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# OBSERVATIONS OF AN sdO STAR IN THE GLOBULAR CLUSTER M22

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## ABSTRACT

Spectra of the hot, UV-bright star II-81 in the globular cluster M22 show absorption lines of H I, He I, and He II, and have been used to estimate a spectral type of O6. The measured radial velocity of $-140$ km s$^{-1}$ agrees well with the published cluster velocity of $-152$ km s$^{-1}$ and supports the probable membership of this star in the cluster. The profile of H$\delta$ implies a value of log $g = 4.2$. Using $M_V = 0.5$ for this star, we also derive a mass of $\mathscr{M} = 0.44\ \mathscr{M}_{\odot}$, in good agreement with previously published results on cluster sdO stars.

Comparison of this and other cluster sdO stars with field sdO stars suggests that the former have systematically lower log $g$ values for the same range of temperatures. Possible interpretations in terms of existing theories for the evolutionary status of sdO stars are discussed.

*Subject headings:* clusters: globular — stars: early-type

## I. INTRODUCTION

Spectroscopic observations of hot stars in globular clusters remain surprisingly rare in spite of their importance in verifying theories of stellar evolution just prior to the white dwarf stage. Only a half-dozen such objects have been observed spectroscopically (see Remillard, Canizares, and McClintock 1980; Bohlin *et al.* 1983), in spite of rather extensive searches for and discussions of the UV-bright objects by Zinn, Newell, and Gibson (1972) and by Zinn (1974). Although a variety of field subdwarfs have been discussed in the literature, discussions of the physical properties of these objects are clouded by the lack of independent estimates of the distances and reddening that can be provided by membership in a cluster.

We present here moderate-resolution spectroscopic observations of the star labeled II-81 by Arp and Melbourne (1959) in the metal-rich globular cluster M22 (NGC 6656). The star is also known as star number 7 in M22 according to Zinn, Newell, and Gibson (1972). In the color-magnitude diagram of the cluster (see Philip, Cullen, and White 1976) this star is located about 1 mag above the extreme blue end of the horizontal branch. We show that this star has the spectral characteristics of an sdO star. We follow the same analytical approach as Greenstein and Sargent (1974, hereafter GS) in order to facilitate comparisons with their work.

## II. OBSERVATIONAL MATERIAL

Two sets of spectroscopic data have been obtained. The initial observations were made using the blue-sensitive, intensified Reticon, photon-counting camera on the Cassegrain spectrograph of the Steward Observatory (SO) 2.3 m telescope on Kitt Peak. A single 12 min observation under clear skies was obtained in which the detector covered the wavelength range 3800–5000 Å. The grating plus camera combination provided 0.4 Å per pixel, with an instrumental resolution corresponding to 2.0 Å full width at half-maximum (FWHM). Fine structure in the system response was removed by dividing the data by normalized flat-field observations. The resulting spectrum is shown in Figure 1.

Additional spectroscopic data were obtained at the South African Astronomical Observatory (SAAO) Sutherland station using the 1.9 m telescope. An intensified Reticon photon-counting camera on the RGO Cassegrain spectrograph was used for a total of 277 min integration over three partly cloudy nights, to yield spectra between 3920 and 4260 Å FWHM effective resolution. Radial velocities were measured separately for each of the three nights when II-81 was observed. For purposes of the line analysis, all SAAO observations were combined to form a single spectrum using the data reduction programs at the Cape Observatory. The final, combined SAAO spectrum is shown in Figure 1.

## III. ANALYSIS

Table 1 details the (heliocentric) radial velocities obtained from the individual spectra. The line positions were determined by fitting a Gaussian function to the cores of the lines. The agreement between the two sets of data is quite satisfactory, and the average velocity of $-140$ km s$^{-1}$ ($\pm 3$ km s$^{-1}$ standard deviation of the mean) agrees reasonably well with the published cluster velocity of $-152$ km s$^{-1}$ (Webbink 1981). This lends strong support to the assumption that II-81 is a cluster member. The interstellar Ca II $\lambda$3933 line at $+67$ km

