STAR FORMATION AT LARGE GALACTIC z?

WILLIAM TOBIN
Department of Physics and Mt John University Observatory,
University of Canterbury, Christchurch 1, New Zealand

ABSTRACT. It seems very probable that young, luminous B stars occur in the galactic halo. An origin in the disc followed by ejection may account for many of these stars; certain proposed formation-ejection mechanisms involve the infall of halo material. The kinematics and supposed locations of some halo B stars seem incompatible with an origin in the disc, suggesting that these stars may have formed in the halo.

1. INTRODUCTION

In this review I present evidence which I believe fairly strongly suggests that young, massive stars occur in the galactic halo, and that these stars are normal in every respect save their location and kinematics. If this 'normal' interpretation is correct, these hot, luminous stars can be used to probe the halo interstellar medium, and indeed have been used for this purpose (e.g. Pettini & West, 1982; Savage & Massa, 1985; Lockman, Hobbs & Shull, 1986; Danly, 1989). Obviously astronomers who use these stars as halo probes should understand the arguments concerning their nature and location, so it is appropriate to discuss them at this Symposium.

Many of these halo stars can plausibly somehow have acquired sufficient velocity for them to be transported from disc birthplaces to their present locations within their evolutionary lifetimes. Some of the formation and/or ejection mechanisms involve the interaction of disc and halo material, and again are appropriate to discuss here.

However the kinematics and apparent locations of some of the apparently-normal B stars are such that, if the stars really are of normal age, then they must surely have formed in the halo of the Galaxy, and it is from these arguments that my review takes its title.

This paper updates my earlier review on the existence of apparently-young stars apparently-far from the galactic plane (Tobin, 1987). Also relevant are reviews by Lambert (1987), Trimble (1988), and Conlon (1989). Studies of blue halo stars all depend heavily on, and develop from, the pioneering paper by Greenstein & Sargent (1974) 'The nature of the faint blue stars in the halo'.

H. Bloemen (ed.), The Interstellar Disk-Halo Connection in Galaxies, 109–119.

2. THE PHENOMENA: APPARENTLY-YOUNG STARS WITH HIGH VELOCITIES AND/OR APPARENTLY LOCATED IN THE HALO OF THE GALAXY

Normal, Population I O stars have lifetimes of only a few million years. No apparently-normal O stars are known far outside the galactic disc, but disc O stars do have a bimodal velocity distribution with half of them in a 'high'-velocity peak of 30 km s^{-1} dispersion, and the remainder in a low-velocity peak of 10 km s^{-1} dispersion (Stone, 1979).

Normal, Population I B star lifetimes range from 10^7 to 10^8 years. Neglecting the complication of Gould's Belt, they have a scale height perpendicular to the galactic plane $\beta_z \simeq 60$ pc.

B-type stars have long been known apparently located at very much greater values of $|z|$ (up to many kiloparsecs in some cases). Spectroscopically these B stars are almost always completely normal, having within the errors of analysis the gravities, temperatures, helium and metal abundances, and projected rotations typical of main-sequence and slightly evolved stars (e.g. Tobin & Kilkenny, 1981; Tobin & Kaufmann, 1984; Keenan *et al.*, 1987; Conlon *et al.*, 1988, 1989). The distances are calculated using standard but secondary methods, such as spectral-type–absolute-magnitude relations. The B stars in question are *not* the hot, high-gravity subdwarfs, helium-poor horizontal branch stars, or other spectroscopically peculiar stars that are also found – and expected – at high galactic latitudes.

Normal A stars have somewhat longer lifetimes, from 10^8 to 10^9 years. During these lifetimes, the disc-heating mechanism can increase the scale height to $\simeq 120$ pc. However in a study of the South Galactic Pole, Rodgers, Harding & Sadler (1981, hereafter 'RHS') found a population of apparently main-sequence 12th-15th magnitude A stars at distances 1-4 kpc from the galactic plane. Unlike the case of the B stars, these stars' abundances are often below solar ([Ca/H] $\simeq$ 0.0 to -0.5).

A young B star in the galactic halo will evolve into a later-type supergiant. The UU (or 89) Herculis class of stars are variable halo A-F supergiants. At one time, they were suspected of being massive objects (e.g. Sasselov, 1983), but they are systematically metal-deficient (e.g. Bond & Luck, 1987), and are probably mass-losing stars of $M < 1M_\odot$ in a brief, pre-planetary nebula phase. Many similar objects are now being discovered amongst cold *IRAS* sources (e.g. Likkel *et al.*, 1987; Trams *et al.*, 1989). I shall not discuss the UU Herculis stars any further.

