SPECTROSCOPY AND RADIAL VELOCITIES OF CARBON STARS IN THE GALACTIC BULGE

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Abstract

We report spectroscopy and radial velocities for the 33 known carbon stars discovered by Azzopardi, Lequeux, and Rebeirot in low extinction windows to the Galactic bulge along l=0. The velocity dispersion is 113 ± 14 km s^{-1} and the mean is -44 ± 20 km s^{-1}, consistent with the kinematics of bulge K and M giants. NaD and CN are much stronger in these stars than in the halo CH stars, and the line strengths decline rapidly with increasing latitude. Fifteen of the 33 are found to have enhanced ^{13}C. The low luminosities and strong ^{13}C are consistent with their classification as early R stars. However the line strengths of NaD and CN in the bulge carbon stars are much larger than that of early R stars in the solar neighborhood and CH stars in ω Cen which, if we infer high abundance, is in conflict with current predictions of carbon star formation.

Introduction

The galactic bulge is a metal-rich population that contains a wide range of abundances (Whitford and Rich 1983, Rich 1986). Color-magnitude diagrams show main sequence turnoffs that imply an age greater than 5 Gyr (Terndrup 1988). For this old, metal-rich population one expects M giants to predominate over carbon stars. Indeed, the low dispersion, infrared grism surveys of the bulge by Blanco and Terndrup (1989) (see also Blanco 1986, 1988, and Blanco *et al.* 1984) show a carbon star to M giant ratio of 0.0023.

Current stellar evolution theory proposes that carbon stars are formed when thermal pulses in the helium burning shell of an asymptotic giant branch (AGB) star causes the envelope's convection zone to dredge the products of helium burning (Iben and Renzini 1983). This dredging scenario enhances carbon relative to oxygen and is most viable for luminous and massive ($M_{bol} \leq -6, M \geq 3M_{\odot}$) AGB stars. For stars with low metallicity dredging will more readily create an envelope with $C/O > 1$. The excess carbon atoms (over the number required to bind with the entire supply of oxygen) forms C_2 and CN molecules whose absorption features dominate their optical spectra. Conversely, stars with high metallicity will reach the planetary nebula phase before the moment when $C/O > 1$.

It was therefore a surprise when Azzopardi *et al.* (1985) using a low dispersion green Grens technique discovered 33 carbon stars in low extinction windows (from $-2.6°$ to $-10°$) toward the galactic bulge. To have eluded the Blanco surveys, it was clear that these must be unusual carbon stars. It is now known from infrared photometry that the carbon stars are relatively blue and under-luminous (Rich *et al.* 1987, Azzopardi *et al.* 1988). The most luminous of these have $M_{bol} > -3$ which is 1 magnitude fainter than the minimum luminosity expected for carbon mixing from the third dredge-up in the thermal pulses of the He shell burning phase (Renzini and Voli 1981). Azzopardi *et al.* (1988) have inferred high abundances for these carbon stars from the comparison of their infrared colors and magnitudes with globular cluster giant branches. It remains to be seen, however, what the kinematics and spectral features of these carbon stars can tell us about their relation to the bulge and their relation to the better-understood disk and halo carbon stars.

To further understand these enigmatic objects in the context of the galactic bulge population we present new spectroscopy for the entire sample, which permits us to study two critical issues: the velocity dispersion and the stellar line strengths.

Observations and Reductions

The 33 carbon stars are in eight low extinction bulge windows identified as Sagittarius I and II, Groningen-Palomar Survey area 3, Baade's Window, NGC 6558, Galactic Window X1, Galactic Window X2, and van den Bergh's Window. The spectra of all carbon stars were obtained with the 2.5-m du Pont telescope of Las Campanas Observatory during six nights between 1986 June 15 and June 25. The 2-dimensional photon counter "2D-Frutti" was used. Data reduction details are identical to those described in Rich (1990) and are here only briefly outlined. Four bulge carbon stars with low S/N and velocity standards were also observed with the CCD Red Air Schmidt Echelle of the CTIO 4-m telescope on 1989 May 29. Seeing ranged from 1 to 2 arc seconds and averaged 1.2 arc seconds. 2D-frutti spectra were recorded in 3040 channels with 128 rows perpendicular to the dispersion. To prepare the data for cross-correlation with a standard template the 33 carbon star frames were flat-fielded, corrected for distortion, wavelength-calibrated from He-Ne-Ar comparison arcs, and rebinned to a linear wavelength scale of 1.4Å per channel. All velocities and line strengths were determined from non flux-calibrated spectra although, for display purposes, the flux standard G158-100 was used to convert all spectra to an approximate monochromatic flux scale. Spectra of the four carbon stars in the Sagittarius I window ($b \simeq -2.6$) are reproduced in Fig. 1.

