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STUDY OF THE OPEN CLUSTER NGC 1528 THROUGH $uvby-\beta$ PHOTOELECTRIC PHOTOMETRY[1]

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ABSTRACT

$uvby-\beta$ photoelectric photometry of sixty-five stars in the direction of the open cluster NGC 1528 is presented. From the $uvby-\beta$ photometry of the cluster we classified the spectral types of the stars which allowed us to determine the reddening (E(b-y) of 0.196 ± 0.054) and hence, their distance, in parsecs, of (954 ± 154). We determined membership of the stars to the cluster and the age (Log age equal 8.04) of the cluster. A metallicity [Fe/H] of -0.31 ± 0.08 was calculated.

RESUMEN

Se presenta fotometría fotoeléctrica $uvby-\beta$ de 65 estrellas en la dirección del cúmulo abierto NGC 1528. Ésta nos permite la determinación de los tipos espectrales de cada estrella y su enrojecimiento (E(b-y) de 0.196 ± 0.054), el cálculo de la distancia a cada una y, por ende, la pertenencia de las estrellas al cúmulo (954 ± 154) pc. Se establece la membresía de cada estrella al cúmulo y la edad de éste (Log age de 8.04). Se determinó una metalicidad [Fe/H] de -0.31 ± 0.08.

Key Words: open clusters and associations: individual (NGC 1528) — techniques: photometric

1. MOTIVATION

The study of open clusters provides many possibilities for the investigation of different astronomical topics. For example, establishing membership of the stars to the cluster throws light on the initial mass function; determining their ages gives clues on stellar evolution; and fixing their distances and chemical compositions helps to accurately establish the chemical enrichment of the galaxy as a function of the galactocentric distance. This line of research began long ago with the work of Villa Vargas (1999) and the purpose of the present study is to complement the previous one with higher precision data, since Strömgren photometry provides both an accurate determination of the distance to the cluster and, through the observation of stars of spectral type F, of their metallicity.

The open cluster NGC 1528 has been a subject of much research since its discovery in 1907 by Holetschek.

According to the compilation of data of open clusters in Paunzen and Mermilliod (2007), WEBDA, NGC 1528 has a distance [pc] of 776; a reddening [mag] of 0.258; a distance modulus [mag] of 10.25; a log age of 8.568 and no reported value for the metallicity.

In this paper, the distances to each one of the stars are determined using $uvby-\beta$ photoelectric photometry with an already tested method, (See for example Peña & Sareyan, 2006).

2. OBSERVATIONS

The observations were carried out at the Observatorio Astronómico Nacional de San Pedro Mártir, México. The 0.84 m telescope, to which a spectrophotometer was attached, was used. The observing season lasted for six nights in December, 2017. NGC 1528 was observed only on one night, that of December 8, 2017. The cluster was also observed in December, 2016 by one of us (DSP). The ID charts used were those of WEBDA, selected for

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TABLE 1

TRANSFORMATION COEFFICIENTS FOR THE OBSERVING SEASON

season	B	D	F	J	H	I	L
2017	0.084	1.013	1.002	0.023	1.020	0.131	−1.309
σ	0.084	0.047	0.040	0.035	0.015	0.029	0.082

TABLE 2

SEASONAL STANDARD DEVIATIONS

σV	$\sigma(b-y)$	σm_1	σc_1	$\sigma\beta$
0.0125	0.007	0.009	0.010	0.002

a limiting magnitude around 12 mag, which is the reasonably reachable limit given by the telescope-spectrophotometer system used during both seasons. A sample of sixty-five stars is presented.

2.1. *Data Acquisition and Reduction*

The procedure followed has been extensively used and a description can be found in Peña et al. (2008), Peña & Martinez (2014) or, more recently, in Peña et al. (2017). What matters in the present paper are the coefficients of the transformation equations to the standard system and the numerical errors which provide the goodness and confidence of our numerical results.

