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ABSTRACT. Study of the late-type stellar content in external galaxies provides numerous clues for the theory of stellar evolution, for star-formation scenarios in galaxies, and for proper models of the luminosity evolution of galaxies which are then used in cosmological studies. In addition, these late-type stars can be used as distance indicators themselves and yield a local value of the Hubble constant consistent with recent Cepheid determinations.

1. SURVEYS OF PECULIAR RED GIANT STARS

For the purposes of this review we will define a peculiar red giant (PRG) star observationally as a star with $(V-I)_o > 1.5$ and $M_{bol} < -4$. This will then include only objects brighter and redder than the tip of the M92 giant branch and will eliminate most first-ascent giant stars. A few supergiants pass the above criteria, but these are so rare (and anyways can be easily eliminated in the surveys via their brightness) that their statistical contribution is entirely negligible. These observational selection criteria will then include virtually all late-type stars that exhibit peculiarities in their spectra including M, MS, S, SC, and C stars. Of course, a pure photometric selection criterion as described above provides no spectral information. Even so, Reid and Mould (1984) were able to use only these photometric criteria to provide important information on the LMC AGB luminosity function. Some of the surveys that have been carried out in external galaxies do provide some spectral information from low dispersion objective prism observations (Westerlund 1960; Sanduleak and Philip 1977; Westerlund et al 1978), or transmission grating spectroscopy (Blanco, McCarthy, and Blanco 1980; Azzopardi, Lequeux, and Westerlund 1985), or from narrow band imagery (Richer, Crabtree, and Pritchet 1984; Cook, Aaronson, and Norris 1986; Pritchet et al 1987).

2. WHY ARE PRG'S IN EXTERNAL GALAXIES IMPORTANT?

Over the past decade the study of PRG's in external galaxies has provided important constraints on a wide range of important astrophysical problems. We highlight 4 of these below.

(1) In the field of stellar evolution theory of late type stars (see review by Iben and Renzini 1983, as well as more recent contributions of Lattanzio 1986a, 1986b, 1987) observations, particularly of carbon stars in the Magellanic Clouds allowed, for the first time, isolation of a complete sample of such objects. This was made possible by the grism surveys of Blanco and his collaborators (Blanco, Blanco, and McCarthy 1978; Blanco, McCarthy, and Blanco 1980; Blanco and McCarthy 1983) as well as Westerlund and his group (Westerlund 1964, 1965; Westerlund et al 1978). Luminosity functions constructed from these data and compared with theory (Richer 1981a, 1981b, Frogel et al 1981) showed conclusively that the existing theory predicted too few low luminosity carbon stars and too many high luminosity ones. This was critical because at the time it was felt that luminous AGB stars were the sole source of s-process elements in the solar system distribution. While some progress has been made in resolving the difference between the theoretical and observed luminosity functions (Lattanzio 1987), the problem of the origin of the s-process elements remains, and must be considered an outstanding problem in stellar nucleosynthesis. The current view regarding the lack of luminous AGB stars seems to have converged on the idea that mass loss rates are much higher than that obtained with a Reimer's mass-loss coefficient between a third and a half (Frogel and Richer 1983, Reid and Mould 1984).

(2) The question of the star formation history in a galaxy is important for understanding galactic evolution. In turn, a model of galactic evolution is critical in interpreting the colors and magnitudes of galaxies at cosmologically interesting red shifts. In NGC 205, Richer, Crabtree, and Pritchet (1984) showed that this galaxy must currently be experiencing a burst of star formation as the number of PRG stars presently observed was much smaller than expected given a constant star formation rate and the number of luminous blue stars found. Effectively, the PRG's and the blue luminous stars allowed the star formation rate to be sampled at two different epochs. An equally important result was found by Reid and Mould (1984), who detected a spatial variation in the AGB luminosity function in several fields of the LMC. More luminous AGB stars were found in regions of more active star formation. Reid and Mould conclude that the AGB luminosity function is a sensitive probe of the star formation history of a galaxy. What is currently required, however, before the AGB luminosity function can be used to model quantitatively this history, is an empirical determination of the relation between stellar age and the height to which a star rises on the AGB.

(3) The evidence is now rather compelling that galaxy colors and luminosities evolve (Djorgovski, Spinrad, and Marr 1985). Thus, in order to use galaxies as probes of the cosmos to determine cosmologically interesting parameters such as the deceleration parameter q_o, their evolution must be understood. For example

to take a simple case, stellar evolution will make a distant galaxy appear brighter, and unless this is taken into account its distance will be underestimated.

Chokshi and Wright (1987) have shown, in a theoretical paper, that a population of AGB stars can make significant changes to the red and infrared color evolution of a galaxy. Lilly (1987) quantified these results by showing that adding the effects of the AGB to galaxy evolution models provides much better fits to the observed (U-V) versus (V-H) plots of distant ($z>0.5$) galaxies.

(4) Theory predicts, and observations confirm (Richer, Pritchet, and Crabtree 1985), that some PRG's (in particular carbon stars) are useful standard candles for the determination of distances to nearby galaxies. Carbon stars have a small dispersion in their absolute I magnitude (+/-0.47 magnitudes for a complete LMC sample, Richer 1981a), are luminous ($<M_I>=-4.75$), are easily detected in galaxies with distances out to 5 Mpc, and should not suffer from undue foreground contamination. While M supergiants are easily confused with Galactic M dwarfs, extragalactic carbon stars suffer virtually no Galactic contamination. Empirical knowledge of the carbon star luminosity function in a wide variety of galaxies is thus desirable to test their utility as distance indictors.