3. ELEVEN POSSIBLE EXPLANATIONS

3.1 Subluminous Hypotheses

The principal parameters furnished by atmospheric analyses are the stellar effective temperature, T_{eff}, and surface gravity, $\log g$. Normal stars have gravities lower than the $\log g \approx 4.2 - 4.4$ (c.g.s.) of the Zero-Age Main Sequence (ZAMS). This can also be the case for highly-evolved stars with masses $M = 0.5 - 1.0 M_\odot$. A normal-helium, low-mass star could conceivably mimic a Population I object, and be confused with it.

(I) POPULATION II EXPLANATION. Low-luminosity B stars with roughly normal helium do exist, and are seen in globular clusters ~ 1 magnitude above the horizontal branch. Barnard 29 in M 13 and von Zeipel 1128 in M 3 are famous examples. However the abundance analyses cited earlier show quite clearly that many halo B stars have Population I metallicities and cannot be Population II objects.

(II) OLD DISC POPULATION EXPLANATION. If the halo B stars were evolved members of an Old Disc Population (ODP), then their metallicities might be closer to solar and their spectra indistinguishable from normal. Astronomers at UNAM have proposed that the high-velocity O stars are ODP objects (Carrasco *et al.*, 1980), but the supporting evidence in a recent paper is not strong (Carrasco, Costero & Stalio, 1987). One high-velocity O star is a double-lined spectroscopic binary for which the values of $m \sin^3 i$ show unequivocally that the components are massive (16.2 and 16.9 $M_{\odot}$ for HD 198846 $\equiv$ Y Cyg, $V_{LSR} = -45$ km s^{-1}; Batten, Fletcher & Mann, 1978).

The case of the high-latitude star PB 166 is pertinent here, and disquieting for supporters of normal luminosity hypotheses. The metal lines in a low-resolution IUE spectrum suggested that this 12th-magnitude early B star was a young object, implying $z > 6.2$ kpc (Tobin, 1986). An analysis of an intermediate-dispersion optical spectrum by de Boer, Heber & Richtler (1988) found a normal helium abundance, but deduced $\log g = 4.8 \pm 0.2$ from the H I and He I absorption profiles. A single, normal star should have a surface gravity rigorously lower than that of the ZAMS, whereas no such constraint would apply to a low-mass, ODP object. However Conlon *et al.* (1989) found $\log g = 4.6 \pm 0.3$ for PB 166 (albeit from Hγ and Hδ profiles that were affected by various instrumental problems) and derived essentially normal abundances for He, C, N, O, Mg, Al, Si and S. They concluded that a normal, main-sequence nature was not excluded for PB 166, and the star's rotation, $v \sin i = 50 - 60$ km s^{-1}, is certainly high for the horizontal branch. If PB 166 is a subluminous object with $M \sim 0.5 M_{\odot}$ and $M_V \sim 2.4$, then $z \sim 600$ pc.

3.2 Normal Luminosity Hypotheses

Even if not yet completely conclusive, the evidence for the normal luminosity of many halo B stars seems overwhelming. The halo B helium and metal abundances are normal, as is the distribution of rotations. There is a spatial correlation with spiral arms if $|z|$ is not too extreme (Kilkenny, Hill & Schmidt-Kaler, 1975). Further, minor peculiarities usual in disc B stars have been found in the halo B stars, including Be stars (Kilkenny, 1989), and two β Cephei stars—HD 129929 (Waelkens & Rufener, 1983; $z = 540$ pc) and PHL 346 (Waelkens & Rufener, 1988; Kilkenny & van Wyk, 1990; $z = -5.3$ kpc). (Incidentally, the variability of PHL 346 presumably accounts for the discrepant IUE SWP flux reported for this star by Heber & Langhans, 1986.)

https://doi.org/10.1017/S0074180900088975 Published online by Cambridge University Press

For many of the halo B stars, the radial velocities are such that the stars could plausibly have been born in the galactic disc and have reached their present locations within the lifetimes available to them. B star radial velocities can be much greater than for the high-velocity O stars, and can exceed 200 km s^{-1} (e.g. Tobin & Kaufmann, 1984; Keenan *et al.* 1987; de Boer, Heber & Richtler, 1988).