In the transformation equations the coefficients D, F, H and L are the slope coefficients for $(b-y)$, m_1, c_1 and Hβ, respectively. The coefficients B, J and I are the color terms of V, m_1, and c_1. The averaged transformation coefficients for each night are listed with their standard deviations in Table 1. Season errors were evaluated using the twenty-one standard stars observed for a total of 37 observed points. These uncertainties were calculated through the differences in magnitude and colors for all nights, for (V, $b-y$, m_1, c_1 and Hβ) as (0.010, 0.011, 0.015, 0.013, 0.001) respectively, providing a numerical evaluation of our uncertainties for the season. Emphasis is made on the large range of the magnitude and color values of the standard stars: V:(5.2, 8.8); $(b-y)$:(0.00, 0.80); m_1:(0.09, 0.68); c_1:(0.08, 1.05) and Hβ:(2.50, 2.90). The numerical results obtained are presented in Table 2. Column 1 lists the V value; Columns two to five the standard deviations of the color indexes $(b-y)$, m_1, c_1 and Hβ. The standard deviations values are a few hundredths or thousandths of magnitude for each color index, and provide an estimate of the accuracy of our photometry.

Table 3 lists the photometric values of the observed cluster stars. In this table, Columns one and two list the ID of the stars in WEBDA (Paunzen and Mermilliod, 2006) and in the TYC2 catalogue. Columns 3 to 6 show the Strömgren values V, $(b-y)$, m_1 and c_1, respectively; Column 7 lists the Hβ. The unreddened indexes $[m_1]$ & $[c_1]$ are also presented. The last column lists the spectral types derived from Strömgren photometry.

3. COMPARISON WITH OTHER PHOTOMETRIES

Since the cluster was observed in 2016 and 2017, the first and obvious step was to compare both seasons. This was done and the results were awkward. Hence, our first problem was to elucidate which season was correct, if any.

Since no $uvby-\beta$ data had been obtained previously for this cluster, a comparison of our values was done with the available UBV photometry reported in WEBDA. However, the intersection of both sets $uvby-\beta$ vs. UBV was very limited (eighteen entries) despite the fact that our sample was significant (sixty-five observed stars). In view of this we compared our photometry from 2016 and 2017 with the much larger sample of WEBDA CCD data. The intersection of both sets was forty-one entries.

The comparison with the 2016 season showed that the data of this season were inaccurate due to bad weather conditions, whereas the 2017 season gave more accurate results. A linear fit between both sets, 2017 $uvby-\beta$ vs. UBV(CCD) yielded the equation $V_{WEBDA} = 0.056 + 0.9994\ V_{pp}$ with a correlation coefficient of 0.9974 and a standard deviation of 0.050. The color relationship yielded $(B-V) = 0.027 + 0.6176\ (b-y)$ with a correlation coefficient R of 0.9954 and a standard deviation of 0.024.

4. METHODOLOGY

Once we were sure of the quality of our $uvby-\beta$ data set, further analysis was necessary in order to determine the physical characteristics of the stars in the cluster.

The main problem was, of course, to determine which stars belong to the cluster. To do this, the distance to each star had to be fixed. To evaluate the reddening we first established to which spectral class the stars belonged: early (B and early A) or late (late A and F stars) types; the later class stars (G or later)

