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AGB Stars in Extragalactic Systems

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Abstract. I review three methods of identifying late-type giants in extragalactic systems, based on the main characteristics of AGB stars (they are infrared-bright, variable, and have spectral peculiarities).

1. Introduction

All main-sequence stars born with masses below $\lesssim 8$ M$_\odot$ have gone or will go through the evolutionary phase called the Asymptotic Giant Branch (AGB). The lower limit in initial mass is set by the age of the Galactic Disk, the upper limit by the mass where carbon can be ignited in the stellar core (but see the presentation by Siess on super-AGB stars in this volume). The AGB is the final phase where intermediate-mass stars have nuclear burning in the form of alternate hydrogen and helium shell burning, before they cross the Hertzsprung-Russell diagram to become planetary nebulae and then white dwarfs.

A summary of the interior structure and stellar evolution up to and on the AGB, and including the post-AGB phase, can be found in the recent textbook *Asymptotic Giant Branch Stars* (Habing & Olofsson 2004).

AGB stars are luminous, [$\sim$0.1 to a few] $\times\ 10^4$ L$_\odot$, and cool, with effective temperatures in the range 3850 to $\sim$2500 K (for M0 to M10 giants, see e.g. Fluks et al. 1994). From this it follows that AGB stars are big (up to a few hundred R$_\odot$), and combining this with the classical pulsation equation $P = 0.038\ R^{1.5}\ M^{-0.5}$ it follows that any fundamental-mode radial pulsations that would occur would have periods of tens to hundreds of days.

Equally important, and typical for the AGB, are the chemical peculiarities that occur during this evolutionary phase (see Chapter 2 in the aforementioned book). Depending in a complex way on initial mass, metallicity, mass-loss, mixing and burning in the envelope (hot bottom-burning), an AGB star may go through several third-dredge-up events whereby mainly carbon, nitrogen, oxygen and *s*-process elements are mixed ultimately into the stellar photosphere. Depending on the C/O ratio different molecules form in the cool atmospheres (TiO, VO, C_2, CN...) and a star can be classified as an M star (C/O $\lesssim$ 0.95), an S star (0.95 $\lesssim$ C/O $<$ 1.0) or a C star (C/O $\geq$ 1.0). Intermediate classes (MS, SC) also exist.

The low effective temperatures makes AGB stars redder than all their main-sequence progenitors. In addition, the formation of different molecules depending on chemical type causes the infrared colors of M and C stars to be different, as will be discussed later.

Furthermore, for spectral types later than $\sim$M4–M5 (e.g. Glass & Schultheis 2002) the region close to the star has the right combination of temperature and density for dust grains to form. Dust absorbs efficiently in the optical and radiates in the infrared. This implies that AGB stars surrounded by dust shells are even redder.

In the present review I will discuss only the most recent results. For earlier reviews covering AGB stars in Local Group (LG) galaxies, see Azzopardi (1999) and Groenewegen (1999, 2002, 2006a,b).

2. Searches for AGB Stars

2.1. Near- and Mid-Infrared Studies

As AGB stars are cool and many lose mass, infrared colors are a natural way to search for them. A disadvantage is that only candidates may be identified, although the *J–K* color is often used to discriminate between M and C stars (see the discussion later). An advantage is that very red colors trace a different population of extreme mass loss and likely of higher initial mass, or stars at the very end of the AGB.

As the 2MASS *JHK* survey (Cutri et al. 2003) was an all-sky survey that went reasonably deep (to $K \approx 15$), it had the potential of discovering AGB stars in nearby LG galaxies. Quite a few studies have used 2MASS data. Demers et al. (2002) correlated spectroscopically-confirmed C stars in the Magellanic Clouds (MCs) with 2MASS and used this to propose 26 C-star candidates in the Fornax DSph. Cioni et al. (2003) studied the spatial distribution of the C/M ratio over the MCs (also using DENIS data) to infer the distribution in [Fe/H]. Tsalmantza et al. (2006) used virtual observatory tools to identify luminous ($M_{\rm bol} < -6.0$) AGB stars with $J{-}K > 1.5$ and $H{-}K > 0.4$ in the MCs, M31, and M33. Groenewegen (2006a) selected 2MASS sources in LG galaxies within 1 Mpc (but excluding the MCs, M31, M32, and M33), retaining objects with $(J{-}K)_\circ > 1.22$, an appropriate $M_{\rm K}$ range for AGB stars, and errors in $J, K < 0.12$ mag, while excluding known objects using the SIMBAD database.

