RADIAL-VELOCITY DETERMINATIONS OF SIX LMC SUPERLUMINOUS GIANT CANDIDATES

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ABSTRACT

Blue spectra at 121 Å mm^{-1} have been obtained for 12 candidate superluminous giant stars (SLGs) in ten clusters of the LMC. For ten of these stars, red spectra at 125 Å mm^{-1} were also obtained. Spectral classes are given for the 12 stars. Of the six measured for radial velocities, four are found to be foreground objects. The possibilities that all SLG stars are foreground objects or the combined light of more than one normal star are discussed.

I. INTRODUCTION

Flower and Hodge (1975) first reported the existence of "superluminous giant stars" (SLGs) in or near the centers of young globular clusters in the Large Magellanic Cloud (LMC). SLGs have luminosities that put them 1–1.5 mag brighter than these clusters' giant branches and have a wide range of $B-V$ running from $B-V$ less than zero to greater than 1.5. Discussions of the SLGs in NGCs 1868, 2156, 2159, 2164, and 2172 can be found in Flower *et al.* (1980) and Flower and Hodge (1975), while those in NGC 1866 are discussed in Flower (1981). There are also three possible SLG stars in NGC 2058 (Flower 1976), about ten in NGC 1831 (Hodge 1963), and possibly one each in SL 791 (Baird *et al.* 1974) and SL 747 (first reported here). Moderate-dispersion spectra of several of the SLGs in NGC 1866 were kindly made available to the authors by Olszewski (private communication): these spectra showed mostly A to F spectral classes, even for some of the reddest SLGs. It became clear that many, and perhaps most, SLGs were much redder than their spectral types suggested.

This paper reports the results of a radial-velocity study of six SLGs, one in each of six LMC clusters. Four are found to have velocities inconsistent with LMC membership. The question of what percentage of SLGs are foreground objects is discussed.

Spectral classes are given for these six stars plus six additional SLG candidates whose spectral features were considered unsuitably blended for accurate radial-velocity determination. These spectral classes are compared with the observed $B-V$ of these stars and a "spectral class" estimated from continuum intensity ratios. Finally, the unpublished speculations that the SLGs are not actual objects but binary systems or the results of crowded, blurred images are seriously discussed.

II. SPECTRAL OBSERVATIONS IN THE BLUE

The spectroscopic observations were made at Cerro Tololo Inter-American Observatory with the 1 m Yale telescope and the image-tube spectrograph. Grating 26 was used to obtain blue spectra with a dispersion of 121 Å mm on IIIa-J plates. Table I gives a log of the observations, listing the cluster, the star identification, the UT date, V, $B-V$, and the reference, which gives a finder chart as well as V and $B-V$.

Six spectra suitable for radial-velocity measurement were measured at Michigan State University using a two-dimensional X-Y measuring machine. After being measured in one direction, each plate was reversed and remeasured. Because of the nature of many of the spectra it was necessary to measure broad lines not best suited for radial-velocity determination. All the radial velocities were reduced to the Sun, but the diurnal motion of the Earth has not been included because it is far below the measuring errors.

III. SPECTRAL CLASS VERSUS COLOR

A series of spectra of standard stars were taken during the same observing run with the same grating and dispersion. These spectra, along with standard spectral atlases (Morgan, Abt, and Tapscott 1978; Keenan and McNeil 1976; Houk, Irvine, and Rosenbush 1974; Houk and Newberry 1984), were used to determine spectral classes for the SLG stars. These are listed in column 2 of Table II. Standard temperature and luminosity criteria were used and an effort made to take into account the possible metal-poor nature of the stars, as many may well be stars in our own galactic halo (see Sec. IV). Particular difficulty in the luminosity classification occurred for NGC 1831 C (a very weak spectrum classified on the basis of hydrogen linewidths alone), NGC 1866 III-20 (outer), which was overexposed, and SL 747's central star, for which the spectrum was very thin. The remaining uncertainty in the indicated luminosity classes of the other stars is due to the combined effects of the intrinsic splotchiness of image-tube plates and the extreme weakness of many of the luminosity-sensitive lines due to the apparent metal-poor nature of the stars.