3. DETECTION OF PRG'S IN EXTERNAL GALAXIES

Within the immediate environs of the Milky Way Galaxy, PRG's can be located from low dispersion objective prism or from transmission grating spectroscopy. A summary of applications of this method to the dwarf spheroidal companions of our Galaxy can be found in Aaronson and Mould (1985). However, in more distant systems, or in more crowded regions of nearby galaxies, the smearing out of a stellar image even in a very low resolution spectrum can produce image crowding to such an extent that all information is effectively lost. Figure 1 provides a dramatic example of this. The upper panel of this Figure contains a direct image of a region of the plane of the Milky Way in the direction of the constellation Circinus. The lower panel is a low resolution prism plate of the same region. The crowding is so severe in this latter frame that classification of the spectra is impossible. However, it certainly does appear possible to carry out stellar photometry on the images in the upper panel.

This was the motivation that led us to develop a purely photometric system that would be capable of providing spectral information for PRG's in extremely crowded systems. The advent of CCD cameras, with their high quantum efficiency and good red response provided the ideal detector for such a system. The photometric system developed uses two narrow band filters which closely mimic bandpasses in Wing's (1971) eight-color system. These two filters are nominally centered at 7800 and 8100Å, both with $\Delta\lambda=140$Å. The 8100 filter measures CN ($\Delta\nu=+2$), while the 7800 filter is sensitive to TiO ($\Delta\nu=-1$) in M stars and serves as a continuum filter for carbon stars. The

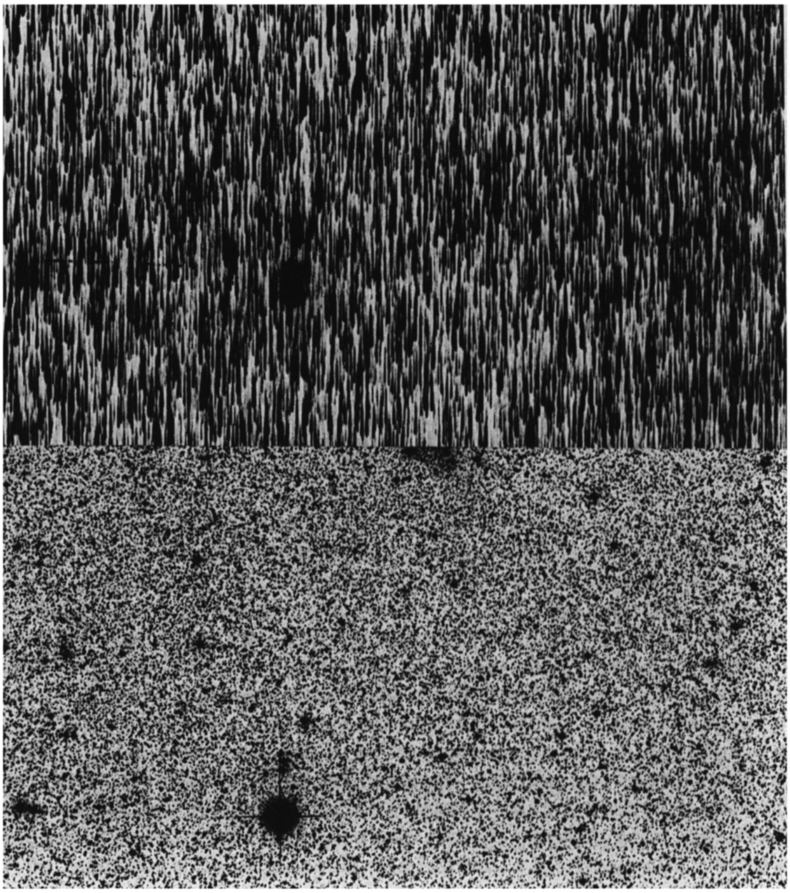

Figure 1: A direct V image of a region of the plane of the Milky Way is seen in the upper panel. In the lower panel an objective prism photograph of the same field is displayed. Crowding in this field makes it almost impossible to classify the spectra.

