Young Halo Stars and Galactic Evolution

Young, high-velocity, early-type stars have been observed in the Galactic halo, many kiloparsecs away from the disk. This finding is inconsistent with standard models of stellar and Galactic evolution. I describe the studies that discovered the young halo stars and identified their characteristics, and examine the theories that have been advanced to account for them. A comparison of their properties shows that high-velocity stars of spectral types A and B have similar characteristics, but they appear to be different from those of high-velocity O stars. The significance of these anomalous stars to our understanding of the structure and evolution of the Milky Way is discussed.

Key Words: *young halo stars, young high-velocity stars, early-type stars, runaway stars, galactic evolution*

INTRODUCTION

In recent decades young O, B and A stars have been observed at great distances from the Galactic plane, far out in the halo, a region which was long thought to be the exclusive domain of ancient stars. We expect young stars to be formed in the disk from collapsing clouds of gas and dust; we certainly don't expect to find them kiloparsecs away from normal star-forming sites in the plane.

How did they get there? If they formed in the disk and some mechanism flung them far away, then it is difficult to imagine what it could be, given that the kinematics of normal B and A stars are modest; they usually oscillate only tens to a few hundreds of parsecs around the plane. The stars are far too young to have been dis-

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persed away from the plane like some older populations. It has been suggested that mistakes had simply occurred, that they aren't young stars at all but evolved ones at similar colours, but high resolution data have now shown that the majority are undeniably young stars.

The history of young stars at vast distances from the Galactic plane illustrates (once again) how it is often the anomalous information that leads to the interesting discoveries. Throughout the 1950s and 1960s there had been random hints in the literature that young stars existed where they weren't supposed to be, but the samples were small, the data ambiguous, and the expectations nonexistent, so the anomaly went unrecognized.

Over earlier decades, major identification surveys of blue stars at high latitudes had been undertaken.[1–7] These surveys had simply mapped stellar positions and approximate colours or spectral types. They were not sensitive enough to reveal the presence of main sequence (MS) stars among the evolved stars even if anyone had been foolish enough to imagine they were there to be discovered. The accepted wisdom was that any blue stars in the Galactic halo were horizontal branch (HB) remnants of old, metal-poor, low-mass stars—stars formed in the collapse of the proto-Galaxy from a spheroid to a rotating disk.

Eventually, in the 1960s, higher precision studies appeared. The major impetus for that work was the delineation of the properties of evolved stars, so the presence of a few apparently young stars in the surveys was either ignored (because it was obvious that young stars did not occur far from the plane) or dismissed as no more than the tail of the disk distribution.

Yet, in hindsight, the clues were everywhere. For instance, Klemola[8] studied blue stars at high Galactic latitudes. Most of them were subdwarf O and B stars, but a number of A-type stars seemed to be a mixture of MS and HB stars. Roman[9] pointed out that in her catalogue of high-velocity stars, three per cent were late B and A dwarfs with no spectral peculiarities, clearly distinguishable from O and B subdwarfs and HB stars. Greenstein[10] found 19 normal A and F stars in a sample of around 120 distant blue stars. The significance of all those interesting and unexpected stars was quite overlooked.

Sargent and Searle[11] also observed blue stars at high Galactic latitudes. Most of the stars were sdB, sdO, or helium-weak B stars, but again, almost half were normal MS A or B stars. Sargent and Searle classified the B stars as runaways (see below) and accounted for the A stars with the far-from-prescient remark that "their presence at distances of up to one kiloparsec from the plane does not call for special comment."

An important study was that of Perry,[12] who examined the Galactic force law, K_z, using early MS A stars at the North Galactic Pole. He found evidence for two different groups of A stars in the Z direction (i.e., perpendicular to the disk). One nearby group had a W velocity dispersion of 7 km s^{-1} and an e-folding scale height of 45 pc, like young disk stars. The other, more distant, group had a dispersion of 49 km s^{-1} and a scale height of 450 pc. This work was criticized[13] on the grounds that some of the stars were actually as late in type as F0, and the larger scale height may have reflected the properties of old disk stars, including possible blue stragglers, at greater Z heights. However, the scale height of normal F stars is 190 pc,[14] much less than Perry's result of 450 pc, which is more like the scale height of evolved stars such as white dwarfs.

