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Very luminous carbon stars in the outer disk of the Triangulum spiral galaxy

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Abstract. Stars with masses in the range from about 1.3 to 3.5 M_{\odot} pass through an evolutionary stage where they become carbon stars. In this stage, which lasts a few Myr, these stars are extremely luminous pulsating giants. They are so luminous in the near-infrared that just a few of them can double the integrated luminosity of intermediate-age (0.6 to 2 Gyr) Magellanic Cloud clusters at 2.2 microns. Astronomers routinely use such near-infrared observations to minimize the effects of dust extinction, but it is precisely in this band that carbon stars can contribute hugely. The actual contribution of carbon stars to the outer disk light of evolving spiral galaxies has not previously been morphologically investigated. Here we report new and very deep near-IR images of the Triangulum spiral galaxy M 33 = NGC 598, delineating spectacular arcs of carbon stars in its outer regions. It is these arcs which dominate the near-infrared $m = 2$ Fourier spectra of M 33. We present near-infrared photometry with the Hale 5-m reflector, and propose that the arcs are the signature of accretion of low metallicity gas in the outer disk of M 33.

Key words. galaxies: evolution – galaxies: spiral – galaxies: individual: M 33 = NGC 598

1. Introduction

Carbon stars are thermally pulsing asymptotic giant branch (TP-AGB) stars with ages between about 0.6 to 2 Gyr. They are observed in the intermediate-age globular clusters of the Large and Small Magellanic Clouds. Although the average number of carbon stars per intermediate age cluster in the Magellanic Clouds is only about 2.5 (Persson et al. 1983), they radiate such a copious amount of near-IR light that they contribute about 50% of the bolometric luminosity of the cluster (Marigo et al. 2003; Maraston 1998). From stellar population synthesis studies, the near-IR K -band (2.2 μm) luminosity is enhanced in galaxies containing a significant intermediate-age stellar population (Mouhcine & Lançon 2003) by up to a factor 2. In this Letter, we present new deep near-IR images of the nearby spiral galaxy M 33 which illustrate the dramatic effect that an intermediate-age population can make to the near-IR light distribution in spiral systems.

Astronomers routinely use near-IR observations of spiral galaxies to minimize the effects of dust extinction, but the actual contribution of carbon stars to the near-IR light of evolving galaxies remains poorly quantified. Little has changed observationally since Aaronson noted the importance of the asymptotic giant branch for understanding the stellar content of nearer galaxies (Aaronson 1986). Disks of galaxies appear to form

from the inside out (Block et al. 2002). Relative to the inner regions of spiral galaxies, the mean ages of the outer regions are known to be somewhat younger and more metal-poor (Bell & de Jong 2000). We can therefore expect the contribution from the intermediate-age stars to be stronger in these outer regions, and the near-IR surface brightness of the outer disk will be preferentially enhanced by the presence of TP-AGB stars. This brightening of the outer disk in the near-IR may well contribute to the apparent sharp radial truncation observed in the disks of many spiral systems (Kregel et al. 2002).

In this context, we present new near-infrared images of the Local Group spiral M 33 from a special set of 2MASS observations. The integration time for these images was increased by a factor of six, extending approximately 1 mag deeper than the standard survey. Three mosaics are constructed for M 33, corresponding to the J (1.2 μm), H (1.6 μm), and “ K -short”, K_s (2.2 μm) bands. At K_s , the image resolves larger-area features as faint as ~ 22.5 mag arcsec⁻².

Foreground Milky Way stars were removed statistically, using the $J - K_s$ histogram of two control star-fields to the East and West of M 33 (but at the same galactic latitude) as a template. Of the ~ 7000 sources in the original image, ~ 2300 were removed as foreground stars.