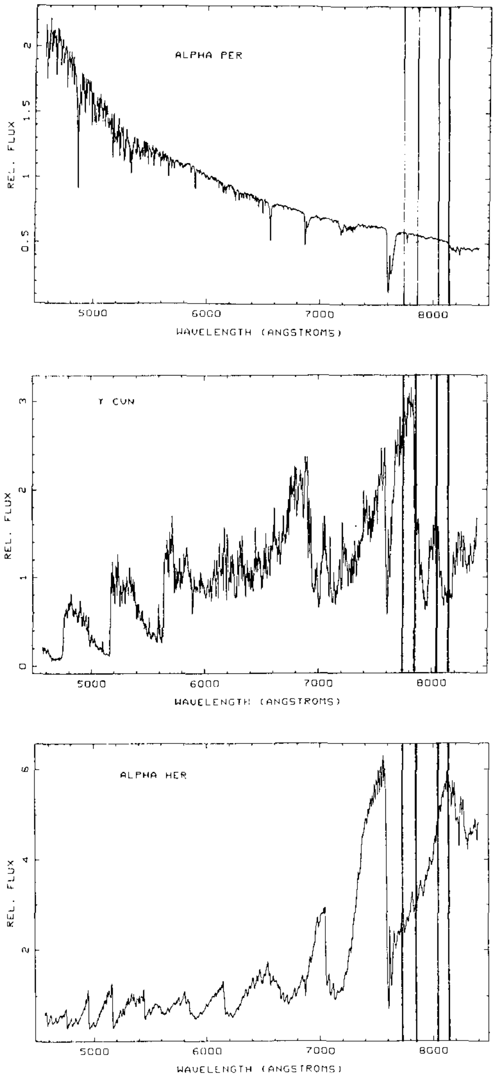

Figure 2: Operation of the photometric system developed to locate PRG's in external galaxies. The 7800 Å filter measures continuum in carbon stars and TiO in M stars. The 8100 Å filter measures CN in carbon stars and continuum in M stars. Very hot stars have (81-78) colors similar to that of carbon stars.

operation of this filter system is illustrated in Figure 2 where the filter bandpasses are overlaid on the spectra of three types of stars; an F star, a carbon star, and an M star. Carbon stars have positive (81-78) colors, while M stars have a negative index in this color. However, measurement of the colors of very hot stars yields colors similar to that of the carbon stars because of the decreasing flux with wavelength through the region of the spectrum defined by the filter system. Hence, with only the single (81-78) color it is not possible to distinguish carbon stars from O and B stars The solution to this is to include in the system two broad band filters (usually V and I). Note also from the spectrum of Alpha Per that the narrow band color index is insensitive to temperature in stars of intermediate spectral classes.

This photometric system was tested on PRG's of known spectral type in the LMC as well as on several Galactic standards of earlier spectral type. The resulting color-color diagram is shown in Figure 3 (taken from Richer, Pritchet, and Crabtree 1985). The main point to note is the insensitivity of early type stars to the (81-78) color (these stars have little or no CN or TiO), and the bifurcation of the diagram for (V-I) greater than 2.0 cleanly into two regions. One of these regions contains exclusively oxygen-rich stars, while the other is occupied only by carbon-rich ones. These two areas are separated by about 1 magnitude in the (81-78) color.

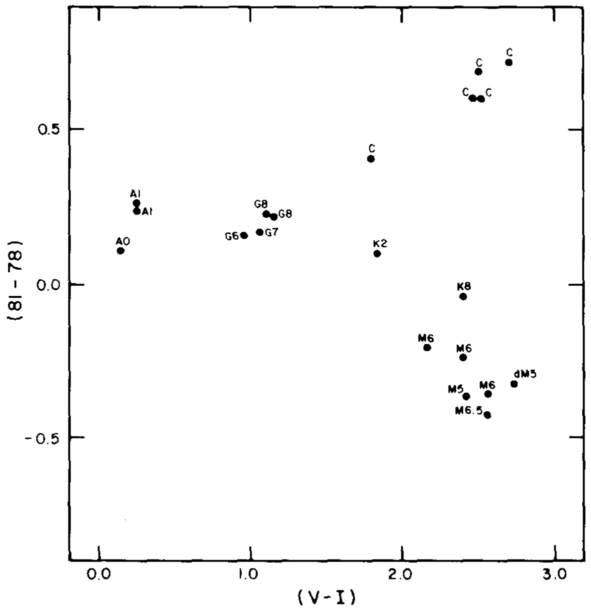

Figure 3: The (81-78) narrow band color plotted against broad band (V-I) for a selection of PRG's in the LMC and some Galactic standards. Note the separation of oxygen-rich and carbon-rich stars for (V-I) >2.0.

We have applied this photometric system to about half a dozen galaxies, while Aaronson and his collaborators (Cook, Aaronson, and Norris 1985) have used a similar photometric system on 5 extragalactic systems. One of the galaxies that both groups have investigated is M31. Figure 4 illustrates this galaxy together with the location and approximate size of the single field which we observed in it in the left panel. The right panel shows the CCD field observed through the two narrow band and two broad band filters. The color-color diagram constructed from this data is shown in Figure 5 (Richer and Crabtree 1985). From a comparison with Figure 3, five carbon stars and numerous M stars are clearly present in this field.