The introduction of the topic of blue stragglers into the problem at this point was unfortunate, as it became somewhat of a convenient carpet under which to sweep the anomalous stars without too much critical analysis. This was possible because, like the distant A stars, almost nothing was known about blue stragglers either. They are discussed in further detail below.

YOUNG HALO A STARS

The recognition that there were anomalous young stars far from the Galactic plane really became inescapable in 1971, when a study by Rodgers of 54 faint A-type stars near the South Galactic Pole[15] showed that around forty per cent of the sample had near-solar calcium abundances, like young disk A stars, yet they had large radial velocities and were at distances of up to several kiloparsecs from the Galactic plane, unlike any known type of young A star. Their W dispersion[16] was 62 ± 8 km s^{-1}.

In 1981, further observations by Rodgers, Harding and Sadler[17] (hereafter RHS) showed that many of the SGP A stars were on the main sequence; hence they were undoubtedly young stars, less than two billion years old (2×10^9 years). There was no plausible explanation for their existence: according to standard notions of galactic evolution, young, relatively metal-rich stars could neither form at, nor travel to, great distances from the Galactic plane. RHS proposed that the young stars were coeval. (The somewhat cavalier usage of the term "young star" in this context may be illustrated by the fact that most of the MS A stars under discussion were formed when animal life on Earth was just evolving onto land.)

The current distances of the MS stars ranged from one to four kpc from the plane, but some had velocities that would eventually take them up to eight kpc away from the disk. Disk A stars have a Z scale height of around 50 pc to 120 pc at most,[14] and in the volume studied by RHS, very few stars with this scale height could travel further than 600 pc from the plane, and *none at all* would be expected to reach beyond 1 kpc: yet 19 stars in the sample were beyond this distance.

The more accurate calcium abundance measurements also showed a surprising distribution, ranging from *one third* of the Population I metallicity to normal values ($[\mathrm{Ca/H}] = -0.5$ to 0.0 dex). This distribution is not only somewhat lower than that usually observed for young disk A stars, but also covers a wider range—young A stars usually show metallicities from -0.1 to 0.1 dex. (Even though the distant A star abundance range is lower than that of normal young stars, it is still substantially higher than that of evolved A stars on the horizontal branch.)

The distribution in abundances for disk stars over the last 15 billion years[18] shows that abundances as low as -0.5 are typical of disk stars formed more than 9 billion years ago, yet young A stars have maximum MS lifetimes of only 1.5 billion years—any that are observed on the main sequence today could not possibly have been formed 9 billion years ago.

In terms of the standard picture of galactic evolution and structure the properties of the distant A stars are quite bizarre. Galactic stellar populations are *defined* by systematic relationships between their ages, abundances, and kinematics, yet not one of those three parameters is consistent with any other in the case of the A stars.

Their kinematics are typical of the very oldest stars; their abundances are those of intermediate-aged stars; yet if they are truly on the main sequence, they can only be very young stars.

RHS considered several hypotheses for their origin, but discarded them as inadequate. They ultimately proposed that a small satellite galaxy had been recently accreted by the Milky Way, and that the stars had been formed from a varying mixture of gas from the satellite with Galactic disk gas. This would account for their youth, their unusual range of metal abundances, and their large velocities perpendicular to the Galactic plane.

Other studies include observations[19] of A stars near the SGP with the Strömgren *uvby* system, which confirmed that there were indeed Population I stars at large distances from the Galactic plane, with surface gravities typical of young A stars. Another study[20] found MS A stars with metallicities like those of RHS's stars at distances of up to five kpc away from the plane at both the North and South Galactic Poles. A sample of high-velocity A stars in the solar neighbourhood were identified,[21] with a radial velocity dispersion of 57 km s^{-1}, in good agreement with the 62 km s^{-1} of the SGP A stars.

Pier[22] studied halo field blue stars, including some of the SGP A stars. He concluded, while otherwise agreeing with RHS's findings in general, that the A stars were members of an old disk population with the scale height of the thick disk. This surprising conclusion was flawed on two counts. First, old or thick disk stars are low-mass late-type stars with long MS lifetimes. A consequence of long stellar lifetimes is evaporation out of the disk, to greater Z heights; that is, the W velocity dispersion increases randomly due to various disk heating mechanisms operating over time. Hence, describing the A stars as members of the old or thick disk shows lack of appreciation of the distinctively *short* lifetimes of MS A stars—they could never get to be as old as those stars, so they simply could not acquire their consequent higher velocity dispersions.

