RED GIANT STARS: COMPARISON OF OBSERVATIONS AND THEORY

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ABSTRACT

Recent observations in both the field and the clusters of the Magellanic Clouds suggest a higher mass loss rate during or at the end of the asymptotic giant branch phase than previously supposed. Recent theoretical investigations offer an explanation for the frequency of carbon stars in the Clouds, but a rich parameter space remains to be explored, before detailed agreement can be expected.

1. INTRODUCTION

The study of the red giants of the Magellanic Clouds, as opposed to the more accessible supergiants, is substantially confined to the period since the last symposium on the Clouds. Since that time, deeper spectroscopic surveys, the development of infrared techniques and analysis of Magellanic Cloud clusters on a broad front have presented us with a wealth of information on the red giants. By even greater good fortune, this period has coincided with the investigation by theorists, principally from Illinois, Mt. Stromlo and Bologna, of the evolution of intermediate mass double-shell-source stars. The result has been exactly what one might hope for, an interplay between theory and observation and a stimulus to our understanding of both the physical processes in red giants and the evolutionary history of the Magellanic Clouds.

Although this review, constrained by time limits, will skip directly into the present to take a current perspective on the issues, it would be wrong not to indicate briefly the milestones of the past few years. The spectroscopic surveys begin with the I-N plate survey at the Uppsala Schmidt by Westerlund (1965) and Westerlund, Olander, Richer and Crabtree (1978). Other surveys followed, in the visible region by Sanduleak and Philip (1977) and in the infrared, using the Curtis Schmidt at Tololo, by Blanco and McCarthy (1975). These have culminated in the most complete survey, in terms of limiting magnitude, with IV-N plates at the

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CTIO 4-m prime focus by Blanco and McCarthy (1983).

Work on the clusters of the Magellanic Clouds has been summarized by Hodge (1984). It is worth recalling that all of 25 years ago Arp (1958) noted the existence of very red stars at the giant branch tips of Cloud clusters. He and van den Bergh (1968) suggested they were carbon stars, but this was not confirmed until Feast and Lloyd-Evans (1973) obtained image tube spectra. The link with the "third dredge-up" mechanism of Iben (1975) was made by Crabtree, Richer and Westerlund (1976) in their field sample and by Mould and Aaronson (1979) in the red globular clusters. Subsequent spectroscopic work is reviewed here by Bessell (1984).

The most significant milestone in the asymptotic giant branch (AGB) theory was the discovery by Iben (1975) that during the thermal pulse power-down phase in model stars of intermediate mass, freshly produced carbon and s-process isotopes are dredged up into the convective envelope. The lure of predicting AGB properties and the consequences for nucleosynthesis with little extra work then became too great. A parameterized dredge-up law was introduced by Iben and Truran (1978), as a substitute for full exploration of the parameter space (X,Y,Z,l/H,M). A parameterized mass-loss law was introduced on to the AGB by Renzini (1977), and a parameterized planetary nebula ejection law by Renzini and Voli (1980). These "fudges" have permitted theoretical predictions to be made, but, not surprisingly, some of them have compared unfavorably with observations, as we shall see in the following sections. An excellent review of theoretical developments is that of Iben and Renzini (1983).

2. THE AGB LUMINOSITY FUNCTION

The prediction (Paczynski 1970) of a core-mass/luminosity relation for AGB stars has as an immediate consequence (since $dL/dt \propto L$) a flat luminosity function : ϕ (stars/mag. interval) = constant (see Renzini 1977). The most direct test is to construct an AGB luminosity function for the most populous intermediate age cluster NGC 419. According to the combined photometry of Mould and Aaronson 1982, Bessell et al. 1982, and Aaronson and Mould 1982, NGC 419 passes this test with 3 or 4 stars per 0.25 mag for $-5.5 < M_{bol} < -4.5$. But the sample is not complete to $M_{bol} = -4$, and the statistics are poor. Another test of the core-mass / luminosity relation is reviewed in § 6.