Radial Velocities

We used the cross-correlation technique to measure radial velocities. The method requires a program star and a velocity standard to use as a template. Because it provided the best correlation peaks with the program stars, ROA153 in ω Cen (actually a field star) was adopted as the template. Its radial velocity of -8.7 ± 0.8 km s^{-1} was determined from cross correlating its echelle spectrum with the radial velocity standard HD111417 (Maurice *et al.* 1984). Nightly zero-point shifts were required to bring the six nights to a common velocity reference. One night required a 53 km s^{-1} shift while all other nights required shifts of less than 20 km s^{-1}. The multiple observations of each carbon star were corrected to the heliocentric system, coadded, and cross correlated with the template. All reported velocities are heliocentric.

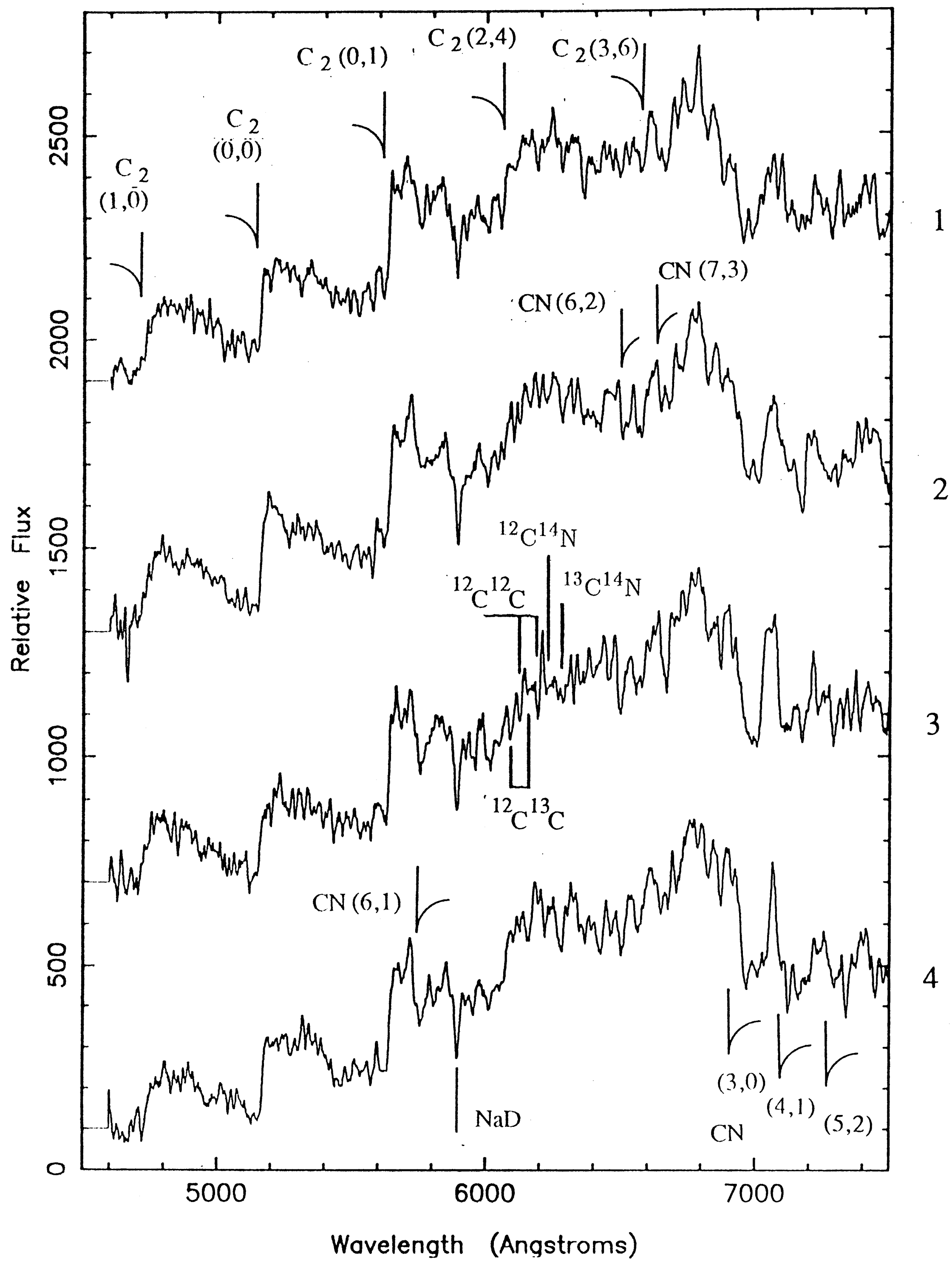

Figure 1: Spectra (smoothed to 8Å resolution) of the four carbon stars in the Sagittarius I window (SgrI). Each spectrum is identified by Azzopardi's ID (1 through 4). Notice the characteristic C_2 Swan bands (shortward of $\lambda\lambda$4737, $\lambda\lambda$5165 and $\lambda\lambda$5635) and the strong CN bands (longward of $\lambda\lambda$6910 and $\lambda\lambda$7050). NaD ($\lambda\lambda$5890, 95) is also strong. Absorption bands of the C_2 molecular isotopes are indicated for SgrI-3.

Velocity Dispersion

The velocity distribution of the 33 carbon stars is approximately gaussian (see Fig. 2) with a dispersion of 110 ± 14 km s^{-1} when corrected for the internal RMS errors of 25 km s^{-1}. This is consistent with that of the bulge K-giants (104 ± 10 km s^{-1}; Rich 1990), and bulge M giants (113 ± 11 km s^{-1}; Mould 1983). We conclude that the carbon stars are genuine members of the galactic bulge.