TABLE 1

RADIAL VELOCITY MEASUREMENTS

| Observatory | JD 2,440,000+ | $V_r$[a] (km s$^{-1}$) | Lines |
|---|---|---|---|
| SO ............ | 5125.91 | $-144$ | H$\gamma$ $\lambda$4340, He I $\lambda$4471, He II $\lambda$4686, H$\beta$ $\lambda$4860 |
| SAAO ......... | 5515.50 | $-145$ | H$\epsilon$ $\lambda$3970, He I $\lambda$4026, H$\delta$ $\lambda$4101, He I $\lambda$4120 |
| SAAO ......... | 5517.60 | $-134$ | H$\epsilon$ $\lambda$3970, He I $\lambda$4026, H$\delta$ $\lambda$4101, He I $\lambda$4120 |
| SAAO ......... | 5519.46 | $-135$ | H$\epsilon$ $\lambda$3970, He I $\lambda$4026, H$\delta$ $\lambda$4101, He I $\lambda$4120 |

[a] Mean = $-140$ km s$^{-1}$ ($\pm 3$ km s$^{-1}$).

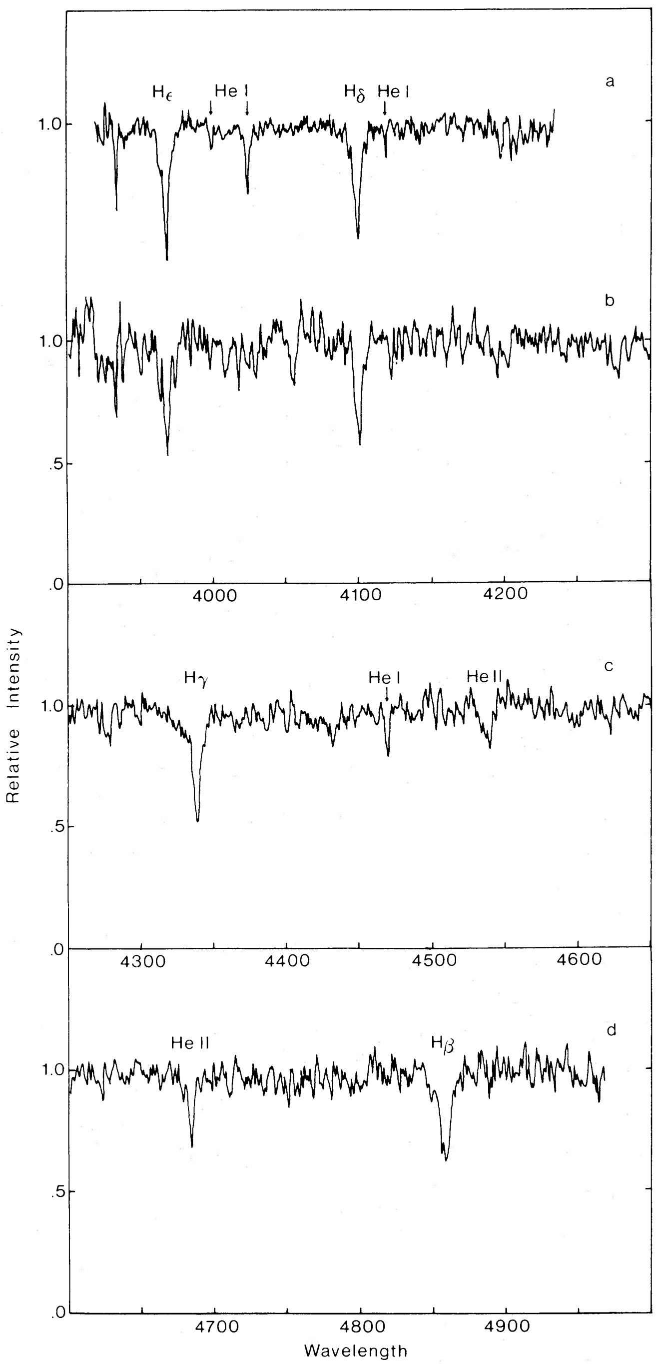


FIG. 1.—Spectra of II-81, smoothed slightly and rectified to a flat continuum: (*a*) moderate-resolution data from SAAO; (*b*, *c*, *d*) low-resolution data from SO. The wavelength scales are identical in spectra *a* and *b*. The signal-to-noise ratio in spectra *b* and *d* is considerably poorer than in spectrum *c*, sometimes giving the impression of absorption features, especially shortward of 4100 Å.

