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EVIDENCE FOR TWO DISCRETE EPOCHS OF STAR FORMATION IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT

An infrared color-magnitude diagram for an unbiased sample of M giants in a 0.12 deg^2 field of the Large Magellanic Cloud (LMC) shows the existence of two distinct asymptotic giant branches (AGBs), one of which is 1.5 mag brighter than the other. Stars on the bright AGB are quite similar in color and luminosity to giants in LMC clusters which have ages of about 10^8 yr; those on the faint AGB look like giants in clusters with ages of a few Gyr. The faint AGB is identified with the star-forming episode found by Butcher and Stryker. The bright AGB is taken to be evidence for a second, discrete episode of star formation corresponding in age to the blue globular clusters in the LMC. At least for main-sequence stars near the turnoff, this recent episode has been only one-tenth as efficient at making stars as was the older episode. The rate of star formation between these two episodes appears to have been significantly lower than in either.

Subject headings: galaxies: Magellanic Clouds — infrared: general — stars: formation

I. INTRODUCTION

Butcher's (1977) main-sequence luminosity function for a small field near NGC 1866, 4° north of the bar of the Large Magellanic Cloud (LMC), shows a well-defined knee at a point nearly a magnitude brighter than a similar feature in the solar neighborhood luminosity function. From this result he concluded that the bulk of star formation in the LMC began 3–5 Gyr ago. This finding has been confirmed for a region 5° northwest of the bar by Stryker (1981; see also Stryker and Butcher 1981). Also Stryker (1981) and Stryker, Butcher, and Jewell (1981) have shown that in the far halo of the LMC around NGC 2257 a major epoch of star formation occurred or began not more than 5–7 Gyr ago. In summary, from the data that these authors have presented it would appear that the bulk of star formation throughout the LMC began about 3–5 Gyr ago.

This *Letter* presents new direct evidence for the active period of star formation in the LMC a few Gyr ago. In addition, it gives evidence that a second, distinct, episode of star formation occurred as recently as 10^8 yr ago. The evidence is based on new transmission grating prism surveys for and subsequent infrared photometry of late-type giants in the Bar West (BW) field of the LMC (Blanco, McCarthy, and Blanco 1980, hereafter BMB) and in more than 40 clusters which are members of the LMC. As emphasized by BMB, the transmission grating prism surveys are essentially complete. For the present study, care was taken not to introduce any magnitude or spectral type selection effects. We feel these results to be of sufficient importance and interest to warrant publication before presentation of the rest of our investigation.

II. COLOR-MAGNITUDE DIAGRAM

In order to study the asymptotic giant branch (AGB) luminosity function of the LMC, the transmission grating prism plates of the BW field (used by BMB in their original study) were reexamined by Blanco (reported in Frogel and Blanco 1983*a*, hereafter FBa). All M stars of type M5 and earlier were noted. When these results are combined with the survey results of BMB, we have a list of M giants in the BW field which should be complete for types M2 and later and with a known degree of incompleteness for types M0 and M1 (Blanco and Münch 1955; but see also Frogel and Richer 1983). This incompleteness arises not because of faintness of the stars (essentially all of the LMC M giants are well above the plate limit), but because of the difficulty of classifying the early M's with a dispersion of only 2350 Å mm^{-1}. Cohen *et al.* (1981) give infrared photometry for some of the M stars from BMB. We have obtained infrared photometry for the rest of the M's listed in BMB, all of the M3–M5 stars, and an unbiased sample of the M0–M2 stars (FBa).

Figure 1 is an infrared $C-M$ diagram for these unbiased samples of M stars in the LMC-BW field. These stars are represented by open and filled circles according to spectral type. Frogel and Richer (1983) have recently completed a 2.2 μm survey of just over

