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THE GALACTIC HALO

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1. Introduction

Although the nature of interstellar gas and early-type stars in the plane of the galaxy has been investigated for many years (see for example, Spitzer 1978; de Jager 1980), it is only comparatively recently that astronomers have considered the possible presence of material at large distances $z$ from the plane. Shklovsky (1952) first suggested that material might exist at large $z$-distances, when he postulated that much of the cosmic radio noise received on Earth might originate in a spherical halo surrounding the Galaxy. However, it was Spitzer (1956) who laid the foundations for contemporary theories on the galactic halo when he proposed the existence of a hot ($T \approx 10^6$ K), low density ($\rho \approx 10^{-4}$ cm$^{-3}$) and extended ($R \approx 10$ kpc) corona to explain the equilibrium of cool clouds at high galactic latitudes and the 3.7 m radio noise observed in these regions (Baldwin 1956). More recent theoretical considerations of the galactic corona have been made by for example, Shapiro and Field (1976), Weisheit and Collins (1976), Chevalier and Oegerle (1979) and Bregman (1980), although they all generally predict similar physical characteristics to those proposed by Spitzer.

As first pointed out by Spitzer a galactic halo would be of great importance as its existence could, for example, explain the equilibrium of spiral arms and of interstellar clouds at large $z$, while the absorption line systems observed in quasar spectra may be due to the intervening haloes of other galaxies (see Section 2c). In Section 2 the evidence, obtained from both visible and ultraviolet spectroscopic observations, for
the existence of galactic and extragalactic halo gas is briefly discussed and a summary is
given of previous research into the nature of early-type stars at large distances from the
galactic plane. Finally, in Section 3, the results of some of the work carried out at
Queen’s University are outlined.

2. Previous Galactic Halo Research

(a) Visible Observations of Clouds at High Galactic Latitudes. The first
survey of interstellar clouds at high galactic latitudes was carried out by Münch and
Zirin (1961), who observed the interstellar Ca II K absorption lines in stars at large
distances from the galactic plane. By considering groups of stars at varying z-distances
from the plane, they showed that the mean number of components per star increased
with z, from which they inferred that some interstellar clouds exist at z ≈ 1 kpc. This
is supported by the more recent work of, for example, Habing (1969), Rickard

The above authors also noted that high velocity clouds (with predominantly
negative velocities) occur at large distances from the galactic plane with greater
frequency than they do in the plane, and that interstellar components in high z stars
show a definite peculiarity (strong Ca II interstellar line strengths relative to those of
Na I) when compared with those in low z ones. This peculiarity has also been
observed by Routly and Spitzer (1952) for high velocity clouds in the galactic plane.
They found a trend of decreasing $N$(Na I)/$N$(Ca II) with increasing absolute radial
velocity (where $N$(Na I) and $N$(Ca II) refer to the column densities of Na I and
Ca II respectively), while later Siluk and Silk (1974) showed that the correlation
actually involved the absolute peculiar velocity (i.e. the radial velocity with respect
to its own Local Standard of Rest) of a cloud. This velocity dependence of the $N$(Na I)/$N$(Ca II) ratio could be due to either clouds being heated due to their movement
through an intercloud medium until their temperatures become high enough
($T \geq 7000K$) to cause collisional ionisation of Na I but not Ca II (Routly and Spitzer
1952; Münch and Zirin 1961; Pottasch 1972a, b), or calcium, which should preferen-
tially adhere to grains in interstellar space (Watson and Salpeter 1972; Field 1974;
Duley and Millar 1978), being sputtered from grain surfaces via grain-grain collisions
in high velocity clouds and returning to the gaseous phase (Jura 1976; Spitzer 1976;

(b) Observations of Ultraviolet Absorption Lines in the Galactic Halo. As
Spitzer (1956) pointed out, the gas in a galactic corona would be in a high state of
ionisation. Hence it would only be spectroscopically observable in the UV part of
the spectrum, where the resonance lines of most ions lie. However, it has only been since
the launch of the IUE satellite (Boggess et al 1978a, b), with its ability to observe faint
objects at high resolution, that the UV spectra of distant halo stars have been obtain-
able.

