A PHOTOMETRIC AND SPECTROSCOPIC SURVEY OF AGB STARS IN M31

JAMES P. BREWER
European Southern Observatory, Santiago 19, Chile
HARVEY B. RICHER
Dept. of Physics & Astronomy, Univ. British Columbia
Vancouver, B.C., V6T 1Z4 Canada
AND
DENNIS R. CRABTREE
CFHT Corporation, Kamuela, HI 96743, U.S.A.

Abstract. We have used a four-band photometric system capable of distinguishing C, S, and M stars to undertake a survey of AGB stars in M31. We discuss the results from this survey and from follow-up spectroscopy.

1. Introduction

The Andromeda Galaxy (M31) is ideal for the study of AGB stars; it is sufficiently close that its AGB population is easily resolved with a four-meter class telescope, while being sufficiently distant that many stars can be observed in a single CCD field. Observations of AGB stars in a galaxy such as M31 allow the interplay between AGB stars and star-forming history, metallicity, and the ISM to be better understood. Additionally, as the distance to M31 is well established, M31's AGB stars make an ideal testbed for models of AGB evolution. With the above in mind, we undertook a survey of AGB stars in M31.

2. A Photometric System for Identifying C Stars

To identify C stars in the crowded fields of Local Group (LG) galaxies, groups led by Richer and Aaronson followed a suggestion by Palmer & Wing (1982) and developed a four-band photometric system (FBPS). The FBPS uses two narrowband filters to provide low-resolution spectral infor-

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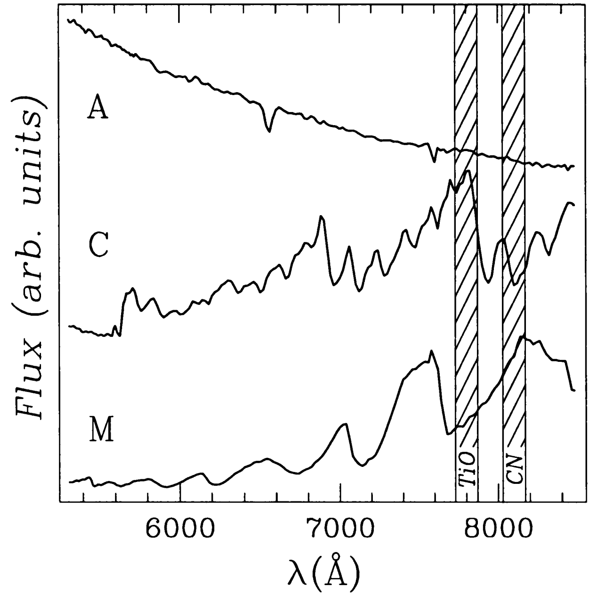

Figure 1. Spectra of stars of types A, M, and C. Superimposed on the spectra are the bandpasses of the *CN* and *TiO* filters.

mation and two broadband filters, typically V and I, to provide a colour temperature. In Figure 1 we plot spectra of A, M, and C stars and superimpose the bandpasses of Richer's narrowband filters. The bluer of the two filters, the *TiO* filter, lies on a strong TiO absorption band in the M–star spectrum and on pseudo-continuum in the C–star spectrum. The other filter, the *CN* filter, lies on a strong CN band in the C–star spectrum and on pseudo-continuum in the M–star spectrum. Fig. 1 shows that the A star will have $(CN-TiO) \approx 0$, while the C star will have a positive $(CN-TiO)$ index and the M star a negative $(CN-TiO)$ index. In Figure 2 we plot a selection of Galactic and LMC stars in a $(CN-TiO,\ V-I)$ diagram, along with their spectral types. This figure shows the bifurcation in $(CN-TiO)$ which splits the stars into C and M types. In the $(CN-TiO,\ V-I)$ diagram, S stars lie between the C and M stars.

3. Photometric Observations

We used the CFHT to image five $7' \times 7'$ fields in M31 at galactocentric distances (henceforth $R_{\rm M31}$) of between 4 and 32 kpc. The fields were imaged through CN, TiO, V and I filters, and calibrated photometry was obtained for the stars in each of these fields (see Brewer et al. 1995, henceforth BRC95).