TABLE 3

$uvby - \beta$ PHOTOELECTRIC PHOTOMETRY OF THE OPEN CLUSTER NGC 1528

WEBDA	TYC2	V	$b-y$	m_1	c_1	Hβ	$[m_1]$	$[c_1]$	SpTyp (photometry)
1	3340-0786-1	8.760	0.190	0.052	0.710	2.697	0.111	0.672	B7V
2	3340-0288-1	9.637	0.183	0.088	1.147	2.833	0.145	1.110	A3
4	3340-1195-1	10.045	0.621	0.168	0.633	2.596	0.361	0.509	LATE
5	3340-1015-1	10.132	0.760	0.343	0.425	2.548	0.579	0.273	LATE
6	3340-0790-1	10.096	0.426	0.131	0.550	2.620	0.263	0.465	F5
7	3340-0782-1	10.094	0.220	0.191	1.086	2.871	0.259	1.042	A4p
8	3340-0290-1	10.430	0.227	0.097	1.222	2.839	0.167	1.177	A0V
9	3340-0429-1	10.390	0.267	0.120	0.918	2.789	0.203	0.865	A4V
10	3340-0905-1	10.803	0.195	0.082	1.162	2.846	0.142	1.123	B9
11	3340-0922-1	11.220	0.194	0.092	1.032	2.839	0.152	0.993	B8V
12	3340-0659-1	11.300	0.189	0.102	1.085	2.790	0.161	1.047	A9V
13	3340-0831-1	11.316	0.225	0.107	0.987	2.787	0.177	0.942	A2
14	3340-0914-1	12.010	0.206	0.201	0.935	2.862	0.265	0.894	A6p
31	3340-0803-1	9.400	0.343	0.139	0.575	2.676	0.245	0.506	F2
32	3340-0819-1	10.112	0.924	0.546	0.278	2.528	0.832	0.093	LATE
33	3340-0311-1	10.185	0.252	0.072	1.283	2.816	0.150	1.233	B9V
34	3340-1090-1	10.505	0.236	0.061	1.129	2.816	0.134	1.082	B9
35		10.477	0.395	0.201	0.315	2.568	0.323	0.236	G2V
36	3340-0812-1	10.746	0.185	0.074	1.049	2.806	0.131	1.012	B8V
37	3340-0890-1	11.008	0.163	0.140	1.001	2.819	0.191	0.968	A3
38	3340-1018-1	11.059	0.200	0.103	0.982	2.779	0.165	0.942	A4
39	3340-1001-1	11.026	0.209	0.091	1.057	2.833	0.156	1.015	B9V
40	3340-0521-1	11.199	0.228	0.062	1.171	2.827	0.133	1.125	A3
41	3340-1192-1	11.254	0.217	0.074	1.157	2.797	0.141	1.114	B9
42	3340-0774-1	11.335	0.271	0.138	1.032	2.799	0.222	0.978	A4V
43	3340-1021-1	11.493	0.198	0.082	1.097	2.815	0.143	1.057	B9V
44	3340-0858-1	11.337	0.152	0.143	0.966	2.815	0.190	0.936	A5
45	3340-1208-1	11.410	0.256	0.158	0.988	2.815	0.237	0.937	A5V
46	3340-0638-1	11.335	0.242	0.119	1.069	2.820	0.194	1.021	A4V
47	3340-0801-1	11.460	0.230	0.088	1.144	2.818	0.159	1.098	F5V
48	3340-0181-1	11.582	0.206	0.084	1.127	2.850	0.148	1.086	B9
49	3340-0685-1	14.427	1.824	−2.017	1.875	2.848	−1.452	1.510	
50	3340-0800-1	11.928	0.342	0.131	0.848	2.689	0.237	0.780	A8V
51	3340-1250-1	11.973	0.190	0.134	1.088	2.956	0.193	1.050	A4V
63		9.949	0.202	0.064	1.202	2.791	0.127	1.162	B9
172	3340-0813-1	11.842	0.219	0.110	1.152	2.790	0.178	1.108	A2V
182	3340-0983-1	11.089	0.202	0.135	0.964	2.820	0.198	0.924	A5
185	3340-1041-1	11.762	0.154	0.098	0.645	2.695	0.146	0.614	B6V
193	3340-1381-1	11.877	0.286	0.128	1.070	2.854	0.217	1.013	A4V
194	3340-1527-1	11.621	0.256	0.160	1.078	2.886	0.239	1.027	A4
195		10.965	1.336	0.803	0.344	2.581	1.217	0.077	LATE
196	3340-1157-1	11.524	0.233	0.071	1.070	2.887	0.143	1.023	A1
197	3340-0784-1	10.769	0.204	0.045	0.609	2.739	0.108	0.568	B6V
204	3340-0136-1	11.597	0.249	0.130	1.146		0.207	1.096	A4V
205	3340-0403-1	11.851	0.209	0.056	1.143	2.849	0.121	1.101	B8V
206	3340-1154-1	11.901	0.390	0.143	0.469	2.619	0.264	0.391	F9
207		11.620	0.652	0.626	0.093	2.467	0.828	−0.037	LATE
209	3340-1222-1	9.068	0.153	0.032	0.565	2.673	0.079	0.534	B5V
210	3340-0846-1	11.962	0.239	0.097	0.997	2.866	0.171	0.949	B8
211	3340-0575-1	9.613	0.151	0.024	0.480	2.682	0.071	0.450	B5V
218	3340-0546-1	11.223	0.498	0.108	0.542	2.663	0.262	0.442	F9

