Resolving Nearby Galaxies into Stars

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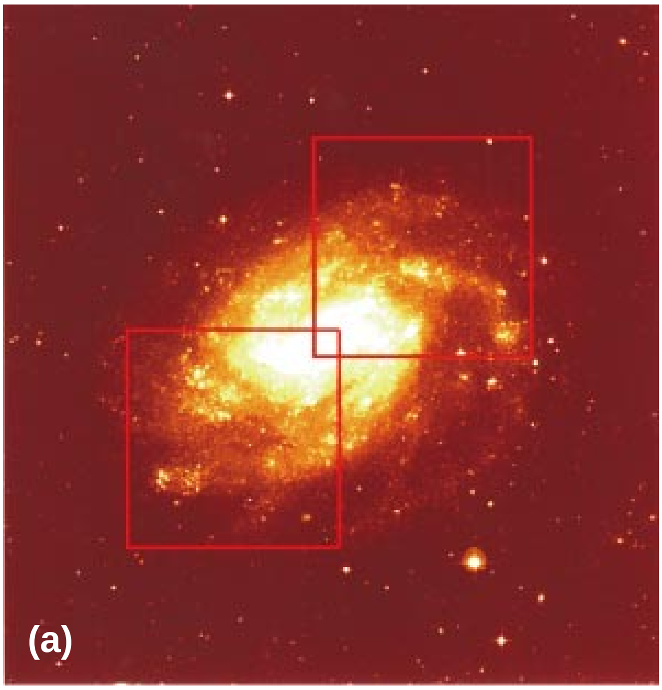
Abstract

The combination of large-aperture telescopes and good image quality has made it possible to resolve the stellar population in many nearby galaxies. Here we present observations carried out at the NTT and CFHT, among others to study the Mira and carbon-star population in different environments, pushing the limits to outside the Local Group. One of the early results of this project has been the discovery of a population-II halo around a dwarf irregular galaxy. We discuss the possibilities for extending such studies with the VLT.

1. Introduction

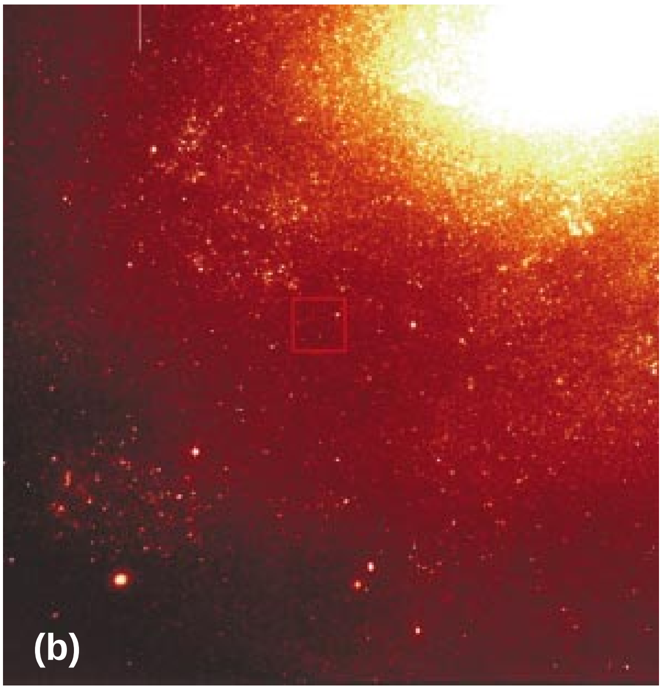
With the advent of modern telescopes, the distinction between extragalactic and stellar astrophysics has become less sharp. This has long been the case for the dwarf spheroidals surrounding the Milky Way, which are so well resolved into stars that they are difficult to identify as galaxies. With the image quality nowadays routinely achieved at major telescopes, many nearby galaxies are similarly resolved into stars. Thus, not only can the integrated properties and structure of galaxies be studied, but also directly their stellar populations.