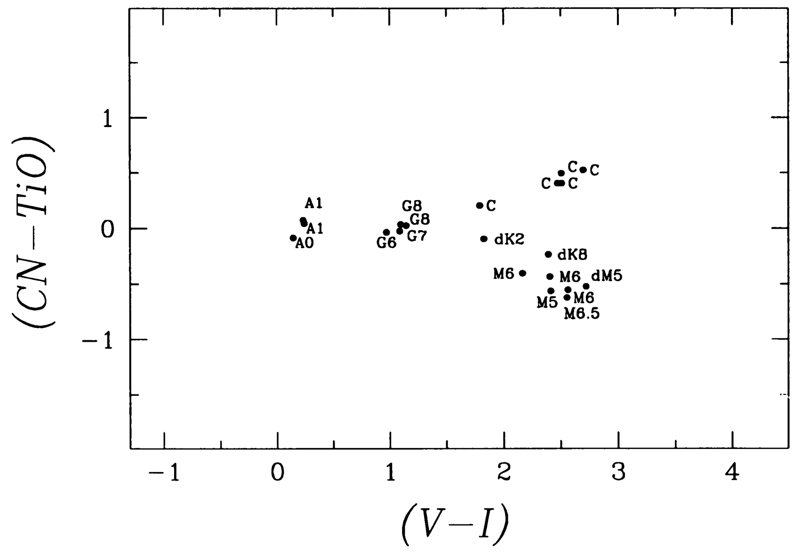

Figure 2. The (CN–TiO, V–I) diagram for a sample of Galactic and LMC stars. The data for this plot are from Richer et al. (1985).

3.1. TWO-COLOUR DIAGRAMS

In Figure 3 we plot the (CN–TiO, V–I) diagrams of our five M31 fields. The lower-right panel of Fig. 3 shows the bounds used to define C and M stars (see BRC95 and Brewer et al. 1996, henceforth BRC96).

3.1.1. *C Stars: Smoky Standard Candles?*

The high luminosity, red colour, and strong spectral characteristics of C stars make them potentially good distance indicators *if* there is a universal C–star luminosity function (LF). In certain types of systems, there is strong observational evidence for a common C–star LF: Richer et al. (1985) concluded that galaxies with [Fe/H] > -1.8 and $M_V < -12.9$ will have similar C-star LFs to those of Fornax, the Magellanic Clouds, the Milky Way, M31 and NGC 205.

We used the well-defined samples of C stars in Fields 2, 3 and 4 to construct a C–star LF whose mean was $I_\circ = 19.61 \pm 0.03$. Taking the mean absolute I magnitude of C stars to be $M_I = -4.75$ (see BRC95) gives $(m - M)_\circ = 24.36 \pm 0.03$ for M31, in agreement with, e.g., Freedman & Madore (1990). Additionally, the mean luminosities of the Field 2, 3 and 4 C stars are consistent with each other. This is remarkable given that: (1) Field 3 has undergone much recent star formation; (2) the AGB LF of Field 2 is dissimilar to those of Fields 3 and 4; and (3) the observations of Blair

