EVIDENCE FOR RECENT STAR FORMATION IN THE GALACTIC HALO

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1. Introduction

Over the past few years the nature and origin of high-latitude early-type stars have been subjects of discussion. Several authors believe them to be subluminous, nearby objects whose spectra mimic those of normal stars at classification dispersions (Kilkenny and Lydon 1986, Carrasco et al 1982 and references therein), similar to the UV-bright stars in globular clusters (de Boer 1985). However, subluminous stars can be differentiated from normal OB stars using accurate quantitative spectral analyses, as the former usually have Population II chemical compositions (Tobin and Kaufmann 1984).

Recent work at QUB has shown that many relatively bright \( (V \leq 10) \) early-type halo stars are indeed normal objects, at distances of typically 2 kpc from the plane (Keenan et al 1982, Keenan and Dufton 1983, 1984). They must either have been formed in the halo (Keenan and Lennon 1984), or alternatively accelerated out of the disc (Keenan and Dufton 1983, Tobin 1986) via close-binary disruption (Stone 1979) or cluster ejection (Gies and Bolton 1986).

In this paper we extend this earlier work to a fainter \( (V \approx 11.5) \), high latitude \( (b \approx -58 \deg) \), early-type star PHL 346. Kilkenny et al (1977) assigned a spectral classification of B1, which would imply that PHL 346 is approximately 5 kpc from the galactic plane if main-sequence, and further if it is a giant or supergiant. It is important to determine the extent of these faint objects, especially as their sightlines may be of great use as tracers of distant halo interstellar gas (see for example Keenan et al 1981, 1983).

2. Observations

Observational data were obtained for PHL 346 with the 2.5 m Isaac Newton Telescope on La Palma, Canary Islands, in August 1985. The IDS spectrograph was used with camera B and the Joyce-Yoon 2400 grooves \( \text{mm}^{-1} \) grating, with an IPCS as the detector. This instrumental combination yielded approximately 8 A \( \text{mm}^{-1} \) spectra in the blue visible region with a resolution \( (\text{FWHM}) \) of approximately 0.3 A. Three wavelength regions were observed, namely 3900 to 4150 A, 4150 to 4380 A, and 4420 to 4660 A.

The observing procedures and data reduction methods were similar to those previously used for spectra obtained with the 3.9 m Anglo-Australian Telescope, where further details can be found (see Keenan et al 1984, 1986a). In Figure 1 the spectrum of PHL 346 is shown from 3990 to 4040 A, to illustrate the quality of the present observational data.
Figure 1. Portion of an unsmoothed INT spectrum of PHL 346. Stellar absorption lines of N II, He I, and N II/O II are clearly visible in the spectrum at 3995, 4009, 4026, and 4035 Å.

3. Method of analysis

The method of analysis has been described in detail by Keenan et al (1986a) and Brown et al (1986). Briefly, it consisted of comparing measured stellar Stromgren colours, hydrogen-line profiles, and helium and metal-line equivalent widths with those predicted by local thermodynamic equilibrium (LTE) model-atmosphere calculations. The derivation of atmospheric parameters and abundances is discussed separately below.

3(a). Atmospheric parameters. An effective temperature for PHL 346 was deduced from the reddening-free Stromgren colour index \([c_1] = c_1 - 0.2(b-y)\), using the \([c_1] - T_{\text{eff}}\) calibration of Relyea and Kurucz (1978). The observed index, \([c_1] = 0.108\) (Kilkenny et al 1977), lead to an effective temperature \(T_{\text{eff}} = 22600\) K, which should be accurate to \(\pm 1000\) K on the Kurucz (1979) fully line-blanketed grid of models on which it is derived. A surface gravity of \(\log g = 3.6\) was determined by fitting theoretical H\(\gamma\) and H\(\delta\) line profiles to the observations, uncertainties in the line profiles leading to an error estimate of approximately \(\pm 0.2\) dex. The microturbulent velocity \((v_t)\), appropriate to an LTE analysis of PHL 346, was derived by constructing
a curve of growth for the O II lines observed in the spectra, the method being similar to that used by Keenan and Lennon (1984). A value of $v_t = 12 \pm 3 \text{ km s}^{-1}$ was deduced, which is in good agreement with those found in previous LTE analyses of giant and supergiant stars (see Keenan and Lennon 1984 and references therein).

3(b). Abundances. Using the atmospheric parameters discussed above, helium and metal abundances were deduced by comparing observed line strengths with those predicted from LTE model atmospheres (see Brown et al. 1986 for more details). Equivalent widths were measured by fitting Gaussian profiles to the observational data as discussed by Brown et al. (1986), and are summarised in Keenan et al. (1986b).

4. Results and discussion

The mean logarithmic helium and metal abundances in PHL 346 (on the scale log $[\text{H}] = 12.0$) are listed in Table 1, along with the normal Population I OB star values (see Keenan et al. 1986b and references therein). It may be seen from an inspection of the table that the results are in excellent agreement with those of normal B-stars, differences being typically less than 0.2 dex. This indicates that PHL 346 is not a subluminous dwarf close to the plane, as these should have Population II chemical compositions and hence should be metal weak (Tobin and Kaufmann 1984, de Boer 1985).

