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THE EVOLUTION OF ASYMPTOTIC GIANT BRANCH STARS IN THE MAGELLANIC CLOUDS. III. THE PROBLEM OF INTERMEDIATE-MASS STARS[1]

JEREMY MOULD
California Institute of Technology
AND
NEILL REID
Royal Greenwich Observatory, and California Institute of Technology
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ABSTRACT

Two samples of red giants in the LMC with bolometric magnitudes in the interval $(-4, -8)$ are examined spectroscopically. These samples are deficient in luminous stars ($M_{\rm bol} < -5.5$) with any evidence of third dredge-up. A number of explanations are considered, of which the most likely (if standard estimates are correct for the maximum mass star that can become an AGB star) is that 2 to 5 $M_\odot$ stars spend their thermal pulsing lifetime in a brief Mira phase, and that their evolution is rapidly truncated by depletion of the stellar envelope by mass loss.

Subject headings: galaxies: Magellanic Clouds — stars: evolution — stars: late-type — stars: mass loss — stars: stellar statistics

I. INTRODUCTION

If we assemble the published infrared photometry on asymptotic giant branch (AGB) stars in the six best studied and most populous 10^9 yr old clusters in the Magellanic Clouds, we find that stars of an initial 2 $M_\odot$ evolve up the AGB to $M_{\rm bol} = -5.5$ (see Mould, Da Costa, and Wieland 1986). On the way they experience third dredge-up (Iben 1975) and turn into carbon stars. It would be very informative if we could do the same thing for clusters aged 10^8 yr and obtain a similarly detailed picture of initial 5 $M_\odot$ AGB evolution. But for obvious reasons we can only expect a tenth as many clusters at this age, and the only really useful one turns out to be NGC 1866. There are only three AGB stars in NGC 1866 brighter than -4.5 in $M_{\rm bol}$. These stars are likely to be on the early–AGB, as they are both M stars (Aaronson and Mould 1985). The important point, however, is that the AGB evolutionary picture that was standard at the time of Iben and Renzini's (1983) review (with a Reimers's mass-loss coefficient between a third and a half) predicts three or four thermal pulsing (TP) AGB stars between -6 and -7 in $M_{\rm bol}$. But there are none. The calculation of three or four TP AGB stars per magnitude is based upon the number of Cepheids in NGC 1866 and their relative lifetimes (Mould and Aaronson 1986). Clearly, it is desirable to base an empirical view of stellar evolution on more than just a handful of missing stars. So we turn to the field of the LMC in the hope of building a statistically stronger picture.

II. A SURVEY FOR LUMINOUS AGB STARS

Reid and Mould (1984) carried out a photographic survey of 15 deg^2 north of the Bar in the LMC to determine the AGB luminosity function. We found fewer stars with $M_{\rm bol} < -5.5$ than were predicted by the standard theory and a constant or mildly declining star-formation history. What luminous red stars there were, were arranged in a clumpy distribution and proved for the most part to be late K or early M types with no sign of the products of third dredge-up in their atmospheres (Reid and Mould 1985—hereafter Paper II).

Subsequently, we have obtained spectra of all stars in the 15 deg^2 field with $-7 < M_{\rm bol} < -6.4$ (true distance modulus 18.4). Bolometric magnitudes were calculated from the V, I photometry as described in Paper II. This is a sample of 20 stars, and the spectra were obtained in an identical manner to those reported in Paper II and extend from 5000 Å to 7500 Å at a resolution of 2.6 Å. Their positions, photometry, and band strengths (as defined in Paper II) are presented in Table 1. Four of these spectra plus spectra of an MS star from 47 Tuc and a Harvard variable in the same field are illustrated in Figure 1. In this sample there are apparently no C, S, Ba, or Li rich stars, and it is therefore easier to understand these stars as young core helium-burning stars than as TP AGB stars. Note, however, that, according to spectrum synthesis calculations, barium enhancements smaller than a factor of 10 above solar abundance would probably be missed in spectra of the present resolution. Only half of the barium stars in the classical sample of Warner (1965) had barium enhancements of this order.

