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THE DISCOVERY OF AN O SUBDWARF IN THE GLOBULAR CLUSTER NGC 6712[1]

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ABSTRACT

Photographic plates of the globular cluster NGC 6712 revealed a star, C49 (Sandage and Smith) with a large UV excess. Spectrophotometry using the 4 m CTIO telescope showed the star to have an O subdwarf spectrum. The spectrum is almost identical to that of the first sdO star found in a globular cluster, star A in NGC 6397, discovered by Searle and Rodgers. A radial velocity is not available for C49, but cluster membership is favored for two reasons: first, if the distance modulus for NGC 6712 is applied to C49, then the deduced value $M_v = 1.0$ agrees with that of star A; and second, the large equivalent width of an interstellar Ca (K) line implies a distance for C49 compatible with that of NGC 6712. Analysis of the spectral data using nonlocal thermodynamic equilibrium (NLTE) models gives surface parameters $T \gtrsim 50{,}000$ K, $\log g = 5.5 \pm 0.5$, and $N(\mathrm{He})/N(\mathrm{H}) \approx 0.1$. The results are consistent with the evolutionary models for low-mass stars that are contracting into white dwarfs. Globular cluster membership provides advantages for establishing this phase of stellar evolution as one explanation of sdO stars.

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

I. INTRODUCTION

U and *B* plates of the globular cluster NGC 6712 were taken at the McGraw Hill Observatory[3] in 1975 as part of the effort to identify the cluster X-ray source. Comparison of the plates revealed a conspicuous highly UV star which is numbered C49 in the cluster analysis by Sandage and Smith (1966). They list a *V*-magnitude of 16.60, but the star is the only one for which $B - V$ was not reported. The spectrum of C49 does not resemble that of any X-ray source counterpart, and the coincident area of the *HEAO 1* (private communication, *HEAO* A-3 group) and the *SAS 3* (Doxsey *et al.* 1977) error boxes and the recent *HEAO 2* position (Grindlay *et al.* 1979) exclude this star from consideration as the X-ray source. However, C49 is a subdwarf, and it has its own significance with respect to the studies of hot subdwarfs and highly evolved stars in globular clusters.

Our spectral observations show C49 to be an O subdwarf, sdO. It has a striking similarity to the first sdO discovered in a globular cluster, NGC 6397 (Searle and Rodgers 1966). To our knowledge this latter sdO, the late O subluminous VZ 1128 in M3 (Strom and Strom 1970), another probable late O subluminous star, K559 in M15, (Zinn 1974), and the nucleus of the nebular K648 in M15 (O'Dell 1968) are the only O temperature stars verified as cluster members by radial velocity measurements. While we do not have such a measurement for C49, other evidence will be advanced in favor of cluster membership.

The classifications sdO and sdB generally include O and B temperature stars located well below the main sequence and above the white dwarf region of an H-R diagram. For sdO stars this is typically determined by the observation of H and He absorption lines having broadened Balmer lines (without the wing development of white dwarfs) and strong He II λ4686. These characteristics are associated with the high log g values that separate subdwarfs from subluminous stars. Studies of sdO and sdB stars include the continuing discovery of hot subdwarfs in both halo and disk populations and efforts to sort them into evolutionary groups. Newell (1973) has shown that the effective temperature versus log surface gravity T–log g plane is an important format for the latter task. Established evolutionary tracks can be mapped there, and spectral data can be fitted to T, log g values by using computed models (to the extent available) without requiring distance information (which is usually unavailable).

The array of O subdwarfs is an impressive list (see Greenstein and Sargent 1974), with a range of M_v of as much as 8 mag, surface temperatures from around 30,000 to over 50,000 K, and surface helium abundance from 10% N(H) to virtually 100% (Garrison and Hiltner 1973; Kudritzki and Simon 1978; and Berger and Fringant 1978). It is anticipated that most sdO's may be highly evolved low-mass stars which are