A test of theory which has no problem from the statistical point of view is the field luminosity function in the Magellanic Clouds. But in order to predict the AGB luminosity function for the field, we need to know 1) the mass-loss law, 2) the star formation history, and 3) (less importantly) the initial mass function. Hence it is less clear what is being tested. The largest observational sample available is that of Reid and Mould (1983), chosen photometrically from a 16 sq. deg field and corrected for foreground stars (a 10% effect). Figure 1 shows the star counts in 0.25 mag bins, together with a prediction (solid line) for a constant star formation rate (SFR) over the last 7 Gyrs (SFR = 0 before that time). An additional contribution from stars with initial mass greater than $4M_{\odot}$ is given by the lower solid curve. Other assumptions which contribute to this prediction are the Reimers (1975) mass-loss law (with an efficiency parameter $\eta_R = 0.45$) and the Renzini and Voli (1981) planetary ejection law (with b = 1).

It is clear that the data do not fit the theory. Yet the data only confirm the picture from a spectroscopic plus infrared survey done at CTIO. The histogram in Figure 1 is a scaling (times 20) of the M(light) and C(heavy) star luminosity function for the Bar West field of Blanco, McCarthy and Blanco (1980). Additional stars found by Frogel and Richer (1983) have been added, scaled appropriately (open histogram).

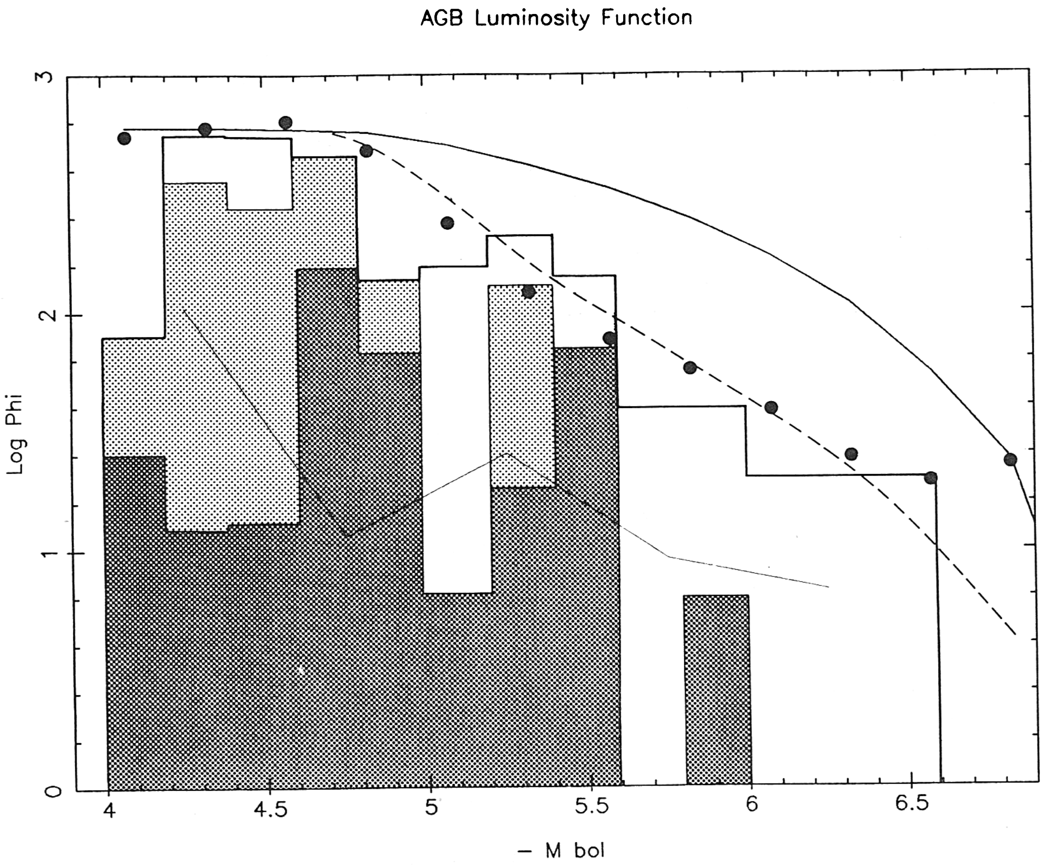

Figure 1
Bolometric Luminosity Functions for AGB Stars in the Large Cloud

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Iben (1981) was the first to notice this discrepancy. It represents one facet of his carbon star `mystery´, "where have all the high mass ones gone?" At that time Iben offered three possible explanations: 1) that envelope burning of carbon to nitrogen in AGB stars was converting carbon stars to (undetected) M stars. This hypothesis is contradicted by the complete samples now available. 2) It was suggested that a pause in star formation in the LMC might be responsible for the missing mass range. This was subsequently ruled out by the identification of cepheids in the Bar West field by Becker (1982). 3) It is possible that massive carbon stars bury themselves in an optically thick dust shell after $M_{bol} < -5.5$. An infrared survey by Frogel and Richer (1983) has excluded objects in half the Bar West Field with $M_{bol} < -6.4$ and blackbody temperature greater than 700 K.