In the last couple of years more studies have appeared that used ground-based IR instrumentation sometimes combined with an optical color. Cioni & Habing (2005a) studied a field of $20' \times 20'$ in NGC 6822 in *IJK*, and Cioni & Habing (2005b) studied a field of $40' \times 30'$ in Draco in *IJK*. At this conference Cioni also presented preliminary results on M33. In her papers she selects O-rich and C-rich AGB stars from their infrared colors and then studies the spatially resolved C/M ratio. Kang et al. (2006) studied a smaller field of $6.3' \times 3.6'$ in NGC 6822 in the *giJHK* bands. Since this galaxy was observed by Letarte et al. (2002) using the narrow-band filter technique (see later), they could identify known carbon stars in various color-color diagrams. The M31 companions NGC 147, NGC 185, and NGC 205 have been studied by Davidge (2005), Kang et al. (2005), and Sohn et al. (2006). Finally, Rejkuba et al. (2006, and this conference) present NIR data on dwarf ellipticals in Cen A.

Turning to the mid-IR, the *Spitzer Space Telescope* has great discovery potential for luminous and especially mass-losing AGB stars in LG galaxies. First results have been published from the S^{3}MC survey of the SMC (Bolatto et al. 2007), the SAGE survey of the LMC (Meixner et al. 2006; Blum et al. 2006), and for M31 (Barmby et al. 2006). Smaller LG galaxies will also be surveyed in both IRAC (R. Gehrz et al.) and MIPS (E. Skillman et al.).

First results on IRAC observations of the WLM galaxy were presented by Jackson et al. (2007, and at this conference). As WLM has been surveyed using the narrow-band filter system (Battinelli & Demers 2004) they could compare the number of detections. Interestingly, they recovered 90% of the known C stars in the IRAC colors, but this represented only of order 20% of the entire AGB population. In particular, stars with $[3.6 - 4.5] \gtrsim 0.3$ were lacking among the known C stars (and one would expect them to be C stars at the low metallicity of WLM).

To aid in identifying AGB stars in the non-standard IRAC and MIPS filters, Groenewegen (2006c) has presented tracks for AGB stars in various optical, near- and mid-infrared colors as a function of mass-loss rate and for both M and C stars. An example is shown in Figure 1. Note that the fluxes and mass-loss rates listed in that paper are for a particular luminosity and distance, and scaling relations need to be applied (as explained in the paper) to compute fluxes and mass-loss rates for other values of luminosity and distance.

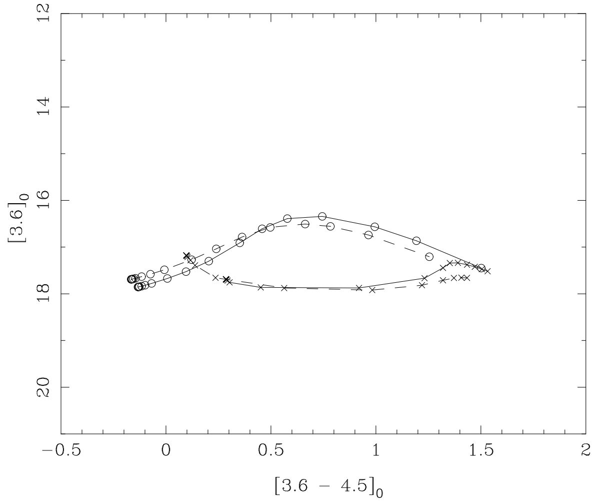

Figure 1. IRAC color-magnitude diagram for models with 3000 $L_\odot$ at 932 kpc (appropriate for WLM). The following sequences of increasing mass loss are shown: Carbon-rich AGB star with $T_{\rm eff}$ = 3600 K and 85% AMC + 15% SiC (*circles* & *solid line*); Carbon-rich post-AGB star with $T_{\rm eff}$ = 2650 K and 100% AMC (*crosses* & *solid line*); Oxygen-rich AGB star with $T_{\rm eff}$ = 3297 K and 60% silicate + 40% Aluminum oxide (*circles* & *dashed line*); and Oxygen-rich post-AGB star with $T_{\rm eff}$ = 2500 K and 100% silicate (*crosses* & *dashed line*). From Groenewegen (2006c).

