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More dwarf carbon stars

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ABSTRACT

We have discovered three very faint carbon stars ($m_V > 19$) in the course of a multicolour survey for high-redshift quasars. Proper motion measurements have been made of these stars to determine their luminosity class. On this basis, the star $0045-259$ is confirmed as a halo dwarf, joining the four dwarf carbon stars already known. These five dwarfs appear to have similar absolute magnitudes and tangential velocities. A second star, $0041-295$, is also a dwarf, yet either its absolute magnitude or its tangential velocity differs from those of the five other dwarfs; it may be the first disc dwarf carbon star found. The time baseline for the proper motion measurement for the third star, $2048-348$, is too small to allow the luminosity class to be determined. It could also be a dwarf, while if a giant it lies at a galactocentric distance of ~ 200 kpc. The surface density of faint carbon stars with $16.0 < m_{or} < 20.0$ at high Galactic latitude is greater than $0.07\ \mathrm{deg}^{-2}$.

Key words: stars: carbon.

1 INTRODUCTION

Until recently, a largely unquestioned assumption of studies of the dynamics of the Galactic halo through radial velocity measurements of carbon stars has been that these stars are giants and at correspondingly large galactocentric distances. Before 1991 only one dwarf carbon star, G77-61, had appeared in the literature (Dahn et al. 1977). The star was found to be a member of a binary system (Dearborn et al. 1986), supporting the conjecture that the explanation of the carbon-rich atmosphere was the earlier transfer of material from an evolved companion, now invisible. From a model atmosphere analysis, Gass, Liebert & Wehrse (1988) found a very low metal abundance, implying the transfer of only a modest amount of material, in agreement with the separation inferred from the 245-d period. The properties of this object suggested that the conditions required to produce a dwarf carbon star are unusual. However, Green, Margon & MacConnell (1991) have recently measured significant proper motions for three other carbon stars, confirming their classification also as dwarfs, and it is therefore possible that several of the carbon stars used in studies of the dynamics of the halo (e.g. Mould et al. 1985; Bothun et al. 1991) are not giants, and hence not at the large distances assumed. These new dwarfs are also interesting in themselves, since the study of G77-61 had led to the conclusion that such objects are rare. If dwarf carbon stars prove to be common, it would suggest that the explanation put forward for the origin of the carbon in G77-61 is incorrect. One would then be forced to seek an alternative explanation, such as primordial composition.

In the course of a multicolour survey for high-redshift quasars, we have discovered three faint ($m_V > 19$) carbon stars in fields at high Galactic latitude. These stars may be compared with the faint ($m_V = 18$) carbon star discovered by Margon et al. (1984). The latter star does not have a measurable proper motion and is believed to be a giant, and depending on the assumed absolute magnitude would be the most distant Galactic star known, at a galactocentric distance $r > 100$ kpc. Our three carbon stars are therefore very interesting: either they are dwarfs, or they lie at even greater distances than does the star discovered by Margon et al.

In the next section we provide details of the positions, photometry, spectroscopy and proper motion measurements for these objects. In Section 3 we draw conclusions about their luminosity class. Further observations of these stars will be useful for understanding the origin of dwarf carbon stars, and in the search for a simple spectroscopic or photometric discriminant between dwarf and giant carbon stars which would allow the dwarfs to be eliminated from samples for dynamical studies.

2 OBSERVATIONS

Our multicolour survey (Warren et al. 1991) was aimed at finding high-redshift quasars, but, because the technique was based on the identification of any stellar object in the fields with unusual colours, rare types of Galactic star were also found. The survey was conducted in two United Kingdom Schmidt Telescope (UKST) fields, the South Galactic Pole (SGP) at $0^h53^m-28°03'$ (1950.0), and UKST field F401 at $20^h48^m-35°00'$. Pairs of plates in six passbands, u, b_j, v, or, r and i, were scanned by the Automated Plate Measuring facility (APM, Kibblewhite et al. 1984), and a catalogue was compiled of all cleanly matching stellar objects in the magnitude range $16.0 \leq m_{or} \leq 20.0$ (we use lower case subscripts to refer to the natural photometric system defined by the UKST emulsion–filter combinations). The total scanned area covers 58.6 deg^2, but the effective area of the survey is reduced to 45.7 deg^2 after allowance for stellar objects eliminated from the catalogue because, for example, they are merged with a neighbouring object on one or more of the 12 plates. Full details of the plate measurement, photometric system, calibration, catalogue compilation and candidate selection may be found in Warren et al. (1991).

