SPECTROSCOPY OF RED VARIABLES AND OTHER LUMINOUS RED STARS

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ABSTRACT

Long period variable stars represent the most advanced stage of asymptotic giant branch evolution prior to planetary nebula ejection or catastrophic core collapse. In the Magellanic Clouds through study of the LPVs it has been possible to identify for the first time, stars on the AGB with luminosities right up to the AGB limit ($M_{bol} \sim -7.1$) providing direct evidence that the more massive AGB stars produce supernovae. Because the stars have well defined periods, knowledge of the temperature and luminosity enables the mass to be derived. This review will highlight spectroscopic observations of the LPVs and discuss what information they provide on nucleosynthesis on the AGB in stars of different mass.

1. INTRODUCTION

The spectra of red giant and supergiant stars have always held a fascination because of their bizarre variety and complexity, being dominated by unusual molecular bands. It is believed that nucleosynthesis occurs in red giants during their late evolutionary stages (e.g., Iben and Truran, 1978), but providing observational data to delineate these last stages has proved difficult. This arises for several reasons, firstly the phenomenon is short lived, secondly the masses and luminosities of individual peculiar red giants in the field are practically impossible to determine accurately, and thirdly the atmospheric parameters of such stars are poorly determined. However, spectroscopic and photometric observations made of luminous red giants, (in particular the long period variables) in the Magellanic Clouds have provided a key to the unravelling of the late evolutionary stages of stars of different mass (Wood, Bessell and Fox, 1983: WBF). Many more observations of such stars over a wide wavelength range combined with detailed spectrum synthesis programs such as those of Wehrse (1981), Schmid-Burgk et al. (1981), Tsuji (1978) and Johnson et al. (1980) should permit a detailed understanding of these significant phases in the life of a star.

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Long period variables are a special subset of the red giants and supergiants that cannot be considered in isolation from the non-variable or non-regularly variable stars. In this review we will first pay a tribute to the major programs which have identified red stars in the Magellanic Clouds and survey the follow-up spectroscopic or photometric observations. In the second section we will discuss the importance of infrared photometry in deriving atmospheric parameters independently of the spectral peculiarities, and the special place that long period variables (LPVs) have in the understanding of the last stages of asymptotic giant branch evolution. The observed luminosities and derived pulsation masses of a large number of LPVs will next be discussed in some detail. Finally, the spectra of these LPVs of known mass and luminosity will be compared with each other and with some galactic stars, and possible nucleosynthesis scenarios proposed.

2. OBSERVATIONAL OVERVIEW

The discovery of red giants in the Clouds has involved three approaches, objective prism surveys of the field, two color photographic photometry of selected fields and clusters, and long period variable star searches. The value of such time consuming search programs cannot be over-emphasized. Some of these programs were initiated many years ago but have only recently begun to pay spectacular dividends as large telescopes and more sensitive IR and red photometers and electronic imaging devices enable the detailed follow-up work to be done.

Westerlund's original 1N objective prism survey in the LMC (Westerlund, 1961) has yielded the brightest, red stars (M and N) (Westerlund et al. 1978) which have been further investigated by Crabtree et al., (1976), Richer et al., (1978), (1979), Richer and Frogel (1980) and Richer (1983). Sanduleak and Philip (1977) have also made a IIIaJ objective prism survey to discover the hotter C_2 stars.

Blanco et al. (1978; 1980) have conducted grism surveys of the LMC and SMC which have discovered large numbers of M stars and carbon stars, some of which have been subsequently investigated at CTIO by Cohen et al. (1981), Frogel and Blanco (1983), Richer (1983) and Frogel and Richer (1983). These grism surveys will continue to be a major source for red giant studies. Humphreys (1979) used both the Westerlund and the Blanco surveys to select stars for her investigations of the brightest M supergiants in the Clouds.

Many red giants have also been discovered by direct photographic photometry. Originally only B and V plates were used, but more recently V and I plates have proved very successful at identifying red stars. Gascoigne (1963) noted that many of the globular clusters in the Magellanic Clouds contain stars redder than any found in galactic globular clusters (e.g., van den Bergh, 1975) and Feast and Lloyd Evans (1973) showed that some of these were carbon stars. From V, I studies of SMC fields, Lloyd Evans (1978a,b) found many more such red stars and argued that these also were carbon stars. Red stars were similarly searched for and found in many Cloud globular clusters of so called "intermediate-age" by Lloyd Evans (1980a), Aaronson and Mould (1982) and Mould and Aaronson (1982). These discoveries were followed up with spectroscopic and IR photometric observations by Bessell, Wood and Lloyd Evans (1983) (BWL), Lloyd Evans (1980b,c; 1984), Mould and Aaronson (1979; 1980) and Aaronson and Mould (1982) in their investigations of the origin of carbon stars and extended giant branches. We will return to some of these results later.