Savage and de Boer (1979, 1981) have observed strong galactic C IV and Si IV
absorption lines towards stars in the Large and Small Magellanic Clouds. They point
out that as these lines are much stronger than those observed towards galactic field
stars (Bruhweiler et al 1980, Black et al 1980, Cowie et al 1981), much of the absorption must occur in gas away from the galactic plane. More recently Pettini and West (1982) have shown (from an analysis of the spectra of halo stars), that these ion states are concentrated between $z \approx 1$–$3$ kpc, and have suggested that this gas may occur in a transition region between cool gas in the plane and an outer halo at $T \approx 10^4$K, which is unobservable with IUE. In addition, they noted that the $N$(C IV)/$N$(Si IV) ratios appear to be independent of $z$ and to show little scatter around the average value of $4.5 \pm 1.5$, suggesting that the ionisation state of the halo gas must be remarkably uniform. This mean value and its small scatter can be used to unequivocally differentiate the hot gas in the halo from the regions producing the C IV and Si IV lines in the disk, for which $[N$(C IV)/$N$(Si IV)]$_{av} = 0.6 \pm 0.5$ (Black et al 1980). If collisional ionisation and radiative recombination are responsible for the state of ionisation and if the Si IV and C IV material is spatially coincident, then a temperature of $\sim 10^4$K is implied, and assuming solar abundances a particle density of $\sim 10^{-6}$cm$^{-3}$ is deduced, in agreement with the theoretical predictions of Spitzer (1956).

(c) Absorption in the Haloes of Other Galaxies. It has been suggested (Bahcall and Spitzer 1969) that many of the absorption line systems in the spectra of quasars are caused by material in the haloes of intervening galaxies which are too faint to be observed. Many quasars are known with multiple absorption systems, for example TON1530 (Bahcall et al 1969), Q0002–422 (Sargent et al 1979) and Q0122–380 (Carswell et al 1982). As pointed out by Bahcall and Spitzer, this ‘intervening galaxy’ hypothesis is attractive as then one would not have to explain how (i) quasars eject mass with $v \geq 0.6$ c and (ii) clouds ejected with such velocities maintain small internal velocity dispersions ($b \approx 30$ km s$^{-1}$), while it would also confirm that quasars are at cosmologically large distances.

Savage and Jeske (1981) have made a comparison of quasar absorption line systems with absorption by the galactic halo and found a number of remarkable similarities, such as the absence of excited fine-structure levels, similar column densities and multicomponent line profiles, and hence they concluded that the original suggestion of Bahcall and Spitzer was probably correct. More recently, Pettini and West (1982) have calculated the $N$(C IV)/$N$(Si IV) ratios of several quasar absorption systems and found a mean value of $N$(C IV)/$N$(Si IV) = 6.5 ± 3.5, which is very similar to that found by them for galactic halo gas (4.5 ± 1.5, see section 2b). In view of this, they concluded that the observed value of the $N$(C IV)/$N$(Si IV) ratio may be a characteristic signature of interstellar gas in galactic haloes.