2.2. Variability

Variability is another main characteristic of AGB stars. Mira variables have peak-to-peak amplitudes larger than 2.5, 0.9, and 0.4 mag in V, I, and K, respectively, and are therefore easy to find. The disadvantage is that pulsation amplitude and period are not sufficient to discriminate O-rich from C-rich objects, and that the observations are (observing) time-demanding. An advantage is that Miras follow a tight period-luminosity relation and hence (relative) distances can be derived.

The bars of the SMC and LMC have been surveyed with the OGLE and MACHO surveys, and the resulting databases have been extensively data-mined

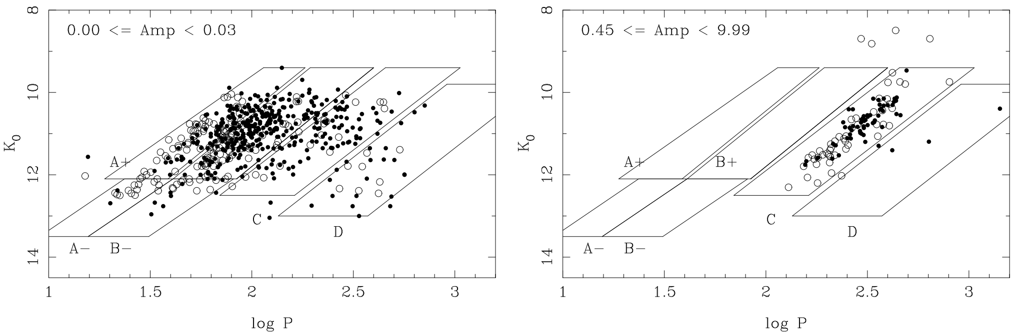

Figure 2. *K*–band *P–L* relation for the LMC. Panels indicate selection on *I*–band amplitude as indicated in the upper left corners. Carbon stars are indicated by filled circles, M and S stars by open circles. Boxes related to the "ABCD" sequences (Ita et al. 2004) are indicated. From Groenewegen (2004).

for red variables, starting with the pioneering work of Wood et al. (1999). By selecting on the basis of pulsation amplitude, different sequences are populated, as illustrated in Figure 2, with the largest amplitude Mira variables belonging to sequence "C". For a summary of the results of the microlensing surveys on red variables in the MCs, I refer to Groenewegen (2006b).

Studies of other LG galaxies are those by (a) Bersier & Wood (2002), who describe 85 LPV candidates in Fornax; (b) Gallart et al. (2004), who propose 6 LPV candidates in Phoenix; (c) Rejkuba et al. (2003) and Rejkuba (2004), who found 1146 LPVs in NGC 5128; and (d) Snigula et al. (this conference), who identify 11 / 2 / 52 / 0 LPV candidates in, respectively, Leo A / GR 8 / Pegasus / DDO 210.

A number of studies have appeared recently on variables in M31. Ansari et al. (2004) present results from the AGAPE gravitational microlensing survey. They present astrometry and photometry on 1579 variables stars in a $10' \times 14'$ field. They observed the field for 3 years and obtained between 40 and 80 epochs. The *B–R* colors and *R* magnitudes suggest that the majority are LPVs. Periods are presented for only 54 objects, however. Fliri et al. (2006) present results from the WeCAPP microlensing survey. A field of $16' \times 16'$ was monitored in *R* and *I* over 3 years with 200–400 epochs. 23781 variable sources are detected, of which 19167 are classified as "regular or semi-regular red variables." Mould et al. (2004) monitored 33 fields covering 5 strips of about $10' \times 60'$ in *I* for over 6 years, with 13–17 epochs per field. Single-epoch *JHK* photometry was also carried out, and astrometry and 4–band photometry is presented for 1915 LPVs. Using the period derived from *I*–band monitoring and single-epoch *K*–band photometry, they present a period–luminosity relation. Naturally there is quite some scatter, but there is more than one would expect even from single-epoch data. Some of the stars that are significantly brighter than the LMC *P–L* relations shifted to the distance of M31 can be identified with supergiants (as they seem associated with the ring of star formation in M31), but there are also objects at periods longer than 600 days that are 2 mag fainter than the *P–L* relation.