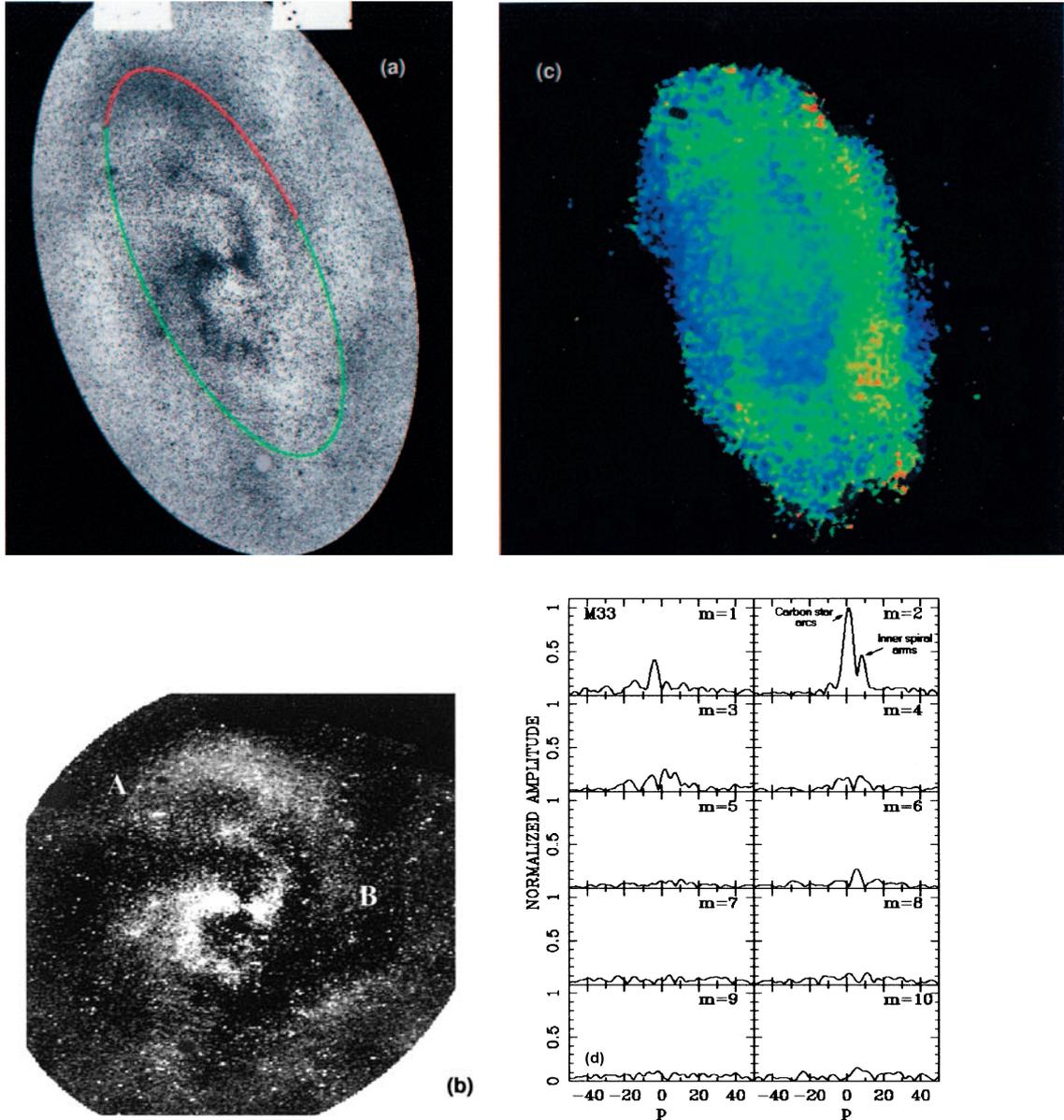


Fig. 1. **a)** Reaching six times deeper than 2MASS is this JHK_s image of M33, with a simple ellipsoid model subtracted. A gargantuan plume-like ring of red stars stretches in a swath (up to $5'$ in width) for over 120 degrees, commencing at $\sim 14'$ north of the galaxy centre. A fainter counterpart is found to the south. The surface brightness of the northern arc is only $\sim 20\text{--}21$ mag arcsec $^{-2}$ at $2.2\ \mu\text{m}$, which explains why it has hitherto not been discussed in previous near-infrared studies. An ellipsoidal swath is selected to pass through the plumes; that sector passing through the prominent northern plume is color-coded red. **b)** As in **a)**, but deprojected, beautifully reveals the plumes as well as the inner arms. The northern plume is labelled A to B. **c)** A $J - K_s$ image of M33, coded blue-green-red in order of increasingly red $J - K_s$ values, from 0.5 to 1.5. The outer arcs (colored green and red) appear to form a partial ring. It is tempting to liken this ring to the one recently reported in the outer disk of our Milky Way (Ibata et al. 2003). **d)** Fourier spectra generated from the deprojected near-infrared K_s mosaic of M33. The dominant $m = 2$ mode in M33 does not arise from the inner pair of spiral arms seen in Fig. 1a, but from the giant outer ring or arcs of stars identified in this study: a prominent plume in the north, and a fainter counterpart to the south. While M33 in the optical shows ten spiral arms (Sandage & Humpheys 1980), the galaxy in the near-infrared has only two low-order modes: $m = 1$ and $m = 2$.