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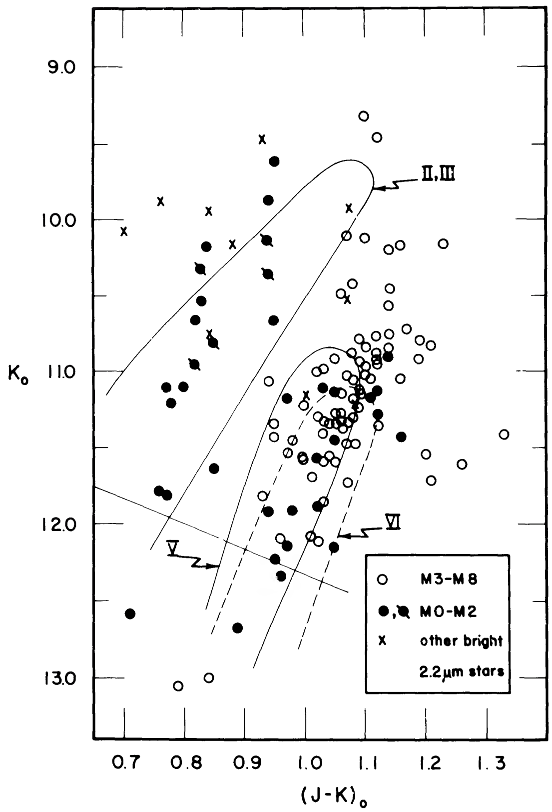

FIG. 1.—An infrared color-magnitude diagram for cool, luminous giants in the LMC-BW field. Simple open and filled circles represent stars in the complete and unbiased samples of M stars from FBa. Filled circles with slashes are additional early Ms with photometry from Frogel and Richer (1983). The crosses are all additional stars with $K < 11.0$ and colors in the range indicated on the horizontal axis which were not previously classified as M stars on the basis of transmission grating prism surveys (BMB and FBa). These objects were found in the course of Frogel and Richer's infrared survey of the BW field. The semienclosed areas indicate the location of giants from LMC clusters of the specified SWB type as discussed in the text. The straight line segment is perpendicular to the long axes of these areas and is used to construct the next figure.

half of the BW field. This survey includes all stars with K magnitudes brighter than 11.0. The filled circles with slashes in Figure 1 are additional M0–M1 stars known from the transmission grating prism surveys, subsequently detected in the course of the IR survey but which are not members of the unbiased IR sample. The crosses are stars found only by the IR survey with colors within the range defined by the horizontal axis of Figure 1. As discussed by Frogel and Richer (1983), there are stars of types late K to early M.[2]

A valuable aid in understanding any $C - M$ diagram is to superpose the loci of stellar sequences from clusters with known physical characteristics. The classification scheme for Magellanic Cloud clusters given by Searle, Wilkinson, and Bagnuolo (1980, hereafter SWB) appears to be one in which all clusters assigned to a particular group are quite similar with regard to age and metallicity (e.g., Rabin 1982; Frenk and Fall 1982; Searle and Smith 1981; Cohen 1982). The semienclosed areas in Figure 1 delineate the regions occupied by late-type AGB stars (excluding carbon stars) from clusters of the SWB types noted in the figure. The surveys and photometry of these cluster giants are described in Frogel and Blanco (1983*b*, hereafter FBb).

Most of the stars in Figure 1, especially the M3–M8 stars, lie along a sequence which coincides with and extends that defined by stars in the SWB groups V and VI clusters. The brightest stars in our sample of SWB VII clusters (FBb) have, with one exception, K magnitudes fainter than 12.0 and hence must not belong to the AGB. Too few M stars were found in the type IV clusters to properly define their locus in Figure 1. Thus it is with the type V–VI clusters that the sequence may best be compared. We will refer to this sequence as "the faint AGB."

Above the faint AGB lie a number of M0–M2 stars from the unbiased sample which appear to define a parallel sequence. If the five additional M0–M1 stars from Frogel and Richer (1983) are added, this appearance is enhanced. Stars along this sequence show reasonable agreement with the locus of AGB stars from SWB type II and III clusters (FBb). The lower boundary of this locus is quite well defined, but the upper boundary is rather uncertain and could lie somewhat higher. The second sequence of LMC-BW giants lies 1.5 mag above the first and will be referred to as "the bright AGB."

In order to determine how well defined these two AGBs are, we have drawn a line in Figure 1 which is perpendicular to the long axes of the regions defining the giants in the various SWB groups and projected the M0–M2 giants onto this line. The result is shown as a histogram in Figure 2. The solid line in Figure 2 represents only the stars from the unbiased sample, while the dashed line includes the five additional M0–M1 stars marked in Figure 1 from Frogel and Richer (1983). In either case it is evident that there are two well-defined peaks in the distribution and not a smooth continuum of stars. These peaks correspond to SWB groups II–III and V–VI.