TABLE 3 (CONTINUED)

WEBDA	TYC2	V	$b-y$	m_1	c_1	Hβ	$[m_1]$	$[c_1]$	SpTyp (photometry)
219		12.240	0.242	0.108	1.082	2.858	0.183	1.034	A2V
220		10.318	0.253	0.069	1.121	2.812	0.147	1.070	B9V
1017		10.466	0.432	0.155	0.371	2.584	0.289	0.285	G0V
1038		11.487	0.353	0.154	0.578	2.689	0.263	0.507	F2
1044	3340-1259-1	11.240	0.837	0.318	0.235	2.511	0.577	0.068	LATE
1551		11.432	0.300	0.151	1.097	2.822	0.244	1.037	A4p
1566		10.592	0.689	0.333	0.362	2.577	0.547	0.224	LATE
1580		11.609	0.820	0.346	0.382	2.530	0.600	0.218	LATE
1582		11.804	0.443	0.111	0.407		0.248	0.318	F8V
1584		11.295	0.437	0.132	0.432	2.611	0.267	0.345	F9
1590		11.299	0.254	0.127	1.015	2.878	0.206	0.964	A5
1613		12.117	0.428	0.105	0.517	2.635	0.238	0.431	F9
1618		10.467	0.333	0.009	1.168	2.749	0.112	1.101	A8I
6465		9.703	1.067	0.724	0.331	2.531	1.055	0.118	LATE

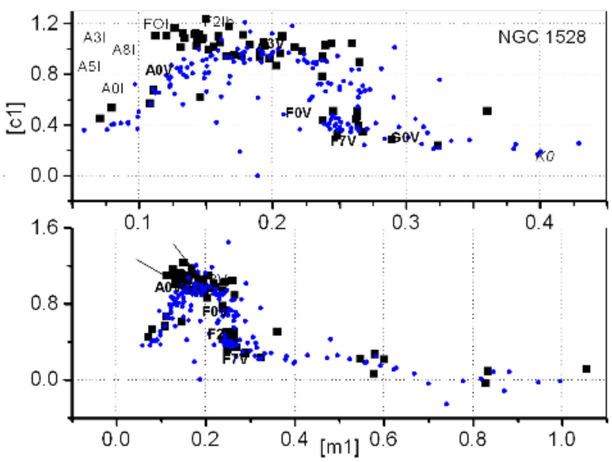

Fig. 1. Position of the stars in the $[m_1]-[c_1]$ diagram of Alpha Per (Peña & Sareyan, 2006)) for NGC 1528. Small crosses are points for Alpha Per; black squares are points for NGC 1528. The color figure can be viewed online.

were not considered in the analysis since there is no reddening calibration for these stars. We determined each star's spectral type through its location in the $[m_1]-[c_1]$ diagram (Figure 1).

The application of the calibrations for each spectral type (Balona & Shobbrook 1984; Shobbrook 1984) for O and early A type and Nissen (1988) for late A and F stars, respectively allowed us to determine their reddening, and hence their unreddened color indexes. The procedure has been extensively described in Peña & Martínez (2014).

5. RESULTS

Figure 1 shows the position in the $[m_1]-[c_1]$ diagram for stars in the direction of NGC 1528, along with that of the stars with well-determined spectral types in the open cluster Alpha Per (Peña & Sareyan 2006). In Table 3 the photometrically determined spectral class is shown. Only a few stars have photometrically determined spectral types in WEBDA and the agreement between both classifications is adequate.

The physical parameters can be determined using the $uvby-\beta$ photometry data and adequate empirical calibrations. These calibrations were proposed by Nissen (1988) for A and F type stars and Balona & Shobbrook (1984) and Shobbrook (1984) for the O and early A types.

The application of these numerical packages gave the results shown in Table 4, where the ID, reddening, unreddened indexes, absolute magnitude, DM and distance (in parsecs), are listed. The last two columns present the membership probabilities described below.

To establish membership of the stars to the cluster the distance modulus or distance histograms (in pc) are built. The goodness of the method has been tested in the past by comparing results to the proper motion studies for a well-studied cluster like α Per (Peña & Sareyan 2006).