The second flaw in Pier's conclusion is the identification of old or thick disk kinematics with those of the distant A stars, when in fact they have *lesser* kinematics than the distant A stars. At similar distances from the plane the thick disk W velocity dispersion[23] is only 40 km s^{-1}, significantly smaller than the 62 km s^{-1} of the

SGP A stars (old disk velocity dispersions are even smaller than thick disk ones). So not only could the A stars not be as old as thick disk stars, but even assuming that they were, thick disk kinematics *still* couldn't account for their very high velocities.

THE A STARS RE-EXAMINED

In 1984 I began a program of re-observations of the SGP A stars, and the compilation of a catalogue of blue stars in a region of 218 deg^2 at the SGP, almost complete to 14th magnitude, for additional observations. I wanted to test rigorously all the theories that had been proposed to account for the A stars.[16,24]

A stars have several properties that make them ideal tracers for this kind of work. They are relatively bright: a 14th magnitude early A star may be seen up to 4.5 kpc away, and a late one to 3 kpc. They have reasonably long lives on the main sequence, from 2×10^8 to 2×10^9 years, long enough to observe some structure in their age distribution, but short enough so that clear limitations are imposed by their evolutionary lifespan. The Kurucz[25] stellar atmosphere models and the Strömgren *uvby* photometric system are particularly well calibrated for the A star range, so realistic model comparisons are available.

In A star spectra at 3933 Å occurs the distinctive calcium K spectral line, an easily measured abundance indicator. Also in that spectral region is Hδ at 4101 Å, which has a sizeable stretch of measurable continuum either side. This is important, because Hδ is a useful temperature and (for earlier A stars) surface gravity indicator. The Balmer Jump, the difference between the continuum above and below 3047 Å, is also an excellent gravity indicator, so observations of this region of A star spectra yield a great deal of information.

In the A star temperature range are two major populations, already referred to: the MS A stars and the HB A stars. They have quite different origins. HB A stars are evolved, post-red-giant-branch, low-mass ($< 1\ M_\odot$), metal-poor stars ([Fe/H] < -1.0), with gravities generally less than 3.6 dex. In contrast, MS A stars are young, 1 to 3 $M_\odot$ metal-rich stars, with gravities around 4.1 dex.

However, the picture is not as simple as this. As A stars evolve in a colour-luminosity diagram, off the main sequence and towards the base of the red giant branch (RGB), they actually pass through the low-gravity region occupied by HB stars. Up to 10 per cent of their pre-RGB lifetimes may occur at gravities lower than normal MS values. Hence gravity *alone* cannot be definitive in distinguishing between MS and HB stars.

Abundance is also a potential discriminant, usually measured via the CaII K line at 3933 Å. But a problem arises with Am stars, which may comprise around 20 per cent of A stars: they have normal metals generally, but many have abnormally small calcium lines. So, a low calcium abundance does not necessarily mean that a star is metal-poor—it may simply be an Am star. Both abundance and surface gravity measurements *together* are needed for reliability in classification, particularly when dealing with the small samples available of distant young stars (a function of survey limits to date). Data of extremely high quality are necessary to be sure that classifications are accurate.

Examination of the range of hypotheses that have been proposed to account for the distant young A stars shows that they fall into three categories:

(1) *ejection* from the Galactic plane of normal young stars,
(2) *misidentification* (HB stars or blue stragglers), or
(3) *accretion* of gas from a merged satellite galaxy.

Hypothesis (1) covers objects such as OB runaway stars: those with higher than normal space velocities, apparently ejected from clusters[26] or accelerated by supernovae in binary systems[27]; stars nudged out of the plane by putative mini black holes[28]; or stars formed by a galactic fountain (hot gas, thrown up into the halo by supernovae, condensing and falling back into the plane[29]). Other possibilities include that the distant A stars are simply a non-Gaussian tail of the disk distribution,[21] or that they were formed from the compression of gas and dust at the outer edges of supernova bubbles.[30]

However, all of the Hypothesis (1) possibilities have two requirements: that these galactic processes form stars stochastically, that is, *randomly over time*, contrary to RHS's suggestion that they are coeval; and that they be formed of *normally enriched disk material* in contrast to their somewhat lower abundance range.[16,17] Hypotheses (1) and (3) are further discussed below.

