Finding Carbon Stars in Nearby Galaxies

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Observations of remote objects in our Galaxy are severely impeded by interstellar absorption; this is particularly true in the direction of the galactic centre. Therefore, the stellar content of our Galaxy is difficult to determine except in our immediate neighbourhood; it can be estimated only by far-reaching assumptions based on local statistical studies. On the other hand, a number of external galaxies can nowadays be resolved into individual stellar members thanks to the existing large telescopes and their modern receivers. The analysis of the composition of the stellar populations of these galaxies permits conclusions regarding the correlations between their morphological structure, age, evolutionary stage and chemical composition. Studies of the distribution of various objects in the external galaxies (e.g. red and blue supergiants, Wolf-Rayet stars, red giants, planetary nebulae) provide also interesting information about changes in chemical abundance and evolutionary stage with galactocentric distance. A great advantage in this kind of studies is that, in each galaxy, we observe the various kinds of objects at the same heliocentric distance and at practically the same galactic reddening.

Survey Techniques

The first step in the study of the stellar content of an external galaxy is to discriminate its members from those of our Galaxy. The higher the galactic latitude of a galaxy is the more easily can the selection be done. Principally, three observational techniques allow the identification of members of an external galaxy: radial-velocity determinations, spectral classification, and photometric measurements. Not unfrequently all three techniques are used to prove the membership of an object. For instance, two-colour photographic photometry may be used to carry out rather deep surveys even in rather crowded regions of a galaxy. Additional photometry or spectroscopic observations may then be required to determine the exact nature of the identified objects. Frequently, objective-prism techniques (with astrographs and Schmidt telescopes) have been applied with success in areas with little crowding and on relatively bright objects; an extremely efficient extension of this kind of low-dispersion spectroscopy has been provided by the GRISM and GRENS devices on large telescopes.

In the objective-prism surveys much effort has been put into reducing the overlapping of stellar images as much as possible. For this to be achieved, unwidened spectra of lowest possible but still useful dispersion are used. A further reduction of the overlapping may result by introducing filters to diminish the spectral range observed to the minimum length which includes sufficient characteristic features for the identification of the class of objects of interest. At the same time an important reduction of the sky background is obtained, which, in turn, permits longer exposures and fainter stars to be reached. This technique has been used extensively by Azzopardi (1984, IAU Coll. No. 78, in press) to survey the Small Magellanic Cloud (SMC) for different types of luminous objects (with the ESO GPO astrograph and the CTIO Curtis Schmidt telescope). Several of the recent GRISM or GRENS surveys of external galaxies apply similar techniques.

Looking for Wolf-Rayet Stars . . .

With the purpose of extending to other nearby galaxies the surveys for Wolf-Rayet stars (WR) performed in the Magellanic Clouds with the ESO GPO astrograph (Breysacher and Azzopardi, 1979, *The Messenger* **17,** 10), we have carried out observations with the ESO and CFH Corporation 3.6 m telescopes, using prime-focus triplet adaptors, GG 435 filters and a GRISM and a GRENS, respectively (see also Breysacher and Lequeux, 1983, *The Messenger* **33,** 21). The GG 435 filter, in combination with the III a-J emulsion, reduces the instrumental spectral domain to the desired range, 4350–5300 Å, and at the same time appreciably diminishes the crowding. However, even with the hypersensitized plates the surveys cannot reach faint enough to reveal fully the WR population in most galaxies. So far we have discovered the only WR known in NGC 6822 (Westerlund et al., 1983, *Astron. Astrophys.* **123,** 159), we have confirmed WR features in the spectra of two giant H II regions in NGC 300 and we have found numerous WR candidates in M 33, whose true nature still has to be determined. We find that rather few galaxies may be explored advantageously for WR stars with the GRISM/GRENS technique. There are mainly the most conspicuous members of the Local Group, namely M 31, M 33, NGC 6822 and IC 1613 ($<V-M_v> \simeq 24.4$), and the major members of the Sculptor Group: NGC 55, NGC 247, NGC 253, NGC 300 and NGC 7793 ($<V-M_v> \simeq 27.2$). Moreover M 31, NGC 55 and NGC 253 are seen more or less edge-on and hence not ideally suited for detection of stellar members. Indeed, as the range in the luminosity of the WR stars is $-2 \lesssim Mv \lesssim -7$ (Breysacher and Azzopardi, 1981, IAU Symposium No. 99, 253) the apparent-visual magnitude ranges of these objects are $17.4 \lesssim V \lesssim 22.4$ and $20.2 \lesssim V \lesssim 25.2$ in the Local and Sculptor Group galaxies, respectively. With a limiting photographic magnitude of $V \simeq 21$ it is clearly seen that only the most luminous WR stars may be detected, except in some of the nearest Local Group galaxies. A more efficient detector would be necessary for a complete survey of the WR stars in the Sculptor Group galaxies.