2.3. Narrow-band Surveys

This technique uses the specific spectral characteristic of late-type stars, where strong molecular TiO bands develop in M stars, and C_2 and CN bands in C stars. First introduced by Wing (1971) and Palmer & Wing (1982) and then applied by Richer et al. (1984) and Aaronson et al. (1984), the method typically uses two broad-band filters from the set V, R, I and two narrow-band filters near 7800 and 8100 Å, which are centered on a CN band in carbon stars (and near-continuum in oxygen-rich stars), and on a TiO band in oxygen-rich stars (and continuum in C stars), respectively. In a [78-81] versus $V–I$ (or $R–I$) color-color plot, carbon stars and late M stars clearly separate redward of $V–I \approx 1.6$. For an illustration of this, see Cook & Aaronson (1989) or Nowotny & Kerschbaum (2002).

By now a large fraction of LG galaxies have been surveyed, at least partially, using these narrow-band filters. For recent reviews see Azzopardi (1999) and Groenewegen (1999, 2002, 2006a,b). The most recent works *not listed in these reviews* include surveys by Battinelli & Demers (2005a), who find 15 C stars in the disk of M31 beyond 30 kpc along its major axis, and Battinelli & Demers (2006), who identify 46 C stars in DDO 190. In addition, Battinelli & Demers (2005b,c) summarize their work on over 10 LG galaxies regarding the standard candle aspect of the C-star I-band luminosity function and the calibration of the C/M ratio versus metallicity. Kerschbaum et al. (2004) report 51 C stars in (the direction of) M32, and Spindler et al. (2006) found 40 C stars in Leo I (19 new), 11 in Leo II (6 new), and 2 in Draco (none new). Finally, Harbeck et al. (2005) found one C-star candidate in And IX.

Figures 3 and 4 show updated versions (cf. Groenewegen 2006a) of the well-known relations between the total number of C stars and absolute (visual) magnitude of the parent galaxy, and the relation between the C/M number ratio and (mean) metallicity of the parent galaxy. The lines are not fits to the data but are taken directly from Battinelli & Demers (2005b,c), who discussed specifically the dozen galaxies they have observed over the last 6 years. The extended dataset fits these lines very well. Outliers are NGC 55, NGC 300, and NGC 2403 whose surveys for AGB stars from the 1980s are incomplete.

Figures 5 and 6 show updated versions of the carbon star luminosity functions. The following changes, relative to Groenewegen (2006a), have been made: (a) the V, I data from Brewer et al. (1995) for M31 (the dashed line) has been converted to $m_{\rm bol}$ using the bolometric correction from Nowotny et al. (2003), as was already the case for the other galaxies in this plot for which V, I data are available, and the LF now agrees much better with the LF of Battinelli et al. (2003, solid line); (b) M33, IC 10 and DDO 190 are added; and (c) the LF of Ursa Minor is not reproduced here for reasons of space.

The fact that LG galaxies are increasingly surveyed in the infrared as well allows one to compare the selection of M and C stars using infrared data with that using the narrow-band filter system. Demers et al. (2006) has done this for NGC 6822. AGB stars are selected as being brighter than the tip of the RGB, with M stars having $1.07 < (J–K)_\circ < 1.36$, and C stars having $(J–K)_\circ \geq 1.36$ (following Cioni & Habing 2005b). In the region of overlap the objects are correlated with the narrow-band data of Letarte et al. (2002). From the 85 infrared selected C-star candidates, 69 fall in the region in the [CN-TiO] versus