Finally, the searches for long period variables. Many of these stars, in particular the most luminous ones, were found by Harvard workers blinking Bruce plates. Identification charts are given in Hodge and Wright (1967, 1977) and periods are given by Payne-Gaposhkin (1971), Payne-Gaposhkin and Gaposhkin (1966), and Wright and Hodge (1971). Periods and charts for additional stars in the SMC were published by Dessy (1959) and Lloyd Evans (1978a). More recently Moore 1983 (private communication), Paltoglou et al. (1984) and Lloyd Evans (1983b) have identified red variables using I plates taken over several years with the SRC Schmidt. These latter programs used automatic measuring machines and promise a steady yield of new red variables as more areas are searched. Infrared photometry of some of these LPVs has been published over the last few years by Glass (1979), Feast et al. (1980) Catchpole and Feast (1981), Glass and Feast (1982) and W.B.F.

3. INFRARED PHOTOMETRY AND LPVS

Although this review ostensibly concerns the spectra of red variables, the IR magnitudes and colors of the stars are of fundamental importance in permitting the bolometric magnitude and effective temperatures to be derived essentially independently of the spectral appearance. Much of the confusion surrounding the properties of the carbon stars and the S stars in the galaxy arises from the adoption of temperature composition and luminosity indicators which are not independent of atmospheric composition. BWL and WBF adopt (J-K)-temperature scales based on occultation measurements of non-variable M giants, Mira variables and carbon stars, (there is some disagreement in the literature as to the correctness of these adopted temperatures and it is hoped that model atmosphere colors can be computed to explore these color-temperature relationships) and use these temperatures for comparing theoretical predictions, such as evolutionary tracks and pulsation properties, with observed magnitude and colors.

The importance of long period variables in stellar evolution studies lies in the fact that these stars are passing through the most luminous phase of their lives, the penultimate short-lived phase on the asymptotic giant branch prior to disruption through envelope expulsion, and that nucleosynthesised elements reaching the surface of the star during this time will be expelled at disruption and enrich the interstellar medium. Study of long period variables should tell us a great deal about these catastrophic events and the processes of nucleosynthesis. But most importantly, the fact that the star has a period means that a pulsation mass can be derived, given knowledge of the luminosity, temperature and value of the pulsation constant Q.

Unlike the galactic field stars, stars in the Magellanic Clouds suffer little interstellar obscuration and are at known distances or at least relatively the same distances in each Cloud, thus the absolute magnitude can be simply derived from the apparent magnitude. As noted above, the (J-K) color can be calibrated in terms of temperature while the bolometric magnitude correction is a function of (J-K) and atmosphere composition (Frogel et al., 1980; Bessell and Wood, 1983b). Finally, the values of pulsation constant Q appropriate for LPVs have been investigated by Fox and Wood (1982) and are further discussed in WBF. Therefore we can derive masses for LPVs in the Magellanic Clouds on the basis of their periods and observed IR magnitudes.

4. THE MASSES, LUMINOSITIES AND SPECTRA OF MAGELLANIC CLOUD LPVS.

In Figure 1 is plotted the absolute bolometric magnitude versus period diagram for the red variables of known period in the Clouds. This data is taken from WBF. The stars seem to fall into two sequences separated by approximately 1 magnitude, and the line of separation appears to coincide with the theoretical luminosity limit for AGB stars. WBF identify the upper group as the young massive core burning supergiants and the lower group as the shell burning (asymptotic giant branch) AGB stars.