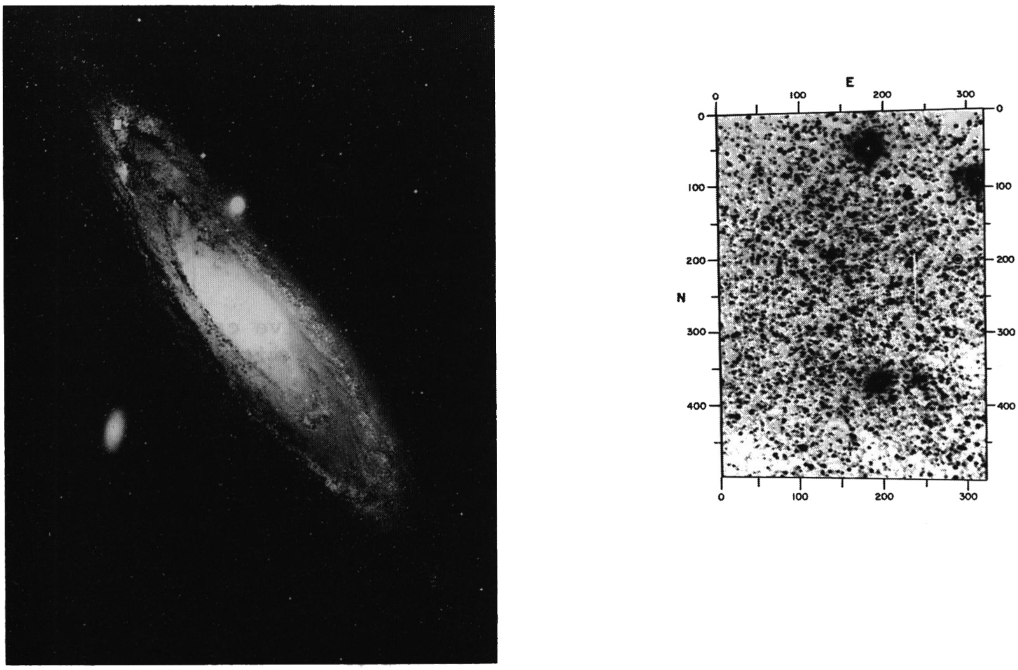

Figure 4: Left panel: The Andromeda galaxy indicating the location and approximate size of the CCD field surveyed in it to locate PRG's. Right panel: The I CCD frame of the field observed in M31. These latter data were obtained at the Cassegrain focus of CFHT.

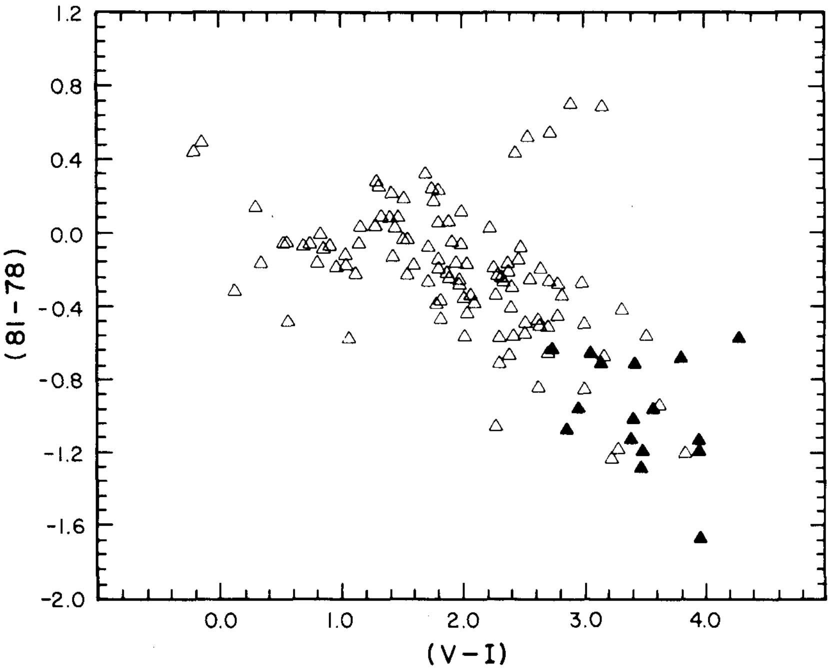

Figure 5: Color-color diagram of the M31 data. Five carbon-rich stars are seen together with 41 M stars with spectral types later than M5.

4. RESULTS OF SURVEYS FOR PRG'S IN EXTERNAL GALAXIES

The surveys carried out by our group, by Aaronson and his collaborators, by Reid and Mould, and by Blanco and his collaborators have resulted in new insight into the uses of PRG's in understanding the late phases of stellar evolution, but especially they have been extremely useful in providing new ideas into the star formation history in nearby galaxies and as distance indicators. In the following three subsections I indicate what, in my view, have been the three most important results from these surveys, and suggest future directions.

4.1 THE CARBON TO M (C/M) STAR RATIO

One of the first results to come out of the surveys for PRG's in external galaxies was the observation by Blanco, Blanco, and McCarthy (1978) that the ratio of the number of carbon to late M type stars (M5 or later) in the SMC, LMC, and Galactic bulge was correlated with the metal abundance of that system. The sense of the correlation is that more metal poor systems possess more carbon stars per late M type star (C/M larger as [Fe/H] lower). The most current version of this correlation involves 9 galactic systems that are spirals or irregulars including two that are outside the Local Group. This correlation is shown in Figure 6 and is taken from Pritchet et al (1987). The correlation is quite remarkable covering more than two dex in C/M and more than one dex in metallicity.