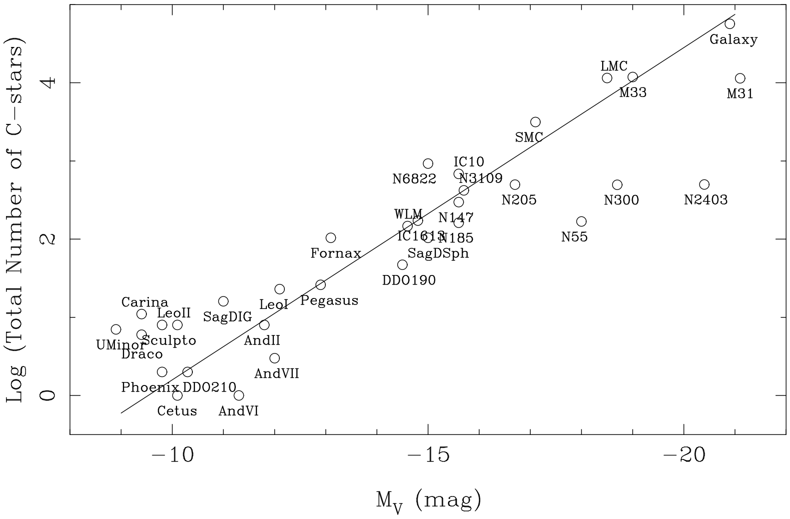

Figure 3. Updated version (cf. Groenewegen 2006a) of the relation between the total number of C stars and absolute (visual) magnitude of the parent galaxy. The line is not a fit to the data but comes from Battinelli & Demers (2005c) who considered mainly the dozen galaxies they surveyed.

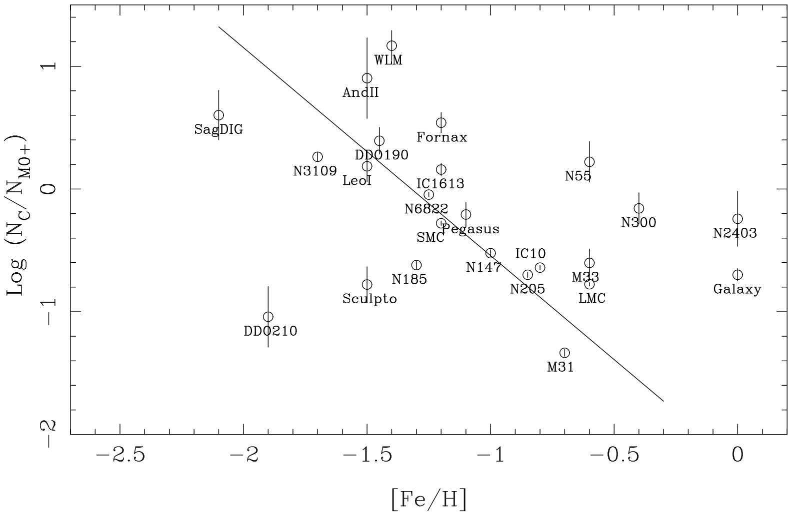

Figure 4. Updated version (cf. Groenewegen 2006a) of the relation between the C/M ratio and the metallicity of the parent galaxy. The line is not a fit to the data but comes from Battinelli & Demers (2005b) who considered the dozen galaxies they surveyed.

R–I color-color diagram occupied by the C stars, and 16 do not (10 are inside the region used to define M stars, and 6 show bluer colors). These stars have a *J–K* color close to the limit used. Of the 207 infrared-selected M-star candidates, 21 are in or close to the region defined by the C stars, 3 have *R–I* colors indicating a cool object but have a [CN-TiO] index intermediate between C and M stars,

