf O and B stars, and the bright post-AGB stars.

First I will briefly describe the properties of the old components of the Galaxy near the sun, to provide a context for the discussion of the early type stars.

2. The Old Components of the Galaxy near the Sun

The **thin disk** has a mean rotational velocity of about 210 km s^{-1} in the solar neighborhood and its velocity dispersion in the usual UVW components is about (40,30,20) km s^{-1}. Its exponential scale height is about 300 pc and its radial scale length is about 4.5 kpc. The chemical abundance of the nearby old disk stars lies typically in the range 0.2 > [Fe/H] > -0.5. The thin disk contains most of the luminous mass of the Galaxy (see *e.g.* Freeman, 1987, 1991).

The **thick disk** is a hotter disk-like component. In the solar neighborhood, its mean rotational velocity is about 190 km s^{-1} and its velocity dispersion is about (60,40,40) km s^{-1} (see Beers and Sommer-Larsen, 1994). Its exponential scale height and scale length are about 1000 pc and 4.5 kpc respectively, and it provides about 5 to 10% of the galactic luminous mass. Most of the thick disk stars have abundances in the range -0.5 > [Fe/H] > -1.0, but the abundance distribution shows a long tail extending down to much lower [Fe/H] values. Beers and Sommer-Larsen show that about 60% of the nearby metal-poor stars with -1.0 > [Fe/H] > -1.6 belong kinematically to the thick disk, as do about 30% of the very metal poor stars with [Fe/H] < -1.6. The total mass of stars in the metal-poor tail of the thick disk is about 10^8 $M_\odot$.

The **metal-poor halo** is the diffuse population defined by the metal-poor halo globular clusters, RR Lyrae stars, blue horizontal branch stars etc. Its radial density distribution follows the power law $\rho(r) \propto r^{-3.5}$, and there is some evidence that its mean age decreases outwards by a few Gyr (*e.g.* Zinn, 1980). Kinematically, the halo population near the sun has a mean rotational velocity near zero, and its velocity dispersion is about (140,100,100) km s^{-1}.

Most people now believe that there is a fairly sharp break between the rapidly rotating components (thin and thick disks) and the non-rotating metal-poor halo. There is little evidence for an old population with intermediate kinematics.

3. What Early-type Stars Could be Expected Away from the Young Disk ?

Other than the stars which I am excluding from this review, the main families of early type stars that we might expect to find away from the young disk include:

- The blue horizontal branch (BHB) stars of the metal-poor halo and the metal-poor tail of the thick disk;
- Blue stragglers of the thick disk and halo;
- Younger main sequence stars, maybe metal-rich or metal-poor, associated with more recent accretion events. These could be stars which formed in accreted satellites, or stars which formed from galactic or accreted material during the accretion event itself.

For practical reasons, to do with the separation of BHB stars and stars of higher gravity, most studies of early type stars away from the galactic plane are of stars in the color range $0.0 < (B\text{-}V)_o < 0.3$. Even in this range, the separation is not easy. A wide variety of separation methods have been used. We should expect that most samples of early type stars (BHB or with main sequence gravities) will be contaminated at some level.

4. Why Study Early-Type Stars ?

Among the early type stars, the BHB stars are excellent probes of the old metal-poor population. It is easy to find candidate BHB stars, even at large distances, although it is not so easy to separate the BHB stars from contaminants like main sequence A stars. Also, it is possible to estimate relatively accurate photometric parallaxes for BHB stars.

The goals of studying the BHB star population are to derive the structure and dynamics of the metal-poor halo and the metal-poor tail of the thick disk. Some specific applications include:

- the density distribution and the mass of the metal-poor halo;
- the dynamics of the halo;
- discovery of moving groups of old stars (*e.g.* Doinides and Beers, 1989; Arnold and Gilmore, 1992) which may be the debris of accretion events or tidally disrupted globular clusters;
- radial population gradients in the metal-poor halo (*e.g.* the radial gradient in the second parameter effect);
- the mass distribution of the galactic dark corona, from the kinematics of the most distant BHB stars.