$s^{-1}$ and the unexplainably asymmetric He II λ4542 line were not included in the nightly means.

According to Arp and Melbourne (1959), the photovisual magnitude for II-81 is $V = 14.00$. Adopting an apparent distance modulus of $(m_V - M_V) = 13.5$ for the cluster (Alcaino and Liller 1983), we calculate $M_V = +0.5$ for II-81. According to GS, this falls within the $M_V$ range typical for sdO stars.

TABLE 2

EQUIVALENT-WIDTH MEASUREMENTS

| Observatory | Line (Å) | Ident. | EW (Å) |
|---|---|---|---|
| SAAO ......... | 3933 | Ca II | 0.63 |
| SAAO ......... | 3970 | Hϵ | 4.16 |
| SAAO ......... | 4009 | He I | 0.15 |
| SAAO ......... | 4026 | He I | 1.24 |
| SAAO ......... | 4101 | Hδ | 4.60 |
| SAAO ......... | 4120 | He I | 0.30 |
| SO ............. | 4340 | Hγ | 4.44: |
| SO ............. | 4471 | He I | 0.79 |
| SO ............. | 4542 | He II | 1.55: |
| SO ............. | 4686 | He II | 1.96 |
| SO ............. | 4713 | He I | 0.30 |
| SO ............. | 4860 | Hβ | 4.84 |
| SO ............. | 4920 | He I | 0.29 |

Estimates of the effective temperature can be derived both from the color index and from the spectral line strength ratios. Arp and Melbourne (1959) measured a color index C.I. $= m_{pg} - m_{pv} = -0.03$. By comparing the photographic photometry of Arp and Melbourne to that of Alcaino and Liller (1983), we derived a transformation equation of $B-V = 0.11 + 1.03$CI. Applying this formula to II-81 yields $B-V = 0.08$ and $(B-V)_0 = -0.24$ for $E_{B-V} = 0.32$. According to the standard relations tabulated by Allen (1973), this intrinsic color corresponds to a spectral type of B2 for normal Population I main-sequence stars.

This spectral type does not agree with the type obtained from the spectral lines. Equivalent widths (EWs) were measured for several lines and are tabulated in Table 2. In Figure 2 we present line ratios for He II λ4542/He I λ4471, He II λ4686/He I λ4471, and He II λ4686/Hβ λ4860 calculated from equivalent widths reported by Scholz (1972) for a range of Population I O-type stars. The corresponding ratios for II-81, 2.0, 2.5, and 0.40, respectively, are also indicated in Figure 2. They are mutually consistent with a spectral type of O6, but certainly cannot be reconciled with type B2. It has been pointed out by

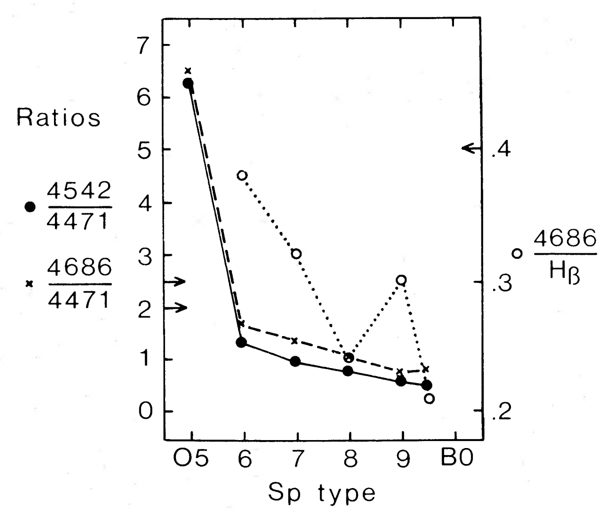


FIG. 2.—The variations of the He II/He I and He II/H I line ratios as a function of spectral type, based on data from Scholz (1972): (*filled circles, solid line*) λ4542/λ4471; (*crosses, broken line*) λ4686/λ4471; (*open circles, dotted line*) λ4686/λ4860. The arrows indicate the observed ratios found in II-81, indicating type O6.