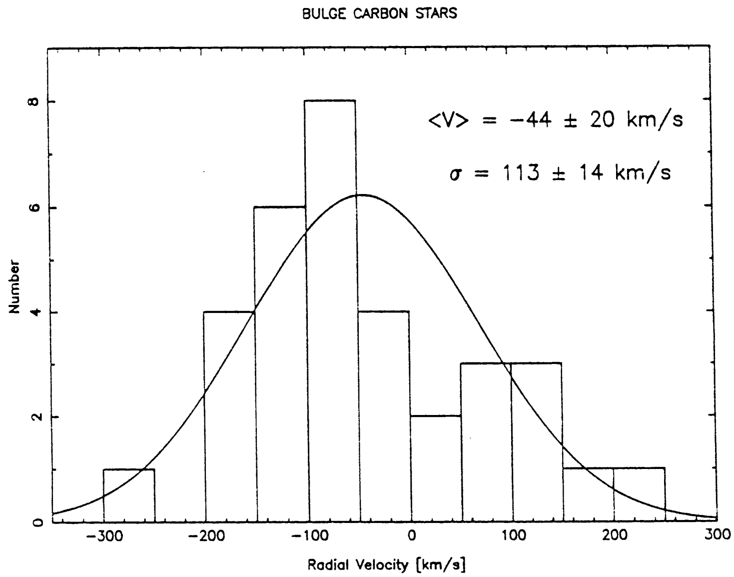

Figure 2: Radial velocity distribution histogram together with the best-fitting normal distribution. The dispersion is 113 ± 14 km s^{-1} and the mean velocity is -44 ± 20 km s^{-1}. The similarity of this velocity dispersion with that of bulge K and M giants suggests these carbon stars are genuine bulge members.

The velocity dispersion falls from 130 km s^{-1} for the eleven inner-most carbon stars ($|b| < 4.1$), through 111 km s^{-1} ($4.1 < |b| < 5.7$) for the middle eleven, to 81 km s^{-1} ($5.8 < |b| < 9.9$) for the outer eleven. We note that the dispersion of 62 km s^{-1} for 18 RR Lyrae stars with $|b| > 10$ (Rodgers 1977) is consistent with this trend.

Line Strengths

There are indications from M giant surveys that the bulge has an abundance gradient (Blanco 1988, Frogel *et al.* 1990). To determine whether line strengths also indicate this trend we measured the equivalent widths of the Swan C_2 absorption systems, the CN(3,0) band and the prominent NaD. We find that NaD and CN(3,0) show a latitude dependence (Fig. 3a, b) which, in the case of NaD, cannot be entirely explained by interstellar absorption. In three cases, M giants extracted from the same long-slit spectrum as carbon stars (in Baade's Window, N6558, and Sgr I) show little or no presence of NaD (see Fig. 4). The NaD equivalent widths are also three to four times larger than can be inferred from an assumed linear dependence on E_{B-V} in the various bulge windows. These findings confirm the conclusions of Azzopardi *et al.* (1985) and Lloyd Evans (1985) that these carbon stars must be rich in sodium.

