Star Formation in the Galactic Halo*

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SUMMARY

Observational evidence for the existence of normal, Population I OB-type stars at
large distances (z) from the plane of the Galaxy is discussed. Possible explanations for
the occurrence of these objects at such z-distances are suggested, including ejection
from the disk via a supernova explosion or the dynamical evolution of a cluster, or
formation in the halo itself. In order to obtain observational data that may be used to
constrain the various theories of star formation or disk ejection, it is necessary to look
at a complete sample of halo stars through spectroscopic surveys, and a number of
such surveys undertaken to date are summarized. Finally, several of the more
important areas of future halo star research are listed.

1 INTRODUCTION

Since the first photographic survey by Humason & Zwicky (1947), it has
been known that there are many thousands of faint blue stars at high galactic
latitudes. Further surveys were made in the 1950s and 1960s (Iriarte &
Chavira 1957; Cowley 1958; Chavira 1958, 1959; Iriarte 1959; Slettebak,
Bahner & Stock 1961; Haro & Luyten 1962; Klemola 1962; McCuskey 1964;
Drilling & Philip 1968; Philip & Sanduleak 1968; Jaidee & Lynga 1969)
and it was assumed that most of the objects detected were old, evolved
Population II (metal-weak) stars, with possibly a few quasars contaminating
the fainter parts of the samples. However some of the blue stars at high
galactic latitudes, such as HD 93521 and HD 219188, were taken to be
young, Population I (metal-rich) OB-type stars at distances (z) from the
galactic plane of \( z \approx 1 \) kpc, and used as tracers of the halo interstellar
medium (Münch & Zirin 1961; Greenstein 1968; Rickard 1972; Cohen 1974;

From the late 1950s, researchers began to perform more detailed analyses
of individual high-latitude faint blue stars. Hill et al. started an extensive
photometry programme (Hill & Hill 1966), which provided targets for
follow-up spectroscopic observations from the 1960s right up to the present
day. In addition, several authors (Feige 1958; Berger 1963; Greenstein 1966;
intermediate-resolution optical spectra of several of these objects, and noted

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that spectroscopically they looked like the young, Population I OB-type stars normally found in the spiral arms or disk of the galaxy, rather than evolved Population II objects. However, probably the pioneering paper in this area is that by Greenstein & Sargent (1974), who analysed primarily 18 Å mm\(^{-1}\) and 40 Å mm\(^{-1}\) photographic plates of 189 faint blue stars (average \(V\) magnitude 10–11), and found 25% of these to be apparently normal Population I B-type objects with \(z = 1–3\) kpc.

More recently, authors have not only examined the optical photographic spectra of faint blue stars (Tobin & Kilkenny 1981; Dworetsky, Whitelock & Carnochan 1982; Tobin & Kaufmann 1984), but also IPCS data (Keenan, Dufton & McKeith 1982; Kilkenny & Lydon 1986), as well as ultraviolet spectra from the IUE satellite (Keenan & Dufton 1984; Tobin & Kaufmann 1984; Tobin 1986). Once again, in all cases they found that many of the high galactic-latitude objects had optical and UV spectra identical to those of Population I B-type stars in the disk.

However, Lamers et al. found that several high galactic-latitude stars, whose intermediate-resolution optical spectra implied that they were Population I F/G supergiants at \(z = 1\) kpc, were in fact highly evolved Population II stars in transition from the Asymptotic Giant Branch (AGB) to the planetary nebula phase, which are called post-AGB objects. Initial evidence for these being post-AGBs came from observations of large IR excesses due to dust shells (Lamers et al. 1986; Waelkens et al. 1987; Waters et al. 1989). This was later confirmed by high-resolution spectroscopic data (Lambert, Hinkle & Luck 1988; Trams, van Hoof & van de Steene 1992), which showed that these stars can have near Population I abundances for light elements (e.g. CNO) due to dredge-up (Trams et al. 1992), but that they still have Population II abundances for heavy elements, such as iron.