3.2.1. Ejection from the Galactic Plane soon after Birth

(III) EJECTION AS THE RESULT OF A SUPERNOVA EXPLOSION IN A BINARY STAR. This idea was first developed by Blaauw (1961), following a suggestion by Zwicky. It supposes that a supernova explodes in a binary star and that the secondary is freed to move off with its previous orbital velocity. For a large velocity, the binary needs to have been tight and massive, but then the binary evolution is complicated because the pre-supernova primary will spill matter onto the secondary as the radius of the primary increases during its evolution away from the main sequence. Stone (1982) has considered all this, and found that only the most massive stars would be accelerated, $M > 11M_{\odot}$. Stone also found that most binaries should not be disrupted by the supernova explosion, but the incidence of binaries amongst the high-velocity OB stars is much less than in the field (Gies, 1987). Further, two of the known high-velocity O stars are double-lined spectroscopic binaries, so cannot contain a compact object (HD 3950 and HD 198846, Gies & Bolton, 1986). Two high-velocity Wolf-Rayet stars do however present evidence for low-mass companions (209 BAC: Moffat, Lamontagne & Seggewiss, 1982; HD 143414: Isserstedt, Moffat & Niemela, 1983). That supernova explosions *can* produce high velocities is indicated by the large velocities of many pulsars [Arnaud & Rothenflug (1981) estimate $< |v_z| >= 130$ km s^{-1} at ejection].

(IV) STAR FORMATION AND EJECTION RESULTING FROM A COLLISION BETWEEN THE GALAXY AND A MAGELLANIC CLOUD-TYPE OBJECT $\sim 6.5 \times 10^8$ YEARS AGO. Pier (1983) analysed photometry and spectroscopy of AB stars in the southern galactic halo. He found no A stars with near-solar metallicities beyond 2-3 kpc from the plane, in conflict with the results of RHS. Working afresh at the South Galactic Pole, Lance (1988a) upheld the RHS findings, attributing Pier's result to a selection effect. (The most luminous and thus most distant main sequence A stars can be confused with horizontal branch stars because the horizontal branch crosses the main sequence near early A.)

For the distant A stars with near-solar calcium ([Ca/H]> -0.5), Lance (1988b, 1989) finds a scale height $\beta_z \simeq 1000 - 1600$ pc (similar to that of the thick disc). However none of these stars with $|z| > 1000$ pc is older than 650×10^6 years, whereas A stars with $|z| < 500$ pc range from zero to 2×10^9 years old. Lance suggests that 'at around 6.5×10^8 years ago, a major source of relatively low abundance hydrogen was accreted by the Galactic disk,' so forming these stars. This mechanism cannot account for the present-day halo and high-velocity B stars which (i) must have formed much more recently, and (ii) show no evidence of reduced metallicity.

(V) STAR FORMATION AND EJECTION RESULTING FROM COLLISION BETWEEN DISC MATERIAL AND INFALLING INTERMEDIATE- AND HIGH-VELOCITY HI CLOUDS. This is similar to (IV), except that the mechanism can act repeatedly. A collision of this sort appears to be happening in the Draco Nebula, and will be discussed later under hypothesis (X).

(VI) MASSIVE STARS FORMED FROM ACCELERATED INTERSTELLAR MATERIAL. Matter might be accelerated (a) due to increase of pressure by ionisation and heating by a massive O star on one side of a cloud (Oort & Spitzer, 1955), or (b) by being swept up by a supernova explosion (Herbst & Assousa, 1977). However when sufficient mass has been swept up for star formation, the velocity may be relatively small (<60 km s^{-1}).

3.2.2. Ejection from the Galactic Plane at a Random Time

(VII) EJECTION DURING THE DYNAMICAL EVOLUTION OF A STELLAR CLUSTER. In my opinion, this is at present the most promising of the ejection mechanisms, and can account for both the high-velocity O and B stars. Numerical simulations by Poveda, Ruiz & Allen (1967) suggested that massive stars could be ejected with velocities up to $\sim$ 200 km s^{-1} during the initial dynamical relaxation of a small, dense cluster of massive stars. Recent N-body simulations by Leonard & Duncan (1988, 1990) have shown that binary-binary collisions within young *low-density* clusters can at any time result in the ejection of stars. The properties of the ejected stars match observations, at least qualitatively. Less massive stars are ejected faster; the maximum velocity is $\simeq$ 200 km s^{-1}; and for $M > 10M_\odot$, binaries can be ejected, but their frequency is reduced, perhaps to 10%. Finally, the very uncertain estimated number of actual high-velocity O and B stars is similar to the number to be expected according to the Leonard & Duncan simulations, given the surface density of young clusters in the galactic disc. The simulations are restricted to clusters of massive stars. An obvious priority is to extend the calculations to predict to what extent lower mass stars with high velocities might be expected.

As will be discussed in Section 3.2.3, some of the apparently normal B stars in the halo *cannot* plausibly have originated in the plane, and the Leonard & Duncan mechanism cannot be the sole explanation of the high-velocity O and B stars.