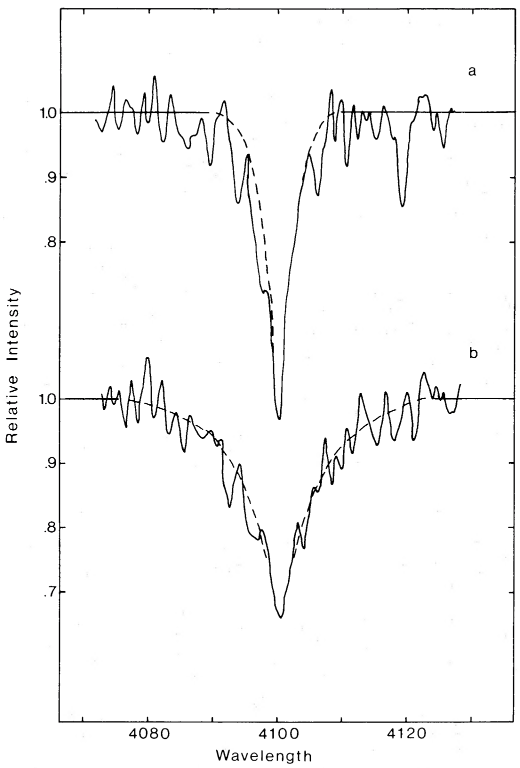


FIG. 3.—The H$\delta$ profiles of (*a*) II-81 and (*b*) Feige 110. The dashed lines indicate the eye-estimated profiles used to determine $D(0.2)$.

GS, however, that the helium line ratios in field sdO stars do not correlate well with the photometric temperature estimates, apparently because of differences in surface helium abundance. Whether or not such abundance effects would bias the He II/H I ratio in the same sense as the He II/He I ratio is difficult to determine. We wish to point out that in comparison to Figure 10 of GS, the EWs for He I $\lambda$4471 and He II $\lambda$4686 for II-81 seem typical of those for sdO stars, but they are definitely weaker than expected for normal OB stars of comparable (spectroscopically determined) temperature.

Our data may also be used to estimate the surface gravity. A frequently used indicator is the width of the Balmer lines at a specified depth below the local continuum. We have used Figure 3 of GS to derive values of log $g$ as a function of $D(0.2)$, the full width in angstroms at a depth of 0.2, and of effective temperature. The latter quantity would normally be determined from the reddening-independent $Q$-index, as shown in Figure 1 of GS, who used the calibrations of $Q$ in terms of $\theta$ by Hyland (1967) and Peterson (1969). Not having ultraviolet photometry for II-81, we used the relations between $Q$ and $(B-V)_0$ and between $Q$ and MK spectral types according to Allen (1973) to derive $\theta$ for the photometric and spectroscopic observations discussed above.

Figure 3 shows the rectified SAAO spectrum of II-81 centered on H$\delta$ which yielded $D(0.2) = 4.6$ Å, corrected for instrumental broadening. (We estimate the uncertainty in this value to be $\pm 1.0$ Å, due to fitting the profile and locating the continuum.) The resulting values of $\theta$ and log $g$ derived by these methods are also presented in Table 3, where we see that the uncertainty in the temperature alone leads to values of log $g$ that differ by an order of magnitude. The uncertainty in $D(0.2)$ of $\pm 1.0$ Å would lead to an additional uncertainty of $\pm 0.4$ in log $g$. An observation of Feige 110 a H$\delta$ taken during the same run at SAAO is also included in Figure 3 to show how narrow the profile of II-81 appears when compared with that of this well-studied, higher gravity, sdO star. GS derived $\theta = 0.13$ and log $g = 6.0$ for Feige 110, using the techniques we have already described. Heber *et al.* (1982) used a model-fitting procedure to derive $\theta = 0.13$ and log $g = 5.0$ for Feige 110, suggesting a systematic difference of 1.0 dex between the two methods of deriving log $g$. On the other hand, using the same models (Kudritski 1976), which give $D(0.2)$ in terms of $T_{\rm eff}$ and log $g$, and assuming log $T_{\rm eff} = 4.6$ for II-81, we derived log $g = 4.3$ and log $g = 4.9$ for $n_{\rm He}/n_{\rm H} = 0.1$ and 1.0, respectively. This is in satisfactory agreement with the value of 4.2 found above.