This intrusion of stellar astronomy benefits both fields. The stellar population holds important clues to age and metallicity and thus of formation history of a galaxy. If planetary nebulae can be found, the dynamics of the old population can also be studied (Arnaboldi et al., 1994). Star counts can determine the extent of a galaxy to much fainter levels than surface-brightness photometry (e.g. Pritchet & van den Bergh, 1994). From the other side, stellar properties and evolution can be studied in environments different from the Milky Way. Especially our understanding of stellar evolution on the Asymptotic Giant Branch, which is strongly metallicity and age dependent, has improved from extragalactic studies.



Much stellar work has been done on the LMC, with its convenient size and distance. Period-luminosity relations such as exist for Cepheids and Miras have been established and calibrated using the LMC. However, with large telescopes, these stars can now be identified at distances of several Mpc, and HST has shown itself capable of finding Cepheids at the distance of Virgo. Planetary nebulae have been found with ground-based telescopes to even larger distances. Clearly this is a field where 8-m-class telescopes can bring significant further development. Crucial are not only the large apertures, but improved seeing expected at a site such as Paranal and the move to wide-field imaging will allow us to push stellar astronomy even further out.

In this report we will discuss recent observations obtained at the NTT and CFHT, aimed at finding and studying extragalactic AGB stars. An unexpected result of these observations has been the discovery of a population-II halo around a dwarf irregular galaxy. We discuss the carbon-star population of M31, and the goals of the NTT project. Finally,



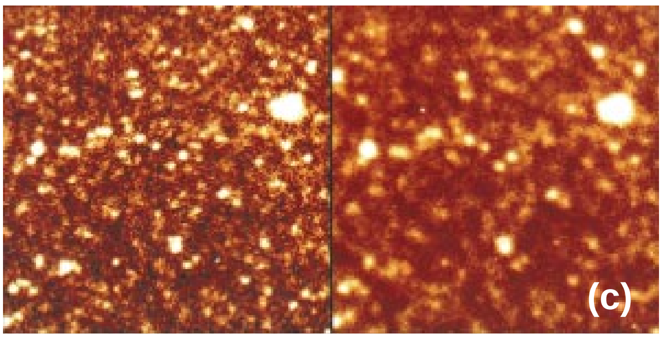


Figure 1: Panel (a) shows the dss image of NGC 300, with two EMMI fields indicated. Panel (b) shows one of these EMMI images. Panel (c) shows two epochs of the central area of panel (b): two variables near the top-right corner and bottom-left corner can be identified.