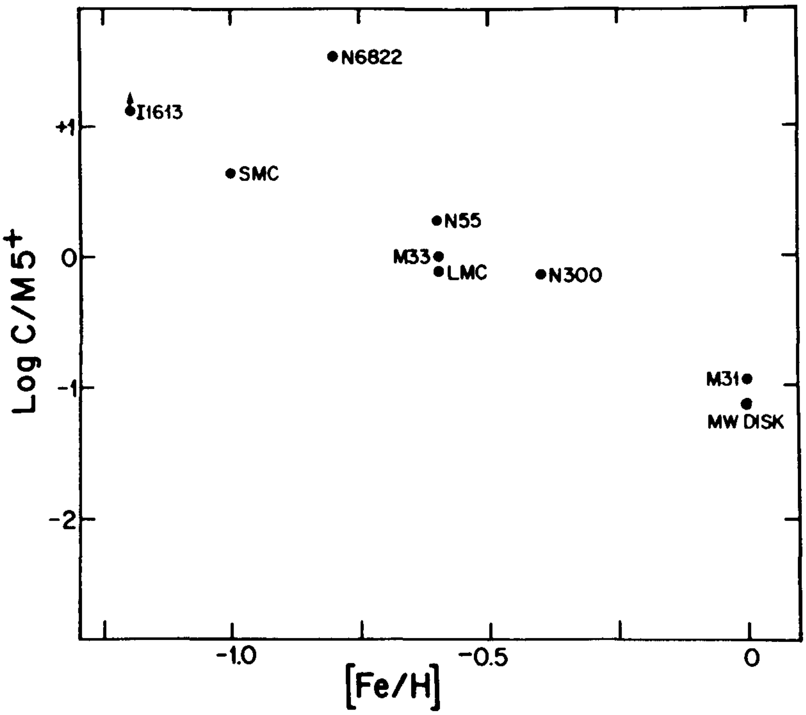

Figure 6: Plot of the C/M ratio versus [Fe/H] for 9 spiral and irregular type galaxies that have been surveyed for PRG's.

There are two major competing explanations for the correlation seen in Figure 6. The first suggests that it occurs because decreasing metallicity drives the giant branch to higher temperatures, thus decreasing the number of oxygen-rich giants with spectral types later than M5. The second explanation suggests that metal-poor stars are more easily turned into carbon stars because they begin with a low oxygen content, and thus a smaller amount of carbon has to be convected to the surface in order to produce C/O>1. It may be possible to distinguish between these two explanations by considering the total population of carbon stars in these different systems. If it is true that the high C/M ratio seen in low [Fe/H] galaxies is due only to the color of the giant branch, then the number of carbon stars in a galaxy should scale simply as the luminosity of that galaxy, and be independent of the metal abundance of that system. However, if the correct explanation to the correlation lies in the ease of producing carbon-rich stars in low metal abundance systems, then one would expect that the number of C stars per unit of galaxy luminosity should exhibit a strong dependance on [Fe/H]. The relation between the number of carbon stars per unit galaxy luminosity, and metallicity is shown in Figure 7 with the data taken from Pritchet et al (1987). The open circles are data points for the dwarf spheroidals surrounding the Milky Way (Aaronson and Mould 1985) while the open circle with a cross in the center is a single point for the Galactic globular cluster system (Aaronson and Mould 1985). Because the number of carbon stars per unit galaxy luminosity varies strongly with [Fe/H], we can exclude the variation in the temperature of the giant branch as the sole cause of the correlation between C/M and [Fe/H].

While the data in Figure 7 yield a correlation between the number of carbon stars per unit of galaxy luminosity and metal abundance, it is important to note that the correlation exhibits much scatter. In particular, the Magellanic Clouds contain an anomalously large population of carbon stars for their luminosities and abundances, while NGC 55 and 300 contain few such objects. This strongly suggests that some parameter other than metallicity strongly affects the carbon star production rate in galaxies. The most likely candidate is star formation history.

At the moment, we lack a complete explanation of the correlation between the C/M ratio and [Fe/H} observed in extragalactic systems. However, it appears that the time is ripe for a detailed theoretical attack on the problem. The observational data with which we can constrain the theory is well in hand. The new carbon star models (Lattanzio 1987) seem capable of producing the required low luminosity carbon stars seen in the Magellanic Clouds, and these coupled to star formation scenarios should be capable of yielding C/M ratios as a function both of metal abundance of the system and its star forming history.