A similarly obtained distribution for the M3–M8 stars in Figure 1, shown as a dotted line in Figure 2, has only a single peak which corresponds to the faint AGB for the M0–M2 stars.

III. CO INDICES AND $(J - H)$, $(H - K)$ COLORS

Examination of the CO indices and a $(J - H)$, $(H - K)$ plot for stars on the two AGBs delineated in the previous section reveal further differences between them.

[2]Essentially all of the stars plotted in Fig. 1 must be AGB members and not first ascent giants. At the distance of the LMC, stars of the latter kind would be no brighter than $K = 12.0$.

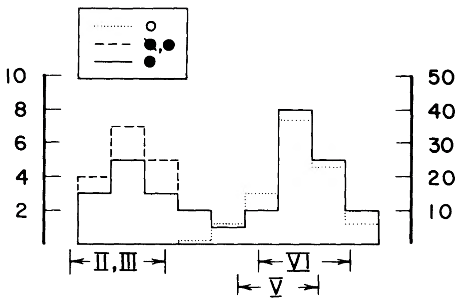

FIG. 2.—The straight line segment from Fig. 1 is divided into nine equal segments. Histograms are constructed by projecting the stars in the indicated subsets back onto this line. The right-hand scale is for the M3–M8 subset; the left-hand one is for the other two subsets.

Figure 3 shows the dependence of CO on color for stars of type M0–M2. The variation of this index with a star's absolute luminosity and metallicity is well established. Baldwin, Frogel, and Persson (1973) showed that for solar neighborhood stars, the CO index is a strongly increasing function of luminosity. The metallicity dependence of the CO index is determined from observations of globular cluster giants (Frogel, Cohen, and Persson 1983). In metal-poor clusters the CO index is quite weak with typical values of 0.00 to 0.05 for stars that would lie on the left-hand side of Figure 3. In the most metal-rich clusters, on the other hand (e.g., 47 Tuc, NGC 5927, and NGC 6553), stars with $(J - K)$ colors in the range 0.7–1.1 have CO indices comparable to or slightly greater than the mean for solar neighborhood giants indicated in Figure 3 by the solid line.

Bright AGB stars in the LMC-BW field have systematically stronger CO indices than faint AGB stars of the same color. Furthermore, the CO indices of the bright AGB stars are, in the mean, 0.05 mag greater than those of solar neighborhood giants. These results are entirely consistent with the luminosity separation of the two groups inferred from Figure 1 and with the fact that the bright AGB stars have luminosities considerably greater than those usually assigned to nearby giants of the same spectral types (e.g., Elias 1978).

Stars on the faint AGB in the LMC-BW field lie above and to the blue of bright AGB stars on a $(J - H)$, $(H - K)$ diagram (Fig. 4). This behavior mimics that of the stars in SWB groups II–III and V–VI clusters in the sense expected from the identification of the field stars with these SWB cluster groups in Figure 1.

IV. DISCUSSION AND CONCLUSIONS

The faint and bright AGBs may have resulted from two distinct episodes of star formation in the LMC-BW —one of which occurred a few Gyr ago and for which there is other convincing evidence in the literature, and one which happened rather recently, in the last 10^8 yr, and which may still be in progress. If star formation had occurred more or less continuously between these two epochs, the two peaks in Figure 2 would not be seen since, as noted below, the lifetime for AGB stars is nearly independent of mass in the relevant range. Hence, it is likely that the bulk of the star formation in the LMC has occurred in an episodic rather than a continuous fashion.