In view of the above results, researchers decided to consider the possibility that some (or all!) of the faint blue stars may be the hotter analogues of the cool post-AGB stars. Several such objects have now been identified (McCausland et al. 1992b), and they are indistinguishable from Population I B-type stars at low or even intermediate spectral resolution, as they can have near-Population I abundances for the lighter elements, while the heavier elements (e.g. Fe) are still under-abundant, but are difficult to measure in B-type stars. As a result, one needs high signal-to-noise (\(\geq 50\)) and high-spectral-resolution (\(\Delta \lambda \leq 0.3\) Å) data to distinguish post-AGB objects from normal Population I B-type stars (Conlon et al. 1991), implying the use of large amounts of telescope time on 4-m class telescopes, such as the AAT or WHT. This is illustrated in Fig. 1, where we plot the high-resolution UCLES AAT spectra of the normal Population I B-type star BD \(-15^\circ\) 115 (Conlon et al. 1992) and the post-AGB object LB 3219 (McCausland et al. 1992b).

These observations appear very similar on first inspection, but a detailed model atmosphere analysis reveals that LB 3219 does not have Population I abundances for most elements. The analysis of such high-quality observational data (Keenan et al. 1986a,b, 1987; Conlon et al. 1988, 1989, 1992; Brown et al. 1989; Lennon et al. 1991) indicates that there remain faint blue stars at high galactic latitudes which are spectroscopically identical to the Population I B-type stars in the disk.

Further evidence for the faint blue stars being Population I objects comes
from the observation of a whole range of different classes of B-type stars at high latitudes, including Be stars (Heber & Langhans 1986), He-weak stars (Kilkenny & van Wyk 1990), δ Cephei variables (Waelkens & Rufener 1988), and the tentative identification of a $2 \times 10^{-6}$ $M_\odot$ spectroscopic binary at $z = 10$ kpc (Viton et al. 1991). One would need a large array of Population I analogues if these stars are indeed evolved Population II objects, which seems unlikely.

One is therefore forced to conclude that many of the faint blue stars at high galactic latitudes are indeed young Population I B-type stars, which lie up to 18 kpc from the galactic disk (Brown et al. 1989), and hence the star-forming regions. In the next section we discuss possible explanations for this.
2 EXPLANATIONS FOR THE EXISTENCE OF B-TYPE STARS AT HIGH z

We have two possible explanations for the existence of B-type stars at large distances from the galactic plane; they have been ejected from the disk, or formed in the halo. Many mechanisms for both ejection from the disk and formation in the halo have been discussed in the excellent reviews by Tobin (1987, 1991). However, in this paper we restrict ourselves to the more popular hypotheses.

2.1 Ejection from the disk as result of a supernova explosion

This was first suggested by Zwicky and developed by Blaauw (1961), to explain the well-known runaway stars from OB associations, such as μ Col. In this scenario, the more massive star in a binary explodes as a supernova, which results in the secondary star being accelerated to a large velocity. Stone (1982) has considered the problem in more detail, and found that only the most massive secondary stars (M ≥ 11 M⊙) would be accelerated, to a maximum velocity of ~ 150 km s⁻¹, and that most binaries would not be disrupted by the supernova explosion.

2.2 Ejection from the disk during the dynamical evolution of a stellar cluster

This was first proposed by Poveda, Ruiz & Allen (1967). Subsequently, Leonard and co-workers (Leonard & Duncan 1988, 1990; Leonard 1989, 1991) performed N-body simulations to show that stars can be ejected from clusters with velocities of up to ~ 200 km s⁻¹ as a result of strong gravitational encounters. In addition, these authors predict that the lower-mass stars should attain the highest ejection velocities.

Observations of high latitude B-type stars by Conlon et al. (1990) would appear to support hypothesis 2.2, i.e. that most stars are ejected via cluster ejection rather than supernova explosions. Further evidence against hypothesis 2.1 comes from analyses of the runaway stars by Gies & Bolton (1986) and Gies (1987), which indicate that most of these objects are not binaries (in contrast to the predictions of Stone), and those that are do not contain a compact object, which they should do after a supernova explosion.