We may also attempt to reverse the methods of GS to estimate a mass for II-81. GS assumed a constant mass for the sdO stars, and then used this assumption to derive bolometric magnitudes. We reverse the GS relation to obtain log $\mathcal{M}/\mathcal{M}_0 =$ log $g + 4$ log $\theta - 0.4M_{\rm bol} - 2.33$. The uncertainty in temperature enters again through the volometric correction (BC), which we took from the dependence of BC on $T_{\rm eff}$ tabulated by Allen (1973). We find that the masses for the two possible temperatures differ by over a factor of 4. Either *UBV* color measurements or, preferably, an ultraviolet spectrophotometric determination of the effective temperature is obviously required to narrow the range of possible temperatures and, possibly, to test for a helium abundance anomaly in the atmosphere of the star.

TABLE 3

DERIVED PHYSICAL DATA

| Star | log $T_{\rm eff}$ | log $g$ | $M_V$ | $\mathcal{M}/\mathcal{M}_\odot$ | Cluster | Ref. |
|---|---|---|---|---|---|---|
| II-81 .................. | 4.58 | 4.2 | +0.5 | 0.44 | M22 | 1 |
| | 4.42 | 3.4 | | 0.1 | | |
| von Zeipel 1128 ....... | 4.54 | 4.9 | −0.5 | 0.6 | M3 | 2 |
| | 4.51 | 4.3 | | | | |
| Barnard 29 ............ | 4.35 | 3.0 | −1.7 | 0.41 | M13 | 3 |
| ZNG 1 ................. | 4.54 | 4.0 | ... | 0.5 | M5 | 4 |
| C49 .................... | ≤4.70 | 5.5 | 1.0 | (3.6) | NGC 6712 | 5 |
| ROB 162 .............. | 4.65 | 4.6 | +0.9 | 0.6 | NGC 6397 | 6, 7 |
| | 4.44 | 3.6 | | | | |

NOTE.—Where there are contradictory temperature indicators, both values of log $T_{\rm eff}$ and the corresponding log $g$'s are shown.

REFERENCES.—(1) This paper; (2) Strom and Strom 1970; (3) Auer and Norris 1974; (4) Bohlin *et al.* 1983; (5) Remillard, Canizares, and McClintock 1980; (6) Caloi, Castellani, and Panagia 1982; (7) Searle and Rodgers 1965.