Roughly half the stars are luminosity class III or fainter and almost certainly members of our galaxy. The radial-velocity studies (Sec. IV) support this. Two objects (NGC 2133 A and NGC 2164 30) are clearly supergiants, based largely on the presence of Fe I λ 4233 and, in the case of the former, Si II $\lambda\lambda$ 4128–31. SL 747's central star remains uncertain because of the poor spectrum. NGC 1868 OB-50 may only be a bright giant, but is clearly brighter than luminosity class III based on several features. However, the two stars whose radial velocities make them possible LMC candidates, NGC 2156 60 and NGC 2164 6, while clearly not the

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TABLE I. Log of 1 m observations.

Cluster	Star	Plate	UT date	V	$B-V$	Ref.
NGC 1831	C	5868 S2	29/11/83	14.67	1.02	a
NGC 1866	III-20*	5846	22/11/83	13.12	0.73	b
NGC 1868	OB 50	5852	24/11/83	14.52	0.73	c
NGC 2133	A	5869 S1	29/11/83	14.9	> 0.6	d
NGC 2134	A*	5849	23/11/83	14.8	0.6	d
NGC 2156	60	5854 S2	24/11/83	13.63	0.49	e
NGC 2159	50*	5853 S1	24/11/83	13.31	0.91	e
NGC 2164	6	5853 S2	24/11/83	13.14	0.28	e
NGC 2164	30	5854 S1	24/11/83	13.26	1.30	e
NGC 2172	17*	5850	23/11/83	13.52	0.39	e
SL 747	Central star	5869 S3	29/11/83	—	—	—
SL 791	9	5868 S1	29/11/83	13.65	0.61	f
Galaxy	HD 30568	5869 S2	29/11/83	8.4	—	g

[a] Hodge 1963.
[b] Flower 1981.
[c] Flower *et al.* 1980.
[d] Hodge 1983 (private communication).
[e] Flower and Hodge 1975.
[f] Baird *et al.* 1974.
[g] Houk and Cowley 1975.
*known foreground object (this study).

highest-luminosity supergiants, still could be luminous enough within the uncertainty of the luminosity classifications made (which is *at least* one luminosity class) to be in the LMC. The situation was aggravated for NGC 2156 60 because its spectra were slightly darker than optimal and the luminosity class was based totally on the width of the hydrogen lines.

Comparison of these spectral types with the measured $B-V$ (column 4 of Table II) confirmed that many stars were substantially redder than an unreddened star of their spectral class. It was considered possible that the large $B-V$ values might have a spurious origin due to the blending of images or the background effects of faint stars on the plates used by the earlier authors to determine $B-V$. As a crude check of the redness of a star, the following procedure was carried out. The spectra of stars of known spectral type (that we obtained at the same time and with the same equipment as the SLG spectra) were visually examined to find the wavelength at which the continua reached their maximum density. We will call this wavelength λ_{max}. This wavelength is a function of the plate sensitivity as a function of λ, the response of the equipment as a function of λ (mirror reflectivities, the image-tube response), and the actual color of the star. Because only the color of the starlight changed as we moved from one star to the next any shift in λ_{max} from one star to another would be due to actual differences in the colors. There was, not surprisingly, a monotonic relation where λ_{max} got redder with later spectral type. Each of the SLG spectra were then examined and their λ_{max} determined. All SLG candidate stars except SL 791 #9 were observed in the blue within $3^h 15^m$ of the meridian. At the declination of the LMC the change in airmass from 0^h to $3^h 15^m$ is $\Delta x = 0.2$, so atmospheric reddening will be unimportant. Each SLG was then assigned a "spectral class" by comparison with the standard stars. These spectral class values, listed in column 3 of Table II, are probably uncertain to half a spectral class.