When the histogram of distance modulii for NGC 1528 was built (Figure 2), the distances of the stars showed a clear accumulation at a distance modulus of 9.8 ± 0.6, a peak determined by a Gaussian fit to the distribution.

TABLE 4

REDDENING AND UNREDDENED PARAMETERS OF THE OPEN CLUSTER NGC 6633

WEBDA	$E(b-y)$	$(b-y)_0$	m_0	c_0	Hβ	V_0	M_V	DM	Distance	[Fe/H]	Membership (Present Paper)	Probab. WEBDA (382)
31	0.079	0.264	0.163	0.559	2.68	9.06	2.18	6.9	237	0.02	N	0.00
218	0.214	0.284	0.172	0.499	2.66	10.30	2.28	8.0	402	0.11	N	0.00
1584	0.093	0.344	0.160	0.413	2.61	10.89	2.77	8.1	422	−0.30	N	0.00
6	0.097	0.329	0.160	0.531	2.62	9.68	1.28	8.4	478	−0.25	N	0.00
2	0.152	0.031	0.134	1.118	2.83	8.98	0.41	8.6	518		N	0.99
7	0.162	0.058	0.240	1.054	2.87	9.40	0.82	8.6	518		N	0.00
9	0.300	−0.033	0.210	0.861	2.79	9.10	0.10	9.0	629		M:	0.00
1	0.236	−0.046	0.123	0.665	2.70	7.75	−1.28	9.0	640		M:	0.00
1590	0.275	−0.021	0.209	0.963	2.88	10.12	1.07	9.1	644		M:	0.00
220	0.242	0.011	0.142	1.075	2.81	9.28	0.18	9.1	661		M:	0.99
206	0.056	0.334	0.160	0.458	2.62	11.66	2.39	9.3	712	−0.25	M	0.00
34	0.220	0.016	0.127	1.087	2.82	9.56	0.22	9.3	739		M	0.99
14	0.126	0.080	0.239	0.910	2.86	11.47	2.11	9.4	744		M	0.99
196	0.239	−0.006	0.143	1.025	2.89	10.49	1.13	9.4	748		M	0.56
8	0.144	0.083	0.140	1.195	2.84	9.81	0.39	9.4	765		M	0.98
51	0.188	0.002	0.190	1.052	2.96	11.17	1.71	9.5	778		M	0.99
1613	0.122	0.306	0.142	0.493	2.64	11.59	2.04	9.6	814	−0.37	M	0.00
39	0.218	−0.009	0.156	1.016	2.83	10.09	0.53	9.6	816		M	0.99
10	0.156	0.039	0.129	1.132	2.85	10.13	0.57	9.6	819		M	0.99
182	0.229	−0.027	0.204	0.920	2.82	10.10	0.46	9.6	848		M	0.00
45	0.143	0.113	0.201	0.959	2.82	10.80	1.11	9.7	864		M	0.99
11	0.209	−0.015	0.155	0.992	2.84	10.32	0.63	9.7	869		M	0.99
63	0.133	0.069	0.104	1.177	2.79	9.38	−0.32	9.7	870		M	0.99
36	0.195	−0.010	0.132	1.012	2.81	9.91	0.17	9.7	885		M	0.72
209	0.210	−0.057	0.095	0.525	2.67	8.17	−1.63	9.8	911		M	0.00
37	0.183	−0.020	0.195	0.966	2.82	10.22	0.40	9.8	919		M	0.99
33	0.097	0.155	0.101	1.265	2.82	9.77	−0.06	9.8	922		M	0.99
193	0.295	−0.009	0.217	1.014	2.85	10.61	0.78	9.8	922		M	0.86
210	0.262	−0.023	0.176	0.947	2.87	10.83	0.96	9.9	943		M	0.98
46	0.249	−0.007	0.194	1.022	2.82	10.26	0.36	9.9	958		M	0.99
211	0.217	−0.066	0.089	0.439	2.68	8.68	−1.33	10.0	1006		M	0.70
197	0.257	−0.053	0.122	0.560	2.74	9.66	−0.40	10.1	1029		M	0.00
40	0.187	0.041	0.118	1.135	2.83	10.39	0.31	10.1	1041		M	0.99
48	0.188	0.018	0.140	1.091	2.85	10.77	0.66	10.1	1052		M	0.99
1618	0.306	0.027	0.101	1.110	2.75	9.15	−1.01	10.2	1075		M	0.00
44	0.177	−0.025	0.196	0.932	2.82	10.57	0.39	10.2	1090		M	0.85
42	0.149	0.122	0.183	1.002	2.80	10.69	0.48	10.2	1104		M	0.00
38	0.224	−0.024	0.170	0.939	2.78	10.09	−0.14	10.2	1114		M	0.99
13	0.249	−0.024	0.182	0.940	2.79	10.24	−0.02	10.3	1127		M	0.99
1551	0.203	0.097	0.212	1.056	2.82	10.56	0.23	10.3	1164		M	0.00

