THE ASTRONOMICAL JOURNAL, 115:658–665, 1998 February
© 1998. The American Astronomical Society. All rights reserved. Printed in U.S.A.

THE METALLICITY OF PALOMAR 1[1]

A. ROSENBERG
Telescopio Nazionale Galileo, vicolo dell'Osservatorio 5, I-3512 Padova, Italy
G. PIOTTO AND I. SAVIANE
Dipartimento di Astronomia, Università di Padova, vicolo dell'Osservatorio 5, I-35122 Padova, Italy
A. APARICIO
Instituto de Astrofísica de Canarias, Via Lactea, E-38200 La Laguna, Tenerife, Spain
AND
R. GRATTON
Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, I-35122 Padova, Italy
Received 1997 August 12; revised 1997 October 21

ABSTRACT

Palomar 1 is a peculiar Galactic globular cluster suspected of being younger than the bulk of Galactic halo objects. However, such a low age can be confirmed only after a reliable determination of the metallicity. In the present paper, we use the equivalent widths, W, of the Ca II triplet on medium-resolution spectra to determine the metal content of Pal 1. From the comparison of the luminosity-corrected W's in four stars of Pal 1 with those of a sample of stars in each of three calibration clusters (M2, M15, and M71), we derive [Fe/H] $= -0.6 \pm 0.2$ on the Zinn-West scale or [Fe/H] $= -0.7 \pm 0.2$ on the Carretta-Gratton scale. We also obtain a radial velocity $v_r = -82.8 \pm 3.3$ km s^{-1} for Pal 1.

Key words: globular clusters: individual (Palomar 1) — stars: abundances

1. INTRODUCTION

Palomar 1 is a very faint ($M_V = -2.54$) and peculiar star cluster discovered by Abell (1955) on the Palomar Sky Survey plates. It is located about 11.2 kpc from the Sun, 17.3 kpc from the Galactic center, and 3.6 kpc above the Galactic plane (Rosenberg et al. 1998, hereafter R98). We have presented a photometric study of Pal 1 in a companion paper (R98), to which the reader is referred for a summary of previous investigations of this object. The most important result from R98 is that the age of Pal 1 is significantly lower than those of the bulk of the Galactic globular clusters, i.e., 8 Gyr on the scale of Bertelli et al. (1994, hereafter B94). This result critically depends on the assumed metallicity of the object.

The first determination of the metallicity was obtained by Webbink (1985). From the correlation between the dereddened giant branch base colors and the high-dispersion spectroscopic metallicities, he found [Fe/H] $= -1.01$, adopting $(B-V)_{0,g} = 1.08$ and $E(B-V) = 0.15$ from unpublished data by G. S. Da Costa. However, R98 demonstrated that the location of the horizontal branch (HB) of Pal 1 is rather questionable, making the estimate of $(B-V)_{0,g}$ very uncertain. Borissova & Spassova (1995) give [Fe/H] $= -0.79$ using the Ψ^2 parameter of Flannery & Johnson (1982) (no error is quoted). This result is based on the global fit of theoretical tracks to the observed color-magnitude diagram (CMD); since there is no other independent estimate of the distance and age of Pal 1, this value of [Fe/H] is considered to be only tentative. In view of the uncertainties in the previous results, we planned a spectroscopic investigation of several Pal 1 stars to have a direct estimate of its metal content.

As a consequence of the large uncertainties associated with the above determinations of [Fe/H], and in view of the importance of a reliable metallicity for an age determination, we investigated whether there were any other possibilities for measuring the metal content of Pal 1. As the brightest stars of Pal 1 have an apparent luminosity $V \geq 16.4$ (see Fig. 1), a direct determination of the metallicity with high-resolution spectroscopy is feasible only with 8 m–class telescopes. As discussed in R98, photometric methods cannot provide a good [Fe/H] estimate. We remain with medium-resolution spectroscopy. The technique of Armandroff & Da Costa (1986, 1991) is perfectly suited for Pal 1. Their method relies on the determination of the equivalent widths W of the Ca II triplet and requires spectra of approximately 2 Å resolution and good photometry.

The observations and the employed reduction techniques are presented in the following section. In § 3, we discuss the metal abundance and radial velocity of Pal 1 that result from our spectra. A summary is presented in § 4. A brief account of the photometric observations required for the calibration of the metallicity is given in the Appendix.

2. OBSERVATIONS AND REDUCTION

2.1. *Selection of Targets*

The method proposed by Armandroff & Da Costa (1986, 1991) allows us to determine the metallicity of a sample of cluster stars by comparing their Ca II triplet equivalent widths with the corresponding W's of a set of stars in clusters of known metal content. Because of the high uncertainty of [Fe/H] for Pal 1, the reference (calibrating) clusters must cover a large metallicity interval. We chose M2, M15, and M71 as reference globular clusters. Their metal content is known with high accuracy: Zinn & West (1984) give [Fe/H] $= -1.62 \pm 0.07$ for M2, -2.15 ± 0.08 for M15, and -0.58 ± 0.08 for M71. These metallicities have been further confirmed by Armandroff (1989). Images

[1] Based on observations made with the Isaac Newton Telescope, operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos, and the IAC-80 Telescope, operated on the island of Tenerife by the IAC in the Spanish Observatorio del Teide, both of the Instituto de Astrofisica de Canarias.