The current consensus in this matter (Frogel and Richer 1983; Reid and Mould 1983) is that none of these explanations is really complete. Envelope burning (C to N) may, or may not, take place: spectroscopy of larger samples is required to determine this. A star formation history could be contrived to reproduce the distribution in Figure 1. For example, the upper dashed curve in Figure 1 supposes SFR = 0 in the LMC until 7 Gyrs ago, followed by an exponential decline with an e-folding time of 2 Gyrs. Such an extreme decline does not seem to fit in with the data available from other sources. The IRAS satellite is expected to put more severe limits on the dust star hypothesis. More probably, the faulty component of the theory is the adopted mass-loss law. We shall return to scrutinize this more closely in § 4. We note in passing that the star formation history in the field does modulate the AGB luminosity function, as shown in the spatial variation detected by Reid and Mould (1983).

3. WHEN DOES AN AGB STAR BECOME A CARBON STAR?

Observationally, this is a spectroscopic question, to be reviewed more fully by Bessell (1983). The question is also a vexed one, in which models and data have been in conflict. So we begin by highlighting the qualitative agreement between theory and observation.

1. Of the Magellanic Cloud clusters surveyed (and published) to date, carbon stars are confined to types III-VI of Searle, Wilkinson and Bagnuolo (1980). These correspond to large enough ages (Rabin 1982) that only in AGB evolution could stars attain the observed luminosities.

2. Mixing on the AGB is predicted by theory to be episodic, i.e. discrete amounts of carbon rich material are added to the convective envelope. This leads naturally to a situation in which M stars evolve into S stars which evolve into C stars, as observed (Bessell, Wood and Lloyd-Evans 1982).

Theory can also be made to predict, however, the luminosity at which this M to C transition takes place. And that is where the trouble began, the other half of Iben's (1981) carbon star `mystery´, "why do the low mass ones become such?"

Initially the problem was that, according to the interpolated dredge-up law, only large core mass stars ($M_{bol} < -5.2$ from Iben 1981) were predicted to become carbon stars (c.f. Figure 1). Since that time the conflict has been softened by the following advances.

1. Carbon star formation can be likened to a titration experiment, in which carbon is added to an oxygen rich envelope (forming CO). If the envelope is metal poor, it takes less carbon to achieve `neutrality´. In this way Renzini and Voli (1981) were able to reduce the transition luminosity to $M_{bol} \sim -4.9$.

2. A refined treatment of the carbon opacity in the vicinity of the helium burning shell allowed Iben and Renzini (1982) to reach a minimum luminosity of $M_{bol} \sim -4$.

3. A much fuller exploration of the parameter space by Wood (1981), Wood and Zarro (1981) and Iben (1983) has led to the discovery that mixing results are critically dependent on the mixing-length assumed for convection and on Y and Z, which control the strength of the instigating thermal pulse.

This last result indicates that firm *a priori* predictions are not an expected product of the theory. Rather, the observations can be expected to lead the theory into a reasonable accommodation with real AGB evolution. Critical in this process will be observations of the transition luminosity in Magellanic Cloud clusters. One wants to know the two dimensional dependence of transition luminosity on age and metallicity (c.f. Lloyd-Evans 1983, Frogel and Blanco 1984).

Two points should be made in passing. First, according to theory (Iben and Renzini 1983) AGB stars spend 20% of their time approximately 0.5 mag below their quiescent luminosity. So in the vicinity of the C-M transition some C stars should be fainter than K, M or S stars. It would be useful to verify this effect, and it is important to make the distinction between minimum and quiescent luminosity. Second, according to Aaronson and Mould (1983) very metal poor dwarf spheroidal galaxies have M_{bol} (transition) ~ -4.2. The distribution of carbon stars suggests that this represents M_{bol} (quiescent).

