LARGE-SCALE STRUCTURE AND KINEMATICS OF THE MAGELLANIC CLOUDS FROM CARBON STAR STUDIES

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ABSTRACT. Initially, carbon stars have been searched for through their CN bands in the near infrared. However, C stars can also be identified efficiently by the C_2 Swan bands in the blue-green spectral region. Schmidt telescopes with objective-prisms have been used intensively for the detection of C stars. More recently, transmission gratings at the prime foci of large telescopes have made possible deeper surveys at limiting magnitudes that insure carbon star detection in the Magellanic Clouds (MCs) with a reasonable degree of completeness; completeness is even better in the regions where both observational techniques have been used. Statistical studies are now possible. The C star surface distribution and global kinematics derived from radial velocity measurements of selected C stars, when compared to those of other objects, show that the field Small Magellanic Cloud (SMC) C stars are not a young population, in agreement with studies of C stars in SMC clusters.

1. Introduction

Carbon stars (C stars), as well as M giant stars are cold and intrinsically bright objects, but whereas M stars have C/O<1, C stars have C/O >1. This means that all the oxygen present in the envelope and the atmosphere of a C star is bound in CO and the excess carbon forms CN, C_2, CH and so on. Using these prominent molecular spectral features, C stars have been intensively searched for in the MCs. MC carbon stars play a fundamental role in our, still limited, understanding of asymptotic giant branch stars (see Iben (1988) and references therein).

2. Carbon star surveys in the Magellanic Clouds

Because they are red, C stars have initially been searched for in the MCs using very low dispersion field spectroscopy in the near infrared (IR). In spite of the poor spectral resolution achieved, the detection of C stars is made possible by the presence of the strong absorption molecular bands, namely CN bands at 7945, 8125 and 8320Å (Nassau & Velghe 1964). Nevertheless, Sanduleak and Philip (1977) have shown that it is also possible to identify C stars efficiently in the blue-green spectral domain through their pronounced C_2 Swan bands at 4737 and 5165Å. Also, JHK photometry of very red stars previously identified on near-IR photographic plates (see Aaronson & Mould 1985 and references therein) and subsequent spectroscopy have been used with success to survey C stars in the MCs' intermediate-age globular clusters.

Due to their relative brightness, early surveys of the field C stars were first carried out in the Large Magellanic Cloud (LMC) with Schmidt telescopes. Westerlund (1960), using an objective-

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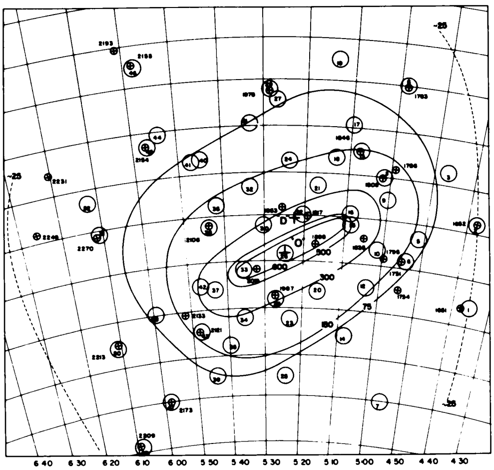

Figure 1. Distribution of LMC sample areas and isopleths of C star frequences by Blanco & McCarty (1983). The isopleths are identified by the frequency of C stars per deg^2. "O" and "D" indicate, respectively, the "optical" and the "dynamic" centres (see the caption of their Fig. 3 for more more information).

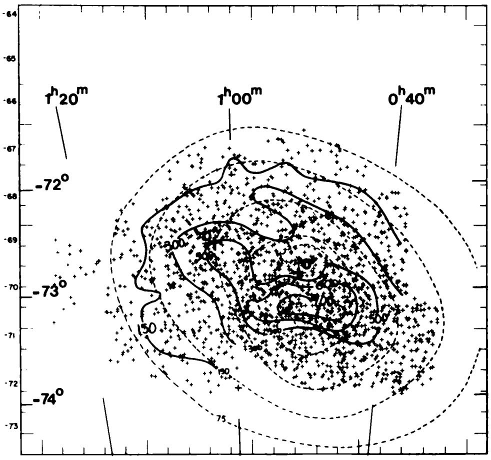

Figure 2. Comparison of surface distribution of the SMC C stars (crosses) by Rebeirot *et al.* (1990) with that by Blanco & McCarthy (1983). C star-count per deg^2 isopleths are displayed for both surveys. While the Blanco & McCarthy isopleths (dotted lines) are derived from 37 SMC sample areas, those by Rebeirot *et al.* (solid lines) are based on real gapless star-counts. "O" and "D" indicate, respectively, the "Optical" and the "dynamic" centres.

distribution decreases smoothly towards the periphery. Fig. 1 reproduces the Blanco & McCarthy LMC survey regions and related star-count isopleths. By integration of the computed or estimated (outer regions) surface densities, Blanco & McCarthy inferred that the total C star populations of the LMC and the SMC are about 11000 and 2900, respectively.