There are three known quasar-galaxy pairs where Ca II absorption has been detected in the quasar at the same redshift as that of the intervening galaxy (see Boksenberg and Sargent 1978, Boksenberg et al 1980 and Blades et al 1981). In each case the line-of-sight to the quasar lies between 16 and 25 kpc from the intervening galaxy at the nearest point, implying that the absorption is occurring far from the galaxy, although one cannot be certain that it arises in a halo. However, as Na I is below the detection limit for the sightlines, the $N$(Na I)/$N$(Ca II) ratios must be small, which may be indicative of a halo origin for the absorption (see Section 2a).
(d) Early-type Stars in the Galactic Halo. As discussed previously, early-type stars in the galactic halo are often used as tracers for the interstellar medium away from the galactic plane. However, if these stars are truly distant, then many of them require ejection velocities of hundreds of km s\(^{-1}\) from the galactic plane in order to reach their present \(z\)-distances during their lifetimes (House and Kilkenny 1978, Tobin and Kilkenny 1981). Alternatively, Carrasco and his co-workers (Carrasco and Crézé 1978, Carrasco et al 1980) suggest that the stars are subluminous, nearby objects (similar to the UV-bright stars in globular clusters, see Norris 1974) and have supported this explanation using statistical parallax data and kinematical arguments. Certainly at least one case is known where an apparently distant halo star (HD 93521, \(z \approx 1.5\) kpc), used as a tracer for halo material (Münch and Zirin 1961, Rickard 1972, Cohen 1974), has later proved to be subluminous and actually only \(-0.8\) kpc from the galactic plane (Bisiacchi et al 1978, Caldwell 1979, Ramella et al 1980). On the other hand, Greenstein and Sargent (1974) have quantitatively analysed the spectra of several spectroscopically normal halo B-type stars and found them to be largely Population I, while Tobin and Kilkenny (1981) using moderate dispersion spectrograms discovered no apparent differences between two groups of OB stars at \(z\)-distances of \(<0.5\) kpc and \(\geq 1.5\) kpc respectively. However, although these surveys suggest that many of the early-type halo stars are normal, their true nature and origin still remains a subject for discussion.

3. QUB Research Programme

Galactic halo research at Queen's University has been based mainly on the high resolution \((\lambda/\Delta \lambda \approx 2 \times 10^4)\) spectroscopic observations of eighteen large-\(z\) OB stars, obtained during two observing runs at the Anglo-Australian Telescope in September 1979 and 1980. The wavelength regions covered were 3890–4020\(\AA\) and 5760–6040\(\AA\), so that both the Ca II and Na I interstellar absorption lines, as well as several hydrogen, helium and CNO stellar lines were observed (see Keenan 1982 for more details). Two aspects of the work, carried out by the author in collaboration with Drs. P. L. Dufton, C. D. McKeith and J. C. Blades, are considered here.

(a) Atmospheric Parameters and Chemical Compositions of the Programme Stars. Stellar effective temperatures \((T_{\odot})\) and logarithmic surface gravities \((\log g)\) were found from Strömgren [\(c^\prime\)] photometric indices and He absorption line profiles respectively. Theoretical [\(c^\prime\)] indices and He line profiles, calculated using the model atmosphere program of Dufton (1972), were compared with the observed values to derive the atmospheric parameters and these were found to be typical of normal OB stars. The stellar elemental abundances, derived using the helium and CNO line strengths in conjunction with the model atmosphere program and the atmospheric parameters, were also found to be similar to those deduced for normal Population I early-type stars (Kane et al 1980). In view of the above, it was concluded that the programme stars are normal and show no evidence of subluminosity nor any other peculiarity. Their \(z\)-distances, derived directly from the atmospheric parameters (see Keenan, Dufton and McKeith 1982 for more details), were found to lie in the range
~0.3–3.5 kpc, making them suitable for use as tracers of interstellar gas in the galactic halo.

(b) Velocity Dependence of the $N$(Na I)/$N$(Ca II) Ratio. The observed interstellar Ca II and Na I line profiles (corrected where necessary for the presence of stellar features), were fitted to theoretical multicloud model calculations using an interactive curve of growth program (Dufton 1982), from which the radial velocities, internal velocity dispersions and column densities of individual clouds in the programme star sightlines could be ascertained (see Keenan et al (1981) for more details).

As discussed previously in Section 2a, Siluk and Silk (1974) have noted that low $N$(Na I)/$N$(Ca II) ratios are usually associated with large peculiar velocities (i.e. large cloud velocities with respect to their own Local Standard of Rest). To investigate this it was decided to follow their work and divide the interstellar clouds into three classes according to their $N$(Na I)/$N$(Ca II) ratios as follows.