III. CONSTELLATION III

Within the 15 deg^2 studied by Reid and Mould (1984) there are two areas of particularly intense star formation which were excluded from the COSMOS photometry because of the crowding of stellar images. It seemed possible that the missing luminous AGB stars might be hiding in these "drilled" regions. In 1984 November we therefore obtained Cassegrain camera plates at the du Pont telescope of one of these regions, Shapley Constellation III. Four V plates and two I plates were processed into a color-magnitude diagram on the Cousins system of a 45′ square region. Calibration and the form of the color-magnitude diagram are discussed by Reid, Mould, and Thompson (1987).

We have carried out a spectroscopic survey of AGB star candidates in this region, obtaining spectra of all stars with $(V-I) > 1.6$ and $M_{\rm bol} < -4$ in three subareas. These spectra

[1] Based on observations obtained at the Las Campanas Observatory of the Carnegie Institution of Washington.

TABLE 1

Bright Star Sample in the LMC North Survey Field

BLMC	R.A. (1950)	Decl. (1950)	V	$V-I$	NaD	D (6180) TiO	D (6475) ZrO	D (7100) TiO	Sp.	M_{bol}	Velocity km s^{-1}	Remarks
1........	5^{h}43^{m}42^s.4	−66°37′40″	13.01	1.74	0.13	0.18	0.06	0.14	M0	−6.6	291	
2........	5 39 29.8	−64 50 08	13.16	1.99	0.14	0.21	0.07	0.20	M0	−6.7	324	
3........	5 41 27.8	−67 28 29	12.76	1.79	0.17	0.04	−0.01	−0.02	K3	...	75	Galactic
18........	5 29 28.5	−66 49 58	13.40	1.90	0.15	0.13	0.06	0.11	K5	−6.4	300	
19........	5 29 46.7	−67 41 38	12.90	1.86	0.17	0.13	0.04	0.12	K5	−6.8	303	
20........	5 28 48.0	−66 37 03	13.62	2.15	0.17	0.30	0.07	0.27	M1	−6.5	292	
28........	5 25 57.2	−66 35 08	18.9	6.4	0.25	0.73	−0.09	0.98	M6	−6.3:	284:	Variable?
29........	5 25 54.1	−66 40 10	13.03	1.70	0.11	0.14	0.06	0.07	K5	−6.5	305	
30........	5 25 27.7	−66 19 27	14.03	2.84	0.21	0.48	0.04	0.55	M3	−6.9	292	
33........	5 23 52.5	−67 26 48	13.54	2.26	0.19	0.36	0.06	0.38	M2	−6.7	299	
35........	5 21 56.6	−66 23 28	13.20	2.18	0.19	0.27	0.05	0.25	M1	−6.9	303	
37........	5 19 53.9	−68 05 21	13.59	2.24	0.16	0.29	0.05	0.31	M1	−6.6	297	
38........	5 19 03.8	−65 36 26	13.22	2.07	0.14	0.21	0.07	0.17	M0	−6.8	298	
39........	5 17 48.3	−67 09 43	13.36	1.98	0.17	0.21	0.07	0.23	M0	−6.5	292	
40........	5 15 51.9	−68 06 23	12.77	1.66	0.14	0.01	0.01	−0.03	K3	...	68	Galactic
41........	5 13 35.2	−65 45 53	13.23	1.75	0.15	0.10	0.05	0.10	K5	−6.4	297	
47........	5 09 02.8	−65 55 50	12.61	1.65	0.13	0.06	0.01	−0.01	K4	−6.9	285	
50........	5 03 50.7	−67 04 10	12.95	1.63	0.57	0.15	−0.01	0.04	K5 V	...	27	Dwarf
54........	5 03 42.1	−66 08 02	12.74	1.75	0.22	0.16	0.06	0.12	K5	−6.9	292	
55........	5 02 43.7	−66 26 31	12.76	1.66	0.14	0.18	0.07	0.10	K5	−6.8	296	

were obtained in the same spectral interval, and with the same resolution and first cathode sensitivity, but with a two-dimensional sensor recording the detected photons (Shectman 1984). Identical band strength measurements were made on these spectra and are recorded in Table 2. Six examples of the spectra are shown in Figure 2.