2. Analysis

M33 is famous for an optically bright pair of spiral arms, but surprisingly, it is not these two arms which dominate the near-infrared $m = 2$ Fourier spectra. The near-infrared images reveal remarkable arcs of red stars in the outer disk of M33, spanning 120° in azimuth angle. The northern arc is dominant although a very faint southern counterpart arc, forming a partial

ring, can also be seen (Fig. 1). A hint of the northern swath can be seen in the study by Regan & Vogel (1994). Fourier analysis of the light distribution (Fig. 1d) shows that the dominant $m = 2$ peak corresponds to the giant arcs. The pitch angle of the dominant $m = 2$ structure is ~ 58 degrees.

The very red color of the arcs is not due to dust. Wilson (1991) derived $E(B - V) = 0.3 \pm 0.1$ mag, which includes

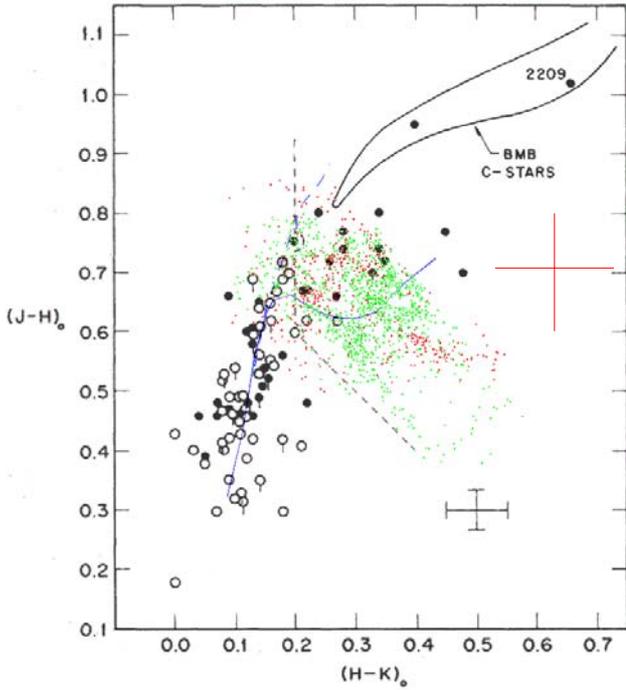


Fig. 2. An overlay of the integrated cluster light in the Magellanic Clouds (from Fig. 4 of Persson et al. 1983), with the integrated colors for plume stars in the NE sector (green dots) and SW sector (red dots) of M33. The open symbols principally show the Searle, Wilkinson & Bagnuolo (1980) (SWB) Magellanic cluster types I, II and III; these do not contain carbon stars. The filled symbols are SWB types V, VI and VII. The red Magellanic carbon-star-bearing clusters lie above and to the right of the black dashed lines, in the Magellanic “IR-enhanced” cluster regime identified by Persson et al. (1983); these are predominantly SWB types V and VI. Red bars show our 1-sigma uncertainty in the color for each point in this figure; the black error bars are from the Persson et al. (1983) analysis. The thin blue dotted and solid lines show the Bessell & Brett (1998) tracks for giants and dwarfs respectively. The overlay provides strong evidence for a carbon star population in the M33 plumes.

both foreground (Milky Way) and internal M33 extinction. The K -band extinction $A(K)$ is estimated ~ 0.09 mag.