4. THE LUMINOUS EXTENT OF THE AGB AS A FUNCTION OF AGE

Renzini (1977) was first to point out that in the absence of mass loss Galactic globular cluster stars would climb 2 magnitudes above the helium flash luminosity in the course of their AGB evolution, before the hydrogen burning shell reached the surface of the star. This is not observed, and mass loss is credited with curtailing the evolution by removing approximately 0.3 $M_\odot$ from the star during or at some point in its lifetime.

The rich intermediate age globular clusters of the Magellanic Clouds offer us the opportunity of learning how this net mass loss varies with increasing initial mass. Figure 2 shows the final luminosity on the AGB (from Mould and Aaronson 1983) for clusters whose ages are known by observation of the main sequence turnoff. The solid symbols are preliminary results from new observations with the prime focus CCD camera at the CTIO 4-m telescope. These color magnitude diagrams are of high quality and go 2 mag fainter than the best published 4-m photographic data. An example (Kron 3) is presented by Rich, Mould and Da Costa (1984). Open symbols are from the compilation by Hodge (1983b) (with the exception that NGC 416 and 419 are omitted for lack of really adequate CM diagrams). Note that only for three clusters were Mould and Aaronson (1983) able to estimate the location of the AGB tip. Other points plotted are lower limits on the luminosity, because of the small numbers of AGB stars available. The expected relation for a Reimers (1975) mass loss law (with η_R = 0.45) and a Renzini and Voli (1981) planetary ejection law (with b = 1) is also shown (from Mould and Aaronson 1983, Table 3).

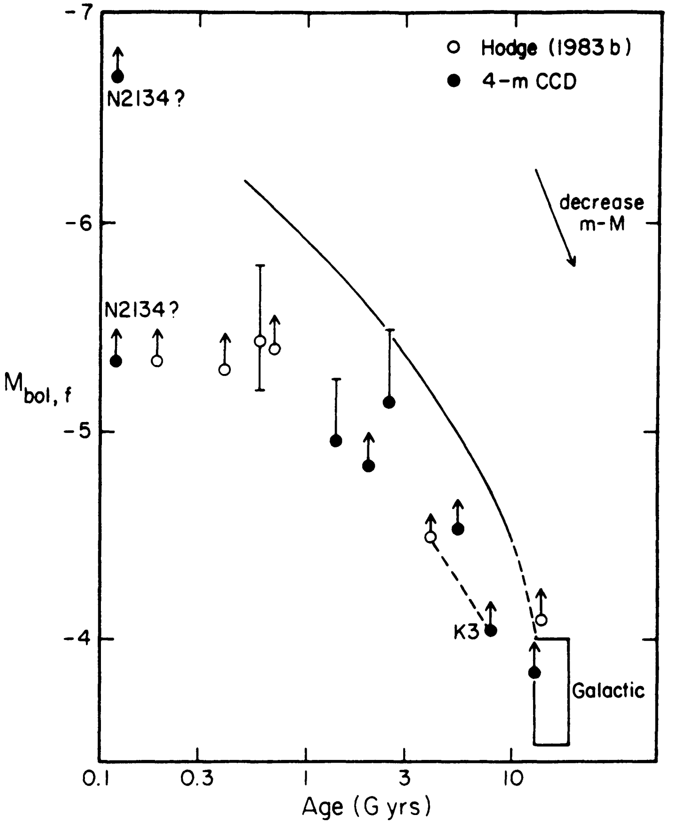

Figure 2
The Peak Luminosity on the AGB as a Function of Cluster Age

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A number of points deserve to be made in respect of Figure 2.

1. The data do not fit the expected relation, even if one is reasonably generous in drawing an upper envelope. A similar point was made by Hodge (1983b). The deviation is in the sense that more mass loss is taking place, either during ascent of the AGB or in the nebula ejection (either the "wind" or the "superwind") than predicted.

2. This conclusion is reasonably independent of the distance moduli adopted for the Magellanic Clouds. The solid symbols are based on $(m-M)_o$ = 18.3 (LMC) and 18.8 (SMC), which is the "short" distance scale for the Clouds (de Vaucouleurs 1978, Eggen 1977). This was done, because a noticeably better fit resulted to theoretical main sequence isochrones. Data from Hodge (1983b) is mostly on the "long" distance scale: $(m-M)_o$ = 18.7 (LMC) and 19.3 ± 0.1 (SMC) (Gascoigne 1972, Martin *et al*. 1979, Sandage and Tammann 1981). A shift indicated by the arrow in Figure 2 will put the latter data on the former scale.