(VIII) GRAVITATIONAL EFFECTS OF A HALO OF VERY MASSIVE OBJECTS. Ipser & Semenzato (1985) and Lacey & Ostriker (1985) have investigated the dynamical effects on the galactic disc of a galactic halo of very massive ($\sim 10^5 - 10^6 M_\odot$), fast-moving objects, such as might be a remnant of Population III. Weak gravitational encounters warm the disc, while rarer strong encounters can eject disc stars with high velocity. If the disc is warmed in this way at the observed rate (Wielen, 1977), any individual disc star has a probability of $\sim 10^{-11}$ per year of being ejected at high velocity, irrespective of its mass. The fraction of ejected stars would then be (ejection rate) $\times$ (lifetime), and the mechanism could eject the Gilmore & Reid (1983) thick disc (20% of G stars). The mechanism could not produce the 50% of high-velocity O stars, but it could produce occasional 250 km s^{-1} B stars. However a fundamental objection to this mechanism is that if it acted, it would act on all stars at all times. Although it would produce the correct number of RHS A stars (0.5% of A stars), it could not produce the observed upper limit on ages. The mechanism would also produce a thick disc of F stars, but no such disc is seen.

3.2.3 Star Formation in situ *in the Galactic Halo*

The suspicion that this is occuring arises because the kinematics of certain individual halo B stars seem incompatible with an origin in the disc.

Many authors have compared the evolutionary ages of halo B stars with the kinematic times needed to get them to their apparent present locations, assuming an origin in the disc (e.g. Greenstein & Sargent, 1974; House & Kilkenny, 1978; Conlon *et al.*, 1989). A rigorous comparison is not possible, because halo B star proper motions are too small to measure from the ground. Only the radial velocities are available observationally. For any particular star it is always possible to assume that the necessary velocity for a disc origin is hidden in the transverse velocity, but this becomes more and more difficult to sustain for stars near the galactic poles, or when the required transverse velocity greatly exceeds the ≈ 250 km s^{-1} maximum of observed radial velocity. Let me cite two stars for which birth in the plane is very difficult to entertain.

PHL 346, mentioned earlier as a β Cephei star ($V = 11.5$), is found at galactic latitude $b = -58°$; has normal abundances; has an apparent age of $\sim 11 \times 10^6$ yr; and is apparently located at $z = -8.7 \pm 1.5$ kpc (Keenan *et al.*, 1986). A velocity perpendicular to the plane $v_z > 800$ km s^{-1} would be necessary to take PHL 346 to its present location within 11×10^6 yr. (There is no need to compute galactic gravitational deceleration at this v_z.) The v_z component of the radial velocity is a mere 56 ± 10 km s^{-1}, so the required transverse velocity would be greater than 1400 km s^{-1}! (This would actually lead to an observable proper motion $\mu > 0.03$ arcsec yr^{-1}, which would be worth searching for.)

It is even worse for another early B star, PG 0832+676 (Brown *et al.*, 1989). Spectra from the Hale 5 m and Isaac Netwon 2.5 m telescopes indicated normal helium and metal abundances for this $V = 14.5$ star at $b = +35°$. The inferred distance is $z \sim 18$ kpc (galactocentric distance $R = 37$ kpc!), and the inferred age is $\sim 13 \times 10^6$ yr. The radial velocity is negative: -73 km s^{-1}. A transverse velocity greater than 1800 km s^{-1} ($\mu > 0.012$ arcsec yr^{-1}) would be needed for an origin in the plane (at $R \sim 45$ kpc).

These enormous transverse velocities, unprecedented in any halo B star radial velocity, have led to the suggestion that stars can form in the halo of our Galaxy.

However PHL 346, and more especially PG 0832+676, are faint. Thus their nature might well be different from that of the brighter halo B stars: but even if they were ODP objects, they would still be located rather far from the galactic plane ($z \sim -1.7$ and $z \sim 3.5$ kpc, respectively, if $M = 0.5 M_\odot$). A fact possibly favouring a smaller distance for PG 0832+676 is that it lies in the direction of High-Velocity Cloud (HVC) A, but van Woerden, Schwarz & Wakker (1990) have failed to detect any interstellar absorption at the velocity of HVC A.