Candidate quasars were selected by identifying outliers from the locus of common Galactic stars that exists in the six-dimensional space defined by the six broad-band magnitudes. The nature of the candidates was confirmed with subsequent spectroscopic observations. Carbon stars have broad-band optical colours that are similar to those of quasars in the redshift range $4.0 < z < 4.5$. Among candidates observed at the Cerro Tololo InterAmerican Observatory (CTIO) 4-m telescope during the nights of 1987 August 18 and 19, three objects proved to be carbon stars. Finding charts for these stars are provided in Fig. 1. In Table 1 we list the seven-figure coordinate designation, coordinates and epoch, and the broad-band magnitudes. In the rest of this paper we use the seven-figure coordinate designation to refer to these stars. The internal photometric errors, estimated from the two plates in each band, are $\sigma \sim 0.1$ mag, or less, except for the u-plate upper limits for which $\sigma \sim 0.2$ mag. Our sample of carbon stars having $16.0 \leq m_{or} \leq 20.0$ in these two fields is likely to be very incomplete, as the stellar locus swells at faint magnitudes, and fainter stars with similar colours to those found would not have been selected as quasar candidates. Therefore the measured surface density of 0.07 deg^{-2} is a lower limit to the true surface density.

The discovery spectra were of low signal-to-noise ratio (S/N). Further spectroscopic observations of 0041 – 295 and 0045 – 259 were made at the European Southern Observatory 3.6-m telescope on 1990 November 13, and of 2048 – 348 on 1991 November 12. In all cases we used the EFOSC instrument, the Blue-300 grating and a 1.5-arcsec slit. The resolution of the spectra is 14 Å and the integration times were 20, 20 and 25 min respectively. Unfortunately for 2048 – 348, the half-full Moon lay close to the field, and the spectrum is of low S/N. We have therefore averaged this spectrum with the original CTIO spectrum over the wavelength range in common. The spectra were corrected for

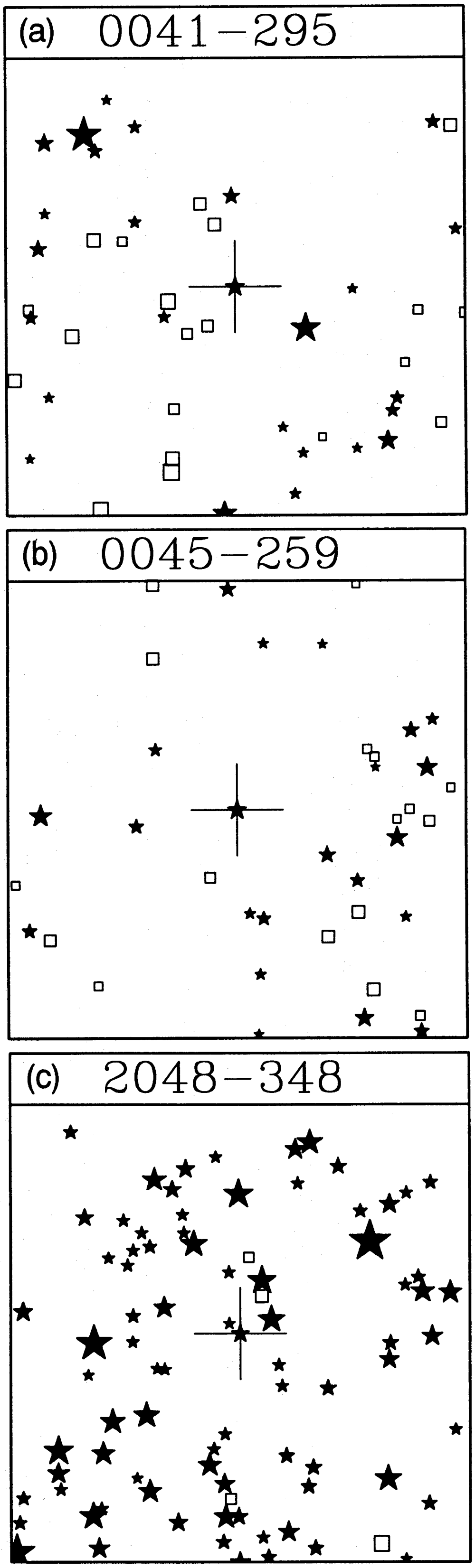

Figure 1. Finding charts for the three carbon stars, showing all objects detected on the deepest *or* plate in each field. For each chart north is up and east is to the left. The charts are 5 arcmin on a side. The filled symbols show stellar images, the open symbols galaxies (or two merged objects), and the size of the symbol scales with brightness.