The color of the northern arc extends to $J - K_s > 1.1$. Very old M giants of solar abundance can reach $J - K_s \sim 1$ (see e.g. Fig. 2 in Bessell & Brett 1998), and even redder if they are super-metal-rich (Frogel & Whitford 1987). However, as reviewed by Pagel & Edmunds (1981), there is a strong radial abundance gradient (Searle 1971) in M33 (-0.09 ± 0.02 dex/kpc in O/H); the outer regions are relatively metal-poor, and solar abundance is reached only within the inner $1''$ of M33. In regions of lower abundance, the giant branch is bluer. If stars with $J - K_s > 1$ are found in the outer low-metallicity regions, they cannot be M-giants. Figure 2 presents the integrated colors of the plumes in the NE and SW sector of M33, overlaid with the integrated colors of the clusters in the Magellanic Clouds (Persson et al. 1983). Figures 2 and 3 provide strong evidence for a carbon star population in the extended M33 plumes. We conclude that the near-IR arcs are probably dominated by a population of very red carbon stars.

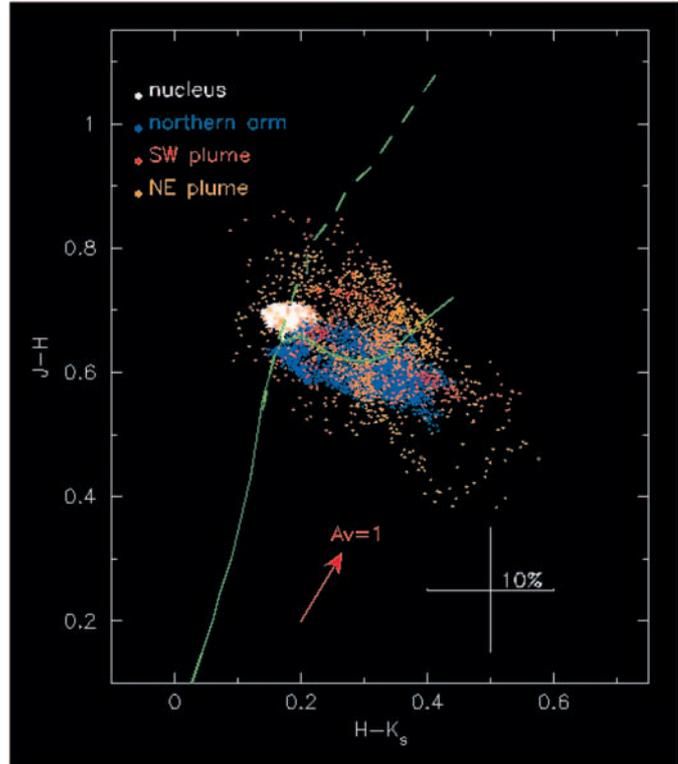


Fig. 3. A $J - H$, $H - K_s$ color-color diagram contrasting the nuclear colors with those of northern inner spiral arm and the NE and SW plume populations. The colors were derived from the integrated flux of regions centered on the N inner arm and NE and SW plumes. The photometry consisted of circular, 10 arcsec radius aperture photometry carried out on the 2MASS J , H and K_s images, cleaned of foreground stars and corrected for disk inclination. The evolved giant and main-sequence dwarf tracks are shown with green dashed and solid lines, following Bessell & Brett (1998).

Only integrated fluxes with a S/N greater than 10 are shown in Fig. 3; hence, the accuracy of the photometry is comparable (to within a factor of two) to that of Persson et al. (1983). Note that individual M33 stars are not resolved by 2MASS (unlike the Palomar observations as discussed below), and so the colors best represent the “local” area (300 sq. arcsec) of the targeted regions. Individual AGB and carbon stars will “redden” the $J - H$ and $H - K_s$ colors, but the overall effect is mitigated by the stellar population in the local region. Consequently, the colors represent a lower limit to the color of the evolved population.

Why are the Fourier spectra not dominated by the inner, very robust spiral arms? In a spiral galaxy with a sustained star formation history, in the first few Myr red supergiants will dominate the infrared light. In the 0.5–2 Gyr range carbon stars dominate, especially in a somewhat metal-poor regime. After this time, the carbon stars die and ordinary RGB/AGB stars dominate. In the first 2 Gyr, the C-stars clearly dominate, as accreted gas in the outer disk is fresh and not yet well mixed by M33’s near-infrared oval/bar. In the inner disk, there presumably are older populations present that dominate in light, and the K_s -band enhancement of the TP-AGB carbon stars is weakened.

