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EARLY TYPE STARS AT LARGE DISTANCES FROM THE GALACTIC PLANE

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1. Introduction

Over the past decade many apparently normal early-type stars have been observed at large distances (\(z\)) from the galactic plane (see for example Keenan and Dufton 1983 and references therein). Such distances imply that several of these stars have been ejected from the disc of the galaxy with velocities of hundreds of \(\text{km} \text{s}^{-1}\) in order to reach their present \(z\) – distances during their lifetimes, unless they are formed in the halo which appears unlikely due to the low particle density (Savage and de Boer 1981). For example, a B1V star at \(z = 2\) kpc requires an ejection velocity of at least \(200 \text{ km} \text{s}^{-1}\). Alternatively, it is possible that the stars are subluminous, nearby objects whose spectra mimic those of normal stars at the low dispersions (50–100\(\AA \text{ mm}^{-1}\))
used for classification purposes (see for example Carrasco and Crézé 1978; Carrasco et al 1980, 1982; Dworetsky et al 1982). Several such objects are known, the most famous probably being HD93521, which for a long time was thought to be a normal O9V star at $z = 1.6$ kpc (Savage and Bohlin 1979). However more detailed analyses have revealed that the star actually belongs to Population II and is only $\sim 600$ pc from the plane (Ebbets and Savage 1982).

Greenstein and Sargent (1974) quantitatively analysed the spectra of several high-latitude blue stars and found them to be mostly Population I, while Tobin and Kilkenny (1981), using moderate dispersion spectrograms, discovered no significant differences between two groups of OB stars at apparent $z$-distances of $\leq 0.5$ kpc and $\geq 1.5$ kpc respectively. More recently, Tobin and Kaufmann (1984) have shown that three early-type halo stars are normal, distant objects from an analysis of optical and IUE observations.

There appears therefore to be increasing evidence to support the large distances derived for early-type halo stars. In the sections below it is shown how the research carried out at QUB provides some insight into the nature and possible origin of these objects.

2. Nature of the early-type stars in the Galactic halo

(a) Atmospheric parameters and chemical compositions. For a large sample of halo stars ($N \approx 70$) effective temperatures, $T_{\text{eff}}$, and surface gravities, $\log g$, were derived primarily from reddening-free colour indices $[c_i]$ and H$\beta$ photometric indices respectively. The method consisted of comparing indices calculated from LTE model atmospheres with observed values and is discussed fully in Keenan et al (1982) and Keenan and Dufton (1983). Effective temperatures were originally derived on the Klinglesmith (1971) hydrogen-line blanketed grid of models but were subsequently converted to those on the more fully line-blanketed grid of models of Morton and his co-workers as the latter give a better estimate of the stellar flux (see Keenan 1982a for more details). For several of the programme stars H$\gamma$ and H$\delta$ absorption line-width data were available which were used to derive gravities using the calibrations of Keenan et al (1982) and Ella et al (1983).

The atmospheric parameters derived using the above methods were found to be typical of normal OB stars, with effective temperatures and gravities lying in the range 14,000–35,000 K and 3.5–4.5 respectively. However, as noted in the introduction, normal atmospheric parameters do not in themselves indicate that a star is normal. One must resort to an abundance analysis as only then Population I and II stars can be distinguished due to their different chemical compositions.

Before an abundance analysis could be performed on the programme stars it was necessary to assign microturbulent velocities $v_t$ to each of them. Previous LTE analyses have yielded microturbulent velocities of 5 km s$^{-1}$ for main-sequence stars (Aller 1970, Kodaira and Scholz 1970, Kane et al 1980) and $\sim 15$ km s$^{-1}$ for supergiants (Dufton 1979, Kane et al 1981, Keenan and Lennon 1984). These values were therefore adopted and for giant stars a microturbulence of 10 km s$^{-1}$ was assumed.

Chemical compositions of the programme stars were derived using the atmospheric parameters in conjunction with stellar equivalent widths (measured primarily
from high quality AAT spectra) and the LTE model atmosphere program of Dufton (1972). The mean abundances are listed in Table 1 as well as the normal OB-star

Table 1

Mean logarithmic abundances in programme stars
(on scale log [H] = 12.0)

<table>
<thead>
<tr>
<th>Element</th>
<th>Mean Abundance</th>
<th>Normal OB Stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>11.00</td>
<td>11.00</td>
</tr>
<tr>
<td>C</td>
<td>8.23</td>
<td>8.20</td>
</tr>
<tr>
<td>N</td>
<td>7.97</td>
<td>7.96</td>
</tr>
<tr>
<td>O</td>
<td>8.88</td>
<td>8.82</td>
</tr>
<tr>
<td>Ca</td>
<td>6.38</td>
<td>6.30</td>
</tr>
<tr>
<td>Mg</td>
<td>7.35</td>
<td>7.40</td>
</tr>
</tbody>
</table>

values (Auer and Mihalas 1973; Mihalas 1972, 1973; Kane et al 1980; Lamers et al 1973). For all elements the halo star abundances are in excellent agreement with those of ordinary Population I objects, from which one is forced to conclude that the stars are indeed normal.