Hypothesis (2) was easily examined in the case of HB stars.[16,24] The analyses available were sensitive enough to establish that the vast majority of the apparently MS stars could not possibly be HB stars: their gravities, abundances, and rates of rotation are unmistakably those of young MS stars. However, the second aspect of Hypothesis (2), misidentification of blue stragglers, requires further examination.

THE BLUE STRAGGLER RED HERRING

Blue stragglers are stars that appear bluewards of the main sequence turnoff in globular and galactic clusters. Stars within clusters are presumed to have been formed at the same epoch as each other. Yet in the case of a few stars, the blue stragglers, some process seems to have delayed their normal evolution, and they appear to have longer than usual lifetimes on the main sequence. The "blue straggler problem" has been around for some decades, with various explanations, none of which has been fully accepted.

Blue stragglers are seen in very young open clusters, old disk clusters, and ancient globular clusters, all with very different kinematic and abundance characteristics. It has never been clearly defined just what sort of blue stragglers the distant A stars were supposed to be.[22,31,32] That they apparently have longer MS lifetimes seems to have been regarded as explanation enough, but a more detailed examination shows serious difficulties with this idea.

Are they young cluster blue stragglers? Eggen and Iben[33] have argued persuasively that the O, B and A blue stragglers that are seen in clusters younger than 1–2 × 10^9 years are in fact products of a *secondary* burst of evolution. The blue straggler "problem" in this case was in the assumption that young clusters could only undergo a single burst of star formation, during which they used up all their gas and dust, making a second astration event impossible. Eggen and Iben show that this assumption is not valid, and that young, cluster "blue stragglers" are simply *normal* early-type stars formed later than the other stars in the cluster. Hence the distant A stars cannot be this variety of (non-existent) blue straggler.

Are they perhaps old or thick disk blue stragglers? The SGP A star abundances are certainly similar to those of intermediate-aged stars. It is not known whether or not old or thick disk blue stragglers actually occur in the field (by *definition* they must be observed in relation to a coeval population), but if some do arise from disk clusters that have dissipated then, as discussed, longer MS lifetimes imply that they would gain a larger *W* velocity dispersion from disk heating. However, models[34] of how blue stragglers might accumulate in a disk population show that most blue stragglers would be only *slightly* older than MS stars of the same colour. For instance, in the same colour range as MS stars aged 2 billion years (i.e., very late A and early F stars) would occur blue stragglers that are only 3 to 5 billion years old. But over a period of even 5 billion years, the *W* velocity dispersion for disk stars[14] is expected to increase from 9 km s^{-1} to a mere 21 km s^{-1}, which is significantly smaller than the A star dispersion of 62 km s^{-1}. So, old or thick blue stragglers, if they exist, cannot explain the distant A stars.

Well then, what about globular cluster blue stragglers? These certainly exist, and are thought to be formed from merged binary stars.[33] The SGP A star velocities are indeed like those of such ancient stars. If a halo globular cluster had dissolved, its blue stragglers might resemble MS stars superficially. However, globular cluster stars are usually extremely metal-poor: from tenths to thousandths of the abundance of normal disk stars. Yet the outstanding characteristic of the distant A star calcium abundances is that they are nearly normal; their lowest abundances are only one-third of the disk A star level, so they are in no way as metal-poor as globular cluster stars.

It seems that there is no particular variety of blue straggler that has *both* of the observed kinematic and abundance properties of the distant A stars. Close examination of the possibilities shows serious shortcomings, yet the catch-all explanation of blue stragglers is often invoked when young stars inconveniently turn up in evolved star samples, seemingly without observers recognizing or elucidating the consequences of such an identification in any detail.