Table 1. Coordinates and photometry.

Coord. no.	Ra 1950.0	Dec 1950.0	epoch	m_u	m_{b_j}	m_v	m_{or}	m_r	m_i
0041-295	00 41 08.11	-29 34 33.4	1986.7	>21.31	20.44	19.09	18.34	18.32	17.91
0045-259	00 45 50.51	-25 54 58.8	1986.7	>21.51	20.88	19.51	18.71	18.56	17.98
2048-348	20 48 54.77	-34 48 50.8	1986.5	>21.94	21.25	19.65	18.67	18.52	18.03

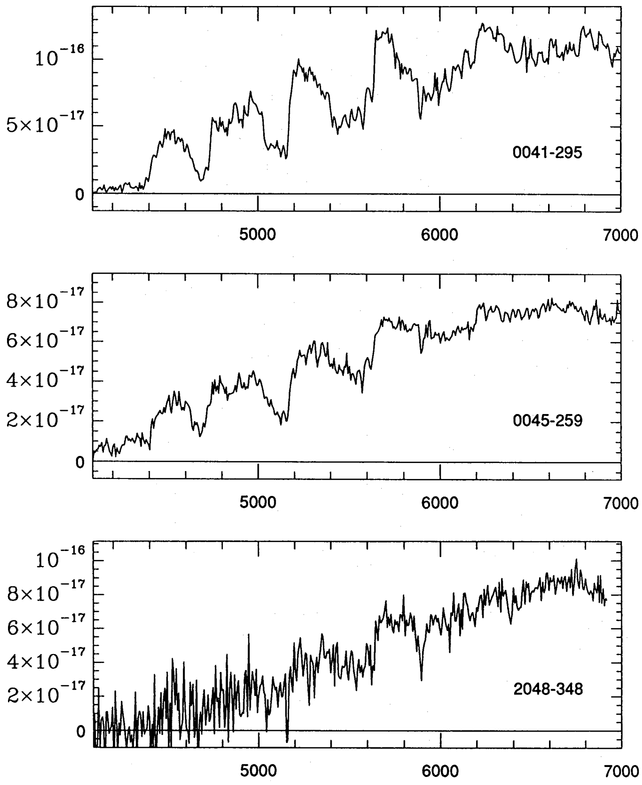

Figure 2. Spectra of the three carbon stars, obtained with EFOSC at the ESO 3.6-m telescope. Flux per unit wavelength (erg s^{-1} cm^{-2} $Å^{-1}$) is plotted against wavelength in Å. The resolution of the spectra is 14 Å.

extinction using a standard relation for the site, and the atmospheric absorption bands were removed by using observations of stars of smooth spectral energy distribution. The spectra were calibrated on to a relative flux scale, using observations of standard stars, and the zero-point for the flux scale was then established from the *or* broad-band magnitude. The three spectra are reproduced in Fig. 2. The upper two spectra are easily recognizable as carbon stars from the strong Swan bands of C_2 at 4382, 4737, 5165 and 5636 Å. The third star is also recognizable as a carbon star, but in this case only the 5636-Å band is clearly visible. We have measured the Keenan and Morgan spectral type (temperature and carbon indices) in the manner prescribed by Cohen (1979), and the results are listed in Table 2. For the star 2048 − 348 the carbon index was measured using only the 5636-Å bandhead, due to the poor S/N. For the two SGP stars we have also measured the Yamashita C^{13} index, again following Cohen (1979). Since the resolution of our spectra (14 Å) is lower than that of Cohen's spectra (7 Å), the temperature and C^{13} indices are somewhat uncertain.

Table 2. Spectral properties and proper motions.

Coord. no.	Spectral type	C^{13} index	μ_α arc sec. / year	μ_δ arc sec. / year
0041-295	C4,2	4/5	0.016 ± 0.006	-0.001 ± 0.006
0045-259	C1,1	5	0.030 ± 0.006	-0.047 ± 0.006
2048-348	C5,2	...	0.015 ± 0.024	-0.003 ± 0.024

Table 3. Photographic plates for proper motions.