The luminosity distributions within the three subareas are shown together with the assigned spectral types in Figure 3. In a very recent observing run we have verified the bolometric magnitudes by means of *JHK* photometry. For a complete sample of stars accessible to aperture photometry drawn from subarea X of Table 2, the mean error in M_{bol} is less than 0.1 mag, and the standard deviation of a single measurement is 0.25 mag. A small bias may be present in the case of carbon stars, however, which are not represented in subarea X. These results are presented in full by Mould and Reid (1987).

Two populations seem to be present in Constellation III: a cool, more uniformly distributed low-luminosity population ($M_{bol} > -5.0$) seen in all three subareas, and a warmer, clumpy population, dominant in area X, which crosses the color threshold at $M_{bol} = -5.5$ and follows a giant branch to $M_{bol} = -7.5$. The following three conclusions emerge.

1. The low-luminosity population consists of highly evolved late-type stars, many of which show signs of the third dredge-up.
2. Carbon stars are among the most luminous of these but have a maximum luminosity of -5 in M_{bol}.
3. There are no carbon stars, S stars, or barium stars in the high-luminosity population.

IV. RADIAL VELOCITIES

Velocities were measured by cross-correlation with respect to three template spectra: HD 63353 (C), HD 24393 (K5/M0), HD 63122 (M3/4). With the exception of the carbon star, none of these stars has very accurate known velocities; so the velocity zero point was obtained by observation of three red giants in 47 Tuc. The standard error with respect to their CORAVEL velocities (Mayor *et al.* 1983) was 2 km s^{-1}. Heliocentric radial velocities for the Constellation III sample are given in Table 2, and their kinematic properties are in Table 3. For the brighter stars ($M_{bol} < -5.5$) the formal errors in these velocities are estimated to be 6 km s^{-1} based on the error analysis of Tonry and Davis (1979). Two of them have CORAVEL velocities, both of which differ from the values in Table 2 by 7 km s^{-1}. However, in the mean our sample has the same redshift of 304 km s^{-1} as that of the CORAVEL stars over the full square degree we have studied (Prevot *et al.* 1985); so one should not necessarily conclude that a systematic error is present in Table 2. Other cross-identifications in Table 2 are to the samples of Rebeirot *et al.* (1983) and Sanduleak and Philip (1977).

Random errors in the velocities of the fainter stars ($M_{bol} > -5.5$) are estimated to be 3 times larger than for the bright sample, according to the average height of the cross-correlation peak. Although this older population may indeed have a higher velocity dispersion, detection cannot be claimed in the present data. The fainter stars do, however, have a systematically lower mean velocity than the brighter sample, and this difference (21 km s^{-1}) is significant.

The mean velocity of the young stellar component of Constellation II agrees with that of the nearside of the expanding shell in the model by Dopita, Mathewson, and Ford (1985), but it is not clear exactly how the mean velocity of the older population relates to their other H I components. More accurate velocities of these 16th visual magnitude stars would be valuable.

V. POSSIBLE EXPLANATIONS

The situation is not quite as simple, however, as Figure 3 would imply. There *are* AGB stars in the Magellanic Clouds in the luminosity range $-7 < M_{bol} < -5.5$ which show signs of third dredge-up. These are the long-period variables studied by Wood, Bessell, and Fox (1983). They have pulsational masses in the range 2–7 $M_\odot$. However, although, as discussed in the context of NGC 1866, TP AGB stars are expected to be approximately as abundant as Cepheids in the LMC, no Miras are present in any of the complete samples studied above.