THE AGES OF THE A STARS

As well as the above arguments there remains yet a final blow, not only to the blue straggler hypothesis, but also to any of the Hypothesis (1) ejection theories: that is, the surprising evidence of the unique nature of the distant A stars, which arose from my analysis of their ages.[16]

For comparison with the distant SGP A stars, I had observed an additional sample of quite normal disk A stars, which showed, entirely as expected, a *random* range of MS A star ages, from those very recently formed to some as old as 2 billion years. In contrast, the ages of the distant SGP A stars (1 to 10 kpc from the plane) had a quite different distribution. They were *all aged less than 0.7 billion years*, that is, they had a distinct cut-off in their ages of one-third of the expected range. This implies that their formation started at a specific epoch in a large-scale event. It seems to have been large-scale because the same type of stars appear not just at the SGP but also at the NGP, and along sightlines to various Galactic radii, so that they are not simply a local phenomenon.[16] Because their formation can be dated to a particular epoch, the stars cannot originate from any galactic activity that is *continuous over time*.

This fact is the most difficult one for either blue straggler of Hypothesis (1) theories to overcome. The distant young A stars actually fall along an isochrone; it would be impossible for a random collection of blue stragglers to imitate such a distribution.[35] With respect to ejection theories, early-type stars ejected by *any* means from the plane must show the random age spread of normal disk stars of the same type—these mechanisms could not simply "turn on" 0.7 billion years ago. This evidence appears to rule out any type of stochastic formation hypothesis.

The anomalous A stars are a widespread phenomenon, yet they have a distinct epoch of formation. They have very high velocities in and out of the disk, and unusual abundances. The only suggestion at present that accounts for all of the A star properties remains Hypothesis (3), the RHS accretion theory. A satellite galaxy would certainly be a reservoir of the necessary large quantity of low-abundance gas; and the merger, at a recent epoch, of this high-velocity gas with disk gas, straightforwardly accounts for all of the

A star properties. Should this proposition be correct, then the distant A stars may be the fossil remnants of an extraordinary event in the recent history of the Milky Way.

Formation of the young high-velocity stars began at around 0.7 billion years ago, but that does not mean that it ended shortly afterwards. Most of the A stars are aged between 0.2 and 0.7 billion years. A few are younger, formed no more than 50 million years ago.[16,35] Some stars would have been created during the initial impact of infalling gas onto the disk, but not all of the mixture of gas would form stars at that time (up to 1 per cent is an accepted efficiency rate). Instead, much of the high-velocity material would simply pass through the disk and continue in its orbit, oscillating through the plane, sweeping up less dense disk gas or being accumulated by denser disk gas, forming stars up to the present era.

There is no question that we do see high-velocity HI gas clouds in the halo. If they resulted from normal random galactic processes, such as supernova-driven galactic fountains, they would be expected to be spatially well mixed. But if some of this gas was part of the proposed A star-forming infall at around three Galactic rotations ago, it would still show spatial asymmetry, which is in fact a puzzling feature of the observed high-velocity clouds. Clouds with negative radial velocities predominate at Galactic longitudes less than 210°, and positive radial velocities at greater longitudes. Many more clouds occur in the first and second Galactic quadrants, and so, overall, it is clouds approaching the plane that predominate.[36] They are certainly not well mixed. It has been suggested[37] that the Magellanic Stream of high-velocity gas was stripped from the existing Large and Small Magellanic Clouds, but RHS's proposal of the accretion of a third Magellanic object suggests that the Stream may have originated from such an infall event.

OTHER SPECTRAL TYPES

Although A stars are primarily discussed above, this does not imply that *only* A stars are involved. In any star-forming event a wide range of stellar masses may be created. Main sequence stars of lower mass than A stars will be fainter and have longer MS lifetimes, so that observing them in the halo or defining their ages is a very difficult task. Any lower-mass MS stars that exist at large distances from the plane are simply too faint to be seen in presently existing studies, limited to 14th magnitude.

On the other hand, MS stars of *higher* mass, the O and B stars, are bright and have easily defined ages. They have certainly been observed far from the plane: Greenstein and Sargent[38] found that 26 per cent of a sample of faint blue halo stars near the Galactic Poles were spectroscopically normal young MS B stars. The radial dispersion of their young stars was 63 km s^{-1}, almost identical to the SGP A stars.

Not only are there a number of O and B stars at large distances from the plane, there are many that are observed locally with substantial space velocities. The local stars are usually termed "OB runaways" and they have been studied in some detail, quite independently of the A stars.