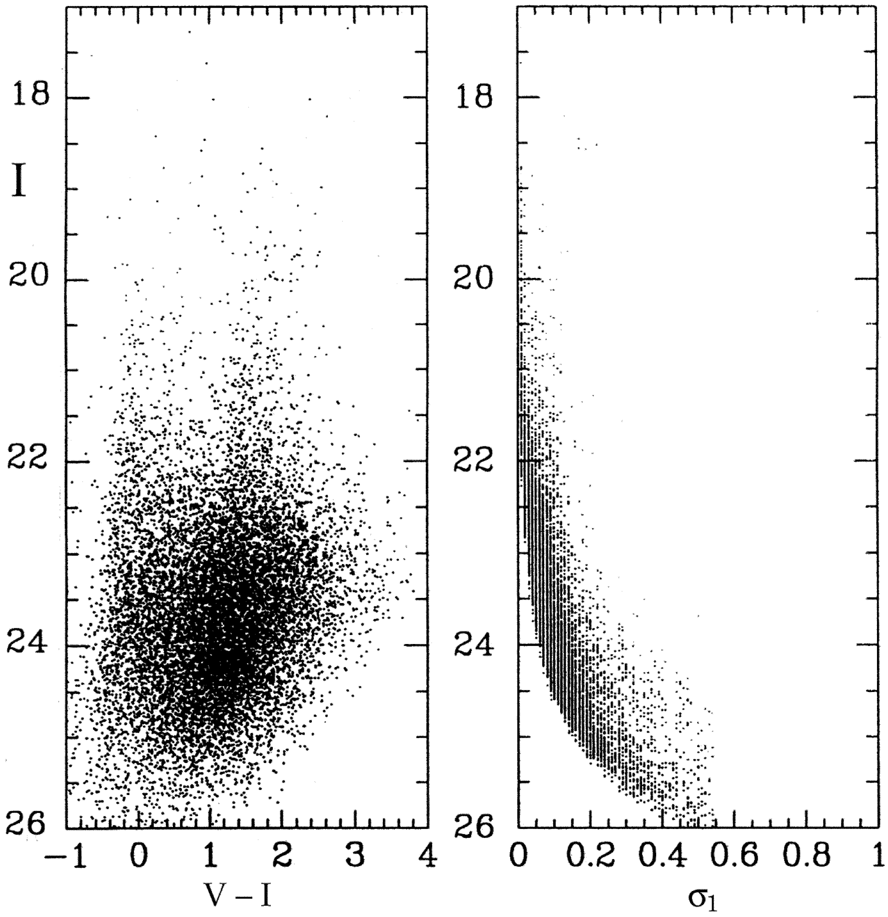


Figure 2: A colour-magnitude diagram for one EMMI field of NGC 300.

the use of the VLT for such studies is discussed.

2. Data and Project

Several galaxies in the neighbourhood of the Local Group were observed with the NTT in the V and I band. The direct aim was to find and monitor Mira variables in these galaxies, with a twofold purpose. The first is to study the properties of the Mira variables as function of metallicity. This has proven difficult in the Galaxy where the distances to Miras are difficult to ascertain. The Magellanic Clouds (mainly the LMC) have a well-studied Mira population, but they provide a limited range in metallicity. The main uncertainty still is the phase at which AGB evolution is terminated. Mass loss is the dominant evolutionary effect on the AGB, and a phase of very high mass loss (the so-called superwind) ends the AGB, leading to the birth of a planetary nebula. The onset of the superwind is a function of the age and the luminosity and thus core mass of the star. It will also depend on metallicity, likely starting later at lower metallicity, which would cause low-metallicity stars to reach higher luminosity on the AGB. This has not yet been observationally disentangled from the dependency on age.

The second purpose is to study the period-luminosity relation of Miras. This relation has long been known and is tight especially when the K-band magnitude is used where the dispersion is only 0.13 mag. However, the metallicity dependence of the relation has been controversial. On theoretical grounds, a shift with Z of ΔM_{bol} = 0.73Δ log Z at a given period is expected, but instead the PL relation in the Galaxy and the LMC appear to be highly similar (Feast, 1996, Whitelock et al., 1994). It is possible that AGB stars reach the Mira phase at different phases depending on initial metallicity, such that the total effect of Z cancels out. This was argued by Feast (1996). Studying the PL relation in various environments could potentially help solve this discrepancy.

The study of extragalactic AGB stars, especially carbon stars, has focused on galaxies within the Local Group. However, with 4-m-class telescopes they can in principle be identified out to several Mpc. We have selected a total of six galaxies which are regularly observed. Of these, the prime targets are WLM and NGC 300: we attempt to obtain data for these galaxies at every epoch. The other galaxies have less time coverage. The furthest galaxy in the sample is NGC 7793 at about 5 Mpc. WLM is a dwarf irregular at the edge of the Local Group. NGC 300 is a large spiral at a distance of about 2 Mpc.

The I band is convenient to find the Miras since it combines the advantages of large field and good sensitivity. However, after the periods will be determined, infrared observations are needed to obtain the luminosity or K-band magnitude of the stars: in the I-band there is no obvious PL relation due to the cancellation of colour correction and luminosity. No PL relation is known for the most luminous, long-period Miras (Zijlstra et al., 1996). It is therefore important to go sufficiently deep to find the less luminous Miras which have periods of 200–400 days.