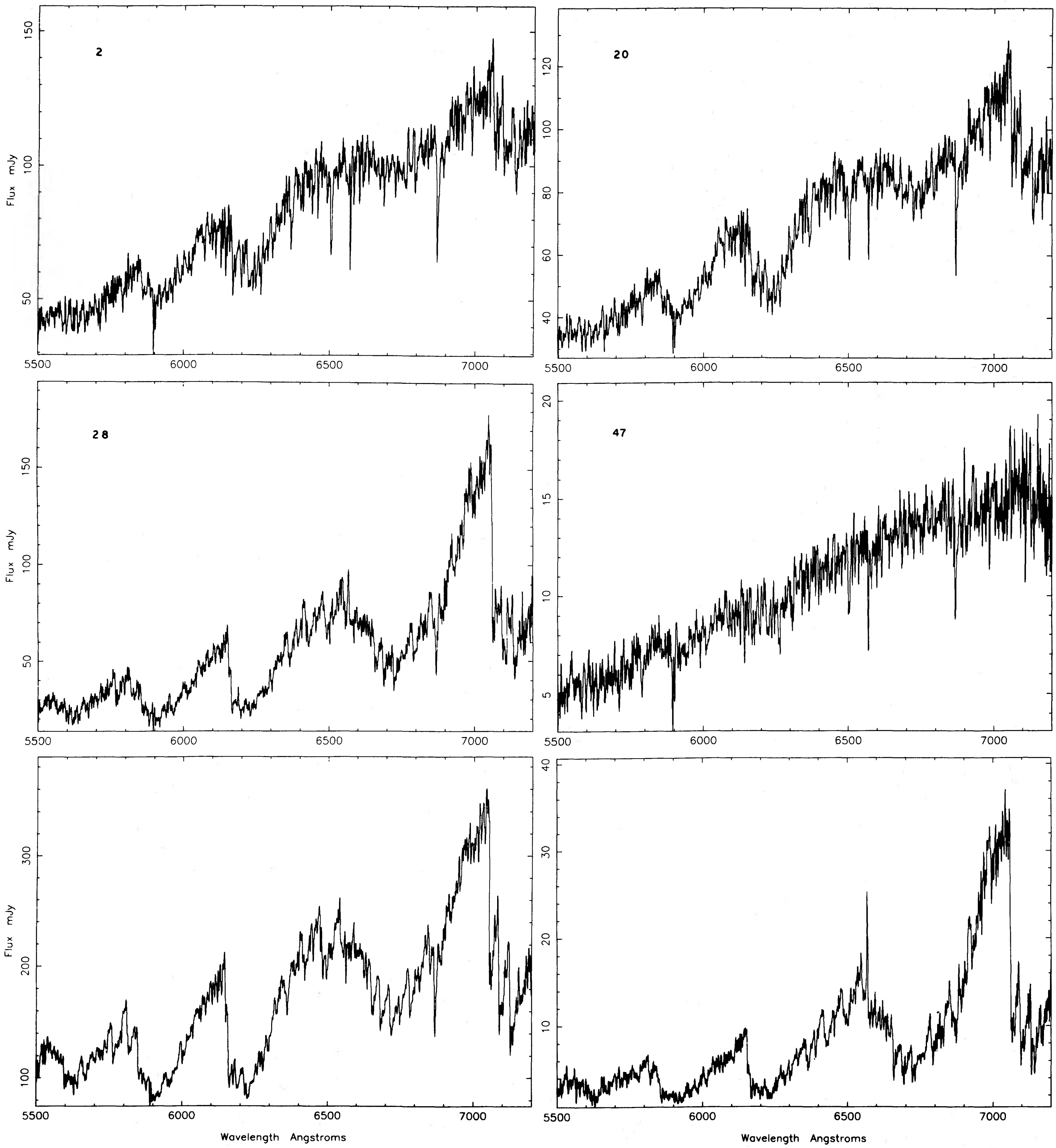

FIG. 1.—Four spectra from the sample of luminous stars in the 15 deg^2 survey field. These are indicated by their BLMC numbers in Table 1. The lower left panel is Lee 1421 in 47 Tuc (note the ZrO at 6472 Å). The lower right panel is HV 6103, a long-period variable with Hα emission.