ARE THE HIGH-VELOCITY A, B AND O STARS ACTUALLY RELATED?

At present there are two main theories to explain O and B runaways. They were first thought to be created by the "binary slingshot" mechanism[39] which proposed that when the primary of a massive multiple system becomes a supernova, the subsequent explosion accelerates the system by a few tens of kilometres per second, to a maximum of around 150 km s^{-1}. Stone[27] showed that the primary of such a system would transfer around 60 per cent of its mass to the secondary before exploding. Hence runaways (the secondaries) in this scenario must all be more massive than early B stars (>10 $M_{\odot}$). This means that late-type B stars (3 $M_{\odot}$ to 10 $M_{\odot}$) and A stars (<3 $M_{\odot}$) *could not become runaways* by this process.

Most runaways are single stars rather than members of observable multiple systems. According to the binary slingshot hypothesis the system should be left with a collapsed companion star, but the system's expected radial-velocity variations would be below the limit of detection,[40] and so the present lack of runaways with radial-velocity variations[26] may not be significant. A sample of massive X-ray binary stars (from systems in which a supernova is believed to have occurred) do indeed show runaway characteristics.[41] It is possible that systems which have been completely disrupted by supernovae explosions appear as single runaways, while those in which the system survives become the massive X-ray binaries.[41]

If supernovae in massive systems instigate runaways, then there should be a positive correlation between mass and velocity, so that the most massive systems have the largest runaway velocities.[40] Stone appeared to find such a correlation from a diagram of high-mass O stars and their peculiar velocities, but the maximum of his velocity axis was only 110 km s^{-1}. He did not plot five stars from his Table I, with velocities between 120 and 160 km s^{-1} and masses from 14 to 100 $M_{\odot}$. When these are included a correlation is not apparent. Larger samples which include B stars also do not show any positive correlation.[26,42]

An alternative to supernovae as the mechanism of runaway formation is cluster ejection.[26] During *n*-body simulations of the dynamical evolution of young clusters, interactions of binary and multiple systems in the core eject high-velocity stars from the cluster.[43] This process could accelerate stars of any mass. Velocities of ejected stars may go as high as 200 km s^{-1}, but typically they are less than 100 km s^{-1}. Leonard modeled such interactions[44] and found that, theoretically, stars could be ejected at many hundreds of km s^{-1}. But if this actually happened with any frequency we would expect to observe an isotropic population of young, extremely high-velocity stars of all spectral types, which we do not.

The cluster ejection mechanism should produce a negative mass-velocity correlation (lower mass stars are ejected at higher velocities). In models, single stars or binaries interact with other binary systems, which causes the orbits of the binaries to shrink, and usually results in the ejection of single stars. Binary systems themselves are rarely ejected.[44] This is consistent with observations, as the relative percentage of multiple systems (visual or spectroscopic) among cluster, field, and runaway O stars is, respectively, 56, 29, and 0 per cent.[43] More high-velocity objects are produced when the dynamical interactions involve high-mass stars, so cluster ejection should lead to the production of more O-type runaways relative to lower-mass stars, but the lower-mass stars should have the higher velocities.

In addition to the supernova and cluster ejection hypothesis it is likely that some high-velocity stars are formed to the present day from infalling gas clouds, some of which may be from the accretion proposed to have formed the SGP A stars. For instance, a complex of very high-velocity clouds is observed in the Galactic anticentre, falling towards and interacting with the disk, creating condensations at the shock fronts that are probably precursors of star formation.[45] Stars of all masses should be produced by this mechanism.

It would be convenient to account for all high-velocity early-type stars with a single explanation. However, direct comparisons between the characteristics of different star types are not straightforward, as selection criteria and definitions of "high-velocity" vary from study to study.