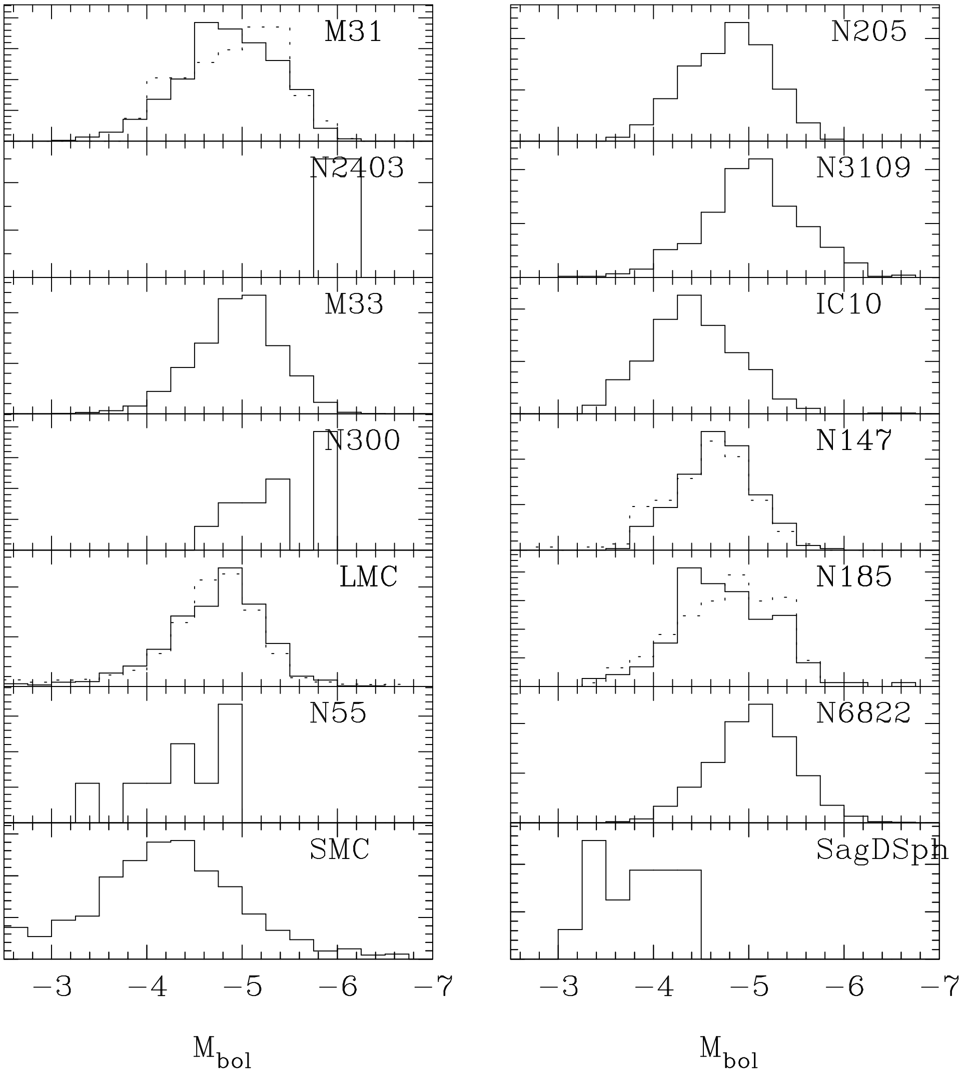

Figure 5. Updated version (cf. Groenewegen 2006a) of the normalized carbon star luminosity functions (LFs), ordered by decreasing M_V of the galaxies, ordered top to bottom, left to right. The number of C stars used to calculate the LFs varies from galaxy to galaxy. In the case of SMC and LMC, the lowest luminosity bin is cumulative.

about 45 have bluer colors than used to define M stars, and about two-thirds of the sample are actually inside the region that defines M stars.

These results indicate that a slightly "purer" sample of infrared-selected C stars might have been obtained by selecting slightly redder objects. It is not clear if this means redder than 1.36 in $(J–K)_\circ$ or if the foreground extinction, which is substantial with $A_V = 0.8$, was slightly underestimated.

It is not discussed in Demers et al. (2006) if increasing the lower limit for M star selection would remove the bluer stars in $R–I$. The current selection criterion implies an oxygen-rich sample that is roughly 10% contaminated by