TABLE 2

CONSTELLATION III SAMPLE

CIII	R.A. (1950)	Decl. (1950)	V	$V-I$	NaD	D (6180) TiO	D (6475) ZrO	D (7100) TiO	Sp.	M_{bol}	Velocity km s^{-1}	Remarks
X114......	$5^h29^m26^s.3$	−67°23′05″	16.71	2.57	0.16	0.64	0.03	0.69	M5	−3.9	280:	
X115......	5 29 26.2	−67 21 25	14.4:	2.17:	0.26	0.01	0.04	−0.01	K3 V	...	22	Dwarf
X116......	5 39 25.8	−67 14 56	13.87	1.73	0.05	−0.01	0.05	0.06	K4	−5.7	297	
X124......	5 29 30.8	−67 16 40	14.54	2.11	0.09	0.06	0.07	0.07	K4	−5.5	303	
X149......	5 29 41.3	−67 21 19	16.44	2.74	0.10	0.30	0.22	0.45	M2S:	−4.4	258	
X162......	5 29 46.9	−67 14 51	13.55	1.80	0.09	0.06	0.04	0.12	K5	−6.1	311	
X245......	5 30 25.5	−67 22 14	12.60	2.52	0.18	0.38	0.05	0.39	M2	−7.9	305	45:38
X274......	5 30 34.7	−67 15 55	16.33	2.43	0.34	0.68	0.01	0.82	M6	−4.1	290	
X275......	5 30 36.0	−67 13 51	13.41	1.78	0.17	0.15	0.05	0.17	K5	−6.2	292	
X285......	5 30 37.8	−67 15 30	14.1:	2.7	0.10	0.07	0.05	0.06	K4	−6.7	321	
X286......	5 30 39.2	−67 14 12	13.17	2.03	0.14	0.14	0.07	0.19	K5	−6.8	303	
X309......	5 30 46.5	−67 19 55	15.01	3.40	0.14	0.12	0.05	0.10	K5	−6.8	307	
X317......	5 30 49.5	−67 22 02	13.68	2.49	0.15	0.22	0.07	0.24	M0	−6.8	309	
X332......	5 30 52.9	−67 18 53	12.27	1.61	0.14	0.15	0.07	0.17	K5	−7.2	292	
Z395......	5 31 19.1	−67 09 16	13.77	1.91	0.12	0.07	0.07	0.09	K4	−6.0	294	
Z410......	5 31 22.6	−67 04 58	16.42	2.61	0.38	0.70	0.08	0.68	M5S	−4.2	320	
Z428......	5 31 31.1	−66 58 20	16.02	2.19	0.12	0.43	0.04	0.38	M2	−4.1	279	
Z438......	5 31 33.7	−67 04 56	16.60	2.56	0.40	0.12	0.28	0.12	C	−4.2	250	
Z448......	5 31 36.0	−67 08 26	13.61	1.71	0.11	0.09	0.09	0.02	K5	−6.0	288	
Z467......	5 31 43.8	−67 05 55	14.01	1.94	0.11	0.04	0.02	0.04	K5	−5.8	303	
Z471......	5 31 47.4	−66 58 52	13.47	2.23	0.18	0.23	0.08	0.26	M0	−6.7	312	
Z510......	5 31 57.7	−67 10 24	13.55	1.86	0.07	0.04	0.04	0.09	K4	−6.2	321	
Z522......	5 31 59.0	−67 06 11	16.5	2.0	−0.01	0.71	0.14	0.63	M5S	−4.4	297	
Z556......	5 32 10.4	−67 08 57	16.35	2.38	0.16	0.50	0.14	0.52	M3S	−4.0	267	
Z569......	5 32 17.8	−67 04 32	13.04	2.26	0.16	0.37	0.05	0.46	M2	−7.2	310	HV2648
Z572......	5 32 14.9	−67 01 18	12.71	2.01	0.15	0.39	0.07	0.46	M2	−7.2	309	HV5914
Z574......	5 32 20.5	−67 05 06	13.59	1.86	0.08	0.05	0.06	0.05	K4	−6.2	268	
Z615......	5 32 29.7	−67 07 16	14.8	3.5	0.14	0.11	0.07	0.10	K5	−7.1	306	
Z627......	5 32 34.4	−67 06 40	13.78	1.60	0.09	0.07	0.07	0.07	K4	−5.7	300	
Z630......	5 32 33.8	−67 01 03	14.8	3.6	0.13	0.15	0.09	0.16	K5	−7.3	316	RM573
Z631......	5 32 34.0	−67 00 16	12.89	2.29	0.14	0.46	0.02	0.58	M3	−7.3	317	
Y737......	5 33 09.5	−67 18 00	13.73	2.16	0.11	0.14	0.08	0.15	K5	−6.4	303	
Y813......	5 33 34.2	−67 22 16	13.75	1.77	0.09	0.01	0.05	−0.04	K3	−5.9	319	
Y825......	5 33 35.3	−67 13 08	15.82	2.36	0.33	0.45	0.02	0.54	M3	−4.5	259	
Y879......	5 33 58.9	−67 19 52	15.95	2.03	0.07	0.80	0.01	0.87	M7	−4.0	258	
Y881......	5 33 59.7	−67 12 03	14.03	1.92	0.76	0.17	0.03	0.08	K5 V	...	22	Dwarf
Y923......	5 34 16.6	−67 21 24	16.62	2.70	0.29	0.05	0.23	0.13	C	−4.4	271	
Y943......	5 34 22.2	−67 17 51	16.72	2.89	0.18	0.17	0.18	0.33	C	−4.6	288	
Y944......	5 34 23.0	−67 16 09	...	...	0.15	0.49	0.34	0.33	M2S	...	303	
Y956......	5 34 32.3	−67 14 37	15.67	1.65	0.07	0.02	0.06	−0.02	K3	−3.9	298	