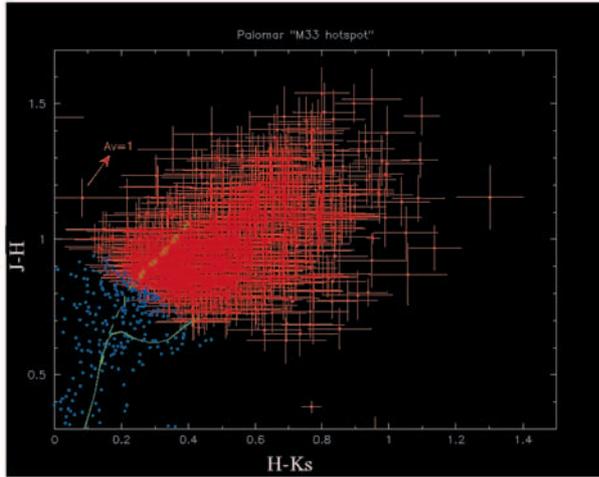


Fig. 4. Observations with the Hale 5m reflector, through a sector of the northern red arc. The sample has been cleaned of all low detection sources, with a $S/N < 10$. The extinction reddening vector is indicated with the red arrow. The evolved giant and main-sequence dwarf tracks are from Bessell & Brett (1998). In this color-color plot, no foreground MW stars were statistically removed, as in the other color-color plot. Here foreground stars appear with blue colors ($H - K_s < 0.2$ and $J - H < 0.8$; $J - K_s < 1.0$), while most of the M33 sources have colors that are redder than $H - K_s = 0.4$ and $J - H = 0.9$ ($J - K_s = 1.3$) mag. The color uncertainties for the red sources are less than 10%.

One of us (THJ) recently imaged a section of the northern plume of M33 with the 5 m-Hale reflector, using the 2048×2048 array near-infrared camera WIRC (see Fig. 4). The field of view is $8.5' \times 8.5'$ with 0.25 arcsec pixels, reaching a limiting surface brightness at K_s of 23.7 mag per arcsec⁻². A plethora of stars is seen toward the C-Star regime in the upper right corner of the figure, with colors exceeding $J - K_s \sim 1.8$ mag.

In their modelling of the HI envelope, Corbelli & Schneider (1997) find that the phase changes at a radius of ~ 20 arcmin, which is precisely the outer domain of the arcs reported in this study. It seems highly plausible therefore, that fresh, low-metallicity gas is being fed to the host galaxy M33, via external accretion. The outer disk from which mass is accreted is inclined to the inner disk of M33, and has a different angular momentum.

The accretion of gas from gaseous filaments is expected to be asymmetric, since it comes from one side only – gas is being accreted and only later becomes bound and finds its way to circular orbits. It takes a dynamical time to relax. In the present epoch, we expect the signature of accreted gas (the external arcs) to be asymmetric. We believe that it is the signature of gas flowing inward and accreting at ~ 20 arcmin, from which the very red, and relatively metal-poor stars have been formed. This is also fully consistent with the recent observations elucidated by Tiede et al. (2004).

3. Conclusion

It is tempting to liken the ring in M33 to the one recently reported in the outer disk of our Milky Way (e.g. Ibata et al. 2003). For the Milky Way ring, the rotation period is ~ 600 Myr. For M33, the rotation time-scale at the radius of the ring would be ~ 240 Myr. Any carbon-bearing clusters of age 0.6 Gyr would have only undergone ~ 2 orbits.

Our discovery of a dominant carbon-star-bearing stellar population in the outer regions of a spiral galaxy (M33) shows how imperative it is to use stellar population synthesis models which include carbon stars with their correct bolometric contributions (Maraston 1998), when analysing the integrated light of spiral galaxies. The outer arcs in M33 are not revealed on standard near-infrared surveys, such as 2MASS, because their integrated surface brightness is fainter than the 2MASS threshold. It is a sobering thought that it takes a groundbased class 4–5 m telescope to resolve individual carbon stars in the outer disk of M33, our second closest spiral.

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