Coord. no.	Plate 1	Epoch 1	Plate 2	Epoch 2
0041-295	SE19	1954.9	*r*11336	1986.7
0045-259	E1199	1954.7	*r*11336	1986.7
2048-348	j6109c	1980.6	*j*11171	1986.5

Proper motions for all three stars were determined using APM measurements of UKST and Palomar Schmidt photographic plates. For two of the carbon stars (0041 − 295 and 0045 − 259), glass copies of first-epoch northern sky survey E plates taken in the early 1950s were available, giving a 30-yr baseline for the proper motion measurements. Furthermore, the E passband is essentially identical to the UKST red passbands, ensuring that effects due to differential atmospheric refraction can be neglected. For the third carbon star (2048 − 348) we used UKST plates spanning a 6-yr baseline (this star is not visible on the plates taken for the Whiteoak extension of the Palomar sky survey). Details of the plates used for the proper motion measurements are given in Table 3.

The APM was used to measure a 2×2 deg^2 region around each carbon star on the first-epoch plate material. For the second-epoch plate material, 30-deg^2 APM measures of all the plates were already available. The measures for the different epoch plates for each carbon star were then matched on to a common coordinate system using the UKST plates as reference. Standard corrections for plate-to-plate distortions were computed using all matching images to map them and finally an inertial reference frame was defined by using the galaxies common to the plates in each series (e.g. Kibblewhite et al. 1982; Evans 1988). Proper motions could then simply be read from the image lists. The typical accuracy of the positional difference estimate between two plates is ~0.2 arcsec for stars at this magnitude.

The proper motion measurements are summarized in Table 2. These results may be compared with the null hypothesis of zero proper motion – the probability that the total proper motion could be *R* arcsec yr^{-1}, or greater, by chance, given Gaussian measuring errors on each axis of σ arcsec yr^{-1}, is given by the Rayleigh distribution function

$$p = 1 - \exp(-R^2/2\sigma^2).$$

The measured proper motions for two of the stars are significantly greater than zero, and form a key part of the discussion in the next section.

3 DISCUSSION

We now comment on each of the stars in turn.

3.1 0041 − 295

The probability of the total proper motion of 0.016 arcsec yr^{-1} occurring by chance is 3 per cent. A giant carbon star of this apparent magnitude would be approximately 200 kpc distant, and even if moving transversely at the Galactic escape velocity would have a negligible proper motion. Further evidence against the star being a giant comes from deep CCD *V*-band images of this field and a control field, obtained for us by L. Pasquini. A distant giant at such a large galactocentric distance would plausibly lie in a hitherto undetected dwarf galaxy, but our CCD images show no evidence for an excess of stars, down to $m_V = 23.5$. We conclude that 0041 − 295 is a dwarf.

There is a discrepancy between the apparent magnitude and proper motion of this star when compared with the measured properties of the four other known dwarfs (Dahn et al. 1977; Green et al. 1991). The absolute magnitude is known for only one dwarf carbon star, G77-61 ($M_V = 10.08 \pm 0.43$, Dearborn et al. 1986), and there is no reason to believe that all dwarf carbon stars have the same luminosity. Nevertheless, the measured proper motions of the four previously known dwarfs are in striking agreement (see Table 4) with the predictions of a naive model, namely constant absolute magnitude (as for G77-61) and stationary halo kinematics [$(U, V, W) = (0, -220, 0)$]. Furthermore, the same is true of the dwarf 0045 − 259 reported below. In contrast, the proper motion of 0041—295 is less than one quarter of the prediction and in the wrong direction. A simple explanation for this difference is that 0041 − 295 is a member of the disc population. A better test of this hypothesis will be possible once radial velocities have been measured for all the dwarf carbon stars, as well as more parallaxes. We have attempted to measure the radial velocity of 0041 − 295, but the accuracy of the measurement is too poor to be very useful. Our result, obtained at the Multiple Mirror Telescope on the night beginning 1990 September 12, is $v = 70 \pm 70$ km s^{-1}.

Table 4. Comparison of observed and predicted proper motions.