At present, it is possible to compare the large-scale structures of the SMC derived either from 37 SMC sample areas by Blanco & McCarthy (1983) or from our own gapless star counts (Rebeirot *et al.* 1987, 1990). Fig. 2 displays C star isopleths that have been obtained for both surface distributions. Note that our C star survey missed the Western and Southern outer regions of the SMC. Within the 300-150 and 150-75 C stars per deg^2 isopleth areas of Blanco & McCarthy, we found 545 and 183 C stars, respectively. Taking into account that only ~75% and ~50% of these areas have been surveyed by us, tespectively, corrections for incompleteness give a total number of about 1100 C stars within the 300-75 C star per deg^2 isopleth area. Integration of the corresponding surface densities allows us to estimate the total number of C stars in the same area at 950. In the inner SMC regions fully covered by our survey, we found 937 stars within the 300 C stars per deg^2 isopleth area, while integration of the Blanco & McCarthy surfaces densities gives about 1000 stars. This shows the large degree of completeness of both surveys. We note that our inner isopleths which are more elongated and shifted a little to the South, do not appear well centred on the "optical" or photometric centre in visual light (marked "0" in Fig. 2) as determined by de Vaucouleurs & Freeman (1972). Both overall star distributions agree fairly well in the sense that we are sure to have missed a few C stars in the most crowded inner SMC regions while Blanco & McCarthy probably have underestimated the number of the C stars in the outer

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prism (2100Å/mm dispersion at the atmospheric A band) in the near-IR, discovered 302 C stars in the LMC (see Westerlund *et al.* 1978) very close to the detection limit (I~13.6). More recently, an objective-prism survey (1360Å/mm dispersion at Hγ) in the blue-green spectral domain allowed Sanduleak and Philip (1977) to identify 474 C stars, with a limiting magnitude V~16. Cross-identification of the stars listed in both catalogues led to the conclusion that the survey by Sanduleak and Philip generally missed the faintest C stars found by Westerlund, but provided identification of 399 stars which escaped the near-IR detection. This is mainly because the limiting magnitudes of these surveys were very close to the expected apparent magnitudes of the C stars, and consequently very much subordinate to the intensity of the CN and C_2 bands, respectively. A new C star survey of the outer regions of the LMC, based on the Swan C_2 band detection, has recently been undertaken by Morgan (private comm.) using deep IIIa-J objective-prism plates (800Å/mm dispersion, 4550-5300Å range) obtained with the UK Schmidt telescope. The scan of the plates is under way; up to now a total of about 1250 C stars have been found in two fields (F33 and F86).

A very efficient low-resolution spectroscopic survey technique for the detection of red stars, even in very crowded fields, is provided by Hoag transmission gratings (GRISM) at the prime focus of large telescopes. The Grism devices, by extending to over 3 mag the limiting magnitude of the previous objective-prism detections made with Schmidt telescopes, allowed MC carbon star surveys to be done with a high degree of completeness. This observational technique was pioneered by Blanco *et al.* (1980) who found a total of 186 C stars in three LMC fields, and 134 C stars in two SMC fields, covering an area of 0.12 deg^2 each. The observations (limiting magnitude I~17) were carried out at the prime focus of the CTIO 4m telescope using hypersensitized IV-N plates and a grism giving a dispersion of 2350Å/mm in the range 6500-8800Å. Later, 49 additional LMC and 35 SMC fields were observed, covering a total of about 6.24 and 6.78 deg^2regions in the LMC and SMC, respectively. This resulted in the detection of 1045 C stars in the LMC and 860 in the SMC (Blanco & McCarthy 1983). Identifications of 849 C stars found in the additional 49 LMC regions have now been released by Blanco & McCarthy (1990). Westerlund *et al.* (1986), adopting the Sanduleak and Philip observational technique, made new MC carbon star surveys (Magnitude limit V~20) using a large field adaptor (0.78 deg^2) and a Hoag grism with a dispersion of 2200Å/mm at the prime focus of the ESO 3.6m telescope. They used Kodak IIIa-J hypersensitized plates and a Schott GG 435 filter (4350-5300Å range) to observe eight selected regions in the LMC and 13 fields, covering altogether the main body of the SMC. Now completed, the survey of the SMC led to the identification of 1707 C stars (Rebeirot *et al.* 1990). A comparison of the C star samples provided by the two observational techniques (see the note added in proof by Westerlund *et al.* 1986) shows that the observations in the near-IR favour the detection of the redder and strong CN band C stars, while surveys in the blue-green spectral domain favour the bluer which display pronounced C_2 bands. This has also been carefully discussed by McCarthy (1987) and Blanco & McCarthy (1990). All recent work leads to the conclusion that the detection of C stars in the MCs sample fields is reasonably complete.