(b) Distances and ejection velocities. Stellar luminosities (and hence distances) were derived using the standard relationship

$$\log L/L_\odot = 4 \log T_{\text{eff}}/T_{\text{eff}\odot} + \log M/M_\odot + \log g/g_\odot$$

where the subscript $\odot$ refers to the Sun and the other symbols have their usual meanings. Stellar masses were estimated from the star's position on conservative and non-conservative evolutionary tracks in the $\log T_{\text{eff}} - \log g$ diagram (see Keenan et al 1982 for more details). Accurate distances to halo stars are of great importance as many authors use these objects as tracers for the intervening halo interstellar medium (see for example Albert 1982; Hobbs et al 1982; Keenan 1982b; Keenan et al 1981, 1983).

From the evolutionary tracks, estimates of the stellar ages may also be made which, when combined with the $z$-distances, allow a lower limit to be placed to the ejection velocity of the star, i.e. the velocity with which it had to be ejected from the galactic plane in order to reach its present position during its lifetime. These were found to exceed 100 km s$^{-1}$ in many cases, with the maximum value being 300 km s$^{-1}$ for HD219188. The problem therefore appears to be one of explaining how stars can be accelerated to such velocities. This is discussed in the next section.

3. Origin of the early-type halo stars

As discussed above it is necessary to invoke some mechanism to accelerate stars to large velocities in order to explain their presence in the halo. One such mechanism is the "runaway" hypothesis of Zwicky (1957) and Blaauw (1961), later refined by Gott et al (1970) and Sutantyo (1975), in which the primary in a close binary system

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Figure 1. Plot of absolute peculiar velocity against mass for stars with $|z| \geq 400$ pc. The labelled points refer to the stars HD179407 and CPD−72° 1184 which have absolute peculiar velocities of 163 km s$^{-1}$ and 208 km s$^{-1}$ respectively.

loses mass in a supernova explosion and the centre of gravity of the system is accelerated by the recoil produced by the ejection of the supernova shell (see also Stone 1979). Gott et al (1970) have calculated that the recoil velocity imparted to the binary system should be proportional to the mass of the secondary (i.e. the observable star), and more recently Stone (1979, 1981, 1982) has found a correlation between the peculiar space velocities of runaway O stars and their masses, indicating that the Blaauw (1961) mechanism may be responsible for their large velocities.

To investigate if the “runaway” hypothesis could explain the presence of early-type stars in the galactic halo, we have searched for a velocity-mass correlation for those programme stars with $|z| \geq 400$ pc. (This minimum $|z|$ – distance was chosen to eliminate from our sample the ordinary OB stars that lie within the galactic disk). As the majority of distant stars have small proper motions with large associated errors (see, for example, the Yale Catalogues of proper motions, Yale Transactions 28–31), the investigation was limited to the peculiar radial velocities (henceforth peculiar velocities) of the stars. This should be adequate, as the peculiar radial velocities will represent lower limits to the peculiar space velocities.

Peculiar velocities $v_{pec}$ were calculated by correcting the measured radial velocities for the effect of galactic rotation. The galactic rotation model of Savage and de Boer (1981) was used to estimate this effect. In Figure 1 the absolute peculiar velocities $|v_{pec}|$ for the 41 programme stars with $|z| \geq 400$ pc are plotted against their masses. A definite correlation between $|v_{pec}|$ and $M$ may be seen from the figure: for stars with $M < 13M_\odot$, the average absolute peculiar velocity is $|v_{pec}| = 25$ km s$^{-1}$, while for those with $M > 13M_\odot$, $|v_{pec}| = 73$ km s$^{-1}$. In addition, of the 19 stars with
$|v_{\text{pec}}| > 30 \text{ km s}^{-1}$ 15 have $M \geq 10M_\odot$. The existence of high-mass, low-$|v_{\text{pec}}|$ stars is not surprising as we have only considered the radial components of the space motion; these stars possibly have large transverse velocities.

Although from the above discussion it appears that the Blaauw (1961) mechanism could be responsible for the occurrence of many early-type stars in the halo, we note that there are 4 low mass stars in Figure 1 with $|v_{\text{pec}}| > 30 \text{ km s}^{-1}$ which would not be expected from the “runaway” hypothesis. However, Poveda et al. (1967) point out that runaway stars may be produced in collapsing protostellar clusters from strong stellar encounters, in which case one would expect the ejection velocity $v$ to be inversely proportional to the square of the mass (Stone 1979). It is therefore possible that the low-mass, high-velocity halo stars are produced in this way, although many more observations would obviously be needed to confirm a $|v_{\text{pec}}|-(\text{Mass})^{-2}$ correlation for low-mass stars in the halo.

Finally we note that if the halo stars have been produced by the Blaauw (1961) theory, then one might expect their atmospheric abundances to differ from normal stars due to the transfer to the secondary of material processed by the CNO bicycle (and possibly other nucleosynthesis processes). However, Stone (1981) has shown that the expected abundance differences should be less than $\sim 0.3$ dex unless the mass-loss rate of the primary is extremely large. Therefore the null detection of significant abundance anomalies as found in the present work and by other authors (Tobin and Kaufmann 1984, Keenan and Lennon 1984) does not constitute a serious objection to the Blaauw (1961) hypothesis.

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