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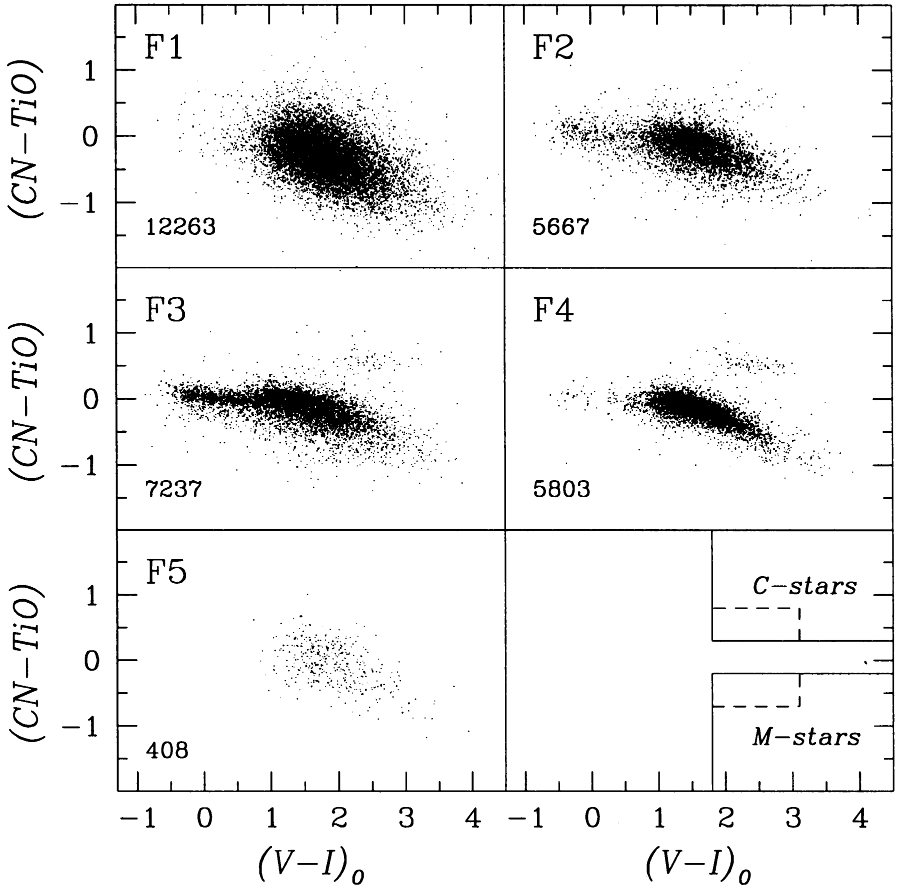

Figure 3. The labeled panels show the (*CN−TiO*, *V−I*) diagrams of the five M31 fields. Field 1, at $R_{M31} = 4.6$ kpc, is the innermost field, while Field 5, at $R_{M31} = 31.5$ kpc, is the outermost. The lower right panel shows the colour criteria used to identify the C and M stars.

et al. (1982, henceforth BKC82) indicate a ~ 0.3 dex metallicity difference between Fields 2 and 4. This suggests that *the C–star LF provides a robust standard candle* and is relatively insensitive to differences in star formation history and metallicity.

3.1.2. *The C/M Ratio*

Blanco et al. (1978) noted that the ratio of C stars to late M stars (hereafter referred to as the C/M ratio) was much greater in the metal-poor Magellanic Clouds than it was in the metal-rich Galactic Nuclear Bulge, a difference they attributed to metallicity and/or age. The C/M ratio is presently believed to be determined mainly by the metallicity of the gas

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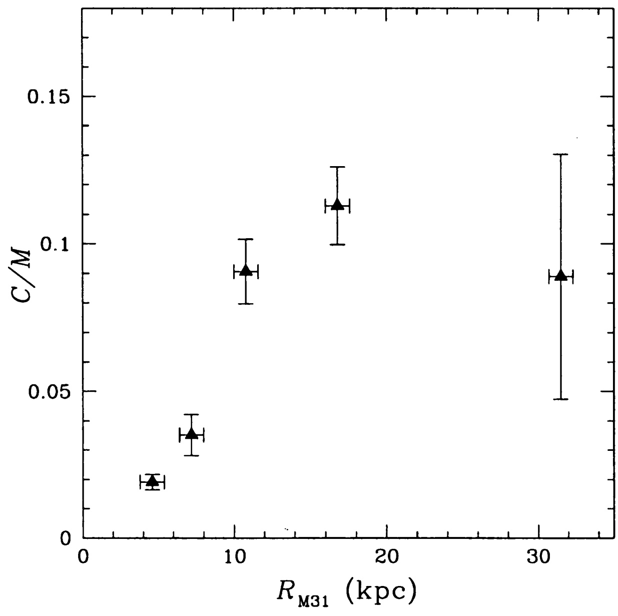

Figure 4. The measured C/M ratios in the five M31 fields as a function of R_{M31}.

from which the stars condensed, though the effects of star formation history and age remain unclear. Although models predict an anticorrelation between the C/M ratio and metallicity, the predictions are *two orders of magnitude* too small (see Scalo 1981).