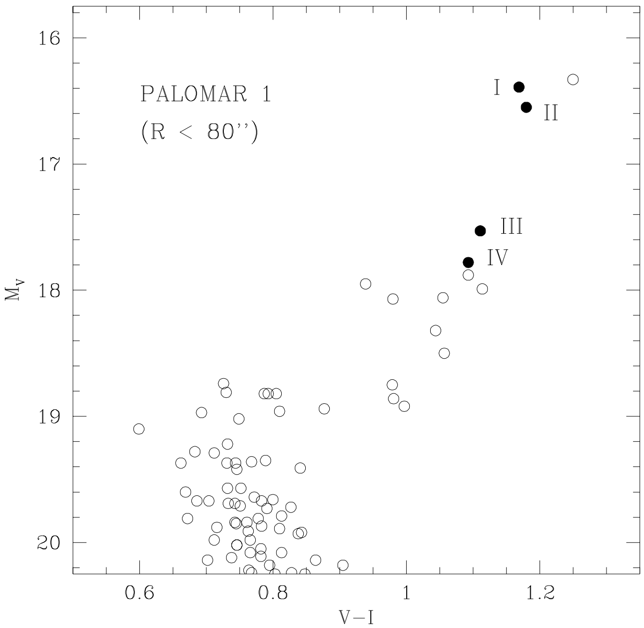

FIG. 1.—$V-I$ CMD of Pal 1. Only stars within the first 80″ are represented. The upper part of the mean sequence and the giant branch are clearly defined. Stars for which spectra have been obtained are identified by roman numerals.

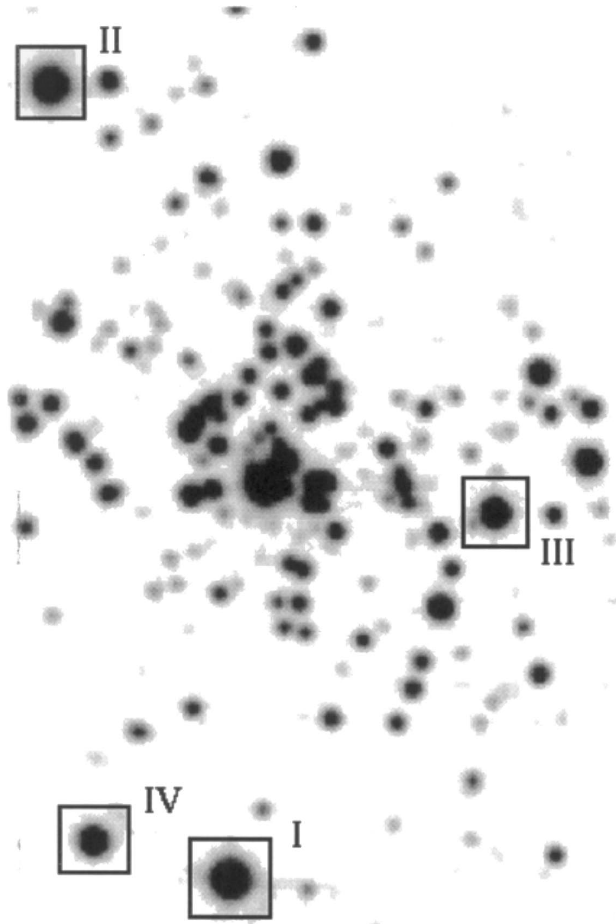

FIG. 2.—A 900 s *I*-band image of the central part of the cluster Pal 1 (1′.4 × 1′.5, north up, west left). The stars for which spectra have been obtained are marked.

in the *V* and *I* bands for these clusters were taken with the IAC-80 Telescope (see Appendix) in order to obtain their CMDs and the positions and magnitudes of the bright giants used as reference stars.

The stars in each cluster were chosen on the basis of their proximity to the cluster giant branch in the CMD (see, e.g., Fig. 1 and Fig. 9 below), although the degree of crowding and the distance from the cluster center were also used as selection criteria. We selected four stars in Pal 1 (Fig. 1) and in each of the reference clusters. The observed stars are marked in Figure 2 and in Figures 6–8 below.

2.2. *Observations*

Three long-exposure intermediate-resolution spectra were obtained for four stars in the direction of Pal 1, M71, and M2, and for three stars in the direction of M15 at the 2.5 m Isaac Newton Telescope (Roque de los Muchachos Observatory) on 1996 September 7 and 8. The intermediate-resolution spectrograph (IDS) was employed with the 235 mm camera and an 831 line mm^{-1} grating centered at 8548 Å to observe the lines of the Ca II triplet ($\lambda\lambda$8498, 8542, and 8662). The detector was a thinned 1024 × 1024 pixel Tektronix CCD with a pixel size of 24 μm. The resulting scale was 1.22 Å pixel^{-1}, and the instrumental resolution was 2.1 Å FWHM. A CCD window of 384 × 1024 pixels was used to obtain 390″ of spatial coverage and ∼1245 Å of wavelength coverage. Exposures for the Pal 1 stars ranged from 3 × 1600 to 3 × 3000 s, and each star exposure was bracketed by exposures of CuArNe lamps for wavelength calibration. In order to save as much telescope time as possible, spectra with two target stars within the slit were taken in each exposure. Details of the observations are given in Table 1.