WLM fits into a single EMMI frame; for NGC 300 two pointings were used. We used DAOPHOT2 to find the stars in each frame. Figure 1a shows a dss image of NGC 300, with the two EMMI fields indicated. Figure 1b shows one of these two EMMI frames. Close to 10^5 stars could be identified in NGC 300 at a limiting magnitude of I = 24.

Miras will be identified based on colour (no detection is expected at V) and variability. As an example, Figure 1c shows two epochs of a small region in the central area of the EMMI field of Figure 1b. Even in this small area, two variables are clearly visible. In the full frame several hundred identifiable Miras can be expected, with an expected average I-magnitude ranging from 20 to 23. Figure 2 shows a colour-magnitude diagram for the south-east field, including a total of 15,000 stars.

For WLM, 45-minute integrations were used resulting in I = 23.5 at 4σ. The limit is worse in the more crowded regions: adding artificial stars at random positions, the completeness at I = 22 was found to drop from 90% in the outer areas to 75% in the central areas of the disk.

A colour-magnitude diagram of NGC 300 is shown in Figure 2. The main features are a red tail of AGB stars, a blue main sequence with mean colour $V - I$ = 0.2, and a red supergiant sequence with $I < 20$, reaching $I \approx 16.5$. Signs for a population of blue loopers are also seen, running parallel to the main sequence, about 0.4 mag redder. The AGB is very extended, and can be traced to V = 24.75, and $V - I$ = 3.88. Unfortunately, the present photometry is not deep enough to reach the horizontal branch of WLM. If $\Delta M_{RGBT-HB} = 4.09 \pm 0.15$ this HB would be located at $I \approx 25$, accessible with HST.

Our star counts around WLM show a low-density tail, stretching considerable distances from the main body (Minniti & Zijlstra, 1996). To confirm this, two fields were observed further away from the galaxy. The total extent of the galaxy is at least 9 arcminutes along the minor axis, twice as large as the surface-brightness maps of Ables & Ables (1977).

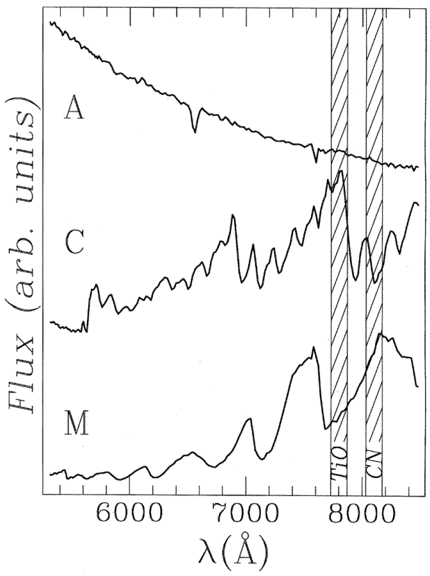


Figure 3: The upper spectrum is that of an A star, the middle spectrum a C star and the lower spectrum an M giant. Superimposed on these spectra are the bandpasses of the CN and TiO filters. Notice how the TiO filter lies on a TiO absorption band in the M star, while the CN filter lies on a CN absorption band in the C star. Data are courtesy of the Canadian Astronomical Data Centre.

3. Extragalactic Carbon Stars

The external abundances of AGB stars are changed by dredge-up following a thermal pulse. An oxygen-rich star becomes a carbon star when sufficient carbon has been brought to the surface to tie the star's oxygen up in CO. Although the internal structure of oxygen-rich and carbon-rich AGB stars is similar, their spectra differ enormously. Spectra of M-stars are dominated by bands of TiO, while, by contrast, carbon stars are dominated by bands of CN and C_2.