Lee (1970) states that Ia, Iab, Ib and II supergiant luminosity classifications correspond approximately to M_{bol} = -7.8, -7.0, -5.7 and -3.6 respectively for M supergiants; thus all the core burning supergiants in fig. 1 should be class Ia or Iab, and the brightest AGB stars should be class Iab or Ib. There are 10 core burning supergiants in fig. 1 which are common to the list of Humphreys (1979). The bolometric magnitudes from the IR colors are on the average 0.3 mag fainter than given by Humphreys, and from the 4 stars with luminosity types, it appears that Iab stars are fainter than -7.5, in good agreement with Lee. We must be aware when interpreting the spectra of stars, that stars classified spectroscopically as supergiants could be either shell burning AGB stars of intermediate mass or core burning supergiants of large mass. Humphreys observed many HV stars which are brighter than any in the WBF sample but this is not significant because WBF only observed stars with known periods, and the brightest supergiants could have periods of over 1000 days and small amplitudes, which makes period determinations very difficult. An additional, complication in the interpretation of the spectra of LPVs is the effect the pulsation has on the atmosphere. One difference between LPVs and class III M giants is indicated by the occultation measurements which show that LPVs have a different (J-K) temperature relation than do non-variable stars. Another noted by Wing (1967), was that TiO band strength versus continuum-temperature relations differ between phases on the rising and falling parts of the light curve in some LPVs. Yet another difference is the existence of strong H_2O bands in

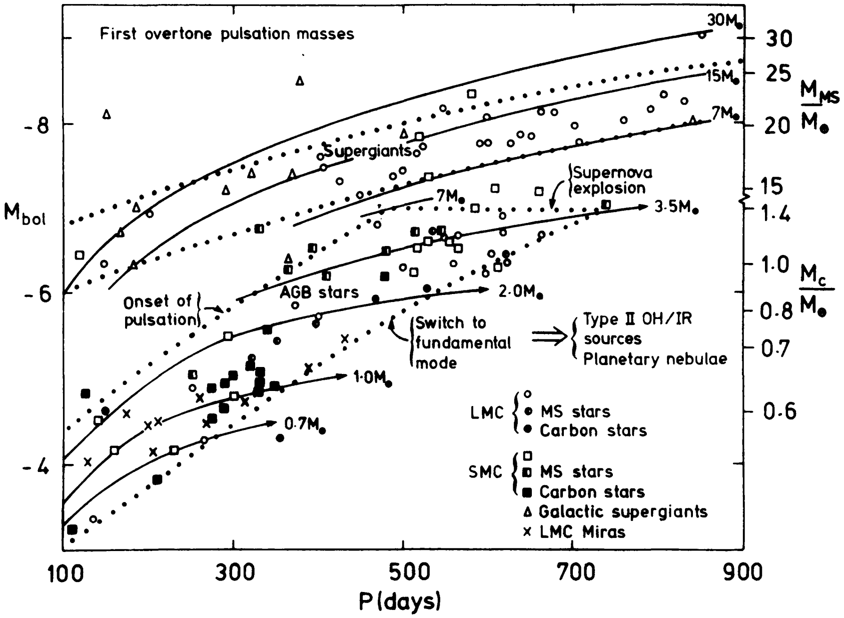

Figure 1. M_{bol} plotted against P for LPVs in the SMC and LMC. Some galactic supergiant variables are also shown. The dotted lines delineate the regions occupied by supergiants and AGB stars and the continuous lines are lines of constant mass assuming that the LPVs are first overtone pulsators. At each luminosity, the core masses (M_c) of AGB stars and the main-sequence masses (M_{MS}) of red supergiants are indicated.

the IR in Miras (LPVs) compared to supergiants (Hyland, 1974). Theoretical exploration of these differences is justified and it seems likely that the degree of "extension" of the atmosphere (Scholz and Wehrse, 1982) is the parameter.

Low dispersion spectra from $\lambda = 0.60\mu$ to 0.85μ have been obtained by WBF for almost all the LPVs of fig. 1. Most of the spectra were obtained with the IDS on the AAT and a sample are shown in fig. 2 together with some galactic stars for comparison. A few SMC stars and comparison stars were obtained with the CCD on the AAT in order to investigate the region of the infrared system bands of ZrO; the spectra cover the range 0.70μ or 0.85μ to 1μ and are shown in fig. 3. Spectral types on the MK system were assigned to all the spectra and details are given in WBF. Many of the stars were observed at different phases and large difference in spectral type were seen. The sample of core-burning supergiant LPVs had spectral types from M0 to M5.5; no unusual heavy elements were evident in their spectra and the CN bands were strong only at some phases for the bluest stars (see eg., HV2255 fig. 2). The spectra of the AGB supergiants