2.3. *Reduction*

The raw data were reduced to wavelength-calibrated sky-subtracted spectra using standard techniques within IRAF (see Massey, Valdes, & Barnes 1992). Figure 3 illustrates the wavelength range covered by the Ca II triplet spectra for one star per cluster. The spectra of star III for M71 and star I for each of the other clusters are displayed. The spectra have been smoothed and normalized to the adopted contin-

TABLE 1

OBSERVATION LOG

Star	Date (1996)	Total Exposure (s)
M2:		
I........	Sep 8	6600
II.......	Sep 8	6600
III......	Sep 7	9900
IV......	Sep 7	9900
M15:		
I........	Sep 7	4500
II.......	Sep 7	4500
III......	Sep 8	6600
M71:		
I........	Sep 8	1800
II.......	Sep 8	1800
III......	Sep 7	4500
IV......	Sep 7	4500
Pal 1:		
I........	Sep 7	4800
II.......	Sep 7	4800
III......	Sep 8	9000
IV......	Sep 8	9000

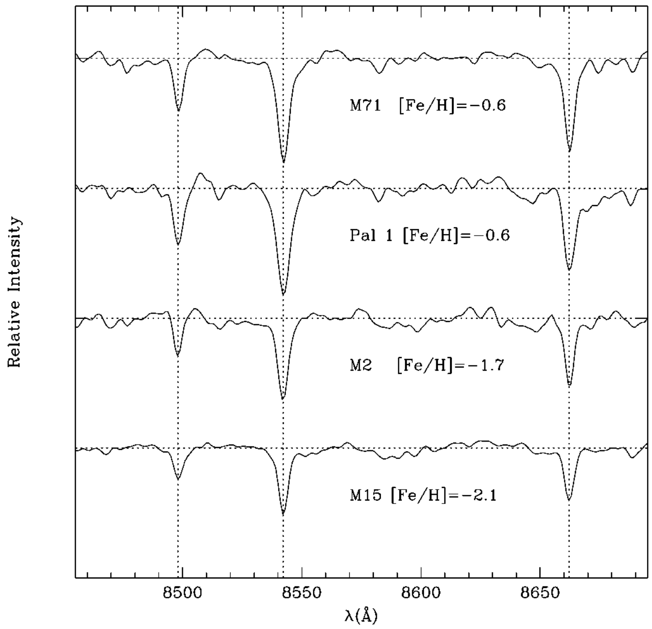

FIG. 3.—Sections of the spectra covering the Ca II triplet region for a single star of each observed cluster.

uum. They have also been corrected to the rest frame, and the three lines of the Ca II triplet are marked by vertical dotted lines. Since all spectra are on the same scale, a direct visual comparison of the areas covered by each line can be made. It is evident that the M71 and Pal 1 *W*'s are comparable, while those of M2 and M15 are clearly smaller. This suggests that the metallicities of M71 and Pal 1 are similar (even taking into account the small correction for the absolute magnitude effect).

The *W*'s of the Ca II triplet lines at 8542 and 8662 Å were then determined from the spectra via Gaussian fitting as discussed by Armandroff & Da Costa (1991). The line $\lambda 8498$ was not used, since its lower strength in most cases contributes to the noise more than to the signal. In addition to the line-strength measures, a radial velocity was determined from each stellar spectrum by measuring the central wavelength of each Ca II line.

The sum of the equivalent widths is denoted by $W_{8542} + W_{8662}$, and the values of this line-strength index for all observed stars are listed in Table 2 together with their estimated uncertainties. The errors were estimated from the uncertainties in the parameters that define the Gaussian fits calculated in the fitting process, as well as from the comparison of the individual measures of the three spectra obtained for each star. These two error estimates produced consistent results.

3. RADIAL VELOCITY AND METAL ABUNDANCE OF PALOMAR 1

3.1. *Radial Velocities*

Obtaining the radial velocities of the Pal 1 stars allows both an estimate of the mean radial velocity of the cluster and an assessment of the membership. The velocities were obtained by first determining the geocentric values and then correcting for Earth's motion. The final heliocentric values for the stars of Pal 1 and the three comparison clusters are presented in Table 2, together with the internal errors estimated from the dispersion in the three measurements of the Ca II lines. A brief account of the procedure that we followed is given below.

First, the central wavelength of each Ca II line was computed using Gaussian fits after wavelength calibration. We checked that no systematic errors were present by comparing the calibration obtained from the lamp spectra with those obtained from the sky lines present in each stellar spectrum. The second step was to apply individual relative heliocentric corrections within IRAF. These corrections were checked by repeating the calculations with a different package (ESO-MIDAS).