Searches for early type main sequence stars away from the galactic plane (mostly A stars for practical reasons) provide the possibility of detecting younger populations in the thick disk and halo, as evidence of more recent

https://doi.org/10.1017/S0074180900108484 Published online by Cambridge University Press

star formation or recent galactic accretion events (*e.g.* Rodgers *et al.* 1981; Rodgers and Roberts 1993a,b; Preston *et al.*, 1994).

Major studies of early type stars away from the galactic plane include:

- The Beers-Preston-Shectman HK survey (1988ff) and Pier's (1982ff) follow-up study which produced 4408 field BHB star candidates;
- Sommer-Larsen and associates' (1986ff) search for halo BHB stars;
- Rodgers (1971), Rodgers *et al.* (1981, 1993a,b) and Lance (1988a,b) on the halo main sequence A stars;
- Norris and Hawkins' (1991) study of the kinematics of distant halo BHB stars;
- Kinman *et al.* (1994) on the halo BHB population.

In the following sections, I will discuss the results of some of these studies in more detail.

5. High Latitude Main Sequence A Stars

Rodgers (1971) and Rodgers *et al.* (1981) found metal rich main sequence A stars at heights of 1 to 4 kpc above the galactic plane. Their vertical velocity dispersion $\sigma_W = 66$ km s^{-1}, their [Ca/H] values are in the range 0 to -0.5, and their ages appear to be < 2 Gyr. They suggested that the formation of these high latitude A stars resulted from a merger of a dwarf galaxy (maybe a third Magellanic Cloud) with the Galaxy.

Their work was followed up by Lance (1988a,b) with Strömgren photometry, measurement of the $D_{0.3}$ width parameter for the Balmer absorption lines, Ca K equivalent widths and radial velocities of a sample of early type stars with V < 15 near the SGP. She found 29 main sequence stars, up to 11 kpc from the galactic plane, again with 0.0 > [Ca/H] > -0.5, well separated from the BHB stars in the (log g, Θ) plane, and with $\sigma_W = 62$ km s^{-1}. About half of the A stars in her sample in the region 1 < z < 4 kpc are main sequence "population I" stars. The histogram of ages for these high latitude A stars is sharply peaked between (2 and 5) $\times 10^8$ yr, compared to the much broader age distribution of the disk A stars which extends up to about 2 Gyr. The age distributions of the high latitude A stars argues strongly against their origin *via* stochastic acceleration from the disk, or the possibility that they are blue stragglers. Lance also measured rotational velocities for a subsample of her stars: their distribution of $v \sin i$ is typical of normal young A stars rather than of BHB stars or blue stragglers. In summary, these high latitude A stars are a young, metal rich and dynamically hot population. One would expect to see evidence of this population in surveys for lower mass main sequence stars above the galactic plane (*e.g.* Wyse and Gilmore, 1990).

The discussion so far has been for A stars near the SGP. Rodgers and Roberts (1993a,b) made a new objective prism survey for A0 to F0 stars with $10 < V < 15.5$ in galactic fields at $l = \pm 90°$, $b = -45°$. This survey was aimed partly at determining the rotational properties of the high latitude A star population, and was followed by slit spectroscopy to derive [Ca/H] abundances and velocities. Of the 320 stars in the final sample, 80 have estimated values of [Fe/H] > -0.5. Their mean rotational velocity $V_{rot} = 210 \pm 12$ km s^{-1} and their line-of-sight velocity dispersion is $\sigma_{los} = 40 \pm 3$ km s^{-1}. We recall that Lance derived $\sigma_W = 62$ km s^{-1}. This is a kinematically unusual population but not grossly different in its kinematic properties from the thick disk. However there are far too many of these stars (relative to other thick disk stars) for them to be blue stragglers of the thick disk, at least according to the statistics of blue stragglers in globular clusters. And from Lance's work, the high latitude A stars are anyway much younger than the thick disk.