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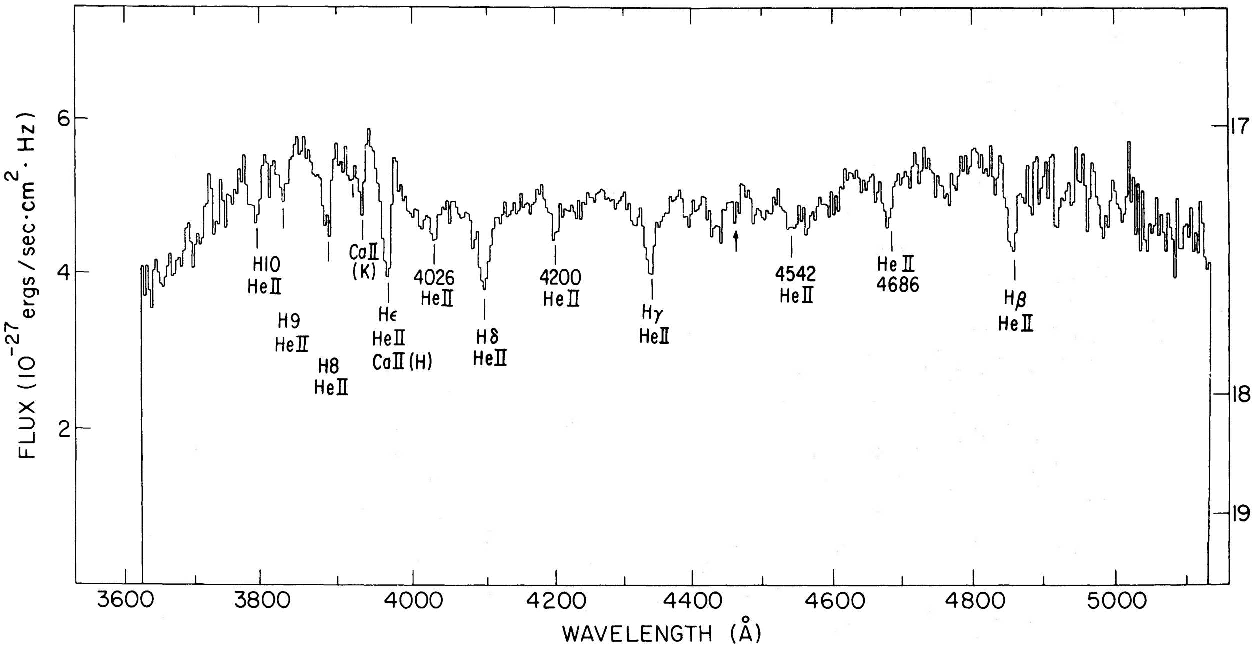

FIG. 1.—Spectrum no. 1 of C49 in NGC 6712. The Balmer blends of H and He II are broadened and present through H10, and the He II Pickering series is seen up to the tick mark to the left of Ca (K). The only other features are He II λ4686 and the interstellar Ca (K) line. The arrow indicates the location of the strongest He I line within the spectral range at λ4471.

contracting into white dwarfs. This paper will discuss the spectral results for C49 with regard to these models.

II. OBSERVATIONS

The *U* and *B* plates mentioned above were taken at the f/7.5 Cassegrain focus of the 1.3 m telescope of the McGraw Hill Observatory in 1975 July. While accurate photometry was not possible because of the crowding of the images, both visual inspection and iris photometry of the plates indicated that C49 has a significant UV excess compared with all other stars in the field.

Spectra were obtained in 1977 August and 1978 June using the CTIO 4 m telescope and Ritchey-Chrétien spectrograph fitted with a SIT (silicon intensified target) vidicon detector and were reduced in the usual manner (Osmer and Smith 1976; Attwood *et al.* 1979). The first of these (Fig. 1) is a 65^{m} exposure and has a resolution of 10 Å (FWHM). The second spectrum (35^{m} exposure 13 Å resolution) is of lower overall quality.

III. RESULTS

The absorption lines of C49 (see Fig. 1) are typical of sdO stars (Greenstein and Sargent 1974). Those features are a broad Balmer series, the He II Pickering lines, strong He II λ4686, and Ca (K) which is assumed to be interstellar. Table 1 lists their equivalent widths as measured directly from the flux-calibrated spectrum.