The radial velocity errors reported in Table 2 have been estimated by taking the mean of the three measures (i.e., spectra) for each star and evaluating the dispersion. The radial velocities allow for the discrimination between cluster members and nonmembers by comparison with published values. We used the data collected in Pryor &

TABLE 2

OBTAINED OBSERVATIONAL DATA

Star	V_r (km s^{-1})	$W_{8542} + W_{8662}$ (Å)	V	$V - V_{HB}$	W' (Å)	Remarks
M2:						
I........	-3.0 ± 2.9	2.98 ± 0.13	16.79	0.74	3.28	
II.......	-1.3 ± 5.9	3.42 ± 0.27	17.00	0.95	3.80	
III......	-12.2 ± 0.8	2.64 ± 0.22	17.47	1.42	3.21	Member?
IV......	-12.8 ± 3.5	2.99 ± 0.24	17.55	1.50	3.59	Member?
M15:						
I........	-109.3 ± 2.6	2.29 ± 0.03	15.87	0.01	2.29	
II.......	-106.0 ± 1.4	1.97 ± 0.07	15.97	0.11	2.01	
III......	-74.9 ± 17.1	2.29 ± 0.45	16.91	1.05	2.71	Nonmember
M71:						
I........	-61.5 ± 2.4	4.92 ± 0.42	15.46	1.02	5.33	Nonmember
II.......	31.4 ± 1.5	5.58 ± 0.36	15.56	1.12	6.03	Nonmember
III......	-22.7 ± 2.3	4.41 ± 0.13	15.96	1.52	5.02	
IV......	-28.3 ± 2.3	4.71 ± 0.22	16.15	1.71	5.39	
Pal 1:						
I........	-81.0 ± 4.6	4.91 ± 0.13	16.39	0.29	5.03	
II.......	-83.2 ± 7.5	5.03 ± 0.22	16.55	0.45	5.21	
III......	-85.5 ± 7.3	4.91 ± 0.63	17.53	1.43	5.48	
IV......	-87.3 ± 11.9	5.22 ± 0.82	17.78	1.70	5.90	

Meylan (1993), who give $v_r = -3.11 \pm 0.90$, -107.09 ± 0.80, and -23.16 ± 0.24 km s^{-1} for M2, M15, and M71, respectively. In order to discuss the differences between these values and our estimates, we must also take into account the internal velocity dispersion of the objects. Pryor & Meylan (1993) give $\sigma_v = 7.39 \pm 0.64$, 8.95 ± 0.59, and 2.16 ± 0.17 km s^{-1} for the same clusters. We have classified as nonmembers those stars whose velocities deviate by more than $3\sigma_v$ from the cluster mean radial velocity. Therefore, we discarded star III of M15 and stars I and II of M71 and have not used them in any of the following calculations. Stars III and IV of M2 have radial velocities that are only $1.2\sigma_v$ and $1.3\sigma_v$ lower than the mean value, respectively. The equivalent widths reported in Table 2 are compatible with those of the other members of the cluster, so, although membership cannot be fully established, these two stars are likely members.

Therefore, our computations were repeated both including and excluding these two stars. We did not discover any significant differences in the results, becaue of the similarity of the *W*'s. In any case, the discussion below is not based on these uncertain objects unless explicitly stated.

An independent estimate of the measurement errors can be made by comparing the published radial velocities of M2, M15, and M71 with our velocities. Excluding the uncertain members III and IV of M2, we find an almost null zero-point offset and a dispersion of $\simeq 3$ km s^{-1}, which is slightly larger than our estimated internal errors but consistent with the velocity dispersion of the stars in these Galactic globular clusters. If stars III and IV of M2 are included in the calculations, the dispersion becomes $\simeq 5$ km s^{-1} (and the offset would be -2.3 km s^{-1}). Taking the weighted mean of the radial velocities in Table 2, we estimate for Pal 1 a radial velocity $v_r = -82.8 \pm 3.3$ km s^{-1}.

3.2. *Abundance*

Da Costa & Armandroff (1995) demonstrated that, for stars in the same cluster (i.e., metallicity), there is a linear relation between their magnitudes and the *W*'s measured for the Ca II lines λ8542 and λ8662. The proposed relation takes the form

$$W_{8542} + W_{8662} = a(V - V_{\rm HB}) + b \ .$$

For $V - V_{\rm HB} < -0.5$, the value of the slope is $a = -0.62$ Å mag^{-1} (Armandroff & Da Costa 1991; Suntzeff et al. 1993; Da Costa & Armandroff 1995). The same authors find a well-defined relation between the metallicity of a cluster and the so-called reduced equivalent width W', which is defined as $W' = \langle W_{8542} + W_{8662} + 0.62(V - V_{\rm HB}) \rangle$.