The preceding sections sum up the observational data on AGB evolution in the mass range $2\,M_\odot$ to M_{UP}. The value of M_{UP} is conventionally thought to be around $9\,M_\odot$ and is the maximum initial mass star which develops a degenerate carbon core. There are a number of possibilities which could help explain the paucity of luminous AGB stars that is evident from the data.

1. Envelope burning (Renzini and Voli 1981) could convert the carbon produced in third dredge-up to nitrogen. This explanation seems contrived, since the stars which are actually observed between −6 and −7 in M_{bol} (with the exception of the Miras) show no sign that their atmospheres have been mixed with *s*-processed material.

2. A pause in star formation in the survey fields could result in a deficiency of post–main-sequence $2\,M_\odot$ to M_{UP} stars. The chief evidence against this is the existence of 180 Cepheids with periods between 3 and 15 days in the 13 deg^2 field. There should be more than 100 TP AGB stars with $-7 < M_{bol} < -6$ corresponding to these Cepheids. But there are only seven known. Similarly, there are nine such Cepheids in our Constellation III field, but only 2 Miras, both too bright to be AGB stars. However, the main-sequence luminosity function in Constellation III suggests that the bulk of star formation in this field occurred approximately 20 million years ago, so that the turnoff mass would be close to or greater than M_{UP}.