Class 1. $N$(Na I)/$N$(Ca II) $\geq$ 1
Class 2. $0.5 \leq N$(Na I)/$N$(Ca II) $< 1$
Class 3. $N$(Na I)/$N$(Ca II) $< 0.5$

For each class the radial velocities (with respect to the Local Standard of Rest) of the components $v_{\text{LSR}}$ have been plotted against their galactic longitudes $l_{\text{II}}$ (see Figure 1), with components in class 1 represented by crosses, class 2 by triangles and class 3 by

Figure 1: Plot of radial velocity (w.r.t. the Local Standard of Rest) versus galactic longitude ($l_{\text{II}}$) for the interstellar clouds in the lines of sight to the programme stars. Solid lines represent the ranges of LSR velocities predicted for the clouds if they participate in galactic rotation.
Figure 2. Plot of sodium column density against colour excess, $E_{B-V}$, for the programme stars. The dashed line refers to the mean relationship determined by Hobbs (1974).

filled circles. Now the predicted Local Standard of Rest velocity for each star (assuming a co-rotating halo*) is given by [see, for example, Cohen and Meloy 1975]:

$$v_{\text{LSR}} = A \sin (2l \cos b)$$

where $A =$ Oort's Constant $= 15$ km s$^{-1}$ kpc$^{-1}$ (Allen 1973) and $b$ and $r$ are the galactic latitude and stellar distance respectively. As the interstellar clouds in each line of sight lie between ourselves and the star, they will have velocities in the range $0 - v_{\text{LSR}}$ if they are partaking in galactic rotation, velocities outside this range indicating that the clouds have non-zero peculiar velocities. In Figure 1 the $0 - v_{\text{LSR}}$ ranges for the programme stars are denoted by solid lines. It can be seen that the class 1 components

* Footnote: Although little is known about the motion of halo material, observational support for co-rotation up to $z$-distances of 1–2 kpc comes from the 21 cm emission measurements of Kepner (1970), while Weisheit (1978) has summarised the theoretical arguments that favour the co-rotation of a gaseous halo.

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with high $N$(Na I)/$N$(Ca II) values generally lie within the velocity ranges predicted by galactic rotation. However, class 2 components of intermediate $N$(Na I)/$N$(Ca II) lie on average further away from the solid lines, while the class 3 components with low $N$(Na I)/$N$(Ca II) ratios frequently occur at large velocities from those predicted by galactic rotation, i.e. at large peculiar velocities. This confirms the findings of Siluk and Silk (1974), although the present results are more detailed as we have analysed individual interstellar clouds in the line of sight to each star. Siluk and Silk generally made the arbitrary assumption of there being only one cloud per sightline.

In Section 2a it was noted that the variation of $N$(Na I)/$N$(Ca II) with cloud velocity may be explained by either (i) the collisional ionisation of Na I or (ii) the sputtering of calcium from grain surfaces. To investigate this point, the total Na I column density in the line of sight to each star was plotted against its reddening, $E_{B-V}$. In Figure 2 the plot of $N$(Na I) vs $E_{B-V}$ is shown, where the dashed line refers to the mean relationship determined by Hobbs (1974) from a study of the sightlines of bright stars in the galactic plane. It may be seen from the figure that the high latitude material obeys this relationship reasonably well, implying that these clouds must have in general the same Na I-to-dust ratios as the normal clouds in the plane. However, if the collisional ionisation hypothesis is correct, then it is strange that the clouds have normal Na I-to-dust ratios. One would expect this to be much smaller due to the decrease in Na I, with all the points in Figure 2 lying to the right of the dashed line. It is possible, of course, that the necessary amount of dust grains are destroyed to keep the Na I-to-dust ratio at its normal value, but this must be considered unlikely, especially as extremely high temperatures ($T \geq 10^6$K) are needed to destroy grains (Barlow and Silk 1977). In view of the above discussion one must therefore conclude that the velocity dependence of the $N$(Na I)/$N$(Ca II) ratio is probably due to the sputtering of calcium from grain surfaces. However, the possibility that, in some cases, collisional ionisation of Na I is responsible cannot be totally discounted.

In the future we intend to apply our ground-based cloud models to the interstellar ultraviolet lines in several of the programme stars that we have observed with the IUE satellite, in order to derive information on the temperatures and particle densities in high-z interstellar clouds. A preliminary analysis of one star (HD 203664) has revealed the presence of strong low and high velocity components which appear to have significantly different physical characteristics (see Keenan 1982 for more details).

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