The magnitude interval used thus far to compute the parameter *a* is composed of all the stars on the red giant branch (RGB) that are brighter than the HB. In the case of Pal 1, this part of the RGB is absent, and we were forced to find a new relation using fainter stars. Indeed, Figure 5 of Suntzeff et al. (1993) shows that the slope of the $W_{8542} + W_{8662}$ versus $V - V_{\rm HB}$ relation flattens for stars fainter than the HB.

The data in Table 2 were used to calculate the appropriate value of *a* according to the following procedure: Lines with fixed values of *a* were fitted to the data and the corresponding values of the intercepts *b* were found for each cluster. The offsets *b* were added to each subset, and a new data set, which now has a common zero point, was created. A linear fit was repeated with the new data set, and the rms value of the dispersion of the data around the fit was computed. These operations were repeated for different values of *a*, and we accepted the value of *a* that minimizes the rms. We found $a = -0.4 \pm 0.2$.

In Figure 4 the summed equivalent widths, with their associated errors, are plotted against $V - V_{\rm HB}$ for the cluster member stars (including stars III and IV of M2). This figure illustrates that the slope *a* is essentially determined by the M2 data. The value of *a* is not too different from the value valid for the commonly used brighter stars, and is entirely compatible with the trend suggested by the fainter stars (NGC 6397) in Figure 5 of Suntzeff et al. (1993).

As in the previously mentioned studies, we can now define a reduced W' as $W' = \langle W_{8542} + W_{8662} + 0.4(V - V_{\rm HB}) \rangle$ and use this W' to determine the metallicity of Pal 1. Figure 5 represents the abundance calibration for the Ca II line strengths. The values of [Fe/H] from Armandroff (1989) on the Zinn & West (1984) scale are plotted versus the weighted means of the W' of the three calibration clusters. The relation between these two quantities changes its slope at [Fe/H] ~ -1.3 (see, e.g., Fig. 3 in Da Costa & Armandroff 1995), so in our figure we show linear fits to the data obtained using the three calibration clusters (*dashed line*) and just the more metal-rich M2 and M71 (*solid line*).

We still need the $V - V_{\rm HB}$ values for Pal 1 in order to compute the $\langle W' \rangle$ and then its metallicity. It is not easy to determine the $V - V_{\rm HB}$ difference for the stars of Pal 1 because this cluster has no HB stars, and it is younger than the comparison clusters. On the other hand, we know that the *W*'s of Pal 1 are similar to those of M71 (even taking into account the small absolute magnitude corrections). All the other parameters being similar, the location of the Pal 1 HB should be close to that of M71. Nevertheless, since the luminosity of the HB depends on both the cluster age and the metallicity, we evaluated the reasonable limits within which the Pal 1 HB could vary. Taking the extreme values,

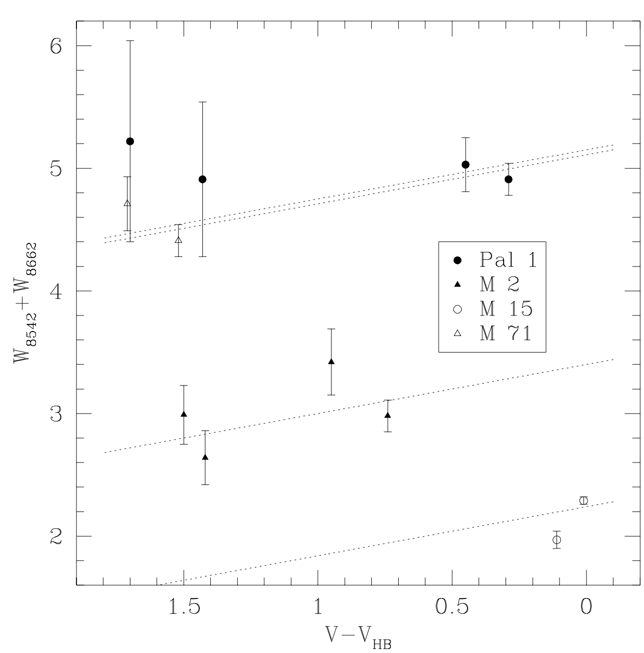

FIG. 4.—Summed equivalent widths and their associated errors plotted vs. $V - V_{\rm HB}$ for the cluster member stars (including stars III and IV of M2). Dotted lines reproduce the adopted best fit, as described in the text.