Is a relatively recent epoch of star formation in the LMC-BW consistent with what else is known about this field? It is instructive to compare statistics for the BW field with star counts for region B (Robertson 1974) of the blue globular cluster NGC 1866, a member of SWB group III. On the basis of available infrared photometry for giants in this cluster (FBb), there are probably eight

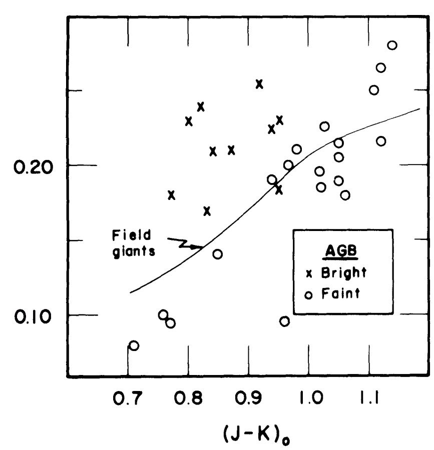

FIG. 3.—The CO index as a function of $(J - K)$ color for M0–M2 stars on the two AGBs. The curved line is the mean relation for solar neighborhood giants from Frogel *et al.* (1978).

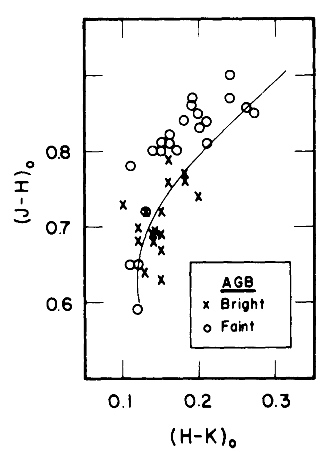

FIG. 4.—A $(J - H)$, $(H - K)$ plot for stars on the two AGBs. The line is for solar neighborhood giants from Frogel *et al.* (1978).

AGB stars in region B of the cluster with $K < 11.0$. Since the Frogel and Richer (1983) survey of one-half of the BW field is complete to this magnitude level, from Figure 1 we estimate that the BW field contains about 3 times as many giants brighter than this magnitude limit than does NGC 1866. Region B also contains two Cepheid variables, whereas Becker (1982) has counted eight such stars in the BW field. If the ages of the cluster and the bright AGB of the BW field are similar, we would expect that the ratios of red giants to Cepheids should be similar as well. They clearly are.

Figure 16 of Robertson (1974) shows that there are about 160 stars on the main sequence of region B in NGC 1866. These stars have $16 < V < 18$ and $0.1 > B - V > -0.5$. Unfortunately, there is at present no way to tell whether there are the expected 500 or so such stars in the BW field. One can, of course examine photometric surveys of other LMC fields. Each of the fields studied by Butcher (1977) and Stryker (1981) has only 0.005 of the area of the BW field. Nonetheless, we note the presence of well-defined blue main sequences extending as bright as $V = 18$, the limit imposed by saturation of the photographic images. A survey of a part of the BW field for these predicted main-sequence progenitors of the bright AGB should be easy to carry out.

Most of the so-called blue globulars in the LMC belong to SWB groups II or III. Gunn (1980) has speculated that they could have arisen from a relatively recent shock-induced star formation episode excited by interaction between the two Magellanic Clouds. Freeman (1977) has noted that from the relative distribution with integrated $B - V$ color of LMC clusters one can argue that the blue globulars are the result of a burst of cluster formation going on right now, although he pointed out that the observed distribution could also result from luminosity evolution of clusters with flat mass functions as he has found to be true for three of the six blue clusters he studied. In any case, since the bright AGB in the LMC-BW field has an age comparable to those of the blue globulars, it seems reasonable to speculate that if these clusters are the result of a discrete star-forming episode, then this same episode has been responsible for the formation of the precursors to the bright AGB stars.

An order-of-magnitude estimate of the star formation rate in the episode responsible for the bright AGB relative to that which resulted in the faint AGB may be made since essentially all of the stars in Figure 1 must be thermally pulsing AGB stars. The lifetime of such stars as calculated by Renzini and Voli (1981) is about 1.6 Myr and is nearly independent of mass in the range 1.0–6.0 $M_{\odot}$. This lifetime, then, should be applicable to stars on either AGB in Figure 1. From LMC cluster data (FBb) we know that about half of the thermally pulsing AGB stars in SWB type V and VI clusters are carbon stars (similar to the ratio for the LMC-BW field) but that there are essentially no carbon stars in the type II or III clusters. To estimate the relative star formation rates, we then count the number of stars in the complete and unbiased samples of Figure 1 for the two AGBs, multiply the number for the faint AGB by 2, and take the ratio. Thus we find that the star formation rate in the recent star forming event is about one-tenth that which obtains for the event which happened 3–5 Gyr ago.

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