Palmer and Wing (1982) suggested that on account of their strong spectral features, carbon- and M stars could be distinguished by the use of narrow-band photometry. This idea was first implemented by two groups, one led by Marc Aaronson and the other by Harvey Richer. In Figures 3 and 4 we illustrate the basis of the "four-band photometric system" (FBPS). Figure 3 shows the spectrum of an A star, a carbon star, and an M star. Superimposed on these three spectra are the bandpasses of two narrow-band filters, henceforth referred to as the "CN" and "TiO" filters. The CN and TiO filters have a width of $\Delta\lambda \sim 140$ Å and are centred on the CN ($\Delta v = +2$, 8100 Å) and TiO ($\Delta v = -1$, 7800 Å) absorption bands respectively. Figure 3 illustrates how the "CN" filter is positioned on a strong CN absorption band in the carbon star and pseudo-continuum in the M star, while the TiO filter is positioned on a strong TiO absorption band in the M star and pseudo-continuum in the carbon star. It can be seen from Figure 3 that: (1) the A star will have a (*CN – TiO*) colour of around zero; (2) the carbon star will have a positive (*CN – TiO)* colour; and (3) the M star will have a negative (*CN – TiO*) colour. In Figure 4 we show a (*CN – TiO, V – I*) two-colour diagram (adapted from Richer et al., 1985) of photoelectric standards and LMC stars of known spectral type. Figure 4 demonstrates the insensitivity of the (*CN – TiO*) colour to early spectral types, and the bifurcation into carbon- and M stars at cooler temperatures. Indeed, the coolest carbon- and M stars show almost a *magnitude of separation* in (*CN – TiO*).

S stars are AGB stars in which the abundance of oxygen is similar to that of carbon. In the (*CN – TiO, V – I*) two-colour diagram these stars lie between the carbon- and M-star "branches", though are sufficiently scarce that no S-star "branch" is observationally seen.

FBPS surveys for AGB stars offer many advantages over surveys in which a dispersive element is used (e.g. Schmidt telescope with an objective prism). Some of these advantages are: (1) the FBPS can be used in crowded fields where spectroscopic surveys are not feasible; (2) as no dispersive element is used, the FBPS is able to reach fainter magnitudes; and (3) when used with a CCD, the FBPS gives data which are easily reduced and interpreted. On the downside, the FBPS is limited for survey work by the small field size of many CCD-based cameras. However, cameras based on large mosaics of CCDs are starting to become common place; such cameras will allow the full utilisation of the FBPS for survey work.

The FBPS has made possible the identification and classification of AGB stars beyond the Milky Way and its dwarf companions; the most distant identified C stars are those in NGC 2403 with a true distance modulus of 27.4 (Hudon et al., 1989). More recently, the FBPS has been used at the CFHT to investigate the AGB population in M31 (Brewer et al., 1995). Five $7' \times 7'$ fields at different radial distances along M31's SW semi-major axis were observed during superb (~ 0.75″) seeing conditions. In Figure 5 we show the (*CN – TiO, V – I*) two-colour diagrams resulting from these observations. The main results of this investigation are:

- The distance to M31 was derived using the carbon-star luminosity function, and found to be in good agreement with that derived from Cepheids. Furthermore, the carbon-star luminosity function appeared to be insensitive to differences in the star-forming history and metallicity of the fields observed.
- It is known that the ratio of carbon- to M-stars (the C/M ratio) is inversely correlated with metallicity (see, for example, Pritchet et al., 1987). The M31 observations showed that the C/M ratio tracked M31's known measured metallicity gradient, and suggested a flattening of the gradient in the outer disk.
- The correlation between the C/M ratio and galactocentric distance in