(IX) FORMATION OF STARS WITHIN INTERMEDIATE- AND HIGH-VELOCITY HI CLOUDS IN THE HALO. Dyson & Hartquist (1983) suggested that shock-induced star formation might occur in the halo as a result of supersonic collisions between individual cloudlets within larger intermediate- and high-velocity H I clouds, assuming that HVCs are themselves halo objects. Shock-induced star formation is believed to favour the production of more massive stars, and a collision between cloudlets of characteristic mass $M_c \approx 1.2 \times 10^4 M_\odot$ (and density $n_H \sim 0.1$ cm^{-3}) might produce $N_{OB} \approx 7 - 70$ O-B0 stars, and $N_{BA} \approx 70 - 700$ B1-A5 stars ($M > 2M_\odot$). If HVCs are the infalling material of a galactic fountain, they might well spawn stars with Population I metal abundances. Assuming ~ 10 cloudlets per HVC, Dyson & Hartquist estimate a cloudlet-cloudlet collision would occur every $\sim 10^8$ yr within any particular HVC. With a total of ~ 100 HVCs, and OB lifetimes $\leq 10^7$ yr, there should thus be $\sim 10^3$ OB stars (and $\sim 10^4$ B-A5 stars) in the galactic halo. Since the cloudlet-cloudlet velocities are typically only ~ 30 km s^{-1}, these stars should be clumped in fairly close association with their parent HVC, both in position and velocity. This does not seem to be the case (e.g. Brown *et al.*, 1989), though a systematic search would be desirable. The absence of any apparently-normal O star in the halo must be a further objection to the Dyson & Hartquist mechanism, since there should have been ~ 10 cloudlet-cloudlet collisions within the last $\sim 10^7$ yr from which O stars should still be visible.

It is pertinent here to note that automated measurements of Schmidt plates have clearly confirmed the existence between the two Magellanic Clouds of a 'bridge' of blue, 15-20th magnitude stars (Irwin, Demers & Kunkel, 1990). The radial velocity of several stars reinforces the association with the Magellanic Clouds. There is a general correlation of the stellar positions with the H I envelope around the Clouds, though the north-south spatial extent of the bridge stars is still unexplored. Since the H I bridge may be $\sim 2 \times 10^8$ yr old (Fujimoto & Murai, 1983) and the Irwin, Demers & Kunkel bridge stars could range in age up to $\sim 1 \times 10^8$ yr (colour index > 0), it would appear that B stars can form in interstellar material similar to that in the bridge. (It would be interesting, however, to know the spatial distribution of the *youngest* bridge B stars.) The H I column densities in the bridge are $\sim 4 \times 10^{20}$ cm^{-2} (Irwin, Kunkel & Demers, 1985). Assuming a distance of 50 kpc, and that the north-south angular extent of the H I is indicative of its line-of-sight depth, this corresponds to an H I density $n_H \sim 0.02$ cm^{-3}, not greatly different from that in HVC cloudlets (if at halo distances).

Even though there are objections to the Dyson & Hartquist mechanism, the evidence of the Magellanic bridge suggests that HVCs must nevertheless be considered serious candidates for sites of halo star birth.

(X) STAR FORMATION IN MOLECULAR CLOUDS OUTSIDE THE GALACTIC PLANE. Mebold *et al.* (1985) have reported finding molecular emission and absorption associated with an extended, faint optical and H I 21 cm nebula (the 'Draco nebula', $l \approx 91°, b \approx +38°$). From *UBV* photometry of foreground stars, and star counts, Goerigk & Mebold (1986) limit the location of the Draco nebula to $500 < z < 1500$ pc. Under a number of assumptions (including $z > 500$ pc), Mebold *et al.* find that two of the molecular concentrations (nicknamed 'Fang' and 'Wart') could plausibly be gravitationally bound. Somewhat boldly, these authors remark that their result *'presents the first clear indication that sites of star formation are located more than 500 pc above the galactic plane'* (their italics). Mebold, Heithausen & Reif (1987) suggest that star formation in bound molecular clumps at high z could be the origin of the halo B stars. A score or more *IRAS* Point Sources are associated with the Draco complex, and may be protostellar Bok globules (Johnson, 1986)—or perhaps artifacts of the Point Source Catalogue detection algorithm.

Other authors (Odenwald & Rickard, 1987) have found it difficult to accept $z > 500$ pc for the Draco cloud. However all authors agree that in Draco halo material is ploughing into matter situated nearer the disc. Odenwald & Rickard believe that the main Draco nebula and nearby, morphologically-similar 'comet-like' structures seen in the *IRAS* 100 μm maps are falling subsonically into disc gas at $z \sim 120$ pc. From a detailed study of the Fang, Rohlfs *et al.* (1989) believe that the Fang molecular clump ($v \sim -25$ km s^{-1}) has resulted from the collision of a HVC ($v \sim -180$ km s^{-1}) with the $v \sim -18$ km s^{-1} Draco material. Odenwald (1988) has conducted optical and infra-red studies on 14 other comet-like structures seen at 100 μm. The morphologies of five of Odenwald's objects 'are found to be consistent with objects moving supersonically through the interstellar medium. These clouds are also active in forming B-type stars in their nuclei...'