The distant SGP A stars were defined as those more than one kpc from the plane, drawn from a sample complete to nearly 14th magnitude. Stars at the solar radius need a Z velocity at the plane of at least 65 km s^{-1} to be even capable of travelling to a distance of 1 kpc away. The A star W velocity dispersion, for stars more than 1 kpc from the plane, is 62 km s^{-1}. Their U (directed outward from the Galactic center) and V (direction of Galactic rotation) velocity dispersions are unknown. Their scale height is 1000 pc and their density at the disk is around 4 per 1000 disk A stars.[16]

Stone[27] selected runaway stars as those with peculiar velocities (velocity corrected for Galactic and solar motion) greater than only 25 km s^{-1}, and on this basis concluded that around 50 per cent of local O stars were runaways, with a scale height of 93 pc. To compare these stars directly to the SGP A stars we must consider only those that have Z velocities greater than 65 km s^{-1}, which is three stars out of 56: while this is a tiny sample, it is still 5.4 per cent of the O stars, more than an order of magnitude greater than the 0.4 per cent of high-velocity A stars among disk A stars. If Stone's sample is unbiased then it appears that a relatively greater proportion of O stars are high-velocity ones compared to A and B stars. Another study of runaway stars,[26] defined as those with peculiar velocities greater than 30 km s^{-1}, finds around 2 per cent of early B stars and 10 per cent of O stars are runaways. Although this sample cannot be compared directly to the SGP A stars, it still shows the same preponderance of O stars relative to B stars among the runaways.

Analysis has begun of a collection of data on a number of high-latitude A and B stars from many sources.[46] Preliminary results suggest that the B stars more than 1 kpc from the plane have a scale height of around 1000 pc, like the SGP A stars, and a density at the plane of around 0.1 per cent of normal B stars. Some of the stars have present positions and radial velocities that indicate that if they were truly ejected from the plane it must have been at velocities *greater* than 250 km s^{-1}.

Table I summarises the stellar properties that would be expected to occur according to runaway formation hypotheses, compared to the observed characteristics of high-velocity O, B and A stars. From Table I it appears that the B and A stars have similar properties, but their properties are different from those of the O stars.

Cluster ejection or gas infall are the most likely formation mechanisms for A and late B stars, because the supernova hypothesis applies only to stars of more than 10 $M_{\odot}$. But cluster ejection is a stochastic process, so it cannot account for the well-defined initial epoch of formation of the A stars. The maximum ejection velocity predicted by most cluster ejection models is also lower than velocities observed for some of the A and B stars. The similarity of the high-velocity B stars to the A stars suggests that both types of stars were formed by the same mechanism, which, from Table I, appears more likely to be gas infall onto the disk. (O and B stars formed at the same time as the 0.7 billion-year-old A stars, of course, would have long since evolved to their final evolutionary stages and would not appear in these samples.)

However, this does not mean that cluster ejection should be rejected, because it is a plausible and well-supported hypothesis, but if it had accelerated a significant proportion of the young stars seen in the halo, then the 0.7 billion years cut-off for the high-velocity A stars would be obscured by older A stars. Since this has not occurred it would seem that gas infall is the more dominant mechanism, particularly among late B and A stars.

Despite their similarities, differences do exist between the high-velocity A and B stars. Distant A stars have somewhat lower calcium abundances than disk A stars; they are up to one third less metal-rich; whereas according to high-resolution spectra,[47,48] distant B stars appear to have *identical* abundances of disk B stars. High-resolution abundance studies of the distant A stars do not

TABLE I

A comparison of the observed characteristics of high-velocity O, B and A stars, with those predicted by high-velocity star formation hypotheses

Property	Supernovae	Cluster Ejection	Gas Infall	Observed O	Observed B	Observed A
Mass-velocity correlation	positive	negative/none	none	negative/none	none	none
Max. Z veloc. (km s^{-1})	150	200	>250	160	>250	>250
% with $Z > 65$ km s^{-1}	. . .	. . .	. . .	5.4%	0.1%	0.4%
System multiplicity	single + multiple	single	. . .	single + multiple	single	single
Stellar mass ($M_{\odot}$)	>10 only (O and early B)	all masses (more high mass)	all masses	>20	3 to 20	<3

yet exist, so the significance and true extent of this difference remains to be established.

Since the numbers of B and A stars in the Galaxy are vast, even proportions like 1 to 4 per thousand result in a reasonable number of high-velocity stars. However, because the O star population is very much smaller than the B or A population, the observable number of O stars that might originate in the same way (from gas infall) should be minute. Yet a large percentage of local O stars in Stone's sample are high-velocity upon the same criterion as the A stars: 5.4 per cent of O stars, compared to 0.1 per cent of B stars and 0.4 per cent of A stars.