The metal-poor stars in the Rodgers and Roberts sample are interesting. They selected a subsample with $H\delta$ equivalent widths between 6 and 18Å, (to avoid old metal-poor turnoff stars and hot main sequence stars) and [Fe/H] values < -1. These are mostly BHB stars, but may include some metal-poor main sequence stars. Among the stars within 2.5 kpc of the galactic plane, a significant fraction has disk kinematics, persisting down to [Fe/H] = -1.7. These are probably the BHB stars of the metal-poor tail of the thick disk.

6. Metal-poor Blue Main Sequence Stars

From the HK survey, Preston *et al.* (1994) generated a sample of stars with UBV photometry and with $0.15 < (B\text{-}V)_o < 0.35$. These stars have main sequence gravities and UBV colors lying to the blue of the most metal-poor globular cluster main sequence turnoff. From their (U-B) color excesses and model atmospheres, they found 175 stars with [Fe/H] < -1 and $V_o > 13$ within about 2 kpc of the sun. It seems unlikely that many of these blue metal-poor (BMP) stars could be halo blue stragglers, because their frequency relative to the halo BHB stars is so high: N(BMP)/N(BHB) ≈ 8, compared with a relative frequency of 0.8 for the metal-poor globular clusters. Preston *et al.* conclude that these BMP stars probably lie on isochrones whose main sequence turnoff lies within or to the blue of this color range $0.15 < (B\text{-}V)_o < 0.35$; *i.e.* they are young objects with ages as low as about 3 Gyr.

The kinematics of these BMP stars is particularly interesting. Their galactic rotation velocity V_{rot} is 128 ± 30 km s^{-1}, and the velocity dispersion is an apparently isotropic 90 km s^{-1}. For comparison, a sample of halo stars

https://doi.org/10.1017/S0074180900108484 Published online by Cambridge University Press

with a similar distribution of [Fe/H] would have $V_{rot} = 55 \pm 9$ km s^{-1}. The line-of-sight velocity distribution is very closely gausssian and shows no sign of a disk component. These early-type metal-poor stars are apparently kinematically intermediate between the halo and the thick disk. There is some indication of a similarly intermediate population in the G-star survey of Wyse and Gilmore (1990): they may be seeing the fainter but similarly young counterparts of the BMP stars.

These stars are young (ages > 3 Gyr), metal-poor ([Fe/H] < -1) and kinematically intermediate. Where would such stars form ? Preston *et al.* note that some nearby satellite systems like the Carina dwarf spheroidal galaxy have major intermediate-age metal-poor components. It seems possible that the galactic BMP stars may have come from accreted dwarfs. They estimate that the accreted population represents about 10% of the local halo density, and that the total accreted mass would be about 10^8 $M_\odot$; this is equivalent to several dwarf spheroidal galaxies.

We have now seen two families of relatively young stars that lie far from the disk and have kinematics that are clearly unlike those of the thin disk. We note that these two families (the BMP stars and the high latitude A stars) have different properties and kinematics. The BMP stars, with their low abundances and intermediate kinematics, may come from accreted objects, as Preston *et al.* suggest. The more metal-rich main sequence A stars of Rodgers and Lance show rapid galactic rotation and may have formed from galactic material during mergers.

7. The Structure of the BHB Star Halo

Kinman *et al.* (1994) studied the structure of the galactic halo outside the solar circle, using halo BHB stars as tracers. They selected their candidate stars from the Case AF star survey in two fields: SA157 (NGP) and an anticenter field (l = 183°, b = 37°). From the survey stars with colors in the range $0 < (B\text{-}V)_o < 0.2$, they made an unusually thorough selection of the BHB stars using three criteria: *(i)* a photoelectric u-B color which measures the Balmer jump, *(ii)* spectrophotometric indices measuring the amplitude and steepness of the Balmer jump, and *(iii)* the $D_{0.2}$ width parameter for the Balmer $H\gamma$ and $H\delta$ lines. They find that the $D_{0.2}$ parameter alone is not a clean discriminant for BHB stars, even from high S/N spectra.