4.2 THE PRG LUMINOSITY FUNCTIONS IN EXTERNAL GALAXIES

Reid and Mould (1984) first pointed out the importance of

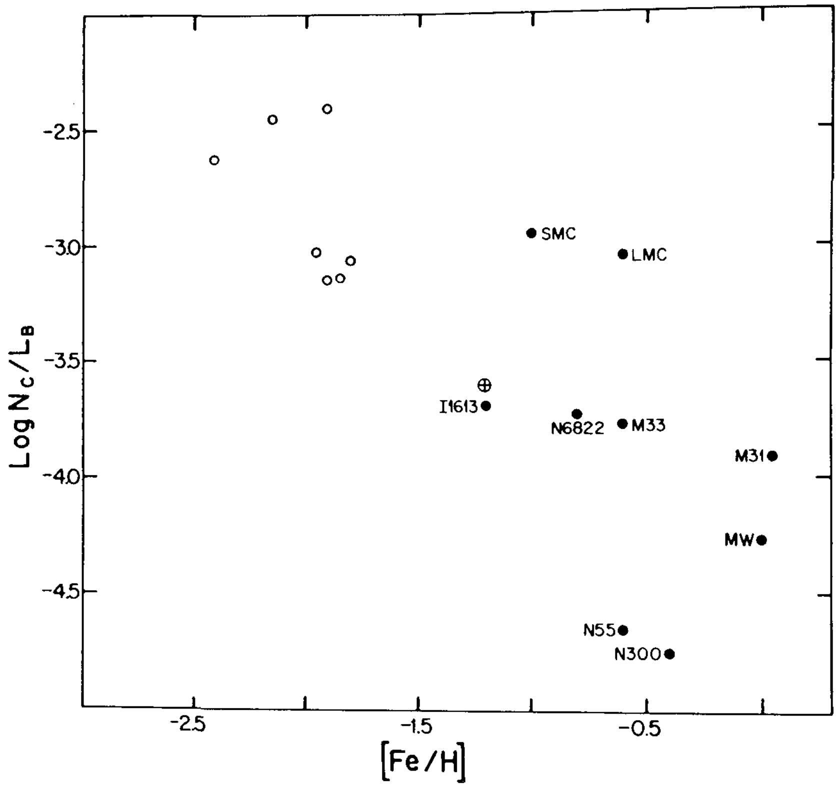

Figure 7: Plot of the number of carbon stars per unit of galaxy luminosity versus metallicity. Open circles-dwarf spheroidals. Closed circles-spiral and irregular galaxies. Cross inside open circle-Galactic globular clusters.

studying the AGB luminosity function in external galaxies. Earlier, several authors (Richer 1981a, 1981b; Frogel et al 1981) had shown that the carbon star luminosity function in the LMC did not agree with theoretical luminosity functions constructed from the models of Renzini and Voli (1981) which were the state-of-the-art models for these stars at that time. Reid and Mould extended this idea to all AGB stars thus ruling out the then fashionable idea that the observed carbon star deficiency at high luminosity was due to nuclear processing of their carbon-rich atmospheres back to more normal composition.

In a series of papers on nearby galaxies (Richer, Pritchet, and Crabtree 1985; Richer and Crabtree 1985; Pritchet et al 1987) we were able to show that the AGB luminosity functions in NGC 300, M31, and NGC 55 were all similar to that in the Magellanic Clouds. These data are collected in Figure 8 wherein we also include the Reid and Mould (1984) LMC AGB luminosity function which is compared to a theoretical function incorporating a constant star formation rate. No reasonable star formation history or IMF slope is capable of producing a model that agrees well with the observations. The agreement between the LMC AGB luminosity function and that in the other galaxies only strengthens the conclusion that star formation history is not the major reason why too few luminous AGB stars are seen. It must be due to the evolution of the stars themselves, and the current idea is that the mass loss rates incorporated into the models have been badly underestimated.

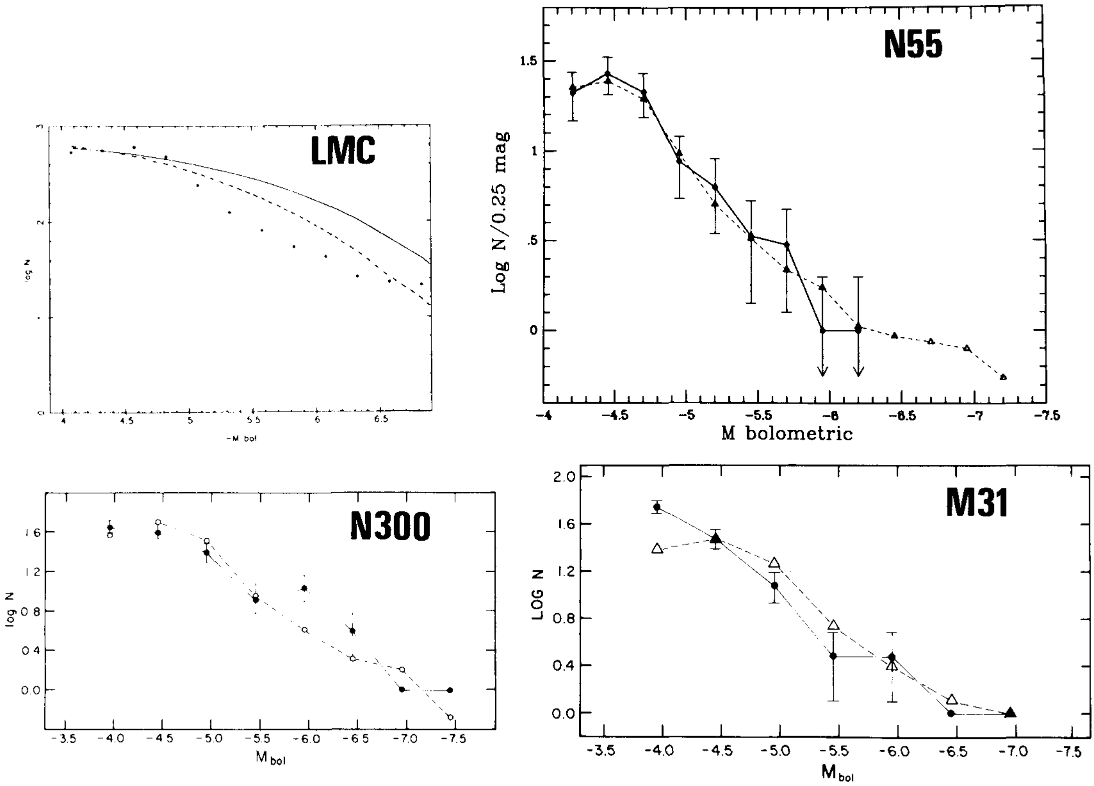

Figure 8: AGB luminosity functions for stars in four different galaxies. The upper left panel is for the LMC. In this panel the points are the data and the solid line is the model AGB assuming a Salpeter mass function and a constant star formation rate. The dashed line is for an IMF with a slope of 3.35. In the remaining three panels the LMC data are replotted for comparison (broken line). In all systems, there is a deficiency of luminous AGB stars compared with the theory.