TABLE II. Spectral class and color

Star	Spectral type	λ_{max}	$B-V$	Note
NGC 1831 C	A5 IV–V	K1	1.02	a
NGC 1866 III-20 (outer)	G0 IV–V?	F5–F0	0.73	b
NGC 1868 OB-50	G2 I–II	G0	0.73	
NGC 2133 A	A0 I	F0–F5	> 0.6	
NGC 2134 A	G0 IV–V	F5	0.6	
NGC 2156 60	A2 II–III	A	0.49	
NGC 2159 50	G2 III	G5	0.91	
NGC 2164 6	F5 III–II	F5	0.28	
NGC 2164 30	A0 I	F5	1.34	
NGC 2172 17	G0 III	F8	0.39	
SL 747 Central star	A0 I ?	A	—	
SL 791 9	F8 III	G0	0.61	

[a] weak.
[b] overexposed.

NGC 2164 30 has λ_{max} of F5, which is clearly inconsistent with the published $B-V$ of 1.34. It has the spectrum of an A star. On the strength of the λ_{max} determination it can be concluded the published $B-V$ must suffer either substantial contamination, or that star 30 is a variable [Flower and Hodge (1975) found the $B-V$ from three sets of plates and calculated $\sigma(B-V) = 0.27$, which are not enough data to rule out variability]. Although other stars have $B-V$ values that are marginally red for their spectral types (i.e., NGC 2133 A, NGC 2156 60, and NGC 2159 50), the uncertainties in the method are too great to claim an important discrepancy.

IV. RADIAL VELOCITIES

The main results reported in this paper are the radial-velocity measurements of the six SLG stars listed in Table III. All six stars had significant hydrogen lines, which at our dispersion of 121 Å mm were about the only unblended features. The Ca II K line was another such feature but when present was in a region of the plate affected by the S-curvature of the image-tube system. When measured it gave discordant results. The table shows the velocities obtained from each of the lines to give the reader an idea of the error, as well as an adopted velocity for the star. Shawl, Hesser, and Meyer (1981) state that 15 km/s should be added to all measured velocities from the 1 m telescope for stars between 50° and 70° south declination, and a more recent analysis (Shawl *et al.* 1985) has reconfirmed the size of this correction. Therefore 15 km/s has been added to all velocities in Table III.

NGC 2156 60 and NGC 2164 6 have velocities appropri-

TABLE III. Radial velocities of hydrogen lines.

	NGC 1866 III-20 outer	NGC 2134 Star A	NGC 2156 #60	NGC 2159 #50	NGC 2164 #6	NGC 2172 #17	HD 30568
3797.900H_{10}			296				
3835.386H_9			254				
3889.051H_8			238				− 139
4101.746H_δ	− 89	148	228	109	214	51	25
4340.475H_γ	4	210	240	− 10	257	20	34
4861.342H_β	− 53	82	314	61	239	18	27
Adopted	− 46	147	262	53	237	30	29

ate for the LMC. The four other stars are apparently foreground objects in our own galaxy (although the case of NGC 2134 A might be left open). As a check on the reliability of our radial velocities we obtained a spectrogram of HD 30568, a star close in the sky to the LMC with a known radial velocity of + 25 km/s (Ardeberg *et al.* 1972). When our velocity is corrected for the telescope by adding the 15 km/s suggested by Shawl, Hesser, and Meyer (1981) we get $V = 29$ km/s, which agrees with the previous value within the accuracy of our measurements.

An independent investigation by Sowell (1986) has determined the radial velocities of two of the stars in this study, NGC 2159 50 and NGC 2172 17. His velocities have been determined using plates of higher dispersion and largely different sets of lines that this dispersion allows him to use. His velocities agree with our present results within the measurement errors.