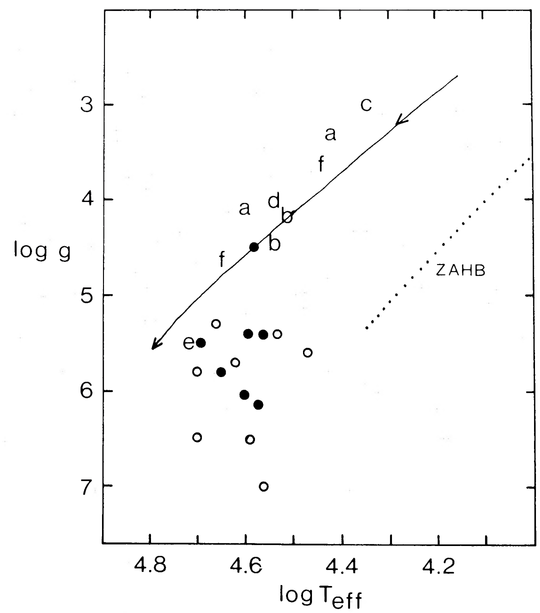


FIG. 4.—The distribution of cluster and field sdO stars in the (log $g$, log $T_{eff}$)-plane. The cluster sdO stars from Table 3 are shown as letters: $a$, II-81; $b$, von Zeipel 1128; $c$, B29; $d$, ZNG 1; $e$, C49; $f$, ROB 162. Part of the track for a 0.435 $\mathscr{M}_\odot$ star from Sweigart, Mengel, and Demarque (1974), representing about $3 \times 10^5$ years of evolution, is shown as a solid line. Field sdO stars are shown as open circles (GS) and filled circles (Hunger *et al.* 1981). The zero-age horizontal branch for $Y = 0.30$, $Z = 0.0001$, and $M_c = 0.475$ from Sweigart and Gross (1978) is shown as a dotted line.

## IV. DISCUSSION

The principal interest in observing more sdO stars in globular clusters is to compare them with other examples of this class of objects. In Table 3 we collect, together with the II-81 results, various parameters of interest for the other cluster sdO stars observed spectroscopically to date.[1] We should point out that the other five objects were analyzed by five independent groups of researchers, often using completely different methods to derive the quantities listed. We show in Figure 4 log $g$ plotted against log $T_{eff}$ for all of these objects, along with the evolutionary track for a 0.435 $\mathscr{M}_\odot$ star from Sweigart, Mengel, and Demarque (1974, hereafter SMD) and the corresponding data for several field sdO stars (GS; Hunger *et al.* 1981). The evolutionary track for the 0.51 $\mathscr{M}_\odot$ model from SMD loops back and forth in the area below and to the right of the 0.435 $\mathscr{M}_\odot$ track and also takes much more time to evolve away from this region of the (log $g$, log $T_{eff}$)-diagram (assuming no mass loss). The 0.60 $\mathscr{M}_\odot$ model of SMD avoids this region, instead passing above and to the blue of the sdO sequence on the way to the white dwarf region. We interpret Figure 4 as indicating that all of the sdO stars plotted have about the same mass (0.4 $\mathscr{M}_\odot$) and that all are in the final stage of pre–white dwarf evolution. According to the SMD model these stars will continue to decrease in luminosity over the next few hundred thousand years, since they do not have sufficient mass to return to the asymptotic giant branch (AGB).

An alternative explanation could be provided by the models of Wesemael *et al.* (1980), which suggest that the lower gravity, cluster sdO stars are *more* massive than the field sdO's, and are evolving along tracks corresponding to cooling, zero-hydrogen, zero-helium cores.

The data in Figure 4 also show that there is apparently no major difference between the gravities and temperatures derived by GS and those derived by others using more recent model atmospheres. (The high log $g$ stars in the GS sample are not included in Fig. 4 because of the unreliability of the models used in their method of determining log $g$ for hot, high-gravity stars.)

Observational constraints have obviously precluded obtaining the appropriate physical parameters for faint, very hot, cluster sdO stars. Since we do not know of any selection effects in the samples of either GS or Hunger *et al.* (1981) which would exclude low-gravity objects, we feel justified in concluding that the field sdO stars have systematically higher surface gravities than the cluster sdO's. The SMD models would suggest that the field sdO's may be generally younger, less evolved, and, therefore, more massive stars than their cluster counterparts.

We note also that Barnard 29, the only cluster sdO star studied extensively for radial velocity variations, may be a velocity variable (Stoeckly and Greenstein 1968). It would be very useful to undertake a systematic velocity study of several cluster sdO stars, since it is generally believed that mass transfer between members of binary systems is an important mechanism leading to the formation of low-mass, evolved stars. Moreover, it would be extremely useful to study a large sample of cluster sdO stars with a single spectrograph/detector combination to obtain a homogeneous set of data that can be analyzed with the non–LTE atmospheres now available for such objects.

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[1] The data for star 2128 in NGC 6397 discussed by Caloi *et al.* (1984) are not included. The values of $T_{eff}$ and log $g$ derived by these authors for star 2128 are quite inconsistent with what we estimated by extrapolating the non–LTE models of Kudritski (1976) to match the EW and $D(0.2)$ measurements of H$\gamma$.

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