. . . and Finding Carbon Stars

During our first observing run with the ESO 3.6 m telescope we observed some fields in the Magellanic Clouds with the GRISM technique in order to obtain some standard spectra of WR stars and, at the same time, test the completeness of the previous WR surveys. We secured short and long exposures (5 and 60 min) of three fields in the Small Cloud. No more WR stars were found, but our plates contained spectra of a number of interesting objects, such as planetary nebulae, M giants and carbon stars. As a consequence of the low dispersion used (2200 Å mm^{-1}) and the limited spectral range, the M giants appear as triangle-shaped continuous spectra. The carbon stars were easily recognized thanks to a marked depression caused by one of the Swan bands.

A comparison of the carbon stars identified on our plates with the aid of the C_2 band in the blue-green spectral range with those identified by Blanco et al. (1980, *Astrophys. J.* **242,** 938) and Westerlund (unpublished) in the near-infrared, also using the GRISM technique but CN bands for the identification, showed clearly that very interesting results were to be obtained from our material. We decided therefore to study the Magellanic Clouds as completely as possible and to extend our search for carbon stars to other Local Group galaxies.

What is a Carbon Star?

Carbon stars, as well as M stars, are cold and intrinsically bright objects lying on the so-called asymptotic giant branch (AGB). Carbon stars have CO > 1 in their envelope and atmosphere, while M stars have C/O < 1 and the rare S stars C/O $\simeq 1$. An AGB star has a shell structure: A degenerate nucleus made of carbon and oxygen, a radiative helium layer and a convective hydrogen envelope. He burns at the base of the helium layer and H at the base of the envelope. After some time the star experiences short thermal pulses due to ignition of helium into carbon within the helium layer, and the energy liberated by this process makes this layer temporarily convective, mixing the newly formed carbon with the helium. The intensity of these pulses grows with time, and eventually the temporarily convective helium layer mixes with the convective hydrogen envelope, dredging up the carbon to the surface. If the intensity of the process is sufficient to inverse the C/O ratio from its initial value (<1) to a value (>1), the star, which was initially an M star, turns into a C star. Conventional models predict that only stars with initial masses $> 1.8\ M_\odot$ will become carbon stars, but this limit depends on metallicity, on the extent of convective mixing and on the intensity of the helium flash (Iben and Renzini, 1983, *Ann. Rev. Astron. Astrophys.* **21,** 271; Iben, 1983, *Astrophys. J.* **275,** L65). At least the first reason is easy to understand: The less there is of oxygen initially in the envelope, the easier it is for the star to become a carbon star, since the reversal of the C/O ratio will be easier. The two latter reasons are less obvious, although supported – at least quantitatively – by numerical evolutionary models. It appears observationally that stars with masses $> 0.9\ M_\odot$ may become C stars in systems of sufficiently low metallicity (Bessel et al., 1983, *Monthly Notices Roy. Astron. Soc.* **202,** 59). It may be that once an AGB star has turned into a carbon star, it will not stay as such during its AGB lifetime, as evidenced by the lack of C stars amongst the brightest AGB stars: ^{12}C may turn into ^{13}C and mainly ^{14}N (with subsequent production of s-process elements like Zr) at the basis of the envelope, and the C/O ratio may turn back to values < 1; these objects may be the MS stars, which are M stars with ZrO bands. The evolutionary picture is complicated and still partly controversial. What is clearer is the spectroscopic discrimination between C and M stars. In M stars, all the carbon is bound in CO, and the excess oxygen forms H_2O, OH, . . . and oxides like TiO. In C stars, conversely, all the oxygen is bound in CO, and the excess carbon forms molecules like CN, C_2, CH, . . . while oxides are absent.