We can also compare our velocities for the two possible LMC stars with the velocities that have been previously obtained for those clusters. A summary of cluster velocity determinations can be found in Freeman, Illingworth, and Oemler (1983). For NGC 2156 they list 285 ± 17 km/s, a value based completely on the work of Ford (1970). This is certainly consistent with our value of 262 ± 30 km/s for NGC 2156 60. Freeman, Illingworth, and Oemler (1983) determined a radial velocity for NGC 2164 of 273 ± 6 km/s based on their own work (275 ± 5 km/s), that of Ford (1970) (271 ± 16 km/s), and that of Andrews and Lloyd Evans (1972) (256 ± 16 km/s). Our value of 237 ± 30 km/s for NGC 2164 6 is a bit low, but is still within the overlap of the errors of the previous work. It should be mentioned that although the SLG stars in these two clusters are generally the brightest stars in their clusters the amount of light they contribute to the total integrated light of the clusters is small. Therefore, one does not have to be concerned that the cluster radial velocities that are determined using the cluster's integrated light have been distorted by the SLG.

A word of caution is necessary in interpreting the velocities of NGC 2156 60 and NGC 2164 6 as indicating LMC membership. Their velocities are also consistent with the reflex solar motion of stars in our galactic halo, particularly for NGC 2164 6, which has the lower velocity of the two. This caution is even more necessary because the luminosity classifications of these stars [which were done in such a way that the classifier (SRB) was unaware that these were the possible LMC stars] indicate these are not the brightest of supergiants. It is therefore possible these are just bright giants in the galactic halo.

V. CLOSING COMMENTS

There are two questions that must be discussed in the light of this work: first, are all SLGs actually foreground objects; second, if not are they instead binary stars or merged stellar images of cluster stars.

The authors feel there is some evidence that not all SLGs are foreground stars, but this evidence is far from conclusive. The evidence in favor of LMC membership is most clearly shown not by the radial velocities in this paper but by the actual clustering of SLG stars toward cluster centers, as shown in the original papers describing these objects. This is particularly evident in the larger clusters. NGC 1866 has a total of 17 SLG stars, 11 of which are in the central region of the cluster (Flower 1981), and NGC 1868 has ten SLG stars in its central region (Flower, Geisler, Hodge, and Olszewski 1980). The SLG stars for which we have obtained radial velocities were selected because they were among those whose spectra were easiest to get. This introduces a bias in favor of selecting not only the brightest stars but those that are in relatively clear areas. This may have produced a selection effect in favor of foreground objects.

Our spectra allow us to make some contribution to the second point mentioned. Although there has been no published literature on the subject, there has been substantial discussion among those interested in SLG stars as to whether they actually exist as single stars, or whether we are really seeing the combined light of two or more stars. Although nothing has appeared in print, the idea has become widespread enough that one reader of an early version of this paper has characterized SLGs as "nonproblem." The spectra of the two stars whose velocities indicate possible LMC membership show no signs of line splitting or of a symbiotic nature. Indeed all 12 SLG candidate stars listed in Table II had both blue and red spectra taken over the same eight-night observing run at CTIO with the exception of the central star of SL 747 and NGC 1866 III-20 (outer). The red spectra were centered at 6500 Å and were obtained with a dispersion of 125 Å mm^{-1} using the 1 m telescope and image-tube spectrograph. A log of the observations is given in Table IV. None of the red spectra showed the late-type fea-

TABLE IV. 1 m red plates.

Cluster	Star	Plate	Date
NGC 1831	C	5865	28/11/83
NGC 1868	OB 50	5862	27/11/83
NGC 2133	A	5866	28/11/83
NGC 2134	A	5863	27/11/83
NGC 2156	60	5859	26/11/83
NGC 2159	50	5858	26/11/83
NGC 2164	6	5862	27/11/83
NGC 2164	30	5857	26/11/83
NGC 2172	17	5860	26/11/83
SL 791	9	5865	28/11/83

tures one would get from a binary where one member was of early type and the other of late type. Instead, the red spectral types agreed with the blue plates, and in many cases were close to featureless at our dispersion. There were also no obvious cases of line doubling or splitting on either the red or blue spectra. Therefore, if the images of any of these stars are the result of the combined light of two or more stars, the component stars must be of roughly the same spectral type and have radial velocities within 30 km/s of each other. This suggests that if the SLGs are not individual stars they are more likely to be widely separated binaries of roughly equal mass or contact binaries sharing a common envelope than the result of accidental image blending on the discovery plates.

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