2.3 Star formation in the halo

For a small number of stars, their kinematics and z-distances are incompatible with ejection from the disk. For example, BD −15° 115 is at \( z = 7 \) kpc and has a velocity in the z-direction of \( v_z = 88 \) km s⁻¹, implying that its flight time, \( T_{\text{flight}} \), to reach its current z-position if ejected from the disk is approximately 47 Myr (Conlon et al. 1992). However, the evolutionary age of the star is \( T_{\text{evol}} < 20 \) Myr, implying that it must have formed in the halo. There are currently six other stars for which \( T_{\text{flight}} \gg T_{\text{evol}} \), implying formation in situ, which include PG 0832 + 676 (Brown et al. 1989), PHL 346 (Keenan et al. 1986b), HD 18100 and HD 217505 (Keenan et al. 1986a), SB 357 and BD −2° 3766 (Conlon et al. 1992).
It is difficult to envisage how star formation in the halo can take place, in view of the very low gas density (Savage & de Boer 1981; Savage & Massa 1985). However, one possible mechanism, proposed by Dyson & Hartquist (1983), is that star formation may occur during collisions between cloudlets within the high-velocity clouds (HVC) that are known to exist at high galactic latitudes (York, Burks & Gibney 1986; Colgan, Salpeter & Terzian 1990). These clouds may have condensed from galactic fountain material, which has its origins in the disk of the galaxy (Bregman 1980; de Boer & Savage 1984). The derivation of Population I abundances for the B-type stars formed in situ, which should reflect the chemical composition of the progenitor halo gas clouds, would appear to support the theory that the material involved originated in the galactic plane.

3 SPECTROSCOPIC SURVEYS

Unfortunately, most of the spectroscopic work performed on high galactic-latitude faint blue stars has been on objects that are positioned randomly in the sky. In order to obtain observational data that may be used to constrain the various theories of star formation in the halo, or ejection from the disk, it is necessary to look at a complete sample of stars in a restricted area of the sky. This would allow the determination of: (1) the number density of Population I B-type stars in the halo; (2) their z-distribution; (3) the distribution of spectral types (masses); and (4) their rate of formation, which may be estimated from the number density of stars formed in the halo combined with their evolutionary ages.

Spectroscopic surveys undertaken to date include the following.

**Palomar Green (PG) Survey.** This covers 10'714 degrees² of sky at northern latitudes between $B \approx 13-16^\circ$ (Green, Schmidt & Liebert 1986). Approximately 1900 hot stars were discovered, and mainly 10 Å resolution spectroscopy of these was performed. Green et al. (1986) did not look for Population I B-type stars, but follow-up high-resolution spectroscopy has identified some, such as PG 0832+676 (Brown et al. 1989).

**HK Objective Prism Survey.** Beers, Preston & Schectman (1985) have obtained objective prism spectra of ~5000 stars from ~2200 degrees² between $V = 13-15$. Follow-up intermediate resolution (~1 Å) spectroscopy of 769 of these reveals four possibly normal B-type stars (Beers et al. 1991).

**United Kingdom Schmidt Telescope (UKST) UBVRI Survey.** This considers all objects brighter than $B = 18$ in a 325 degrees² region of sky (Mitchell, Miller & Boyle 1990). Holmgen et al. (1992) have obtained low-dispersion (100 Å mm⁻¹) spectra of 49 B-type stellar candidates from this survey with $12 \leq B \leq 16$, and found four possibly normal Population I stars.

**Crosowell et al. Survey.** Crosowell et al. (1991) have obtained ~1 Å-resolution spectra of all stars between $V = 13.3-17.9$ in a 1 degree² area of sky. They found 247 stars, but all are F, G or K types.

**Laget Survey.** Laget (1980) surveyed ~200 degrees² down to $V = 14$ at balloon UV wavelengths (2000 Å), and found 92 hot stars. Low-resolution (90 Å mm⁻¹) follow-up spectroscopy indicates that 2 of these may be normal Population I B-type stars.

**Spacelab 1 Wide Field Survey.** The Very Wide Field Camera flown on
Spacelab 1 performed a wide field survey of UV excess objects over ~20% of the sky down to $m(1950\text{ Å}) = 9$ (Viton et al. 1988). Follow-up intermediate dispersion (40 Å mm$^{-1}$) spectra of 7 stars has revealed three to be possibly normal Population I B-type objects (Viton et al. 1991).

Edinburgh Cape (EC) Survey. This covers 10000 degrees$^2$ of southern sky down to $B = 16.5$, with follow-up uvby photometry and low-dispersion (100 Å mm$^{-1}$) spectroscopy being obtained for all stars (Stobie et al. 1987). The first spectroscopic results (Kilkenny, O’Donoghue & Stobie 1991) indicate that there are 20 possibly normal Population I B-type stars in a 1000 degrees$^2$ region of sky, four of them with $z < 1$ kpc, 12 with $1 \leq z \leq 5$ kpc and 4 with $z \geq 5$ kpc.