3. Large-scale structure of the Magellanic Clouds

The high degree of completeness now achieved in the recognition of field C stars in the MCs makes statistics possible. We note that the probability of finding galactic foreground C stars is very low at those galactic latitudes. Blanco & McCarthy (1983), using the surface distributions of their 52 LMC and 37 SMC selected survey regions, drew C star-count isopleths based on the surface densities they found for these star samples. In both Clouds these isopleths are remarkably smooth: they show that the C stars lie predominantly in the bars and that their regular surface

SMC regions, due to the restricted sample survey areas they used. We conclude that the total C star population of the SMC within the 75 C stars per deg^2 isopleth is about 2100, slightly larger than the 1950 stars estimated by Blanco & McCarthy.

It is interesting to compare the overall C star distribution of the SMC (1707 objects) to those of other population objects of different ages. Fig. 3 shows the overall surface distribution of the small nebulae, early- and late-type supergiants, Hα emission-line stars, and planetary nebulae (PN). The distribution of the O-G supergiant stars (506 objects), dominated by the O, B, A type stars (~95%), as shown by Azzopardi & Vigneau (1977), is from the catalogue of Azzopardi & Vigneau (1975) while the distribution of the K and early M type stars (370 objects) comes from the recent list of Sanduleak (1989). The distributions of the small nebulae (92 objects), PN (65 objects) and Hα emission-line stars (1742 objects), have been obtained from the Curtis Schmidt survey of Hα emission objects now completed by Meyssonnier & Azzopardi (1990). The surface distributions of the young objects (small nebulae, blue and red supergiants as well as Hα emission -line stars) show more or less the same pattern: a strong concentration of objects in the SMC bar, more extended in the NE than in SW, and in the so-called SMC wing (region of the young clusters NGC 456, 460 and 465). The PN distribution shows this trend in part, but is also much smoother. Although many of those objects, in the upper part of the luminosity function, must be of type I, thus relatively young (a few 10^8 years), some must belong to an older population. The overall C star surface distribution is markedly different (taking into account the limits of our survey): it is more extended, almost elliptical, with no special concentration, more especially in the "wing". This resembles the distribution of the red light (de Vaucouleurs & Freeman 1972) showing that the PN and C stars are not young objects.

4. Kinematics of the SMC Carbon stars

Kinematical structure of the MCs is extremely complex and has been the subject of several studies based on various components such as supergiant stars, planetary nebulae, and neutral and ionised gas. However, very little has been done for the kinematics of the MCs from their field C stars although their number, distribution and spectral features favour this kind of study. So far, only one paper in this field, relating to the SMC has been published by Hardy *et al.* (1989), hereafter HSA.

These authors have observed spectroscopically 150 SMC field C stars from the lists of Westerlund *et al.* (1986) and Blanco *et al.* (1980) in the near-IR (7700-8200Å) at the CITO 4m telescope with an individual accuracy of ±1.8 km s^{-1} in velocity. From the samples available at this time, the surface distribution of the selected C stars, belonging to three groups located in the SW and NE of the bar and in the wing, respectively, is, unfortunately, rather uneven. To emphasise the global properties in the velocity distribution, HSW have plotted, for all their observed C stars, the galactocentric velocities versus the respective position angles, measured about a fiducial centre (α_{1950}=$00^h49.5^m$, δ_{1950}=-73°20'), in the plane of the sky. Since no systematic trends appear in their Fig. 2 they concluded that there is no evidence of overall rotation of the SMC carbon star population. They found (their Fig. 3) no velocity gradients for the C stars along either the major or minor axis of the bar (3.2±2.7 and 13.3±10.3 km s^{-1} deg^{-1}, respectively), while they detected a statistically significant gradient along the minor axis of the wing. Since other SMC components, such as HI, HII and supergiant stars, have a velocity gradient of about 10-30km s^{-1} increasing along a SW-NE direction close to the adopted major axis, HSA inferred that the C star population is kinematically very different from the younger