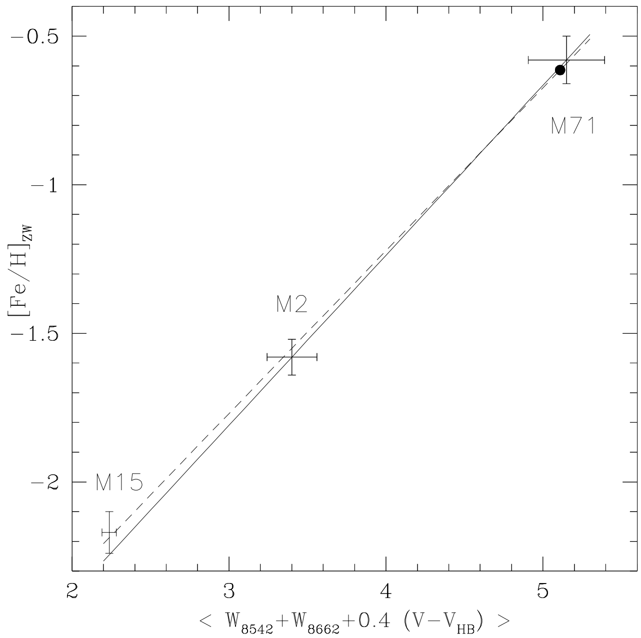

FIG. 5.—Abundance calibration for the Ca II line strengths. The reduced equivalent width W' is plotted against [Fe/H] on the Zinn & West (1984) scale for the three calibration clusters. The dashed line was fitted to the three calibration points by least squares, while the solid line was fitted to M2 and M71. Both lines represent the adopted calibration relations.

we will have an estimate of the maximum error on the metallicity determination.

It has been established that Pal 1 has an age of $\simeq 8 \pm 2$ Gyr on the Bertelli et al. (1994) scale (Rosenberg et al. 1997), which is ~ 8 Gyr lower than the "standard" value often adopted for the globular cluster ages on the same scale. According to equation (12) of B94, this change in age would make the HB V absolute luminosity ~ 0.2 mag brighter. Hence, taking an absolute value for the HB luminosity of 0.7 ± 0.2 mag for M71 (cf. Appendix), the corresponding luminosity of the Pal 1 HB is 0.5 ± 0.2 mag. Even taking a variation for the Pal 1 metallicity of ± 0.3 dex (see below), this would imply a change in the HB luminosity of only ~ 0.06 mag (see again B94). The error on $V_{\rm HB}$ is therefore almost entirely due to the error in the location of the M71 HB. An absolute magnitude of 0.5 mag corresponds to an apparent magnitude $V_{\rm HB} = 16.3 \pm 0.35$ at the distance of Pal 1 (R98), where the error on the distance modulus has been added to the total error on $V_{\rm HB}$. It is important to note that even if we adopt a typical GC age for Pal 1, the resulting estimate of its metallicity would vary only by ~ 0.04 dex.

With this value, the weighted mean of the Pal 1 W can finally be computed and entered into the relations of Figure 5. The resulting metallicity is $[{\rm Fe/H}] = -0.6 \pm 0.2$ for both relations previously defined. Using the Carretta & Gratton (1997) metallicity scale, the result would be $[{\rm Fe/H}] = -0.7 \pm 0.2$ (see Table 3).

TABLE 3

REDUCED EQUIVALENT WIDTHS AND METALLICITIES

Cluster	$\langle W' \rangle$ (Å)	$[{\rm Fe/H}]_{\rm ZW}$	$[{\rm Fe/H}]_{\rm CG}$
M15	2.24 ± 0.05	-2.17 ± 0.07	-2.12 ± 0.01
M2........	3.40 ± 0.16	-1.58 ± 0.06	-1.34 ± 0.03
M71	5.15 ± 0.24	-0.58 ± 0.08	-0.70 ± 0.03
Pal 1......	5.11 ± 0.15	-0.60 ± 0.20	-0.71 ± 0.20

The error has been estimated taking into account the following contributions: the error on the slope for finding the single W' values and their weighted means, the error on the metallicity of the calibration clusters, and, finally, the error in the determination of the $V - V_{\rm HB}$ value.

4. SUMMARY

Medium-resolution spectra were collected and reduced for a sample of stars in Pal 1, M2, M15, and M71. We measured the equivalent widths for the Ca II triplet in each spectra. A linear correlation was found between the W's and their luminosities, $W_{8542} + W_{8662} = a(V - V_{\rm HB}) + b$. The luminosity-corrected W's were calibrated as a function of metallicity by using the stars in M2, M15, and M71. Applying the same relation to the W's of Pal 1, we obtained $[{\rm Fe/H}] = -0.6 \pm 0.2$ on the Zinn & West (1984) scale or $[{\rm Fe/H}] = -0.7 \pm 0.2$ on the Carretta & Gratton (1997) scale.

A reliable estimate of the metallicity of Pal 1 is fundamental for an estimate of its age and is particularly important in view of the peculiar properties of this cluster (R98). We also measured the heliocentric radial velocities for all the observed stars. A comparison between the published radial velocities of M2, M15, and M71 with those of our sample has been used to identify the cluster members. Our average velocities are in agreement with those already published, excluding any systematic errors in our measurements. For the first time, we can give the heliocentric radial velocity of Pal 1: $v_r = -82.8 \pm 3.3$ km s^{-1}.

This project has been partially supported by the Agenzia Spaziale Italiana. The observation run has been supported by the European Commission through the Acces to Large-Scale Facilities of the Training and Mobility of Researchers program, awarded to the Instituto de Astrofísica de Canarias to fund European astronomers' access to its Roque de Los Muchachos and Teide Observatories (European Northern Observatory) in the Canary Islands. We recognize partial support by the Instituto de Astrofisica de Canarias (grant P3/94) and by a Spanish-Italian integrated action. We thank J. Sulentic for his careful reading of the manuscript.