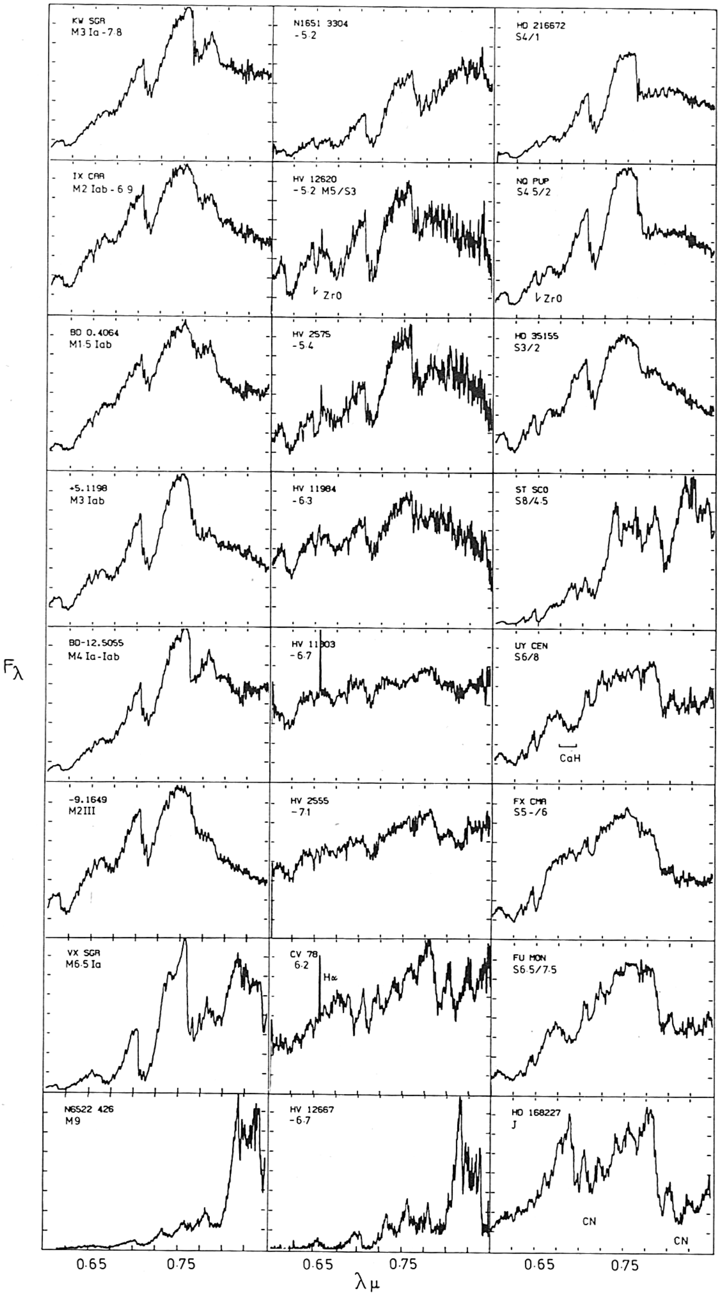

Figure 2. F_λ plotted against λ for a sample of LPVs in the Magellanic Clouds, and a variety of galactic comparison stars. Absolute bolometric magnitudes are given for the LPVs. Data were obtained with the IDS.

and giants were more interesting. No carbon stars were found brighter than $M_{bol} = -6.2$ (CV78), which is close to the known upper luminosity limit for cloud carbon stars (Cohen et al., 1981; and Richer et al., 1979) but more luminous O-rich stars were found, many of which showed strong ZrO bands near $\lambda = 0.65\mu$. Comparison of these S stars with the galactic standards show clearly that none of them are pure S stars with C/O = 1; they all have very strong TiO. In searching for enhanced ZrO, the γ-system of ZrO bands around 0.65μ can be seen reasonably well up to spectral types as late as M5. Later than this, the infrared system bands can be used. Unfortunately there is some confusion due to possible H_2O absorption at these wavelengths, which occurs in LPVs at some phases. It is also not clear in late M stars how much TiO bands with heads at 0.9224μ and 0.9284 contribute to the 0.93μ feature, or how strong the IR ZrO bands are in "normal" M stars. Clearly more CCD spectra of standard M stars are needed. With regard to normality it is interesting that two of the random galactic supergiant stars observed and shown in fig. 2 (i.e., -9°1629 and +5°1198) have quite strong ZrO bands. These stars could be galactic counterparts of these intermediate age Cloud S stars. Many of the upper AGB stars had spectral types later than M7, and one star, shown in fig. 2, HD 12667 ($M_{bol} = -6.7$) had a spectral type of M9+. There was also another interesting carbon star HV 2379 which lay beyond the maximum period line indicated by the other stars. Bessell and Wood (1983a) have discussed the properties of this star in detail. It appears to have ejected a shell during November 1981.