Carbon Star Selection Criteria

It follows from the previous section that the bands of the cyanogen (CN) and the carbon (C_2) molecules dominate the visual spectrum of the carbon stars. They are the main characteristic features for the identification of these objects. The most prominent features are the bands of the Swan C_2 system; particularly sharply defined are the (0.0) and (0.1) bands at 5165 and 5636 Å, respectively. Some carbon stars have also very strong bands of the CH molecule, mainly seen in the G-band. They are frequently called CH stars and form a special group.

Our selected spectral range makes the 4737 and 5165 Å C_2 bands available for the identification of carbon stars. In addition, the short spectra permit an estimate or a measure-

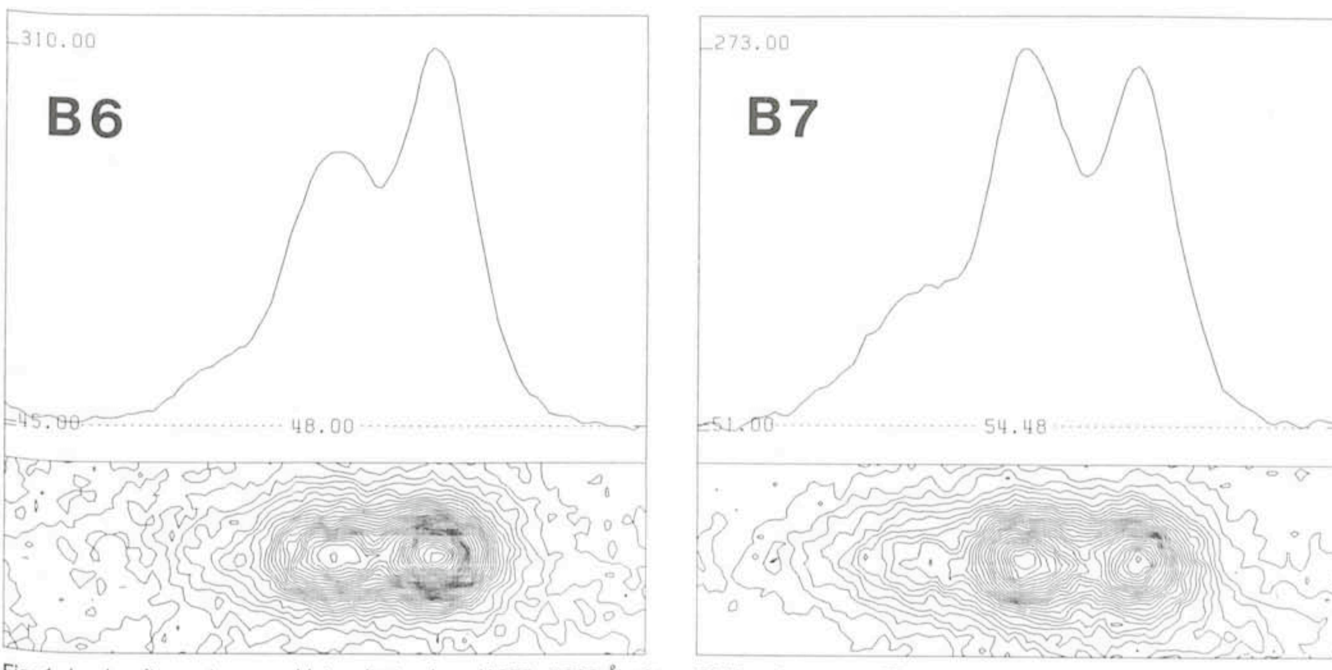

Fig. 1: *Isodensity contours and intensity tracings (4350–5300 Å) of two SMC carbon stars. The pronounced central depression is the Swan C_2 band at 5165 Å. The star B7 is clearly bluer than the more "normal" star B6. Graphs obtained from PDS scans of an ESO 3.6 m telescope GRISM plate (dispersion 2200 Å mm^{-1}) using the Munich Image Data Analysis System (MIDAS).*

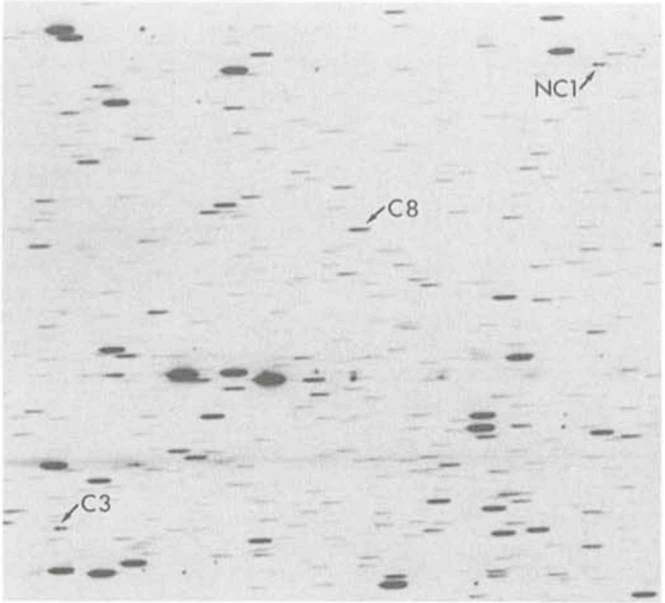

Fig. 2: *The central part of the Carina dwarf spheroidal galaxy obtained, in a 2^h exposure, with the ESO GRISM at the prime focus of the 3.6 m telescope. The carbon stars C3 and C8 have been detected previously by Cannon and associates while NC1 is one of the newly discovered C stars (see text). The strong depression of the Swan C_2 band at 5165 Å appears clearly in the spectra of C3 and NC1.*