In Figure 4 we show the dramatic variation of the C/M ratio as a function of R_{M31}. What is the cause of this? The AGB LFs of the five fields were found to have significant differences (see BRC95), though a comparison of the AGB LFs with C/M ratios showed no correlation. From this we concluded that star-forming history, and hence age and mass, is not the dominant factor driving the C/M ratio in M31.

3.1.3. *C/M: An Alternative Abundance Indicator?*

As seen in Fig. 4, the C/M ratio increases with R_{M31}. This is expected as in M31 metallicity is inversely correlated with R_{M31}. The metallicity gradient in M31 has been most recently investigated by BKC82. How well do estimates of the metallicity in our fields (derived via C/M ratios) compare with BKC82's measurements? We obtain abundance estimates in our fields by using measurements from other LG galaxies to derive a relationship between the C/M ratio and abundance (see BRC95). In Figure 5 we plot M31 abundance estimates derived by BKC82 and by us. Reasonable agreement is seen between the abundance estimates up to the limit of the BKC82 data,

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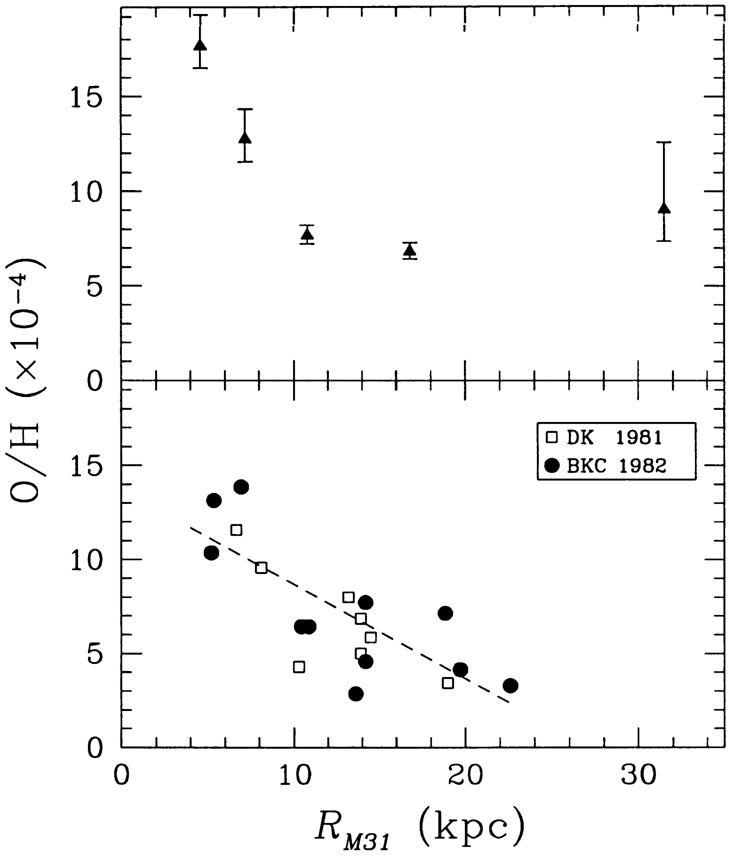

Figure 5. The O/H ratio *vs.* distance $R_{\rm M31}$ from the centre of M31. Data in the lower panel are from Fig. 6 of BKC82. The dashed line is the fit of BKC82 to their data (filled circles), while open squares are data from a previous study (see BKC82). In the upper panel we show the O/H number ratio derived from our measurements of the C/M ratio.

while beyond this the Field 5 datum hints at a flattening of the metallicity gradient.