What then do the spectra of these LPVs indicate about nucleosynthesis on the asymptotic giant branch? Let us first consider what investigations of non-variable red stars have shown. The intermediate-age cluster investigations of BWL and Aaronson and Mould and the field carbon star investigations of Richer et al. show that stars in the Magellanic Clouds with masses as low as ~1 $M_\odot$ will all become carbon stars, which is not the case in our galaxy. Using the results of dredge-up calculations, BWL show that there is a minimum stellar mass for which dredge-up and carbon star formation can occur once the luminosity exceeds a critical value and that this minimum mass depends on the envelope metallicity. The metallicity difference between the Clouds and the Galaxy is sufficient to restrict carbon star formation in the galaxy to more massive stars ($M \gtrsim 1.4\ M_\odot$). In a most significant discovery BWL found that many M stars in these intermediate-age clusters with luminosities close to the transition (M→C) luminosity showed strong ZrO bands in their spectra indicating enhanced s-process elements. This was clear evidence that the S stars occur during asymptotic giant branch evolution and that the sequence is M→S→C. Lloyd Evans (1984) and Mould (private communication) have verified this phenomenon in many other clusters. Now theoretical stellar evolution calculations show that helium shell flashes on the AGB produce ^{12}C via the 3-α process and also s-process elements due to neutron capture on heavy nuclei. Furthermore, the carbon and s-process elements can be dredged up to the stellar surface during helium shell flashes (e.g., Iben 1975). The existence of the three spectral types M, S and C among the AGB stars is direct evidence for the above-mentioned nucleosynthetic processes. The carbon stars have dredged up sufficient carbon during shell flashes to produce C/O > 1 as required in a carbon star atmosphere. The S stars which lie on the AGB between the pure M and C stars, have begun dredging up ^{12}C and s-process elements so that the bands of ZrO are enhanced; however, insufficient ^{12}C has been dredged up to produce a ratio C/O > 1. Since the envelopes of AGB stars are lost to the interstellar medium via stellar winds, planetary nebulae ejection and supernova explosions, these stars make a major contribution to the enrichment of the interstellar medium in ^{12}C and s-process element (Iben and Truran 1978; Renzini and Voli 1981).

However, the O-rich spectra of the luminous AGB LPVs, and the upper luminosity limit to the field carbon stars indicates that there is an upper mass limit, above which C stars are no longer produced. WBF discuss two possible reasons for this observation that C/O > 1 in the upper AGB stars.

1. the envelope mass is so large that the cumulative amount of ^{12}C dredged up by successive shell flashes on the AGB is not sufficient to produce a ratio C/O > 1 before the termination of AGB evolution, or

2. the ^{12}C dredged up is converted to ^{14}N during quiescent evolution between shell flashes (Iben 1975; Renzini and Voli 1981). The direct way of distinguishing between these two cases would be to measure ^{14}N abundances in the upper AGB stars.

There is some observational evidence which favors explanation (2). In the sample of carbon stars given by Cohen et al. (1981), the J stars (i.e., those carbon stars with a high $^{13}C/^{12}C$ ratio) all tend to lie near the upper limit ($M_{bol} \cong -6$) of carbon star luminosity. One of the results of CNO cycling is an increase in the $^{13}C/^{12}C$ ratio from ~1/90 to ~1/4. Hence, we interpret the existence of J stars at $M_{bol} \cong -6$ as evidence for some CNO cycling occurring in the envelopes of these stars during quiescent evolution. Theoretical calculations indicate that the amount of envelope CNO cycling increases with both mass and luminosity (Scalo, Despain and Ulrich 1975) so that it seems reasonable to assume that the AGB stars of type S that we have found and which have luminositie above the most luminous carbon stars have indeed converted their dredged up ^{12}C to ^{14}N. From Figure 1 we would estimate that the critical initial mass above which nitrogen rich stars rather than carbon stars are formed is ~3.5 $M_\odot$ (in the Magellanic Clouds). Another piece of observational evidence that appears to favor the existence of nitrogen rich AGB stars is the existence of nitrogen enhancements in planetary nebulae of Type 1 and in some supernova remnants.