The suspicion that these stars may be chemically peculiar or have their NaD enhanced from high surface gravity is supported by Fig. 3b where 26 of the 33 bulge carbon stars define a locus of NaD and CN line strengths. This locus excludes the ω Cen CH stars (Bond, ROA55, ROA70, ROA3881) and field early R stars of approximately solar abundances (BD+332399, HD90395, HD16115; Dominy 1984) which suggests two distinct populations although the differences are most likely due to abundance variation. We emphasize that the ωCen CH stars and the field early R stars are indistinguishable in these indices, as well as in luminosity and color (Scalo 1976).

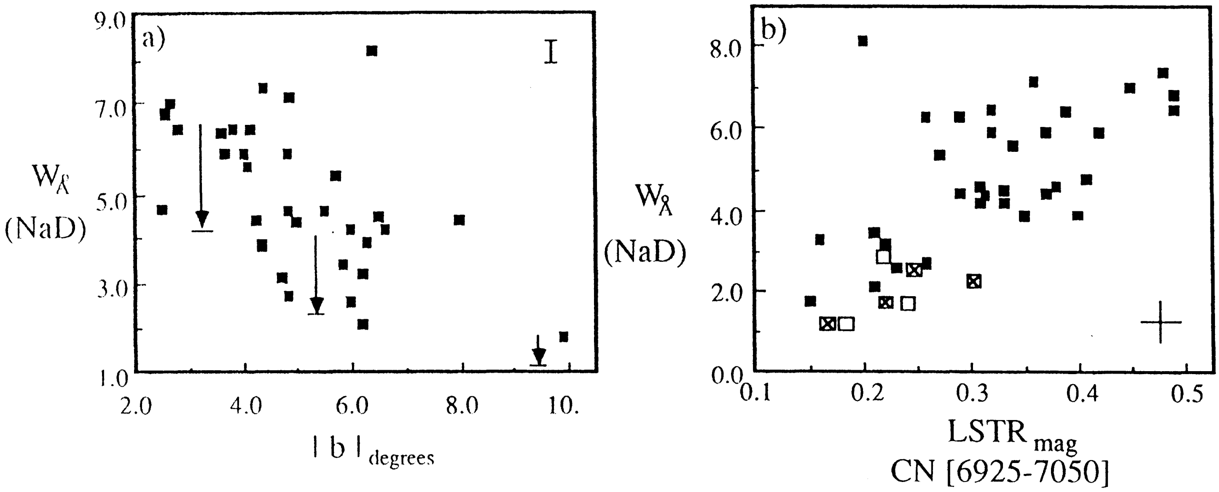

Figure 3: a) NaD equivalent width as a function of galactic latitude. The equivalent widths of the NaD lines are two to three times larger than can be explained from interstellar absorption. We indicate with arrows, based on measurements in Baade's window of NaD in K giant spectra (Rich 1986), the possible contribution to the equivalent widths assuming a linear dependence on interstellar extinction.
b) NaD correlates with CN. Unfilled squares are ω Cen CH stars. Squares with an 'x' in their center are disk carbon star standards. Notice that the standards define an isolated area that excludes most of the bulge carbon stars.

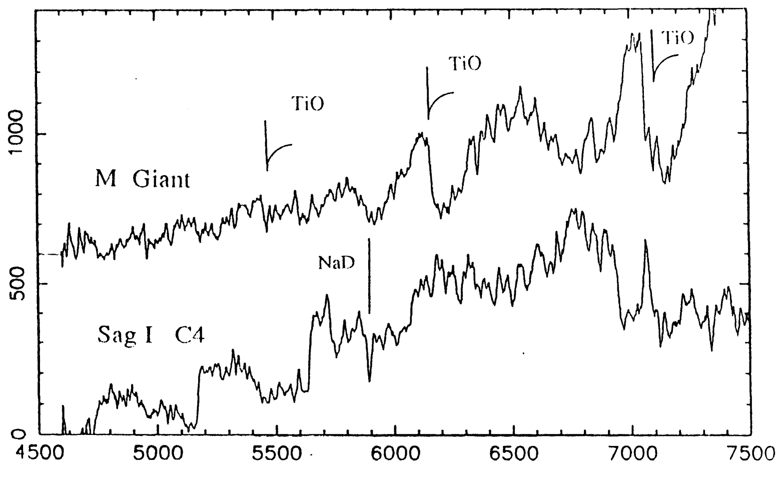

Figure 4: Comparison of the carbon star SgrI-4 (b = −2.65) with an M giant extracted from the same long slit spectrum. The two stars are thus subject to similar interstellar absorption. Notice the absence of significant NaD absorption ($\lambda\lambda$5890, 95) in the M giant's spectrum.