This suggests that an *additional* process must act upon the most massive stars. This is consistent both with the supernova mechanism (because that results in a population of high-velocity stars more massive than 10 $M_\odot$), and also with the cluster ejection process (because that ejects more high-velocity objects when high-mass stars are interacting). However, the supernova theory predicts that the most massive stars will be those with the highest velocities, while the cluster ejection hypothesis predicts that it will be the lower-mass stars with the highest velocities. Early suggestions that the higher-mass runaways had the higher velocities[27] are not supported by more complete samples,[26,42,46] which find that O stars have similar or lower maximum velocities relative to B stars.

Overall, then, it appears that high-velocity stars of all spectral types may be formed from the merger of infalling clouds with the Galactic disk; while an additional group of high-velocity stars exists, possibly the result of ejection from clusters.

Interestingly, a study[49] of the proper motions of pulsars, the neutron star remnants of recent supernovae, shows that almost all are moving away from the Galactic plane, some at velocities substantially *higher* than those of the OB runaway stars, or of the maxima predicted by either the supernova (150 km s^{-1}) or the cluster ejection (200 km s^{-1}) processes. The pulsars have a Z velocity dispersion of around 107 km s^{-1}, much greater than even the 62 km s^{-1} of the high-velocity A stars. Perhaps, after high-mass stars are initially ejected from clusters, some gain an additional "kick" during the supernova phase, so that the resultant velocity of the remnant pulsar is larger than the velocity attainable from either process alone.

Finally, one of the oddest aspects of high-latitude blue star studies remains to be mentioned, that is, that some O and B stars appear to be at distances such that their travel times from the disk are longer than normal main-sequence lifetimes would permit: either their MS lifetimes are very different from normal, or the stars have *not* been created in, nor ejected from, the plane.[47] An example of this type of star is one that is 18 kpc above the Galactic plane, with the atmospheric properties and chemical abundances of a normal B1 V star.[50] The MS lifetime of a B1 V star is around 14 million years. If this star had been ejected from the plane at the maximum W velocity shown by other young high-velocity stars, of around 250 km s^{-1}, it would have taken it nearly 170 million years to travel to that distance, more than twelve times its expected MS lifetime.[46]

An alternative possibility is that the star did *not* originate in the plane. Instead, it might have formed in the halo. This is theoretically possible,[51] but has not been observationally tested; searching the halo for such a rarity as a protostar would be daunting, and perhaps we simply have to accept that if undeniably young, massive stars are observed many lifetimes away from the plane then they may be the best evidence we have that star formation (on a miniscule scale) may actually occur out there.

CONCLUSION

So it would seem that the relatively simple picture of earlier times, that the halo is a static void populated by elderly stars and tidy globular clusters, must now give way to a far more interesting scenario: an environment that also contains plunging gas clouds and bizarre young stars, perhaps the remnants of a dramatic occurrence in the recent history of the Milky Way. If this is so, then we can no longer operate from the assumption that the Galaxy has had a classical smooth evolutionary path, from homogeneous gas cloud to well-behaved disk and halo, unperturbed by significant interaction with the intergalactic environment.

For instance, by analogy with elegant grand-design spirals, much effort has gone into trying to observe and unravel the spiral arm pattern of the Galaxy, so far without striking success. It appears to be a very complex arrangement, which may simply be a function of observational limitations. But if that is not the case, then it's possible that the reason for the confusion is that the Milky Way is actually a complete mess, from a recent vast infall of gas all over its hitherto beautifully delineated arms, and to attempt to reveal its design may turn out to be a hopeless endeavour. (On the other hand, we now recognize that many galaxies have undergone or are presently undergoing such interactions, and so the Galaxy may yet be useful as a template for comparison with perturbed galaxies.)

Whatever has been the true evolutionary path of our galaxy, we must find out what it was. We must be prepared to recognize that perhaps it never was a statistically normal member of its class, provided for our contemplation by a benevolent cosmological principle, but that it has its own unique and significant history that is *different* from any other galaxy in the Universe. So this testing of our assumptions (and prejudices) about the populations, structure, and evolution of the Galaxy turns out to be the quite unexpected reward for the decades of patient observation, data reduction and analysis, of the extraordinary young halo stars.

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