3. The major uncertainty in Figure 2 is in the interval 0.1 < age < 1 Gyrs. The cluster NGC 2134 has been plotted twice, because it is unclear whether star 3 of Mould and Aaronson (1983) is a member or not. With a little work other clusters could readily be added to tie down the high mass end. The trend in the data towards an upper limit to $M_{bol,f}$ at young ages should not be given too much weight at present. For there is evidence of AGB stars in the LMC field at M_{bol} = -7 (see § 6).

4. A revised mass loss law based on Figure 2 (or preferably more complete data) would undoubtedly produce a better fit to the field luminosity function (Figure 1) also.

5. ANOMALOUS OR SUPERLUMINOUS GIANTS

According to Flower *et al*. (1980) and Hodge (1981) several Magellanic Cloud clusters younger than 1 Gyr contain numbers of unaccountable giant stars spread over a range of color and averagely 2.7 mag above the main sequence tip. A number of possibilities have been discussed in respect of these stars:

1. They are field stars. Control fields analysed close to the cluster seem to rule this out. Radial velocities (Olszewski 1982) are comparable with that of the Magellanic Clouds for most of these stars.

2. They are coalesced stars. This suggestion (Flower 1980) does not seem to be realistic.

3. They are post-AGB stars. Given the problem (§ 2) of the missing AGB stars, this might seem like a welcome solution. Post-AGB stars, however, would be expected to cross from red to blue on a short timescale and at a luminosity $M_{bol} \leqq -5$. Most of the anomalous giants

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are much fainter.

4. A further possibility, which seems to have received less attention, is that mass transfer in binary systems may be responsible. After the primary had evolved to a red giant, a binary system with a mass ratio of order 1 would concentrate most of its mass on the secondary, which would appear as a superluminous giant in its core helium burning (blue loop) stage. The long lifetime of the blue loop would not require an excessive fraction of binaries even in the archetypal anomalous cluster, NGC 1868.

Further work is required to resolve the problem of the anomalous giants. High dispersion spectroscopy would seem particularly valuable.

6. PERIOD LUMINOSITY RELATIONS

We conclude this review by pointing out a remarkable confirmation of theory in observations discussed by Wood, Bessell and Fox (1981). These authors constructed a period-luminosity diagram for long period variables in the LMC, using infrared magnitudes, which relate readily to bolometric luminosities. They discovered a bifurcation of the general period luminosity correlation. Stars which they interpret as massive supergiants continue on to the highest luminosities, while a second sequence with the characteristics of AGB stars ceases abruptly at $M_{bol} = -7.0$. According to the Paczynski (1970) relation this corresponds to a core mass of 1.4 $M_{\odot}$ i.e. the Chandrasekhar mass. Confirmation that such an AGB limit exists and occurs at the predicted luminosity validates the core-mass/luminosity relation observationally.

Other observations of LMC Miras (Glass and Lloyd-Evans 1981, Glass and Feast 1982) have assisted materially in determining the luminosities of these stars. The question of the mode of pulsation of long period variables remains in debate, because of uncertainties in their radii/temperatures.

7. CONCLUSION

It is clear that the study of red giants in the Magellanic Clouds is a rich area just opening up for fuller investigation. Key issues at present are the amount of mass loss as a function of initial stellar mass and the details of observed and predicted nucleosynthesis.

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DISCUSSION

Wood: The results of Wood, Bessell and Fox (1983 Ap.J., in press) show that AGB stars do exist at luminosities brighter than $M_{bol} \simeq -6$ and, in fact, that the stars extend up to the AGB limit $M_{bol} \simeq -7.1$. We therefore disagree with the "consensus" view that mass loss terminates the AGB for all initial stellar masses at M fainter than $\simeq -6.5$. Our pulsation masses indicate that only stars with ages less than about 100 million years will reach luminosities near the AGB limit.

Mould: That is not the "consensus" view! Figure 2 suggests that a higher rate of mass loss occurs on the AGB than is normally assumed. The luminosity function in Figure 1 is in agreement with your result that AGB stars with $M_{bol} = -7$ exist in the LMC in small numbers. We need to examine more clusters to find out what initial mass stars are their progenitors. The pulsation masses, as you know, are highly contentious.