It is also known that R stars have enhanced ^{13}C in their spectra (Dominy 1984) and show a normal binary frequency (McClure 1985). Further analysis in the spectral region $\lambda6100 - \lambda6300$ reveals that 15 of the 33 bulge carbon stars show enhanced ^{13}C in the form of $^{12}C^{13}C$ and $^{13}C^{14}N$, which, if the bulge stars are genuine early R stars (though metal rich), also argues against binarity.

Discussion

When we combine what was previously known about these bulge carbon stars with the kinematic and spectroscopic data herein we are left with several thoughts. 1) Line strengths of NaD and CN can be enhanced with high abundance, high surface gravity, or cooler effective temperatures. We favor a latitude gradient in abundance to explain the CN and NaD line strength gradient (Fig. 3) since it is consistent with what is already known to be true for the bulge M giants. 2) With the low luminosity of these carbon stars it is not clear how the convective zone can reach deep enough, and how the H burning shell can be hot enough to cycle ^{12}C to ^{13}C (via intermediate products of the CNO cycle) at the base of the envelope. 3) If the carbon stars are metal-rich then it is also not clear how convective dredging can provide enough carbon to make $C/O > 1$ in the envelope before the planetary nebula stage without some modification to our understanding of ^{12}C mixing during the He flash.

The carbon stars discovered by Azzopardi are kinematically indistinguishable from bulge K and M giants and appear to exhibit a strong abundance gradient as do the bulge M giants. We conclude that the carbon stars are genuine members of the bulge and may be metal-rich. Based on the low luminosities and presence of carbon isotopes in their spectra we classify the bulge carbon stars as early R. However, the clear segregation in NaD and CN line strengths between the early R stars of Dominy (1984) and the bulge carbon stars may signal a sub class of R stars or a new class altogether.

Acknowledgements

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DISCUSSION

BLANCO: This is beautiful work. My remarks will be about a comparison of the two methods for finding C stars; the method based on the Swan bands, and the McCarthy – Blanco method based on near infrared CN bands. We find that although the Swan band method favors the bluer stars, there actually is an overlap in the methods. In two areas (each ~12 deg^2) in Baade's window we found 2 C stars. In these same areas, the Azzopardi *et al.* survey found the same two stars plus other outlying ones which were outside our search area.

Now in defense of our search method, we should remember that C stars are a rather heterogeneous group of objects. They include the CH stars and the R Cr Borealis stars. It turns out that practically all of these odd-ball objects are among the early C types in the Keenan-Morgan scheme. We tend to miss these stars but, importantly, not the classic N types, which are a much more homogeneous group, and one that can be intercompared whether found in the bulge, the disk, the Magellanic Clouds, or elsewhere.

TYSON: Thank you for the clarification. I should have made it clearer that your grism method missed these carbon stars precisely because these carbon stars are like no others.

FROGEL: Is there a real difference in C stars found by Blanco and in your sample? Since there is a significant difference in M_{bol} distribution of the two groups, this indicates that there is a real physical difference.

TYSON: Yes. These C stars have no counterpart. As Azzopardi (1988) has noted, these C stars are over two magnitudes dimmer than M-giant standards in globular clusters and Magellanic cloud Carbon stars. It is interesting to note that the Bulge M-giants are also two magnitudes dimmer than the M-Giants standards.

FROGEL: Is velocity dispersion of C stars a function of latitude? If so it would be of interest to compare with results Terndrup, Wells and I are getting for bulge M stars.

TYSON: With just 33 stars it is difficult to be conclusive about a trend in the velocity dispersion. I can tell you that the two largest radial velocities have $|b| < 4°$.

PIŞMIŞ: I was wondering whether some of your Carbon stars would not be the nuclei of old C rich planetary nebulae.

TYSON: Mike Rich and I have considered that possibility only recently. We have yet to work through the details. The extreme blue colors of the carbon stars suggest that such a scenario be taken seriously.

SUNTZEFF: If these stars are CH stars they should have enhanced Barium lines, which will be seen at low resolution. On the higher S/N spectra, or Echelle spectra, do you see enhanced S-process elements?

TYSON: Since McClure has shown that most (if not all) CH stars are binary systems, the presence of enhanced barium lines in these C stars would, indeed suggest binary mass transfer. The S/N of these spectra are typically 5 to 8 in the region where you expect barium lines. Consequently, I am hesitant to believe features other than the broad molecular absorption bands, and of course, the NaD. We plan to obtain higher resolution spectra of all 33 stars to establish the presence (or limits) of S-process elements as well as Carbon isotope shifts.