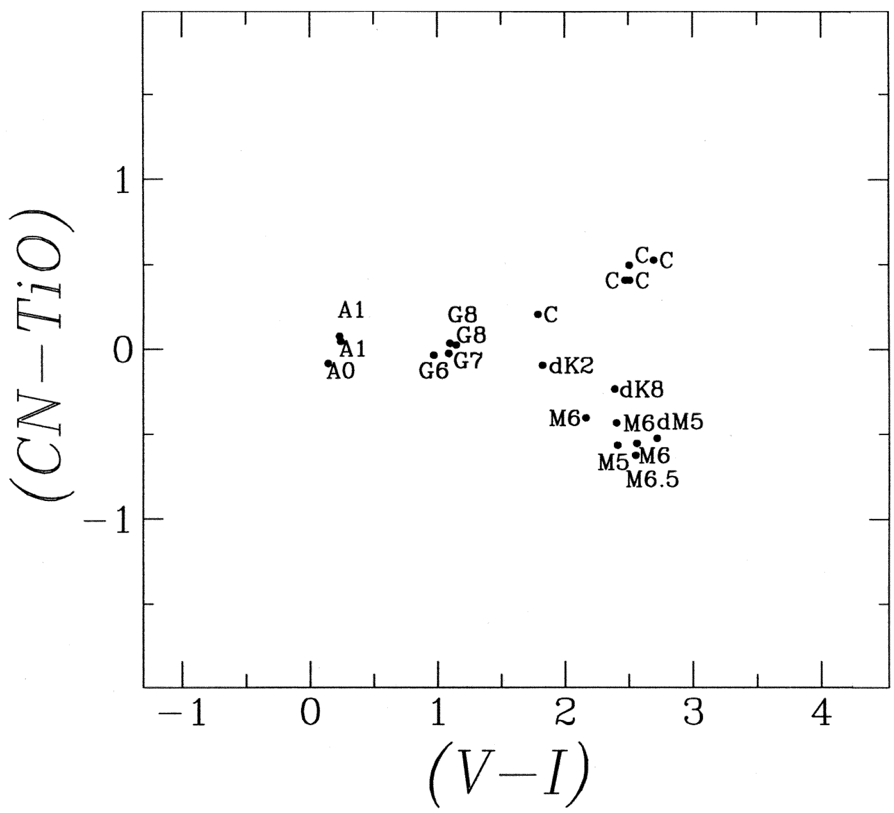


Figure 4: A plot of the (CN – TiO) narrow-band colour versus (V – I) broad-band colour for a sample of photoelectric standards and LMC stars. The data for this plot are adapted from Richer et al. (1985).