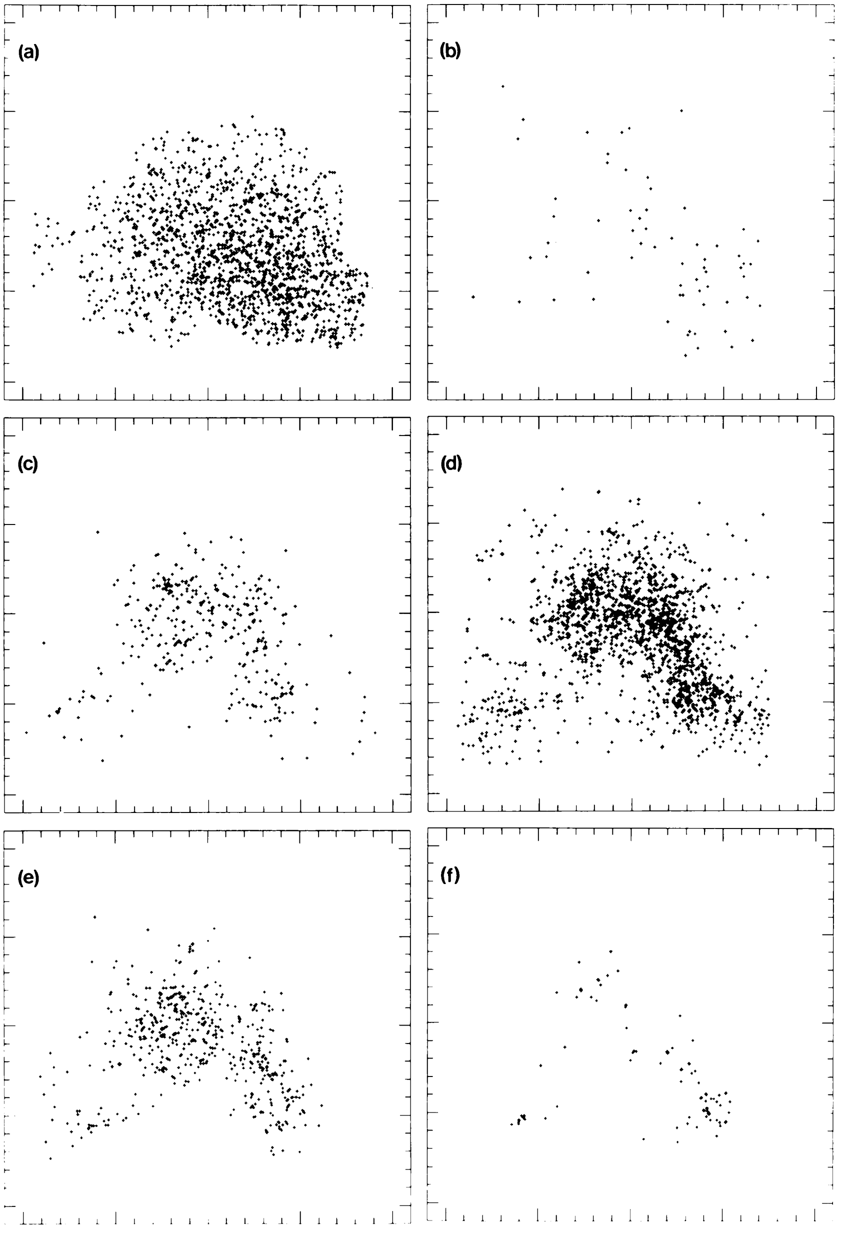

Figure 3. Comparison of the overall surface distributions for various SMC populations: (a) Carbon stars (1707 objects); (b) planetary nebulae (65 objects); (c) late-type supergiants (370 objects); (d) Hα emission-line stars (1742 objects); (e) O-G type supergiant stars (506 objects); (f) small nebulae (92 objects). The boundaries of each distribution depend on the extent of the SMC area prospected by the corresponding survey.

population defining the SMC main body rotation curve. This lack of organized rotation was previously found by Dopita *et al.* (1985) from the study of the kinematics of 44 SMC planetary nebulae. Furthermore, the velocity dispersion they obtained ($25.3^{+2.6}_{-2.9}$ km s^{-1}) is comparable with the value of $26.8^{+1.6}_{-1.7}$ km s^{-1} determined by HSA for the SMC bar. These results, with the spatial distribution of C stars over the face of the SMC as shown in Fig. 2, support the hypothesis that the C stars, like the PNs, form, on the average, an intermediate age or old stellar population. As for the velocity gradient of 165±53 km s^{-1} deg^{-1} detected by HSA, which is increasing in the NW-SE sense along the minor axis of the wing, this can be interpreted as streaming motions along the LMC-SMC bridge.

Using the same technique, subsequent observations have been performed by Hardy and associates to extend their sample of C star velocities to the SMC peripheral regions and, consequently, to have a better spatial baseline. From this work in progress, a better knowledge of the kinematics of the SMC is expected.

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