Irrespective of its distance, it seems clear that Draco provides evidence of halo material interacting with near-disc material in a way that might produce stars. But for the problem of the halo stars, it is disappointing that the velocity of the Fang molecular clump is so low, and a quick *SIMBAD* check showed that the velocities of the B stars in Odenwald's comet-like structures are also low.

Other evidence which suggests that stars may form at high z are the Orion-Nebula–like HII region seen $\sim$ 800 pc from the disc of the edge-on spiral galaxy NGC 4244 (Walterbos, this Symposium), and Blitz's report (this Symposium) that Leisawitz & de Geus have found that the space velocity of the open cluster NGC 457 is directed towards the galactic plane.

Greater velocity after interaction, or molecular clouds well into the halo, will be necessary if high-$|z|$ molecular clouds are the origin of stars such as PHL 346 and PG 0832+676.

3.3 Extended Lifetime Hypothesis

(XI) THE HALO STARS HAVE EXTENDED EVOLUTIONARY TIMESCALES. Blue stragglers are stars seen above the main-sequence turnoff in star clusters of all ages. Consequently, their ages are thought to be greater than those implied by their absolute magnitude and colour. Shields & Twarog (1988) suggested that the RHS A stars might be A-type blue stragglers: their larger scale height would result from a greater number of scatterings in the disc. Lance (1988b, 1989) notes, *inter alia*, that the age cut-off she found is incompatible with this hypothesis.

A blue straggler explanation also seems unlikely for the halo B stars. Early-B blue stragglers are predominantly Be stars, and late-B blue stragglers mostly present Ap/Bp abundance peculiarities (Mermilliod, 1982).

4. CONCLUDING REMARKS

The problem of young halo and/or high-velocity stars has been evident since at least the 1950s (e.g. Blaauw & Morgan, 1954; Münch, 1956). Resolution of the problem still seems very distant. It seems likely that several processes may be acting simultaneously. In my 1987 review I stressed the need for (and difficulty of!) a systematic search for halo B stars over a wide area, over a wide range of colour, and to deepish magnitudes ($V \sim 14$). Surveys such as the Edinburgh-Cape Town one are now under way (e.g. Kilkenny & Pauls, 1990), and the TYCHO package aboard Hipparcos should discover many new halo B stars.

An immediate priority must be to establish unequivocally the nature of the halo B stars, and thus the validity of arguments based on Population I metallicities. PB 166 must be reobserved and reanalysed, both absolutely, and differentially with respect to some clearly disc stars, so that all doubt about its gravity is removed. Should the high gravity be upheld, the normal luminosity hypothesis for the halo B stars will be severly undermined, because a major argument for this hypothesis is the Population I abundances.

The cameras aboard the Hubble Space Telescope have sufficient sensivity—provided the images are good—to detect any blue stars of Population I luminosity that may exist in the halos of nearby edge-on spiral galaxies.

Viton *et al.* (1991) appear to have discovered a $2 \times 10 M_{\odot}$ double-lined spectroscopic binary located at $z = -10$ kpc. Further observations of this star (already underway) may produce unequivocally large lower mass limits, though the required observations may be lengthy, because an orbital period of as long as 30 yr could still result in observable velocity variations.

Magnitudes fainter than $V \sim 10$ and the later B spectral subtypes have barely been explored, and interesting results may well arise from individual objects haphazardly found. (Irwin, Demers & Kunkel report a B7 V star, $V = 14.25, v_r = +268$ km $s^{-1}, z \sim -6$ kpc.) The strong selection effect that most analysed halo B stars are Henry Draper objects makes any analysis of group properties as yet unconvincing. In addition, it is only at fainter magnitudes that any further stars clearly indicative of halo star formation will be found. Deep, multi-colour searches for blue stars in the Magellanic Stream would be appropriate. The Draco nebula merits further study for evidence of actual star formation, and a better distance limit.

For interstellar astronomers seeking new sight lines, it should be noted that the fraction of clearly abnormal B stars increases at fainter magnitudes (e.g. the absence of metal lines in most stars reported by Kilkenny & Lydon, 1986; or the peculiar helium lines found by Möhler *et al.*, 1990), and the distance to each probe star should be evaluated with care. Savage (private communication) notes that interstellar Ti II appears smoothly distrubuted in both the Galaxy's disc and halo, and can provide an additional indication of distance. It would be interesting to see if a consistent picture of halo gas would arise if it were assumed that the B star probes used to investigate it were subluminous with $M \sim 0.5M_{\odot}$.