ment of the colours of the stars. Likewise, modern techniques permit reliable measures of the C_2 band strengths to be obtained.

In the near-infrared spectral range, which has been used extensively for surveys for red stars, the carbon stars are identified with the aid of the CN bands at 7945, 8125 and 8320 Å. The use of this spectral range obviously favours the reddest carbon stars, whereas surveys using the 4350–5300 Å range favour the bluer ones. It is, thus, not obvious that identical samples will be found with the two methods.

Carbon Star Surveys

Near-infrared surveys have been summarized by Westerlund (1979, *The Messenger* **19,** 7). Since then, a number of near-infrared GRISM-type surveys have been carried out for carbon stars in Local Group galaxies (cf. Richer and Westerlund, 1983, *Astrophys. J.* **264,** 114, and Aaronson et al., 1983, *Astrophys. J.* **267,** 271). The C_2 bands in the blue-green region were used by Sanduleak and Philip (1977, *Publ. Warner & Swasey Obs.* **2,** 104) for the identification of carbon stars in the Large Magellanic Cloud (LMC); their observations were carried out with the CTIO Curtis Schmidt telescope equipped with a thin prism (1360 Å mm^{-1} at Hγ). More recently, Mould et al. (1982, *Astrophys. J.* **254**, 500) used the UK Schmidt telescope equipped with a low-dispersion prism (2400 Å mm^{-1} at 4300 Å) to search for carbon stars in the Carina dwarf galaxy.