In a new study, Hudon and Richer (1989) have determined the luminosity function for the AGB in a field in the galaxy NGC 2403. This galaxy, a member of the M81 group, probably represents the limit for ground based photometric studies of PRG's in external galaxies. The apparent distance modulus in V to this system is about 27.4. Thus typical carbon stars are found at about V=26. The luminosity function constructed for this galaxy is shown in Figure 9. Even in this remote system, far removed from the Local Group, we see that, within the errors, the AGB luminosity function remains similar to that of the LMC.

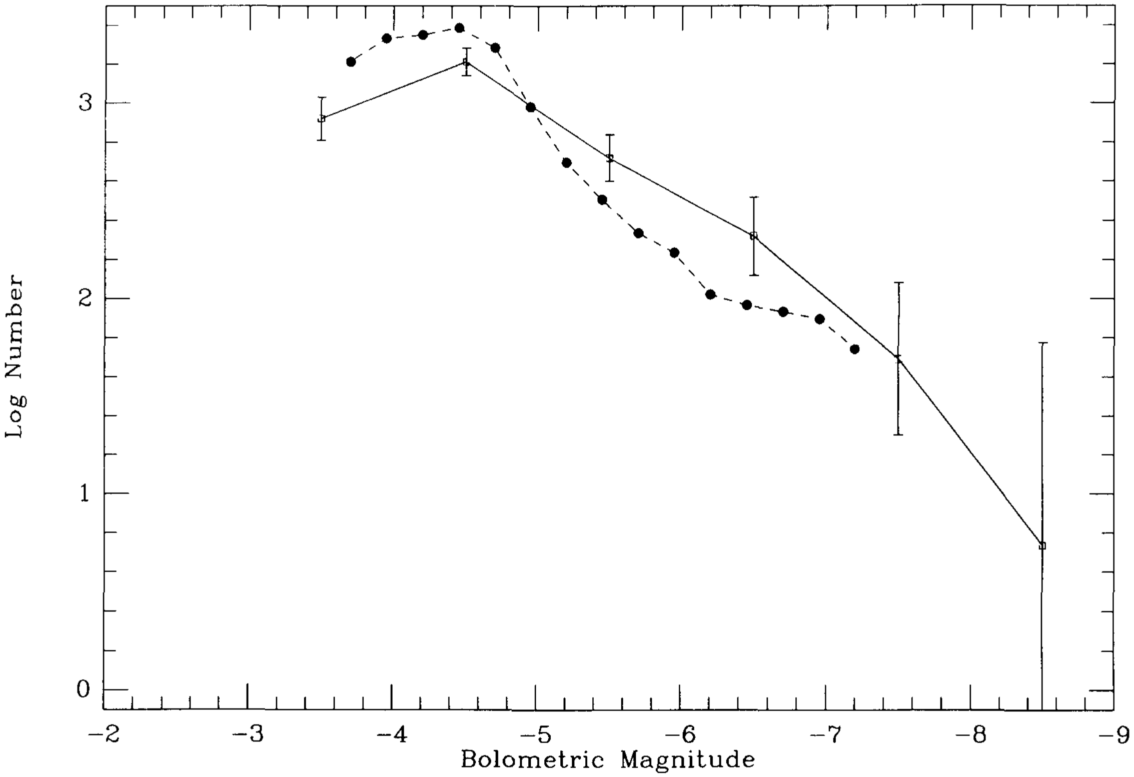

Figure 9: AGB luminosity function for a single CCD field in NGC 2403. The dots refer to the LMC luminosity function.

It should not be concluded, however, that star formation history plays no part in controlling the AGB luminosity function. Reid and Mould (1984) did find some variation in the LMC AGB luminosity functions with position in the galaxy in the sense that more luminous AGB stars were found in regions of more active star formation. An important study that could easily be carried out on several nearby galaxies is to observe their AGB luminosity functions in fields with widely differing star formation rates. This may provide the much needed observational input into the role that star formation history plays in controlling the AGB.

5.3 CARBON STARS AS EXTRAGALACTIC DISTANCE INDICATORS

Richer, Pritchet, and Crabtree (1985) have outlined the reasons why carbon stars should be useful extragalactic distance indicators. Briefly, these reasons are as follows. Carbon stars are luminous, have a small dispersion in their absolute luminosity, have the same luminosity function (within the errors) in diverse extragalactic systems, are fairly easy to locate in an external galaxy, are relatively numerous, and are unlikely to be contaminated by foreground stars in our own Galaxy. A summary of the distances derived to nearby galaxies using carbon stars exclusively is contained in Table 1. These distances are actually obtained differentially with respect to the LMC whose true distance modulus is taken to be 18.45 (Welch et al 1984).

Table 1

Distances to Nearby Galaxies Using Carbon Stars

Galaxy	D(Mpc)	H	M_H	ΔV (km s^{-1})
M 31	0.77	0.91	-23.52	548
M 33	0.78	4.38	-20.08	236
NGC 55	1.34	....	......	...
NGC 300	1.50	6.87	-19.01	222

Also included in Table 1 is the apparent H magnitude of the galaxy (Aaronson, Mould, and Huchra 1980) its absolute H magnitude using the distance derived from the carbon stars, and, in the last column, the observed 21-cm velocity width (van den Bergh 1984).