The nitrogen produced in these massive AGB stars is primary in origin as it is synthesized from the hydrogen and helium in the star at its birth. Thus the AGB stars may be the source of the primary nitrogen that some observations require (Alloin et al. 1979; Bessell and Norris, 1982; Tomkin and Lambert, 1983). Furthermore Tomkin and Lambert find that [N/C] ≅ 0 and [N/Fe] ≅ 0 is the rule for the disk dwarfs and the majority of halo dwarfs, suggesting that these three elements C, N and Fe are formed in the same stars or in stars of similar evolution i.e., the carbon core asymptotic giant branch stars.

We believe that spectroscopic observations and IR photometric observations of LPVs in the Magellanic Clouds can be used to follow the entire story of AGB evolution, but it is essential that quantitative analysis of the data be pursued and that a larger sample of stars be observed.

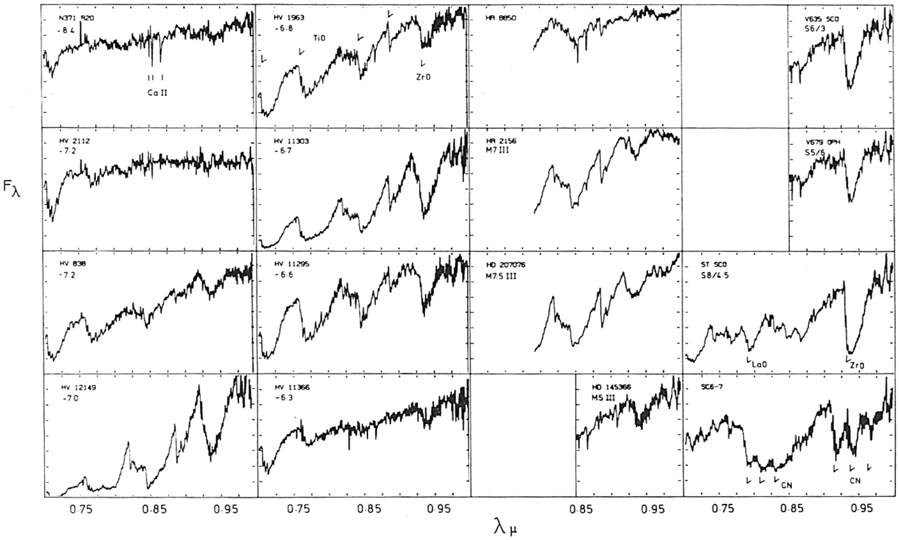

Figure 3. F_λ plotted against λ for selected LPVs in the SMC and some galactic comparison stars. Spectra were obtained with the CCD in order to show the region of the infrared system bands of ZrO near 0.93μ. Absolute bolometric magnitudes are given for the LPVs.

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DISCUSSION

Mould: What lower limit on the supernova rate in the LMC, from this source alone, can you put from the counts of stars at the AGB limit?
Wood: The number of pulsating supernova precursors in Wood, Bessell and Fox indicates one type I supernova in 50.000 years. This is a very minimum supernova rate as the search of LPVs is very incomplete, and periods are known for only a small fraction of them.
Shull: Some SNRs are rich in N compared to their ambient ISM. How much N is produced, expressed as a percentage of C mass or stellar mass?
Bessell: We have not been able to measure N abundance in these AGB stars, but one might expect that the amount of N produced would be from one to several times the initial envelope carbon abundance.
Frogel: Two remarks on temperature scales:
a) my comments don't affect your fundamental conclusions;
b) my comments don't imply your scale is incorrect, just that there is an alternative interpretation. For C stars I think J-K is strongly affected by CN blanketing. Cool M stars, LPV's included, have strong water absorptionbands which will affect JHK colors. Also hot dust (800 to 1200 K) will affect JHKL colors. This latter effect is probably not important for hotter M's in LMC.
Bessell: We chose the (J-K) - T_e relations found for M stars, Miras and carbon stars based on lunar occultation measurements. Admittedly these are few in number but we cannot ignore them. With regard to the blanketing possible in the JHK bands of these late stars I don't think that it seriously affects the temperatures of most of our stars, but it is a very important problem that we should attack both observationally and via model atmospheres.
Pel: What is known about the presence of OH/IR stars in the Clouds?
Bessell: There have been no serious OH surveys of the Clouds because it is anticipated that they would be too faint to observe. In view of the very luminous AGB stars that we have seen, an OH survey of the LMC Bar would be a very worthwhile exercise.
Gardner: No detections have been reported to date. With present sensitivity detections would not be expected.