Of (35,37) blue stars with $13 < V < 16.5$ in the two survey fields respectively, they selected (16,15) BHB stars, which are believed to represent a complete sample. The non-BHB stars are mostly metal-poor (78%,64%) with [Fe/H] < -0.9. Again, using the halo globular clusters for reference, there are far too many of these metal-poor non-BHB stars (relative to the BHB stars) to be blue stragglers of the galactic halo. Probably they are the

BMP stars of Preston *et al.* (1994): see §6.

Augmenting their BHB sample with stars from Arnold and Gilmore (1992) and Sommer-Larsen and Christensen (1986), Kinman *et al.* show that the density distribution of the BHB star halo is well represented by $\rho \propto r^{-3.5}$ for $|z| > 5$ kpc. The BHB star distribution in the NGP field is well fit by the spherical $\rho \propto r^{-3.5}$ model with a local density of 6 BHB stars kpc^{-3} at the sun. However the distribution in the anticenter field requires an additional flatter component with a scale height of about 2 kpc at the sun and a local density of 24 BHB stars kpc^{-3}. What is this extra (and dominant) flatter component in the BHB star distribution ? Is it the metal weak tail of the thin disk again ? This is not yet clear. The survey fields are not well suited to measuring the galactic rotation V_{rot}; however the line of sight velocity dispersions σ_{los} in the two fields have similar values of about 140 km s^{-1}, which is much higher than the velocity dispersion of the thick disk (see §2).

8. The Color Gradient among the Field BHB Stars

Globular clusters in the galactic halo show a gradient in the second parameter effect with galactic radius (see *e.g.* Zinn 1980). This is now conventionally interpreted as an age effect: the globular clusters in the outer parts of the Galaxy formed later and over a longer time interval than the clusters in the inner Galaxy (although there are other factors which affect the morphology of the HB). Preston *et al.* (1991) investigated the change in the mean color of field BHB stars with galactic radius. They selected the BHB stars from their distribution in the $(U\text{-}B)_o$, $(B\text{-}V)_o$ diagram. With an adopted M_V - $(B\text{-}V)_o$ relation and the galactic density distribution $\rho \propto r^{-3.5}$, they showed that a constant BHB mean color with galactocentric radius is inconsistent with the observed color distribution of BHB stars over B_o.

For BHB stars in the color window $-0.02 < (B\text{-}V)_o < 0.18$, Preston *et al.* find that the mean unreddened (B-V) color increases outwards with galactocentric radius by about 0.025 over the interval 2 to 12 kpc. This indicates that the mean age of the field BHB stars decreases outwards in the halo systematically by a few Gyr, similar to the implications of the second parameter gradient for the halo globular clusters.

Preston *et al.* used their BHB star sample to measure the total density of the metal-poor halo near the sun. Using *(i)* their estimate of 42 HB stars kpc^{-3}, *(ii)* the observed ratio of integrated V luminosity to HB star numbers for globular clusters: $L_V/N_{HB} \approx 540$, and *(iii)* the typical mass-to-light ratio $M/L_V \approx 2.5$ for globular clusters, they derive a halo density of about 5.7×10^4 $M_\odot$ kpc^{-3} locally, which is within the range of previous estimates.

https://doi.org/10.1017/S0074180900108484 Published online by Cambridge University Press

9. Kinematics of BHB Stars in the Outer Galactic Halo

Sommer-Larsen *et al.* (1994) and Sommer-Larsen *et al.* (1994) compiled a list of faint field BHB stars covering a very large interval of galactocentric radius, from about 5 to 50 kpc. These stars come from catalogs in four galactic fields [the SGP, (270°, -45°), (38°, -51°), and (0°, -47°)] by Flynn *et al.* plus a sample of very distant BHB stars (40 to 65 kpc) by Norris and Hawkins (1991). They also observed a sample of BHB stars at (0°, -29°) in the inner regions of the Galaxy, chosen from the Beers *et al.* (1988) survey. Their goal was to study how the velocity ellipsoid of the metal-poor stellar halo changes shape with radius; this provides a useful constraint on the formation process for the metal-poor stellar halo. The BHB stars are ideal tracers for this purpose, because they can be classified at great distances.