Accuracy is limited by the instrument's channel-to-channel fluctuations and uncertainty in the continuum location. An estimation of the statistical uncertainty was made empirically by measuring the channel-to-channel fluctuations from the mean for several spectral intervals expected to be featureless and applying the equation

$$1\,\sigma = \frac{\text{rms of (fluctuations/continuum)}}{\sqrt{(n)}} \times (\text{dispersion for } n \text{ channels}),$$

where n is the minimum number of channels for a

TABLE 1

EQUIVALENT WIDTHS MEASURED FROM FLUX-CALIBRATED SPECTRUM

Line	Equivalent Width (Å)
H10 λ3798 and He II λ3796	2.0 ± 0.7
H9 λ3835 and He II λ3834	0.9 ± 0.7
H8 λ3889 and He II λ3887	3.0 ± 0.7
He II λ3923	0.5 ± 0.35
Ca (K) λ3933	1.1 ± 0.35
He λ3970, He II λ3968, and Ca (H) λ3968	4.0 ± 0.5
He II λ4026	0.7 ± 0.35
Hδ λ4102 and He II λ4100	4.2 ± 0.5
He II λ4200	0.8 ± 0.35
Hγ λ4340 and He II λ4339	4.1 ± 0.5
He II λ4541	1.0 ± 0.35
He II λ4686	1.3 ± 0.35
Hβ λ4861 and He II λ4859	3.3 ± 0.8
He I λ4471	<0.30

spectral line for the 300 μm slit width. Comparison spectra show $n = 4$, and the rms value of (fluctuations continuum) is 0.023 over the range $\lambda\lambda$3900–4700 where the spectrum is most stable, 0.04 for the adjacent interval that includes H8 to H10, and 0.05 for Hβ. We adopt 2 σ values as the statistical uncertainties, which are 0.31 Å for $\lambda\lambda$3900–4700, 0.53 Å for H8 and H10, and 0.67 Å for Hβ. These numbers also indicate the 2 σ level for line detection. It is noted that Hβ is in a statistically poor interval, and its low equivalent width is suspect. There is also a continuum-position uncertainty which can change equivalent width measures by about 0.15 Å for the weaker lines and 0.45 Å for the Balmer blends. The resultant errors due to fluctuations and the position of the continuum are listed for each line in Table 1.

There is useful line width information in spectrum number 1. A reliable estimate can be made of the true full width at half-maximum (FWHM) line depth of Hγ and Hδ, and the half-maximum points happen to occur at line depths of 0.094 and 0.104 of the local continua, respectively. In the literature, D (0.1) is defined as the full width at the point where the line depth is 0.1 of the continuum, and this is a useful quantity tabulated from the NLTE models which apply to O subdwarfs. We therefore have the fortunate circumstance for both Hγ and Hδ in spectrum number 1 that the true FWHM $= D$ (0.1). The instrumental profile for a slit width of 1".4 is indicated by the comparison lamp spectra, which show consistent FWHM of 9.0–11.0 Å for a large range of line strengths. Considering the observed FWHM as a root quadratic sum of instrumental and true widths, we calculate the true FWHM $= D$ (0.1) $= 11.9$–13.5 Å for Hγ and 12.6–14.1 Å for Hδ.

Auer and Mihalas (1972) have shown that NLTE effects become important for sdO stars, and they have published NLTE models for part of the subdwarf domain. Similar work has been carried to higher values of log g and for two helium abundances [N(He)/N(H) = 0.1 and 1.0] by Kudritzki (1976). The spectral data can be fitted to these calculations as follows. The ratio of equivalent widths for He II to He I lines is a temperature-sensitive quantity. The models show λ4471 as the strongest He I line in the range of our spectra; however, it is not present above the noise level (see the arrow in Fig. 1). He II λ4686 is best suited for comparison with the λ4471 upper limit, since it is the strongest He II line and is less sensitive than the Pickering lines to log g in the applicable region. An (He II/upper limit He I) equivalent width ratio determines a line in the T–log g plane which is the edge of an allowed region extending toward higher T. For an assumed He abundance, each equivalent width value for H and He lines determines an additional curve, while the D (0.1) ranges for Hγ and Hδ specify narrow, overlapping bands in the plane. A sequence of helium abundances must be investigated to find the best convergence point for the equivalent width curves and D (0.1) bands on the high-T side of the He II/He I limit.