Name	Gal. coords		Observed p.m.		Pred. dist.	Predicted p.m.[a]	
	l	b	μ''/yr	p.a. deg.	pc	μ''/yr	p.a. deg.
LHS1075	85	−80	0.62	179	100[b]	0.46	150
G77-61	183	−42	0.77	166	(58)[c]	0.80	138
CLS31	190	64	0.13	202	400[b]	0.12	197
LP328-57	48	48	0.27	225	170[b]	0.24	228
0041-295	341	−87	0.016	94	700[d]	0.066	148
0045-259	97	−88	0.056	147	850[d]	0.055	147
2048-348	9	−39	0.015	101	930[d]	0.050	184

Notes: [a]predicted proper motion assumes solar apex of $l = 90°$, $b = 0°$ and a circular rotation velocity for the Sun of 220 km s^{-1}; [b]assumes the same M_K as G77-61; [c]from parallax; [d]assumes Johnson $m_V = m_v + 0.01 + 0.16(m_{b_j} - m_v)$ (Warren et al. 1991), and the same M_V as G77-61.

Photometric observations of 0041—295 in the near-infrared (*JHK*) were obtained on our behalf by the staff of the Anglo-Australian Observatory on the night beginning 1991 February 2, using the Infrared Imaging System (IRIS). From these data we have measured the following infrared magnitudes: $J = 17.34 \pm 0.11$, $H = 16.39 \pm 0.06$ and $K = 15.98 \pm 0.11$. These observations were obtained during commissioning of the instrument, using a mode (so-called double-double correlated sampling) that has since been made redundant, as poor flat-fielding results were sometimes obtained. There is therefore an additional uncertainty to these magnitudes.

3.2 0045 − 259

This star has a significant proper motion and is therefore a dwarf carbon star. The probability that the total proper motion could be 0.056 arcsec yr^{-1} or greater by chance is negligibly small. Furthermore, as shown in Table 4, the measured proper motion is in perfect agreement with the value predicted assuming the simple kinematic model described above. Therefore 0045 − 259 is a member of the halo population.

3.3 2048 − 348

The measured proper motion of this star (Table 2) is not significantly different from zero, but the measurement errors are larger than for the other two stars. This star is not visible on the POSS (Whiteoak extension) plate, so we have been limited to using UKST plates for the measurement, and the time baseline is only 5.9 yr. This compares with the 30-yr baseline available when using the POSS for the first-epoch plate. It is therefore not possible at this time to determine whether this star is a dwarf or a giant. Nevertheless, the interpretation that the star is a giant requires it to lie at a galactocentric distance that is improbably large. Using colour equations in Warren et al. (1991), we find $m_V = 19.9$ (Johnson system), which implies that $r = 290$ kpc assuming an absolute magnitude $M_V = -2.4$, as is appropriate for a metal-poor star. Even for $M_V = 0.4$, as found for the metal-rich Galactic bulge population, one derives a distance of $r = 80$ kpc. There is no evidence for a putative dwarf galaxy at the position of this star on photographic plates that reach $m_{b_j} = 22$. Given that there are now six dwarf carbon stars known, we incline towards the less exotic explanation that this star is also a dwarf. If this were so, the star would be of lower luminosity than the other known dwarfs, given the redder $m_{b_j} - m_{or}$ colour. The Na I 5892-Å doublet is stronger than in the other dwarfs, but is not unlike that seen in Population II M subdwarfs, where the lower continuum opacity more than compensates for the decrease in Na abundance. The possibility that the star is a giant is, however, not yet ruled out. A spectrum at redder wavelengths to measure the CN bands near 8000 Å might help to determine the luminosity class of this star.

3.4 Further comments

Green et al. (1992a) note that the four previously known dwarf carbon stars display a strong C_2 bandhead at 6191 Å, and suggest that this may be a common feature of all dwarf carbon stars. In addition, they find that these four dwarfs have similar near-infrared colours: $m_H - m_K \gtrsim 0.25$, $m_J - m_H \lesssim 0.7$. The combination of these properties uniquely selects the known dwarfs from their sample of carbon stars with high Galactic latitude, and may prove to be a useful indicator of luminosity. Both of the dwarfs reported here do indeed show the 6191-Å bandhead. The infrared colours of 0041 − 295 ($m_H - m_K = 0.41 \pm 0.13$, $m_J - m_H = 0.95 \pm 0.13$) lie outside the suggested colour domain, but not significantly so. Clearly, accurate *JHK* photometry of the three stars presented here is desirable, as well as a higher S/N spectrum of 2048 − 348. Measurement of the radial velocities would be useful not only to establish the space motions, but also, by searching for radial velocity variations, to test the hypothesis that all dwarf carbon stars lie in binary systems.

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NOTE ADDED IN PRESS

Green et al. (1992b) report the measurement of a significant proper motion for the carbon star CLS50. The total number of confirmed dwarf carbon stars is therefore now seven.

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