We stress that the major problem with all the surveys discussed above is that spectroscopic data are only being obtained at intermediate or low dispersion. Such spectra are very useful for identifying and removing HB or subdwarf stars from a sample but, as noted previously, high spectral-resolution observations are required to reliably distinguish normal Population I B-type stars from post-AGB objects (Conlon et al. 1991), which implies a major commitment of time on 4-m class telescopes, such as the AAT. However, we note that such high-resolution work is currently under way for the EC Survey, and is planned for both the PG and HK Surveys.

4 EXTRAGALACTIC OBJECTS

As normal Population I B-type stars are found in the halo of our galaxy, it is not unreasonable to wonder if they might be found in the haloes of other galaxies. To look for stars in the halo of an external galaxy, we need a galaxy that is: (1) spiral (similar to our own), (2) near edge-on (so that halo stars can be clearly distinguished from disk objects); and (3) relatively bright (so targets are observable in reasonable periods of time). A galaxy that satisfies these criteria is M31, which has an inclination of only 15° and is at a distance of 670 kpc. At this distance, even supergiant B-type stars will be too faint ($V \geq 18$) for high-resolution spectroscopy. Hence one must use the radial velocity of M31 ($v_r = -280$ km s$^{-1}$) as a discriminator between foreground stars and those in the halo of M31. A normal Population I B-type star in the halo of M31 would have $V \simeq 20$, compared with $V \geq 25$ for a highly evolved star such as a subdwarf, so that the observation of a $V \simeq 20$ blue star in the direction of the halo of M31, with a stellar radial velocity of $v_r \simeq -280$ km s$^{-1}$, would imply that the object lies in the M31 halo, and is not a low-luminosity foreground star.

McCausland et al. (1992a) have identified possible B-type stars in the halo of M31 from APM measurements of Palomar plates. Low-resolution observations of these stars, performed at the WHT in 1991 September, revealed one $V = 20.5$ star at the radial velocity of M31, which is therefore believed to be associated with this galaxy and to be $\sim 22$ kpc from its disk. Unfortunately, however, the colours of this star derived from the available plate material are very unreliable, so there exists the possibility that it is a much cooler (F/G-type) post-AGB object in the halo of M31.
5 FUTURE WORK

Research on Population I B-type stars in the halo is currently being extended in many ways by personnel at Queen's University Belfast, in collaboration with workers at other institutes (ROE, RGO, SAAO, KPNO, NRAL, etc.). Some of the more important of these research areas are listed below.

Extension to higher z stars. It is important to extend the high spectral resolution work to other (possibly more distant) objects, to investigate how far from the disk Population I B-type stars may occur. For example, Beers et al. (1991) have found a star which is at $z = 100$ kpc if it is a Population I object.

Survey work. High-resolution follow-up spectroscopy of stars from the EC, PG and HK Surveys is important, in order to determine the space density, $z$-distribution and rate of formation of Population I B-type stars, for comparison with theory.

Astrometry. Proper-motion estimates for B-type halo stars will lead to reliable space motions (for better comparison with ejection hypotheses), and will also allow a firmer identification of those stars that are believed to have formed in the halo.

Classes of B-type stars. The identification of further β Cephei and binary halo stars will strengthen the evidence for these being normal Population I objects.

Stars in the halo of M31. Currently, deep UBV imaging of the halo of M31 is planned, in order to better identify blue targets for follow-up low-resolution spectroscopy. Radial velocities measured from these spectra will allow the reliable identification of further B-type stars in the halo of M31.

A search for HVC near halo stars. If B-type stars have been formed from collisions between cloudlets within HVC, one would expect the star to be close to its parent HVC. Optical and 21 cm observations of interstellar lines towards halo stars will allow both a search for such HVC to be undertaken, and their distances (and hence possible association with the star) to be constrained.

A search for an excess of cooler stars. Dyson & Hartquist (1983) have pointed out that star formation should not occur in isolation, and that $10^4$ B1–A5 stars should be formed for every object earlier than B1. A search is therefore currently underway for an excess of cooler stars surrounding those objects that are believed to have formed in the halo. We note that Rodgers, Harding & Sadler (1981) and Lance (1988, 1989) have found a population of young ($T_{\text{eff}} \leq 650$ Myr) A-type stars at the South Galactic Pole with $z$-distances of 1–4 kpc, which Lance suggests may have been formed due to the accretion of a major source of relatively low-abundance hydrogen by the galactic disk.

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