Why is the C/M ratio anticorrelated with metallicity? The C/M ratios can be explained if either: (1) the number of late M stars increases with metallicity; (2) the number of C stars decreases with metallicity; or (3) a combination of (1) and (2). A physical reason for (1) is the redward shift of the AGB with increasing metallicity, and the classification of more AGB stars as M type stars. If it is this which determines the C/M ratios, then it would be expected that the C–star density should scale with field luminosity. This is clearly not so. Although the colour of the AGB may play a small role in determining the C/M ratio, we look to the second possibility for an explanation.

Why might it be easier to make metal-poor C stars? Possible reasons are: (1) a metal-poor star will have a less extended envelope, and so convection does not need to reach so deep for dredge-up to occur; and (2) in a metal-poor star, less dredge-up is needed to drive C > O. A competing explanation for the decreasing number of C stars with metallicity is that metal-rich C stars have higher mass-loss rates and are either comparatively short-lived or evolve into infrared C stars. Clearly more investigation (by both observers and theoreticians) is needed if the cause of this *very pronounced* effect is to be fully understood.

3.1.4. *The C/M Ratio and the Interstellar Medium*

Iben & Renzini (1983) note that the different proportions of C stars in the SMC, LMC and Milky Way should lead to different relative proportions of carbonaceous and siliceous grains in the ISM of these galaxies. They mention that the differences between the ultraviolet extinction curves of these three galaxies correlate with their C–star abundances. If extinction laws are affected by grain composition then M31's varying C/M ratio might lead to a radial dependence of the extinction law. Searle (1982) found evidence for M31's reddening law varying systematically with R_{M31}. Searle & Thompson (1985) speculate that the radial variation in the dust properties is due to a change in M31's C/M ratio. We have shown that such a variation does exist, and consequently have added weight to the hypothesis that the C/M star ratio has a significant impact on the ISM.

4. Spectroscopic Observations

Follow-up multi-object spectroscopy of C, S, and M star candidates was made at the CFHT. The spectra showed that the FBPS did an excellent job in identifying the C stars; all the stars within our chosen C–star region were found to be C stars, while only a handful lay just outside this region. Furthermore, the spectroscopy confirmed the identification of an S star, making it the first known S–type star in M31 and also the most distant S star known. Of the 48 C stars for which we obtained spectra, we found 7 with strongly enhanced ^{13}C bands (J stars), 2 with strong Hα emission, and 3 which exhibited enhanced Li absorption. In Fig. 6 we show spectra of M, S, and C stars in M31.

4.1. COMPARISON WITH MODELS

To compare AGB models with our observed stars, we applied a bolometric correction (BC) to our stars' M_I magnitudes. Our BCs are provisional as they were derived from a fit to 4 C stars with known BCs (see BRC96).

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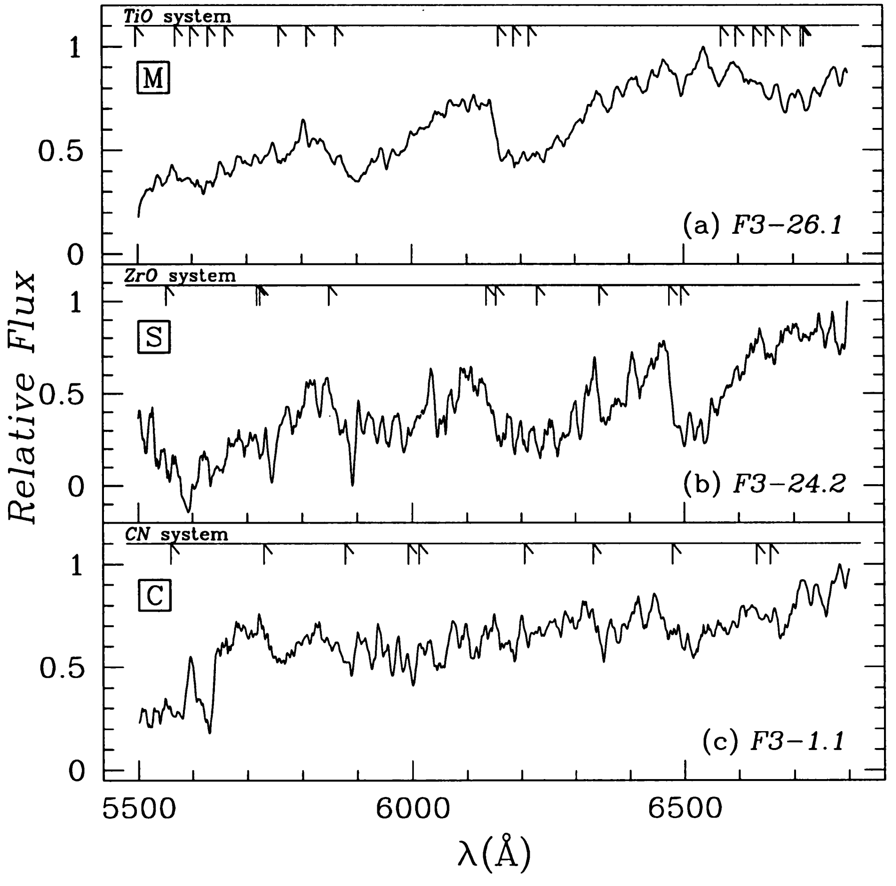