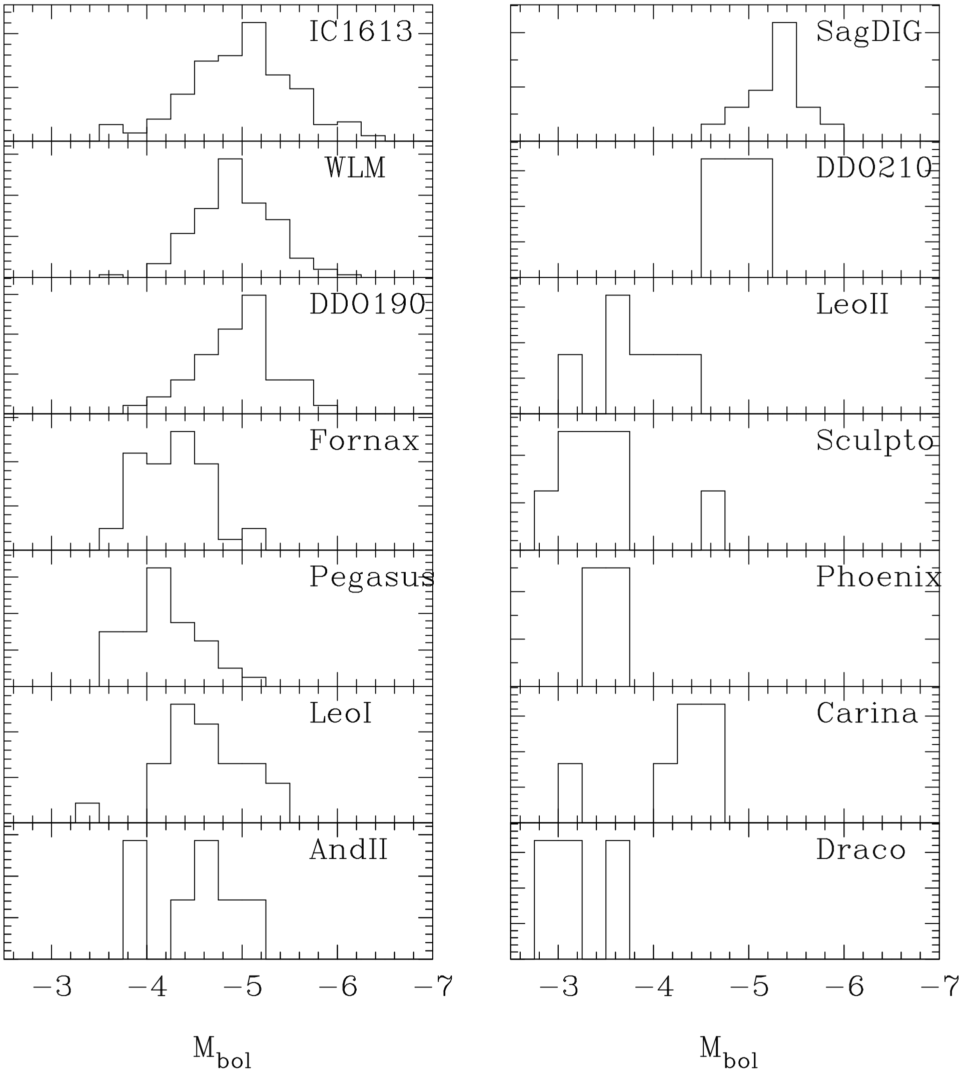

Figure 6. Luminosity functions (continued).

C stars, and with 20% stars that are bluer than used to define M stars in the narrow-band surveys.

A different view on the same topic is the following. Letarte et al. (2002) identify 904 C stars and derive a C/M ratio of 1.0 ± 0.2 in a $28' \times 42'$ field centered on NGC 6822. Cioni & Habing (2005b) observed a $20' \times 20'$ area in *IJK*. Selecting stars above the RGB tip and using 1.36 as the division between C and M stars in J–K, they find 1511 C stars and a C/M ratio of 0.32. Kang et al. (2006) observed a $6.3' \times 3.6'$ field. They use the criterion J–$K > 1.53$ and H–$K > 0.5$ to select 141 C stars and derive a C/M ratio of 0.27. Their selection criterion is based on the NIR colors of the known C stars from Letarte et al.

The fact that Kang et al. assume a redder limit for the selection of C stars probably explains why they have relatively fewer C stars compared to Cioni & Habing; 141 × (20 × 20) / (6.3 × 3.6) is about 2500 while Cioni & Habing have

1511 C stars (the density of C stars is not uniform as well). As the C/M ratio is very similar, their selection based on J–K and H–K must also have led to fewer M stars than in Cioni & Habing.

The large discrepancy in C/M ratio between the infrared studies and the narrow-band work is likely due to a larger number of "M stars" in the infrared work. As already mentioned earlier in discussing the results by Demers et al., even selecting M stars as having $1.07 < J{-}K < 1.36$ results in more M stars than found by the narrow-band surveys. **No** lower limit on the selection of M stars in J–K, as appears to be the case in Kang et al. and Cioni & Habing (the bluest stars included have $J{-}K = 0.8$), will therefore lead to too many "M stars" and hence to a lower C/M ratio.