REFERENCES

Arnaud, M., Rothenflug, R. (1981) *Astron. Astrophys.* **103**, 263

Batten, A.H., Fletcher, J.M., Mann, P.J. (1978) *Publ. Dom. Ap. Obs. Victoria* **15**, 121

Blaauw, A. (1961) *Bull. Astron. Inst. Netherlands* **15**, 265

Blaauw, A., Morgan, W.W. (1954) *Ap. J.* **119**, 625

Bond, H.E., Luck, R.E. (1987) in *The Second Conference on Faint Blue Stars*, IAU Colloquium No. 95, A.G. Davis Philip, D.S. Hayes, J.W. Liebert (Eds), L. Davis Press, Schenectady, p.149

Brown, P.J.F., Dufton, P.L., Keenan, F.P., Boksenberg, A., King, D.L., Pettini, M. (1989) *Ap. J.* **339**, 397

Carrasco, L., Bisiacchi, G.F., Cruz-González, C., Firmani, C., Costero, R. (1980) *Astron. Astrophys.* **92**, 253

Carrasco, L., Costero, R., Stalio, R. (1987) *Rev. Mexicana Astron. Astrof.* **14**, 301

Conlon, E.S. (1989) *Irish Astron. J.* **19**, 59

Conlon, E.S., Brown, P.J.F., Dufton, P.L., Keenan, F.P. (1988) *Astron. Astrophys.* **200**, 168

Conlon, E.S., Brown, P.J.F., Dufton, P.L., Keenan, F.P. (1989) *Astron. Astrophys.* **224**, 65

Danly, L. (1989) *Ap. J.* **342**, 785

de Boer, K.S., Heber, U., Richtler, T. (1988) *Astron. Astrophys.* **202**, 113

Dyson, J.E., Hartquist, T.W. (1983) *Monthly Notices Roy. Astron. Soc.* **203**, 1233

Fujimoto, M., Murai, T. (1983) in *Structure and Evolution of the Magellanic Clouds*, IAU Symposium No. 108, S. van den Bergh, K.S. de Boer (Eds), Reidel, Dordrecht, p.113

Gies, D.R. (1987) *Ap. J. Suppl. Ser.* **64**, 545

Gies, D.R., Bolton, C.T. (1986) *Ap. J. Suppl. Ser.* **61**, 419

Goerigk, W., Mebold, U. (1986) *Astron. Astrophys.* **162**, 279

Gilmore, G., Reid, N. (1983) *Monthly Notices Roy. Astron. Soc.* **202**, 1025

Greenstein, J.L, Sargent, A.I. (1974) *Ap. J. Suppl. Ser.* **28**, 157

Heber, U., Langhans, G. (1986) in *New insights in astrophysics: 8 years of UV astronomy with IUE*, E.J. Rolfe (Ed.), ESA SP-263 p.279

Herbst, W., Assousa, G.E. (1977) *Ap. J.* **217**, 413

House, F., Kilkenny, D. (1978) *Astron. Astrophys.* **67**, 421

Ipser, J.R., Semenzato, R. (1985) *Astron. Astrophys.* **149**, 408

Irwin, M.J., Demers, S., Kunkel, W.E. (1990) *Astron. J.* **99**, 191

Irwin, M.J., Kunkel, W.E., Demers, S. (1985) *Nature* **318**, 160

Isserstedt, J., Moffat, A.F.J., Niemela, V.S. (1983) *Astron. Astrophys.* **126**, 183

Johnson, H.M. (1986) *Ap. J.* **309**, 321

Keenan, F.P., Lennon, D.J., Brown, P.J.F., Dufton, P.L. (1986) *Ap. J.* **307**, 694

Keenan, F.P., Brown, P.J.F., Conlon, E.S., Dufton, P.L., Lennon, D.J. (1987) *Astron. Astrophys.* **178**, 194

Kilkenny, D. (1989) *Monthly Notices Roy. Astron. Soc.* **237**, 479

Kilkenny, D., Hill, P.W., Schmidt-Kaler, Th. (1975) *Monthly Notices Roy. Astron. Soc.* **171**, 353