Figure 6. Spectra of three M31 AGB stars whose initial spectral classification was made using the FBPS.

4.1.1. *J Stars*

The third dredge-up mechanism can lead to an increase in the $^{12}C/^{13}C$ abundance ratio of a star by bringing to the surface ^{4}He that has been burnt to ^{12}C by the triple-α process. However, J stars exhibit a $^{12}C/^{13}C$ ratio which is lower than the ratio at the onset of the thermally pulsing AGB! Hot bottom convective envelope (HBCE) burning, in which the CN cycle converts ^{12}C to ^{13}C and ^{14}N, is able to explain this unusual ratio.

The models of Boothroyd et al. (1993) predict the existence of two C–star luminosity boundaries. The first boundary, at $M_{\rm bol} = -6.4$, is the maximum magnitude at which C stars can exist, while the second boundary, at $M_{\rm bol} = -6.3$, divides the C stars from J stars. Our observations are inconsistent with these models; we found our J stars to be around 1 to 2 magnitudes fainter than model predictions. Indeed, we found the J stars to be amongst the fainter C stars.

4.1.2. *Stars with Enhanced Lithium*

Sackmann & Boothroyd (1992) modeled the surface abundance of Li produced by the Cameron-Fowler mechanism (Cameron & Fowler 1971) and predicted that super-rich Li stars should lie in the range $M_{\rm bol} \approx -6.2$ to –6.8. Our C stars which show enhanced Li are around 2 magnitudes fainter than predicted by these models.

The observations of the J stars and the Li stars strongly suggest that HBCE burning *occurs at fainter magnitudes than AGB models predict.* There is now evidence for this in both the LMC (Richer et al. 1979; Smith et al. 1995) and M31 (this study). It appears that modifications to existing theory must be made. Another possible explanation for the disagreement lies in the BC applied. Could it be that some of the C stars observed are evolving into infrared C stars and require larger BCs than applied? We urge future observers undertaking similar spectroscopic surveys to obtain infrared photometry.

5. Conclusions

Unlike observations of Galactic C stars, observations of C stars in LG galaxies allow us to easily explore the interplay between C–star populations and environment. The distances to LG galaxies are generally well known, making possible comparison between observations and models. Further investigation of AGB stars in LG galaxies can only increase our understanding of the carbon star phenomenon.

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Discussion

Frogel: The ratio of M stars to C stars is a strong function of distance from the center of the Milky Way, but there is no evidence for variation in the reddening law as you claim for M31.

Brewer: Our location in the galactic plane means that it is hard to observe at large heliocentric distances in the galatic plane, and also that we are uncertain of where the material responsible for any reddening lies. Obviously external galaxies are the best place to test whether the C/M star ratio has an impact on the interstellar medium.

Gustafsson: Could you trace any tendencies for the fraction of J stars to change with distance from the center of M31?

Brewer: Unfortunately our statistics are insufficient to explore this question.