In Figure 2 we show the NLTE curves for the spectral data of C49 on the T–log g plane. The D (0.1) bands for Hγ and Hδ and the equivalent width curves for Hγ, Hδ (they almost exactly overlap), and He II λ4686 are plotted for N(He)/N(H) = 0.1. Higher helium abundance would cause the D (0.1) bands and H-line equivalent width curves to move up, and cause the He II equivalent width curve to move down. Also shown is the He II λ4686/He I λ4471 equivalent width

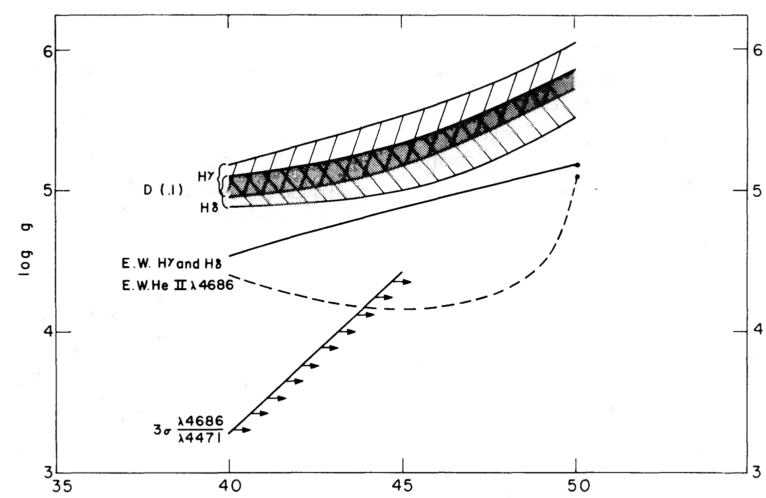

FIG. 2.—NLTE curves for the spectral data of C49 in the T–log g plane. The D (0.1) bands for Hγ and Hδ and the equivalent width curves are plotted for N(He)/N(H) = 0.1. Higher He abundance would cause the D (0.1) bands and the H-line equivalent width curves to move up and cause the He II λ4686 equivalent width curve to move down. Also plotted in the curve for the equivalent width ratio of the He II λ4686 and the 3 σ upper limit of the He I λ4471, with a set of arrows indicating the allowed region. The only convergence area is around $T = 50{,}000$ K, log $g = 5.5$, at the above He abundance, since the other He II equivalent widths become increasingly discrepant with model predictions for higher He abundances (*see text*).

ratio at the 3 σ maximum for λ4471, with a set of arrows indicating the allowed region toward higher T. An analogous 3 σ ratio for He II λ4541/He I λ4471 produces a very similar result. The hydrogen curves are derived from Kudritzki (1976) and the helium curves from Auer and Mihalas (1972). The only acceptable area of convergence is near $T = 50{,}000$ K, log g = 5–6 for $N(\mathrm{He})/N(\mathrm{H}) = 0.1$. In this area the strongest Pickering line, He II λ4541, is about 30% weaker than the model prediction, and the discrepancy increases for higher helium abundance. In view of the limitations in spectral accuracy and model coverage, we would express the best fit as $T \gtrsim 50{,}000$ K, log $g = 5.5 \pm 0.5$, and $N(\mathrm{He})/N(\mathrm{H}) < 0.2$. A surface temperature of 50,000 K places C49 among the hottest sdO stars, while log g of 5.5 is midrange for the group. It must be emphasized that this is a "first look" at the spectral data of C49. The NLTE models do not extend beyond $T = 50{,}000$ K, nonlinear extrapolations were made where there were only two parameter values, and only four spectral lines and an upper limit determined the fit.

IV. DISCUSSION

a) Cluster Membership

The spectral analysis of § III is independent of cluster membership. The star is neither a foreground white dwarf nor a hot supergiant seen through the cluster; but, as was mentioned, subdwarfs may range considerably in luminosity. To our knowledge no radial velocity is available for C49; however, there are two arguments which support cluster membership.