Kilkenny, D., Lydon, J. (1986) *Monthly Notices Roy. Astron. Soc.* **218**, 279

Kilkenny, D., Pauls, L. (1990) *Monthly Notices Roy. Astron. Soc.* **244**, 133
Kilkenny, D., van Wyk, F. (1990) *Monthly Notices Roy. Astron. Soc.* in press
Lacey, C.G., Ostriker, J.P. (1985) *Ap. J.* **299**, 633
Lambert. D.L. (1987) in *Stellar evolution and dynamics in the outer halo of the Galaxy* M. Azzopardi, F. Matteucii (Eds), ESO Conf. Workshop Proc. No. 27, p47
Lance, C.M. (1988a) *Ap. J. Suppl. Ser.* **68**, 463
Lance, C.M. (1988b) *Ap. J.* **334**, 927
Lance, C.M. (1989) *Nature* **337**, 513
Leonard, P.J.T., Duncan, M.J. (1988) *Astron. J.* **96**, 222
Leonard, P.J.T., Duncan, M.J. (1990) *Astron. J.* **99**, 608
Likklel, L., Omont, A., Morris, M., Forveille, T. (1987) *Astron. Astrophys.* **173**, L11
Lockman, F.J., Hobbs, L.M., Shull, J.M. (1986) *Ap. J.* **301**, 380
Mebold, U., Cernicharo, J., Velden, L., Reif, K., Crezelius, C., Goerigk, W. (1985) *Astron. Astrophys.* **151**, 427
Mebold, U., Heithausen, A., Reif, K. (1987) *Astron. Astrophys.* **180**, 213
Mermilliod, J-C. (1982) *Astron. Astrophys.* **109**, 37
Möhler, S., Richtler, T., de Boer, K.S., Heber, U. (1990) *Astron. Gessel. Abstract Ser.* **4**, 44
Moffat, A.F.J., Lamontagne, R., Seggewiss, W. (1982) *Astron. Astrophys.* **114**, 135
Münch, G. (1956) *Publ. Astron. Soc. Pacific* **68**, 351
Odenwald, S.F. (1988) *Ap. J.* **325**, 320
Odenwald, S.F., Rickard, L.J. (1987) *Ap. J.* **318**, 702
Oort, J.H., Spitzer, L., Jr. (1955) *Ap. J.* **121**, 6
Pettini, M., West, K.A. (1982) *Ap. J.* **260**, 561
Pier, J.R. (1983) *Ap. J. Suppl. Ser.* **53**, 791
Poveda, A., Ruiz, J., Allen, C. (1967) *Bol. Obs. Tonantzintla y Tacubaya* **4**, 86
Rodgers, A.W., Harding, P., Sadler, E. (1981) *Ap. J.* **244**, 912 (RHS)
Rohlfs, R., Herbstmeier, Mebold, U., Winnberg, A. (1989) *Astron. Astrophys.* **211**, 402
Sasselov, D.D. (1983) *Inf. Bull. Var. Stars* No. 2314
Savage, B.D., Massa, D. (1985) *Ap. J. Lett.* **295**, L9
Shields, J.C., Twarog, B.A. (1988) *Ap. J.* **324**, 859
Stone, R.C. (1979) *Ap. J.* **232**, 520
Stone. R.C. (1982) *Astron. J.* **87**, 90
Tobin, W. (1986) *Astron. Astrophys.* **155**, 326
Tobin, W. (1987) in *The Second Conference on Faint Blue Stars*, IAU Colloquium No. 95, A.G. Davis Philip, D.S. Hayes, J.W. Liebert (Eds), L. Davis Press, Schenectady, p.149
Tobin, W., Kaufmann, J-P. (1984) *Monthly Notices Roy. Astron. Soc.* **207**, 369
Tobin, W., Kilkenny, D. (1981) *Monthly Notices Roy. Astron. Soc.* **194**, 937
Trams, N.R., Waters, L.B.F.M., Waelkens, C., Lamers, H.J.G.L.M., van der Veen, W.E. C.J. (1989) *Astron. Astrophys.* **218**, L1
Trimble, V. (1988) *Nature* **336**, 111
van Woerden, H., Schwarz, U.J., Wakker, B.P. (1990) in *Structure and Dynamics of the Interstellar Medium*, IAU Colloquium No. 120, G. Tenorio-Tagle (Ed.) Springer, p.379
Viton, M., Deleuil, M., Tobin, W., Prévot, L., Bouchet, P. (1991) *Astron. Astrophys.* (submitted)
Waelkens, C., Rufener, F. (1983) *Astron. Astrophys.* **119**, 279
Waelkens, C., Rufener, F. (1988) *Astron. Astrophys.* **201**, L5
Wielen, R. (1977) *Astron. Astrophys.* **60**, 263

https://doi.org/10.1017/S0074180900088975 Published online by Cambridge University Press