3. Bertelli, Bressan, and Chiosi (1985) have suggested that convective overshooting reduces the real value of M_{UP} toward $5\,M_\odot$. In that case, the stars we are looking for with initial masses exceeding $5\,M_\odot$ have ignited carbon and become supernovae.

4. The final possibility, and the one which we tend to favor, is that mass loss has been underestimated in the standard

TABLE 3

KINEMATICS IN CONSTELLATION III

Sample	Mean Velocity (Heliocentric)	Dispersion (km s^{-1})	No. Stars
$M_{bol} > -5.5$	283	20	14
$M_{bol} < -5.5$	304	12	23
CORAVEL	304	9	46
H I material	270	36	Note

NOTE.—The dispersion indicated for the H I material is the expansion velocity of a spherical shell in the model by Dopita, Mathewson, and Ford 1985.

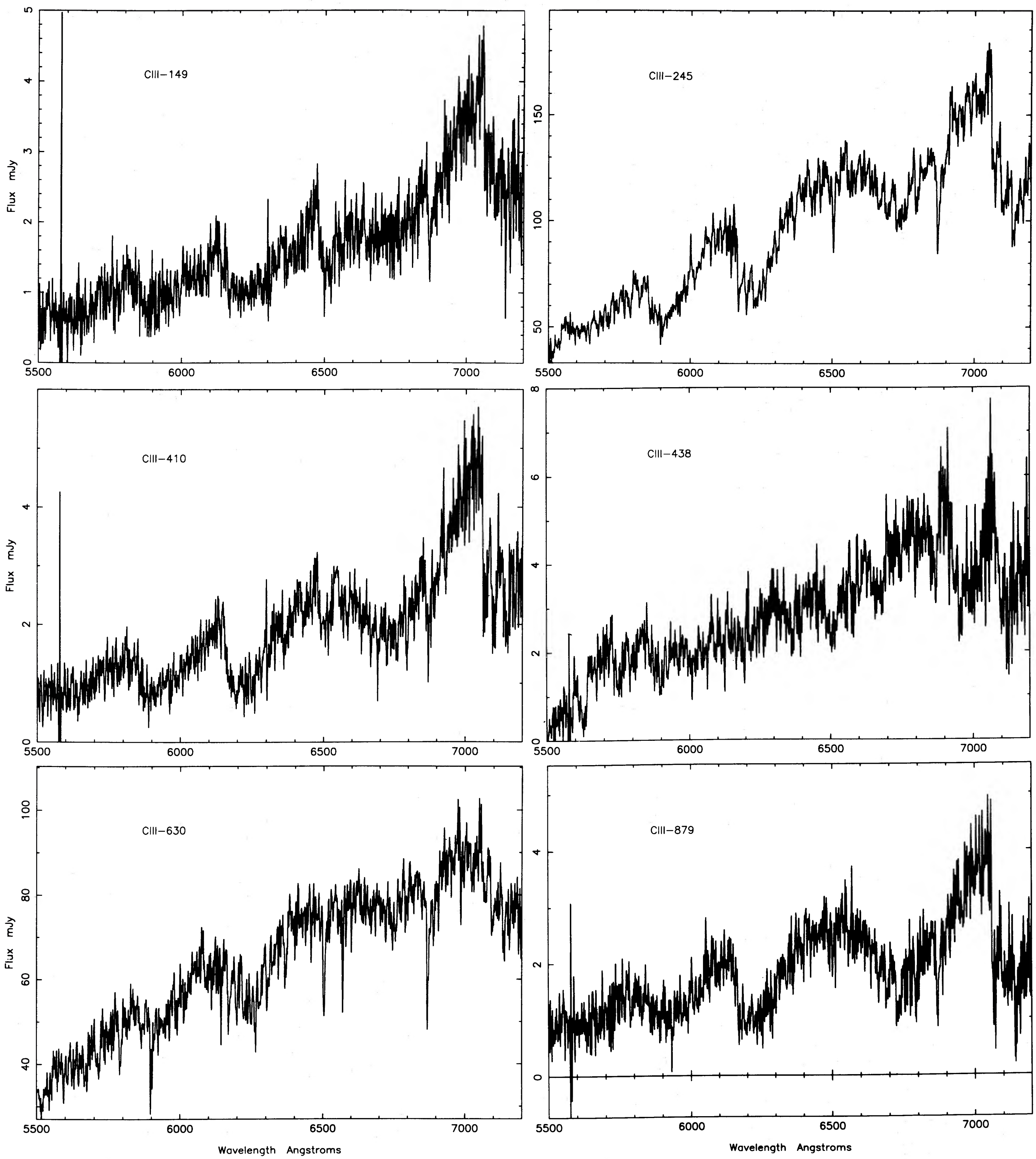

FIG. 2.—Spectra of six stars from the sample in Shapley Constellation III