<table>
<thead>
<tr>
<th>Element</th>
<th>Mean Abundance</th>
<th>Normal B-star value</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>10.99±0.16</td>
<td>10.93</td>
</tr>
<tr>
<td>C</td>
<td>8.3 ±0.2</td>
<td>8.2</td>
</tr>
<tr>
<td>N</td>
<td>8.0 ±0.2</td>
<td>8.0</td>
</tr>
<tr>
<td>O</td>
<td>8.6 ±0.2</td>
<td>8.8</td>
</tr>
<tr>
<td>Mg</td>
<td>7.5</td>
<td>7.4</td>
</tr>
<tr>
<td>Al</td>
<td>6.3 ±0.2</td>
<td>6.3</td>
</tr>
<tr>
<td>Si</td>
<td>7.5 ±0.2</td>
<td>7.5</td>
</tr>
<tr>
<td>P</td>
<td>5.6 ±0.2</td>
<td>5.5</td>
</tr>
<tr>
<td>S</td>
<td>7.2 ±0.1</td>
<td>7.2</td>
</tr>
<tr>
<td>Fe</td>
<td>7.6</td>
<td>7.5</td>
</tr>
</tbody>
</table>

From the atmospheric parameters, the mass and lifetime of PHL 346 were derived using the evolutionary tracks of Maeder (1981), and found to be $M = 13 \pm 2 M_\odot$ and $t_{\text{erol}} = 11 \times 10^6$ yr, a maximum value of $t_{\text{erol}} = 17 \times 10^6$ yr being deduced by changing both the effective temperature and gravity by their estimated uncertainties. The distance, estimated from $T_{\text{eff}}$, log $g$ and $M$ using the methods discussed fully by Keenan et al. (1982) is $r = 10.2 \pm 1.7$ kpc, giving a distance from the galactic plane of $z = 8.7 \pm 1.5$ kpc.

Due to the high galactic latitude of PHL 346 ($b \simeq -58$ deg.), its radial velocity ($V_r$) should give a good estimate of the velocity in the $z$-direction, $V_z$ (Keenan and Lennon 1984). A radial velocity of $V_r = +66 \pm 10$ km s$^{-1}$ was determined from the
wavelength shifts of stellar lines in the spectra and, after correcting for the effects of galactic rotation (Keenan and Dufton 1983), a value of $V_z = +56 \pm 10 \text{ km s}^{-1}$ was found. This velocity, coupled with the gravitational acceleration $g(z)$ from House and Kilkenny (1980), implies that the star would have taken $63 \pm 7 \times 10^6 \text{ yr}$ to reach its present position if it were ejected from the galactic plane, which is approximately a factor of 4 larger than the maximum lifetime of the star. Conversely, the present velocity would have to be $V_z \gtrsim 500 \text{ km s}^{-1}$ for it to have reached its current $z$-distance in less than the maximum lifetime, which is clearly incompatible with the observational data. We must therefore conclude that PHL 346 has been formed far from the galactic plane. Although it is difficult to envisage how this process could occur in view of the low gas density present in the galactic halo (Savage and de Boer 1981), one possible mechanism has been proposed by Dyson and Hartquist (1983). In their model, shock-induced star formation may take place during collisions between cloudlets within intermediate and high-velocity clouds at high galactic latitudes, resulting in approximately $10^5$ early-type stars being formed in the halo every $10^7 - 10^8 \text{ yr}$.

From the maximum lifetime of PHL 346, its velocity $V_z$ and the gravitational acceleration $g(z)$, it is possible to calculate the minimum $z$-distance from the plane at which the star could have been formed, a value of approximately 6 kpc being inferred. Lockman et al (1986) point out that the HI layer in the Galaxy does not extend much beyond $z \simeq 1 \text{ kpc}$, although Kaebel et al (1985) and West et al (1985) found high-velocity material that may exist up to 6 kpc from the disc, and which is probably returning to the plane in a "galactic fountain" type flow (de Boer and Savage 1984). Therefore the most plausible explanation for the existence of PHL 346 at its present position is that it formed out of galactic fountain gas at a considerable distance ($z \simeq 6 \text{ kpc}$) from the disc.

We plan to extend this work by analysing the spectra of other faint early-type high-latitude stars. Such studies should lead to estimates both of the fraction of halo stars formed in situ, and the range of $z$-distances over which this occurs.

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References


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OPPORTUNITIES FOR OBSERVING ON THE JKT USING THE QUB ECHELLE SPECTROGRAPH WITH THE RGO-CCD CAMERA

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1. Introduction

The QUB echelle spectrograph (McKeith, Dufton, Kane, 1978a, McKeith, Kane and Dufton, 1978b) is a compact, high spectral resolution, stigmatic spectrograph which was designed originally for use with photographic plates (130 mm × 100 mm) at the Cassegrain focus of moderate aperture f/15 telescopes. The two-dimensional format of the familiar echellogram and the large photographic plate areas were exploited to record simultaneously the dominant visible lines of carbon (C II, λ4267 Å), nitrogen (N II, λλ3995, 4630 Å) and oxygen (O II, λλ4638, 4641, 4649 Å) which occur near the centre of the focal-plane field on three consecutive spectral orders. This configuration was employed in an extensive programme of CNO abundances in early-type OB stars of loose associations and clusters (Kane, McKeith and Dufton 1980, 1981; Dufton, Kane and McKeith 1981). During this investigation, the wider potential of the echelle spectrograph for a range of programmes, such as investigations of cosmic abundances and gas kinematics in the gaseous interstellar medium, became apparent as demonstrated by the ability to record weak spectral lines (EW > 10 mA) with high signal-to-noise (S/N > 20 : 1). This capability subsequently led to initiating further programmes, e.g., on the formation of interstellar CH, CH⁺ (λλ4232, 4300 Å) in the Pleiades cluster (Younan 1982; Younan and Dufton 1984), the occurrence of