We can use the data in Table 1 to provide an infrared calibration of the Tulley-Fisher relation (Tulley and Fisher 1977). The linear least squares fit between H and log ΔV yields

$$M_H=5.36-10.55 \log \Delta V \qquad (1)$$

using the data for the three calibrating galaxies. This relation can be used to estimate a value of the Hubble constant using galaxies in the Virgo cluster. The infrared Tulley-Fisher relation defined by the Virgo galaxies yields

$$H=36.69-10.77 \log \Delta V \qquad (2)$$

(van den Bergh 1984), an equation with a slope remarkably similar to that of the calibrating galaxies. Ignoring the small difference in the slope of the two equations, we can then derive a Virgo distance modulus of 31.33. This corresponds to a distance of 18.5 Mpc. From this value and the cosmological redshift of 1322 km s^{-1} for the Virgo cluster, one obtains a Hubble constant H=71.5 km s^{-1} Mpc^{-1}.

This preliminary result appears promising. What is currently needed are several more calibrating galaxies. Good candidates here are NGC 2403, M81, NGC 247, and NGC 253. Studies of the PRG content of these systems should provide rich rewards.

References

Aaronson, M., and Mould, J.R. 1985, Ap.J., 290, 191.
Aaronson, M., Mould, J.R., and Huchra, J. 1980, Ap.J., 237, 655.
Azzopardi, M., Lequeux, J., and Westerlund, B.E. 1985, Astr. Ap., 144, 388.
Blanco, V.M., Blanco, B.M., and McCarthy, M.F. 1978, Nature, 271, 638.
Blanco, V.M., McCarthy, M.F., and Blanco, B.M. 1980, Ap.J., 242, 938.
Blanco, V.M., and McCarthy, M.F. 1983, A.J., 88, 1442.
Chokshi, A., and Wright, E.L. 1987, Ap.J., 319, 44.
Cook, K.H., Aaronson, M., and Norris, J. 1986, Ap.J., 305, 634.
Djorgovski, S., Spinrad, H., and Marr, J. 1985, in New Aspects of Galaxy Photometry, ed. J.L. Nieto (Lecture Notes in Physics, 232), p. 193.
Frogel, J.A., Cohen, J.G., Persson, S.E., and Elias, J.H. 1981, in Physical Processes in Red Giants, eds I. Iben Jr., and A. Renzini (Dordrecht:Reidel), p. 159.
Frogel, J.A., and Richer, H.B. 1983, Ap.J., 275, 84.
Hudon, D., and Richer, H.B. 1989, in preparation.
Iben I. Jr. and Renzini, A. 1983, Ann. Rev. Astr. Ap. 21, 271.
Lattanzio, J.C. 1986a, Ap.J., 311, 708.
Lattanzio, J.C. 1986b, in Calgary Workshop on Late Stages of Stellar Evolution, ed. S. Kwok and S.R. Pottasch, (Dordrecht:Reidel), p. 235.
Lattanzio, J.C. 1987, Ap.J. (Letters), 313, 15.
Lilly, S.J. 1987, M.N.R.A.S., 229, 573.
Pritchet, C.J., Richer, H.B., Schade, D., Crabtree, D., and Yee, H.K.C. 1987, Ap.J., 323, 79.
Reid, N., and Mould, J.R. 1984, Ap.J., 284, 98.
Renzini, A., and Voli, M. 1981, Astr. Ap., 94, 175.
Richer, H.B. 1981a, Ap.J., 243, 744.
Richer, H.B. 1981b, in Physical Processes in Red Giants, ed. I. Iben Jr., and A. Renzini (Dordrecht:Reidel), p. 153.
Richer, H.B., and Crabtree, D.R. 1985, Ap.J. (Letters), 298, L13.
Richer, H.B., Crabtree, D.R., and Pritchet, C.J. 1984, Ap.J., 287, 138.
Richer, H.B., Pritchet, C.J., and Crabtree, D.R. 1985, Ap.J., 298, 240.
Sanduleak, N., and Phillip, A.G.D. 1977, Pub. Warner and Swasey Observatory, Vol. 2, No. 5, p. 105.
Tulley, R.B., and Fisher, J.R. 1977, Astr. Ap., 54, 661.
van den Bergh, S. 1984, Q. Jour. R. Ast. Soc., 25, 137.
Welch, D.L., McAlary, C.W., McLaren, R.A., and Madore, B.F. 1984, in IAU Colloquium 82, Cepeids: Observations and Theory, ed. B.F. Madore (New York: Cambridge University Press), p. 219.

Westerlund, B.E. 1960, Uppsala Astron. Obs. Ann., 4, No. 7.
Westerlund, B.E. 1964, M.N.R.A.S., 127, 429.
Westerlund, B.E. 1965, M.N.R.A.S., 130, 45.
Westerlund, B.E., Olander, N., Richer, H.B., and Crabtree, D.R. 1978, Astr. Ap. (Suppl.), 31, 61.
Wing, R.F. 1971, in Proceedings of the Conference on Late-Type Stars, eds. G.W. Lockwood and H.M. Dyck (KPNO Contr. No. 554), p.145.