Our GRISM/GRENS material permits us to identify carbon stars with the aid of the 5165 Å band to rather faint magnitude limits. If we assume that the absolute visual magnitudes of most carbon stars fall in the range 0 to −4, we are, nevertheless, limited to galaxies within about 0.2 Mpc for reasonably complete surveys, i.e. to our closest neighbours, the Magellanic Clouds and the dwarf spheroidal galaxies. The most luminous carbon stars may be seen in galaxies out to about 1 Mpc.

The Magellanic Clouds

Blanco and McCarthy in a recent preprint have given the results of an extensive sampling of the red-star population of the Magellanic Clouds. For this, they applied the GRISM technique in the near-infrared, and used, at the prime focus of the CTIO 4 m telescope, a field of 0.12 deg^2 – except for 9 regions in the Small Cloud where a field of 0.38 deg^2 was used – to observe 37 SMC and 52 LMC regions. They covered a total of 6.8 and 6.2 deg^2 in the two Clouds, respectively, and they estimated the total number of carbon stars to be 2,900 in the SMC and 11,000 in the LMC.

Our survey, with a field of 0.78 deg^2, will cover the main body of the SMC and give a sufficient coverage of the LMC for conclusions about the distribution over the two galaxies of the various types of carbon stars that we can distinguish from our low-dispersion GRISM spectra. Richer, Olander and Westerlund (1979, *Astrophys. J.* **230,** 724) showed that the carbon stars in the LMC could be divided into a number of natural spectroscopic groups, lying in distinct, well-defined regions of the colour-magnitude and colour-colour diagrams. The natural groups have, undoubtedly, a high correlation with the evolutionary status of the stars. Thus, we expect to be able to describe in detail the evolutionary phases of the carbon stars in the various parts of the Clouds from our material.

In order to do this, we scan the identified carbon star spectra in a PDS machine and transfer the digitized density values to intensity. We are then able to measure in our tracings: a magnitude, m (5220), a colour equivalent, m (4850) – m (5220), and the strength of the 5165 Å Swan band. The latter may be expressed as an equivalent width, or a depth under the pseudo-continuum. By combining the measured quantities we can produce diagrams permitting a number of natural groups to be identified. It should also be noted that we calibrate our criteria with the aid of IDS spectra obtained with the ESO 3.6 m telescope of a number of selected stars in our fields. So far we have investigated two fields in the SMC: (A), centered at 0^h 48^m, −73°37′; and (B), at 1^h 01^m, −72°19′ (1950). Field A contains 306 carbon stars, field B 132. We have been able to measure 247 and 109, respectively, without disturbing overlapping. Among the group of stars that we can separate into groups are, of course, the very red and the very blue carbon stars (Fig. 1); they may then show very strong,

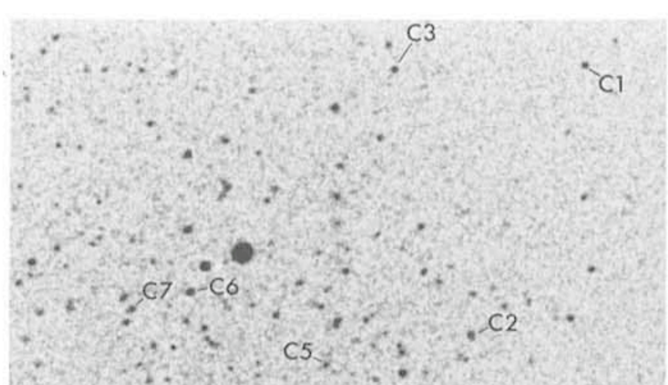

Fig. 3: *Finding chart for the 7 carbon stars we detected on a CFH 3.6 m telescope GRENS plate of the Leo II dwarf spheroidal galaxy. C2 and C6 are two uncertain candidates. Copy of a part of the Palomar Sky Survey R plate No. E 1353.*

"normal" or weak C_2 bands. Our IDS calibration shows also that our criteria permit the ^{13}C rich J stars (Bouîgue, 1954, *Annales d'Astrophysique* **17,** 104) to be identified. We have also noted some differences between the two fields, which are in significantly different parts of the SMC. Thus, we may hope that our investigation will contribute to the understanding of the structure of the SMC, which, indeed, appears to become more and more complex (Mathewson and Ford, 1984, IAU Symp. No. 108, 125).