Frogel: The problem is that luminous AGB stars do not exist in anywhere the numbers required by theory. There may be a few of them, but mass loss seems to operate in such a way that nearly all luminous stars are evaporated.

Aaronson: Might not a star burst model be able to produce better agreement with the observed luminosity function?

Mould: Yes.

Demarque: In connection with your comments on the "superluminous" giants reported by Flower et al., I wish to draw attention to a paper by Alan Hirshfeld (published in 1981 in the Ap.J.) which treats the problem of mass transfer binaries in the core helium burning phase. Hirshfeld's calculations were made in the context of anomalous Cepheids, but they might also be applicable to the superluminous giants.

Westerlund: I do not believe that the surveys for carbon stars in the Magellanic Clouds are as complete as suggested here. Already the Schmidt telescope surveys by Sanduleak and Philip (IIIa-J plates) and Westerlund et al (I-N plates) showed that the former survey contained a large number of hotter carbon stars than the latter. A IIIa-J GRISM survey of SMC by Azzopardi, Breysacher, Lequeux and myself gives about 15 percent carbon stars not found by Blanco et al. in their field in the Bar. GRISM surveys by us of the Fornax dwarf galaxy show similar results. Possibly these carbon stars, which may be among the more luminous, fill the gap in Mould's Figure 1.
Also the number of luminous ZrO-rich M giants in the LMC is higher than previously known, as found recently by Lundgren and myself. They may contribute to filling the gap, too.
Blanco: Remarks: 1) In regard to incompleteness, as far as the carbon and very late M stars are concerned, the surveys by Westerlund based on near-infrared spectra and the ones in the blue-green spectral region (Swan bands) by Sanduleak and Philip are found by McCarthy and myself to be very incomplete. This explains the lack of overlaps when the Westerlund and Sanduleak-Philip surveys are intercompared and has no bearing on the incompleteness problem discussed by Mould. In our CTIO GRISM surveys with the 4 m Telescope one can be very sure of completeness because the carbon and very late M giants are extremely bright. Also please notice that the missing stars are supposed to be the bright ones which are the easiest ones to find in any survey.
2) Another myth that should be cleared up is that in the Swan band surveys hot carbon stars were discovered that do not show up in the near-infrared surveys based on CN-bands. In numerous examples examined by us an extremely high percentage of carbon stars showing Swan bands also show CN-bands in the near-infrared. I know of only one exeption to this general rule and that star showed CN-bands and no or very weak Swan bands. Thus we cannot say either that the near-infrared surveys missed hot luminous carbon stars. Nevertheless, in Westerlund's survey the brighter carbon stars found were the brighter ones that could be found in the near-infrared and his star list even though very incomplete does include the more luminous carbon stars except in the bars of the Clouds where spectral overlaps caused him to miss many carbon stars. It follows from all this that the missing luminous AGB stars must be something other than carbon stars for sure and it is also unlikely that they are late M giants.
Renzini: The missing AGB stars are not necessarily carbon stars, they can be something else, for example, even luminous K stars; this is expected from theory, and supported by the existence of the long-period variables (which are not carbon stars).
My impression is that current theory with a mass loss rate calibrated on Galactic globulars is OK for MC clusters older than $\simeq$ 1 Gyr, which is to say for stars less massive than $\simeq 2\ M_\odot$. The same applies to the comparison with field MC stars. So the difficulty seems to arise only for stars more massive than $\simeq 2\ M_\odot$. Maybe that it is not by chance that this occurs just at $\simeq 2\ M_\odot$, as less massive stars develop a degenerate He core during the first red giant branch phase, while more massive stars do not. Perhaps the <u>rotational</u> history of the core of

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stars more massive than 2 M⊙ is correspondingly different from that of lower mass stars, and this may provide a hint to understand the apparent lack of bright AGB stars. However, still I'm not totally convinced of the completeness of existing surveys, particularly as far as late K and early M type stars are concerned.

Mould: A final word on this subject of survey completeness. I believe that the order of magnitude agreement between spectroscopic surveys and photometric surveys, such as the one I have reported here, implies that there is a real deficiency of luminous AGB stars in the LMC.

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