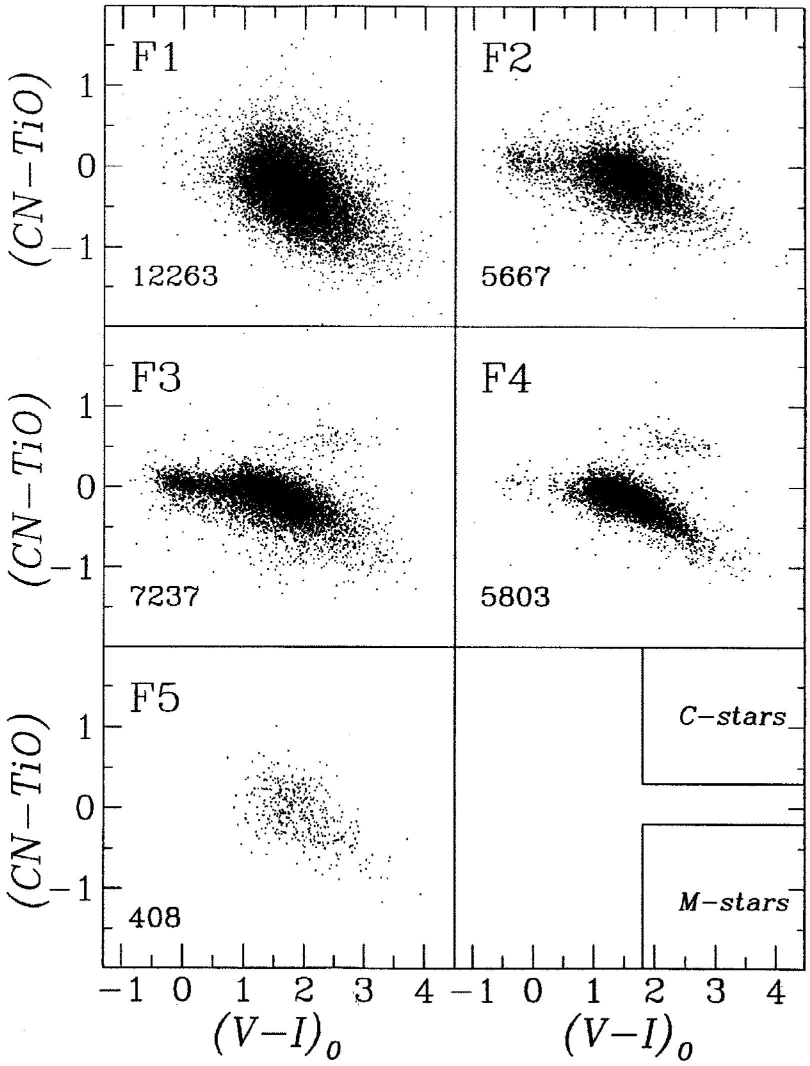


Figure 5: The labelled panels show the (CN – TiO, V – I) two-colour diagrams for the five M31 fields. The number of stars measured in each field is indicated. The (V – I) colour has been calibrated onto the Johnson-Cousins system and corrected for reddening, while the (CN – TiO) colour has been shifted such that the mean value of (CN – TiO) for stars bluer than (V – I) = 1 is zero. In the above labelled panels, stars with I0 < 18.5 are excluded (such stars are likely to be foreground stars or M31 supergiants). The lower-right panel indicates where the C and M stars are expected (from spectroscopic observations) to lie in the (CN – TiO, V – I) two-colour diagram.

M 31 may lead to differences in the properties of the ISM on account of the different types of grain produced by carbon- and M stars. For example, the differences observed in M31's extinction law are compatible with what would be caused by the observed C/M ratio gradient.

• The identification, and subsequent spectroscopic confirmation, of the most distant S star currently known.

Having identified the carbon- and M stars in the M31 fields, follow-up spectroscopy of some of the candidates was made using the multi-object spectrometer at the CFHT (Brewer et al., 1996). The spectra demonstrated the high reliability of the FBPS, more than 95% of suspected carbon stars were confirmed as such by spectroscopy. It also allowed for the identification of carbon stars with spectral peculiarities, such as high Li abundances and high C^{13}/C^{12} ratios. Both of these types of spectroscopically peculiar carbon stars were found at luminosities fainter than predicted by current AGB theory. (N.B. The distance to, and consequently luminosity of, most Galactic AGB stars is unknown, making them unsuitable for comparison with theoretical AGB models).

The large aperture and expected good seeing of the VLT will be a boon for the investigation of AGB populations in Local Group Galaxies and beyond. Such studies will enhance not only our intrinsic knowledge of AGB stars, but will also shed light on areas like the spectral evolution of distant galaxies and ISM enrichment.

4. Conclusion

Clearly, there is much that can be done with the present 4-m-class telescopes: AGB stars and Miras can be identified and studied at distances much larger than has been done so far. The NTT is useful because of a relatively large field of view and a good image quality. However, a larger field of view, such as available on CFHT, would be advantageous as illustrated by Figure 1.

For the VLT, it can be expected that the limits can be pushed to far outside the Local Group. The increase in collecting area alone significantly increases the possible distance. A second advantage can be expected from the seeing at Paranal which will allow point-spread functions of 0.4–0.5 arcsec to be routinely achieved. Together, a distance limit of 10–15 Mpc can be expected for these studies. A second advantage is the good IR quality of Paranal. For the study of Miras, it is crucial to obtain infrared photometry in addition to optical I-band photometry.

A drawback is the small field of view foreseen for the VLT. At larger distances, crowding becomes more important in the inner regions, and the outer regions should be included in the field of view. For a galaxy such as NGC 300, a good field of view would be 10 arcmin at a distance of 10 Mpc. It is important that instruments which give this field with optimum image quality will be available. This point is also strongly relevant to infrared cameras: their field of view will have to be comparable to that of the optical cameras on the VLT. Together, such instruments will keep the VLT at the forefront of extra-galactic stellar astronomy.

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