The Dwarf Spheroidal Galaxies

These satellites of the Galaxy appear to be old Population II systems with no evident central concentration and a noticeable lack of gas or dust. Their stars are of relatively low luminosity. Due to their rather low surface brightness their detection has been rather difficult. At present, seven dwarf spheroidal galaxies are known, namely the Sculptor, Fornax, Leo I, Leo II, Draco, Ursa Minor and Carina Systems. The last one was not found until 1977 (Cannon et al., *Monthly Notices Roy. Astron. Soc.* **180,** 81 P).

The Sculptor and Fornax dwarf galaxies have been surveyed for carbon stars previously by Frogel et al. (1982, *Astrophys. J.* **252,** 133) and by Richer and Westerlund (1983, *Astrophys. J.* **264,** 114), both groups using the GRISM technique in the near-infrared. Frogel and his associates discovered two carbon stars in Sculptor and considered three more as possible carbon stars. Richer and Westerlund found the two carbon stars and added one carbon star outside the other survey. They did not confirm the three possible candidates. In our survey, which covers a larger area than the previous ones, we confirm the three known carbon stars and added three. In the Fornax galaxy, a total of 49 carbon stars were known from the previous surveys. We have now found a number of new objects so that the total number of certain carbon stars is 60 and additional 16 may be considered as possible carbon stars. The total numbers of carbon stars known in the two galaxies agree thus rather well with the estimates by Richer and Westerlund, 5 and 64, respectively.

In the Carina dwarf galaxy, Cannon et al. (1980, *Monthly Notices Roy. Astron. Soc.* **196,** 18) discovered two carbon stars which were selected as the two brightest members. Then, by carrying out a systematic survey with the UK Schmidt telescope Mould et al. (1982, *Astrophys. J.* **254,** 500) increased the number of certain carbon stars to seven; they also suggested one possible candidate. We have found the seven carbon stars and have added three certain and one possible carbon star. We were unable to confirm the character of the possible carbon star (C8), suggested by Mould and associates (see Fig. 2).

The Draco, Leo I, Leo II and Ursa Minoris systems have been surveyed recently by Aaronson et al. (1982, *Astrophys. J.* **254,** 507; 1983, *Astrophys. J.* **267,** 271). They did not detect any carbon stars on their KPNO IV-N GRISM plates of the Leo dwarf galaxies. Nevertheless, they found spectroscopically, from a selection of very red stars, one and four C stars in Leo I and Leo II, respectively. On our CFHT GRENS plates we have found twelve certain carbon stars and four possible ones in Leo I, and five certain carbon stars and two possible ones in Leo II (Fig. 3). Unfortunately, since Aaronson and his associates have not provided identification charts in their paper of the carbon stars they identified, we do not know to what extent our identifications agree.

In the Draco and Ursa Minoris systems, Aaronson and his associates found three and two carbon stars, respectively, on their near-infrared GRISM plates. We have not yet had the opportunity to observe these systems, but we expect to search them for carbon stars in the near future.

In general, the new carbon stars that we have detected are either outside the fields of earlier surveys, or bluer, and possibly fainter, than those previously found. The latter may indicate that carbon stars can form lower on the asymptotic giant branch than usually assumed.

Although the absolute magnitudes, masses and luminosities of the dwarf spheroidal galaxies are rather uncertain, it is clear that there is some relation between the number of carbon stars per unit luminosity and the luminosity or the metallicity of the galaxy in the sense that as the luminosity or/and the metallicity decrease carbon stars form more easily.

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