First, there is the remarkable resemblance between C49 and star A, the sdO in NGC 6397 (Searle and Rodgers 1966; this is star number 162 for Woolley *et al.* 1961 and Graham and Doremus 1968; and number 375 for Alcaino 1976). The spectral description by Searle and Rodgers (1966) names the same lines found in Figure 1, with an additional very weak λ4471, and lists equivalent widths that are almost identical to those quoted above for C49. The cluster distance modulus of NGC 6397 gives $M_v = 0.9$ for star A. If the distance modulus of Sandage and Smith (1966) for NGC 6712 is applied to C49, the result is $M_v = 1.0$. Thus the assumption of cluster membership means that stars A and C49 not only share nearly identical spectra but occupy the same point on the H-R diagram as well (near the horizontal branch [HB] magnitude but far hotter than blue HB stars). If the spectra imply similar values of T and log g, then the extension of the similarity to luminosity depends only on the stars' having similar masses, a condition thought probable for the entire group of sdO stars (Greenstein and Sargent 1974).

The second point which favors cluster membership is the strength of the Ca (K) line. Searle and Rodgers (1966) attempt to quantify the Ca (K) equivalent width, W (K), versus color excess, $E(B - V)$, correlation with an equation that covers 80% of the observations they reviewed. With the Sandage and Smith (1966) result, $E(B - V) = 0.48$ for NGC 6712, the equation gives an upper limit for W (K) of 0.54 Å. The C49 spectrum shows about twice that, and there is sufficient resolution to separate Ca (K) from the weak He II line at λ3923 [see tick mark to the left of Ca (K) in Fig. 1]. This indicates that C49 is probably at least as distant as NGC 6712, and a greater distance requires M_v brighter than 1.0, which is rare among sdO stars. The most reasonable conclusion is that C49 is at the cluster distance. We are seeking spectra of other hot stars in NGC 6712 to compare W (K) values with that of C49.

With cluster membership C49 has $M_v = 1.0$, which would place it among the brightest O subdwarfs (Greenstein and Sargent 1974). At $T = 50{,}000$ K, with a bolometric correction of -4.46 (Kurucz, Peytremann, and Avrett 1974), we deduce $M_{\mathrm{bol}} = -3.46$ ($\log L/L_\odot = 3.28$).

b) Evolutionary Considerations

The stars that enter the sdO region of the T–log g plane (see Newell 1973) are thought to be the following:

1. Highly evolved stars that are contracting toward the white dwarf region. This includes the central stars of planetary nebula, which show an absorption spectrum when the nebula becomes optically thin (Lutz 1977; Katz, Malone, and Salpeter 1974), and stars which evolve without envelope ejection. Model evolutionary tracks for the latter are given by Sweigart, Mengel, and Demarque (1974), who propose that sdO stars are of this type, and Gingold (1974, 1975).
2. Stars which lose their envelope because of mass transfer in binary systems (Baschek and Norris 1975; Mengel, Norris, and Gross 1976; and Kilkenny, Hilditch, and Penfold 1978).

The absence of a secondary spectrum favors the first category. Much of the detail concerning mass loss, envelope stability, and surface abundance enrichment for highly evolved stars is not understood. However, it can be said that the hydrogen-dominated spectrum of C49 and its position on the H-R diagram do resemble the Sweigart, Mengel, and Demarque (1974) model stars, which evolve without significant helium enrichment of the hydrogen envelope and advance across the H-R diagram in time scales that correlate reasonably with the numbers of stars on, above, and to the left of the horizontal branch in globular clusters. The mass implied by $T = 50{,}000$ K, log $g = 5.5$, and the cluster-distance luminosity is larger than is acceptable for this category, but the magnitude of uncertainties greatly affects the mass determination, and a low-mass ($<1\ M_\odot$) region occurs near log $g = 5.0$.

Important insights may well be gained from globular cluster sdO stars. The provision of information on distance, age, and initial composition is a substantial improvement over observations of halo and old-disk sdO stars, and the globular cluster subdwarfs may contribute toward a coherent resolution of problems in advanced stellar evolution in conjunction with the studies of "UV bright stars" (stars above the HB) in globular clusters (Strom *et al.* 1970; Zinn, Newell, and Gibson 1972; Zinn 1974, and Norris 1974).

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