3. Conclusions and Future Work

The narrow-band surveys of the LG are fairly complete. Notable exceptions are Fornax DSph* (at 140 pc distance), LGS3 (620 pc), Leo A* (800 pc), Sextans B* (1320 pc), Sextans A* (1440 pc), IC 5152 (1700 pc), and GR 8 (2200 pc). It might also be worthwhile to re-do NGC 55* (2200 pc), NGC 300* (2200 pc), and NGC 2403* (3600 pc), for which only incomplete data from the 1980s exist. A search for AGB stars would certainly be successful as PNe are known to exist in almost all of these galaxies (those marked by a *). Crowding may be an issue from the central parts of the most distant galaxies (e.g. DDO 190 at 2.8 Mpc), but is not an issue in e.g. NGC 3109 at 1.3 Mpc.

The largest telescopes which currently have the CN, TiO narrow-band filter system installed are SOAR (4.1-m, 5.2′ FoV), CFHT (3.6-m, $42' \times 28'$ FoV), WIYN (3.5-m, 9.6′ FoV) and the TNG (3.5-m, 9.4′ FoV).

The first results of the IRAC *Spitzer* observations of WLM presented at this conference reveal a significant population of red stars not detected in the narrow-band survey for this galaxy. In the near future, analysis of IRAC observations of other LG galaxies will reveal if this is a more general phenomenon. We may need to revise our understanding of mass loss at low metallicity if the presence of obscured AGB stars is more widespread than we now believe.

Related to this, an increasing number of LG galaxies are being observed in the near-infrared. Simple infrared criteria have been used to separate C from M stars but a comparison with the results obtained using the narrow-band filter system suggests that the infrared criteria need refinement as they lead to the selection of too many C stars, and far too many oxygen-rich stars that are earlier than spectral type M (as defined by the narrow-band surveys).

Additional information that might be used in classification is variability. Projects like super-MACHO and OGLE–III continue to observe the MC and Galactic Bulge regions. Some work on LG galaxies is being carried out using the SIRIUS camera on the IRSF in South Africa. A revolution is this respect in the more distant future will be the LSST (see Ivezić, this conference) which will observe the entire visible sky every few days.

In a nearer future abundance studies of AGB stars in LG galaxies will become available. Some results have been presented by de Laverny et al. (2006) for the SMC and for C stars in the Sag DSph using VLT/UVES, and by Wahlin et al. (2006, and this conference) who have observed 50 C stars in the MCs, Sculptor, Carina and Fornax using VLT/ISAAC. With the commissioning of VLT/CRIRES a very high resolution infrared spectrograph will become available that is well suited for abundance studies.

Observations that also will be significant in the intermediate future are heterodyne observations with ALMA. For a few dozen bright and red AGB stars it will be possible to detect the lower-transition CO lines (Groenewegen 1996) and thereby determine the expansion velocity and the gas mass-loss rate, and by comparison to the dust mass-loss rate, the important dust-to-gas ratio.

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Discussion

Woitke: Can you estimate the total number of AGB stars in the Galaxy? What is the fraction of embedded IR sources (O-rich/C-rich)?

Groenewegen: The number of AGB stars is based on an extrapolation of the surface density of carbon stars in the solar neighborhood (Groenewegen et al. 1992, A&A 253, 150) and a C/M ratio of 0.2. Therefore the number is $\pi(15)^2 \cdot 80 \cdot (1 + 1/0.2) \cong 340\,000$. The estimated number of embedded sources is about 10%.

Wing: When counting C and M stars by narrow-band photometry, a change in filter width affects C and M stars differently and so changes the ratio. Most of this work, as in your illustration, is based on filter widths of about 50 Å. If you widen the filter to 100 or even 150 Å, you will still catch the same C stars, but you reduce the number of M stars. In some of the early work relatively wide filters were used and only M stars later than about M4 were counted. What data were used for the C/M ratio you quoted for the Galaxy?

Groenewegen: The C/M ratio of ~ 0.2 is based on the work of Herman (1988, A&AS 74, 133) and Jura & Kleinmann (1992, ApJS 79, 105; ApJS 83, 329).