The authors use a simple model of the radial and tangential velocity dispersions as functions of galactocentric distance r_G, together with the Jeans equation, to show that the radial component σ_r of the halo velocity dispersion decreases fairly rapidly with radius beyond the solar circle. The decrease in σ_r is from about 140 km s^{-1} at the solar circle to an asymptotic value of about 80 km s^{-1} at large radius. This decrease in σ_r is matched by a corresponding increase in the tangential velocity dispersion component σ_θ with increasing radius, from about 95 km s^{-1} at the solar circle to about 130 km s^{-1} at large radius. This indicates that the velocity ellipsoid changes from radial anisotropy near the sun to tangential anisotropy at large r_G. In the inner galaxy ($r_G \approx 4$ to 5 kpc), the radial anisotropy is even more extreme than at the solar circle: the derived velocity ellipsoid is $(\sigma_r, \sigma_\theta) = (215 \pm 34, 78 \pm 19)$ km s^{-1}. This behaviour, with the tangential anisotropy in the outer regions, is probably more consistent with the formation of the halo by accretion of small subsystems, rather than by the early collapse of a monolithic overdensity in the early universe.

10. Summary

Away from the young disk, the early type stars are a heterogeneous collection. We find

- old halo BHB stars, with evidence for flattened and approximately spherical components, and with strong tangential anisotropy of the velocity ellipsoid at large galactocentric radius;
- BHB stars of the metal-poor tail of the thick disk;
- metal-rich young main sequence A stars, in a rapidly rotating system ($V_{rot} \approx 210$ km s^{-1});
- metal-poor young main sequence A stars in intermediate rotation ($V_{rot} \approx$ 120 km s^{-1}).

The early type stars are useful probes of different populations, and provide insight into the formation of the metal-poor halo of the Galaxy and into the continuing accretion events suffered by the Galaxy; however some practical problems of classification (*i.e.* BHB *vs.* main sequence) remain.

References

Arnold, R. and Gilmore, G., 1992, M. N. R. A. S. **257**, 225
Beers, T.C., Preston, G.W. and Shectman, S.A., 1988, Ap. J. Suppl. **67**, 461
Beers, T.C. and Sommer-Larsen, J., 1994, preprint
Doinides, S.P and Beers, T.C., 1989, Ap. J. **340**, L57
Flynn, C., Sommer-Larsen, J. and Christensen, P.R., 1994 M. N. R. A. S. **267**, 927
Freeman, K.C., 1987, Ann. Rev. Astron. Astrophys. **25**, 603
Freeman, K.C., 1991, *Dynamics of Disk Galaxies*, ed. B. Sundelius, Göteborg, p.15
Kinman, T.D., Suntzeff, N.B. and Kraft, R.P., 1994, preprint
Lance, C.M., 1988a, Ap. J. Suppl. , **68**, 463
Lance, C.M., 1988b, Ap. J. **334**, 927
Norris, J.E. and Hawkins, M., 1991, Ap. J. **380**, 104
Pier, J.R., 1982, A. J. **87**, 1515
Preston, G.W., Shectman, S.A. and Beers, T.C., 1991, Ap. J. **375**, 121
Preston, G.W., Beers, T.C. and Shectman, S.A., 1994, preprint
Rodgers, A.W., 1971, Ap. J. **165**, 581
Rodgers, A.W., Harding, P. and Sadler, E., 1981, Ap. J. **244**, 912
Rodgers, A.W. and Roberts, W.H., 1993a, A. J. **106**, 1839
Rodgers, A.W. and Roberts, W.H., 1993b. A. J. **106**, 2294
Sommer-Larsen, J. and Christensen, P.R., 1986, M. N. R. A. S. **219**, 537
Sommer-Larsen, J., Flynn, C. and Christensen, P.R., 1994, preprint
Sommer-Larsen, J., Christensen, P.R. and Flynn, C., 1994, preprint
Wyse, R. and Gilmore, G., 1990, *Chemical and Dynamical Evolution of Galaxies*, eds. F. Ferrini, J. Franco and F. Matteucci, Pisa:ETS, p.19
Zinn, R., 1980, Ap. J. **241**, 602