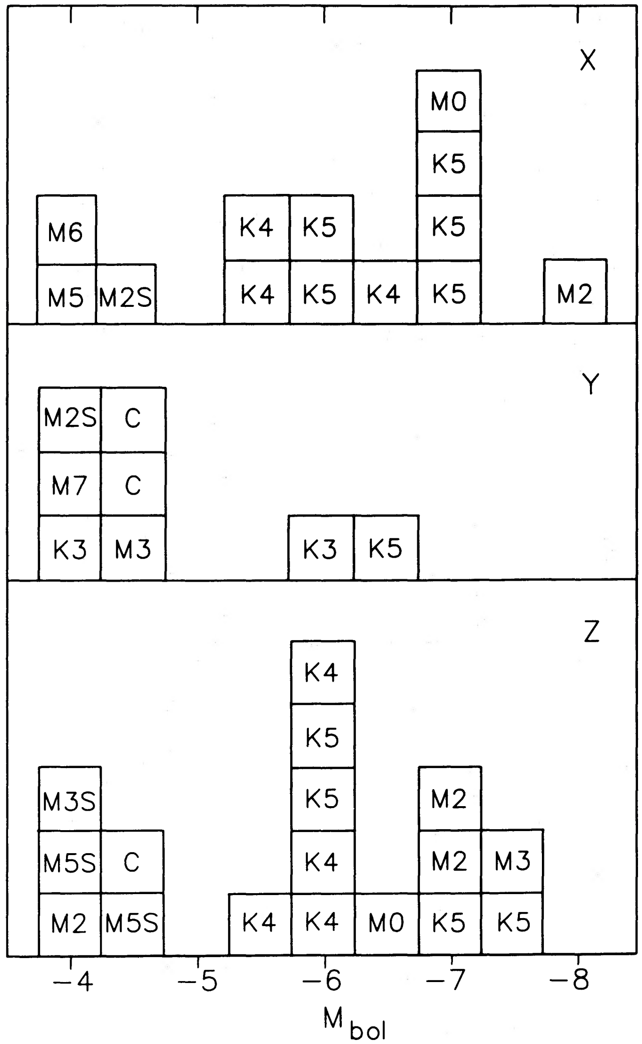

FIG. 3.—Spectroscopically coded luminosity functions in the three areas sampled in Constellation III.

theory and actually truncates AGB evolution at $M_{\rm bol}$ approximately -5.8. However, for consistency with the existence of long-period variables as luminous AGB stars, it is necessary to suppose that the Mira phase occurs briefly after thermal pulses are ignited. This would lead to the superwind phase, which might last 10^5 yr. In that case, we would expect approximately 10 undetected IR/OH stars in the 15 deg^2 survey field.

Note added in manuscript.—A recent survey by Reid and Glass (preprint) has raised the number of Miras in the 15° survey field with $M_{\rm bol}$ in the range $(-6, -7)$ from 7 to 12.

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J. R. MOULD and I. N. REID: Caltech 105-24, Pasadena CA 91125