APPENDIX

OBSERVATIONS OF M2, M15, AND M71

Three long exposures of M2, M15, and M71 in the V and I bands (1200 and 900 s, respectively) were collected with the IAC-80 Telescope on 1996 August 11 and 12, at the Teide Observatory in Tenerife, Canary Islands, Spain. These frames cover the northwest quadrant of each cluster and were obtained with the aim of selecting the target stars to be observed in the

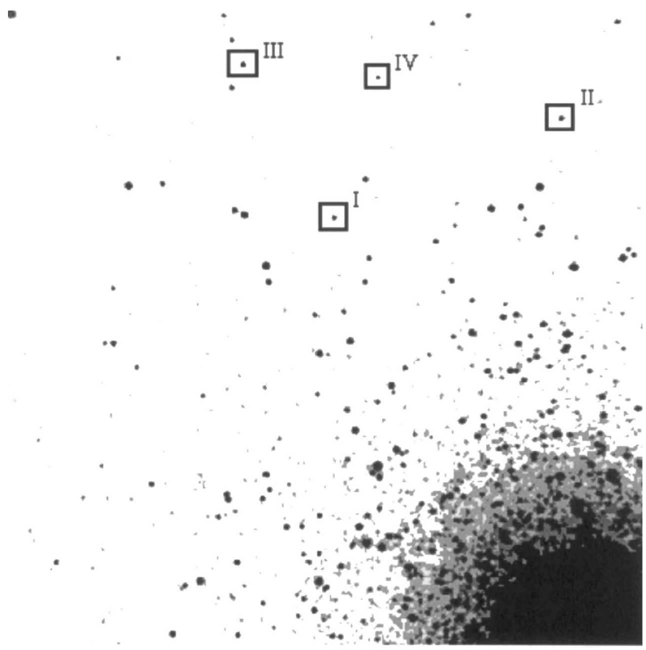

FIG. 6.—A 900 s *I*-band image of 5′ × 5′ of M2, showing the observed stars (north up, west left). Again, the target stars are marked and numbered.

spectroscopic run. The resulting fields are shown in Figures 6, 7, and 8, and the target stars have been marked and numbered. During the two nights the weather conditions were stable, although the seeing, on average, was poor (1″.8–2″.1).

The camera was equipped with an EEV CCD at the Cassegrain focus, and the resulting scale was 0″.41 pixel^{-1}. The CCD format was 1024 × 1024 pixels, giving a field of view of 7′.0 × 7′.0.

The raw data frames were first bias-subtracted and trimmed using the standard procedures within IRAF. Pixel-to-pixel sensitivity variations were then removed by dividing each frame by a normalized high signal-to-noise ratio mean flat field.

The calibration of the raw photometry was accomplished in the same way as in Rosenberg et al. (1997). Exposures in each filter of 15 standard stars from Landolt (1992) were taken, allowing a total of ∼50 individual measures per night. The nights were photometric, and a good calibration of the data was obtained. The total zero-point errors are of order 0.01 mag in both filters.

Figure 9 shows the calibrated CMD for the cluster M2 and illustrates the photometric quality. The RGB and HB are clearly defined and well sampled. This allows an easy selection of the target stars for the spectral analysis. They have been chosen on the basis of the following criteria:

1. Luminosity in the same range as the stars to be used for Palomar 1;
2. Proximity to the RGB;

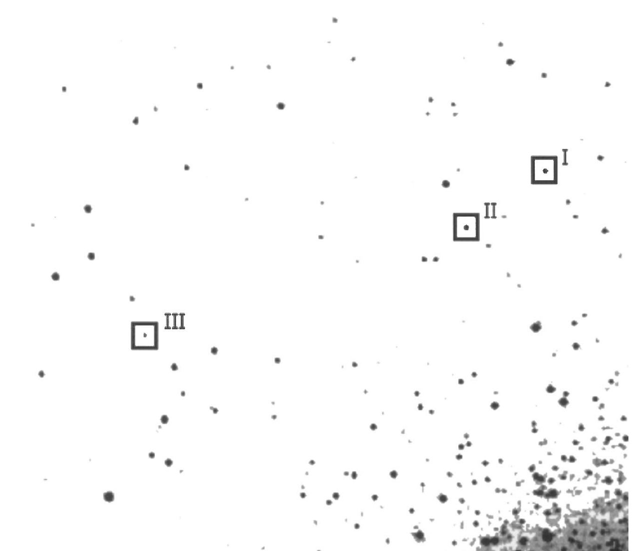

FIG. 7.—Same as Fig. 6, but for M15

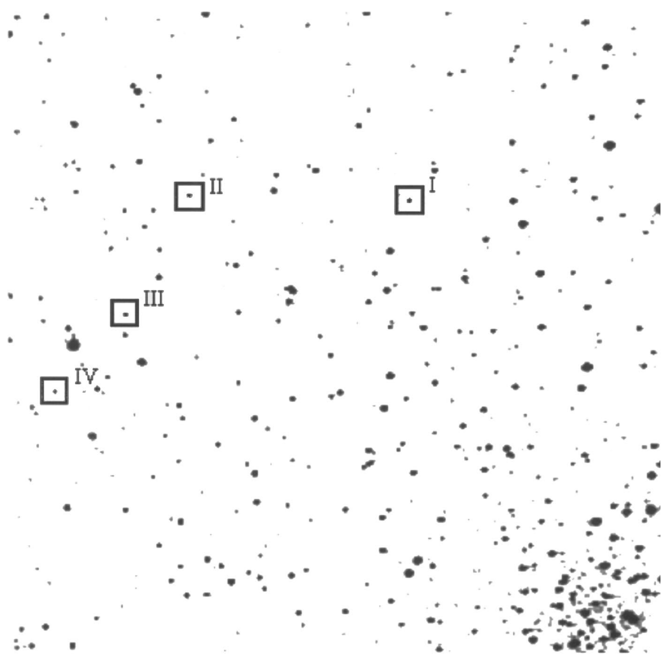

FIG. 8.—Same as Fig. 6, but for M71

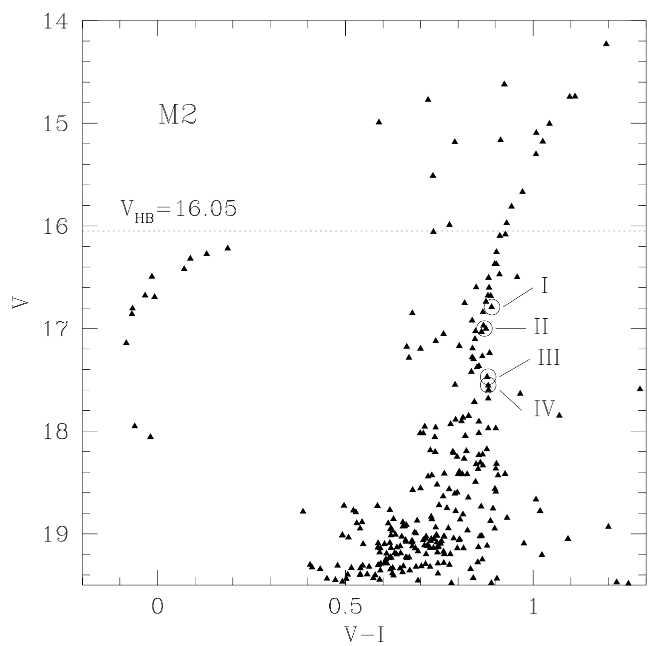

FIG. 9.—V vs. $V-I$ CMD of M2 obtained at the IAC-80 Telescope. The stars used for spectroscopic observations are numbered with the same notation in Table 2 and illustrate the selection criteria. Stars that are close to the RGB and fainter than the HB were used, matching the same luminosity range covered by Pal 1 stars.

3. Sufficient distance from the cluster center to avoid contamination of the spectra; and
4. Possibility to simultaneously put two stars of similar luminosity into the slit, optimizing the available telescope time.

These four criteria were met by the stars marked in Figures 6–9. Stars I, II, III, and IV in Figure 9 are all on the RGB, having the same luminosity within 0.7–1.5 mag below the HB. Looking at Figure 6, it is also clear that they are located at more than 4′ outside the cluster center and that their separation allows simultaneous observations in pairs. A similar selection has been applied to the stars of M15 (Fig. 7) and M71 (Fig. 8).

REFERENCES

Abell, G. O. 1955, PASP, 67, 258
Armandroff, T. E. 1989, AJ, 97, 375
Armandroff, T. E., & Da Costa, G. S. 1986, AJ, 92, 777
———. 1991, AJ, 101, 1329
Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, A&AS, 106, 275 (B94)
Borissova, J., & Spassova, N. 1995, A&AS, 110, 1
Carretta, E., & Gratton, R. 1997, A&A, 121, 95

Da Costa, G. S., & Armandroff, T. E. 1995, AJ, 109, 2533
Flannery, B. P., & Johnson, B. C. 1982, ApJ, 263, 166
Landolt, A. U. 1992, AJ, 104, 340
Massey, P., Valdes, F., & Barnes, J. 1992, A User's Guide to Reducing Slit Spectra with IRAF (Tucson: NOAO)
Pryor, C., & Meylan, G. 1993. In ASP Conf. Ser. 50, Structure and Dynamics of Globular Clusters, ed. S. G. Djorgovski & G. Meylan (San Francisco: ASP), 357
Rosenberg, A., Saviane, I., Piotto, G., Aparicio, A., & Zaggia, S. 1998, AJ, 115, 648 (R98)
Suntzeff, N. B., Mateo, M., Terndrup, D. M., Olszewski, E. W., Geisler, D., & Weller, W. 1993, ApJ, 418, 208
Webbink, R. 1985, in IAU Symp. 113, Dynamics of Stars Clusters, ed. J. Goodman & P. Hut (Dordtrecht: Reidel), 541
Zinn, R., & West, M. J. 1984, ApJS, 55, 45