To determine membership to the cluster we assumed that to be a member, the distance to the star should be within one sigma of the mean average distance. The mean distance modulus value of these stars is 9.87 ± 0.35. For the accumulation of stars, membership is indicated by an M in the twelfth column of Table 4. There are some stars close to these limits and they are indicated by M. Those beyond the membership limits are denoted by N, non-members.

We compared our membership assignation with that reported in WEBDA for NGC1528. The membership probabilities reported are listed in the last column of Table 4. It is remarkable that out of the thirty-four stars we found to be members, twenty-seven have a high membership probability and only nine have low membership probabilities in WEBDA. However, some stars that we classified as non-members have high membership probabilities in WEBDA.

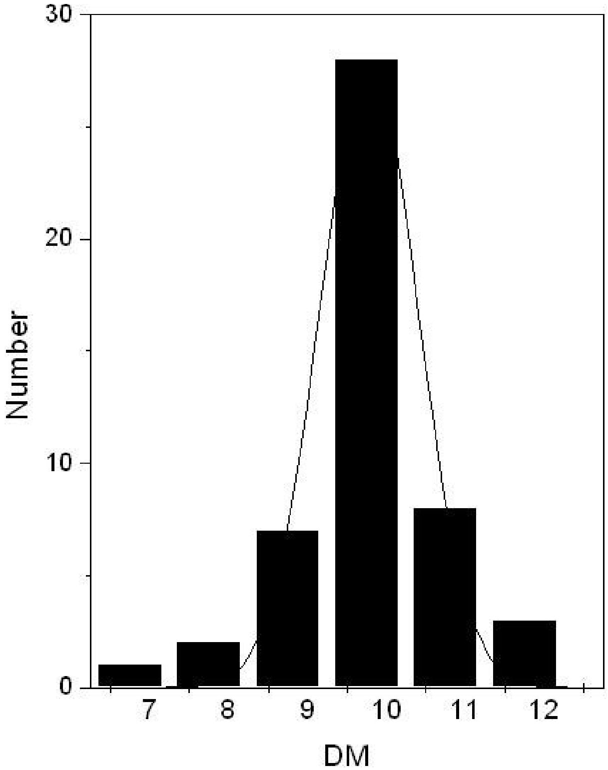

Fig. 2. Histogram of the DM of the stars in the direction of NGC 1528. The peak is at 9.8 ± 0.6.

The effective temperature of the hottest stars was fixed by plotting the location of all stars on the theoretical grids of Lester, Gray & Kurucz (hereinafter LGK86), after calculating the unreddened colors (Figure 3) for the correct chemical composition of the model considered. The metallicity of NGC 1528 was not reported by WEBDA but it is reported by Linga (1987) as -0.10. We found two F type stars to be cluster members for which metallicity can be evaluated. The metallicities of these stars, W206 and W1613 are -0.25 and -0.37, respectively. However, the membership probability assigned in WEBDA is, in both cases, 0.0. In view of this, we will consider models of solar metallicity.

We used the $(b-y)$ vs. Hβ diagram of LGK86 which allows the determination of the temperatures of the hottest stars with an accuracy of a few hundredths of degrees. The temperature for the hottest star, W211, is around 16200 K. W211 has a membership probability of 0.70 according to WEBDA and is a member of the cluster according to our results. The second hottest star is W209 with a Te of 15500 K; according to WEBDA it is a non-member star although it belongs to the cluster in our findings. However, both W211 and W209 have $\log g$ values of 3.0 and

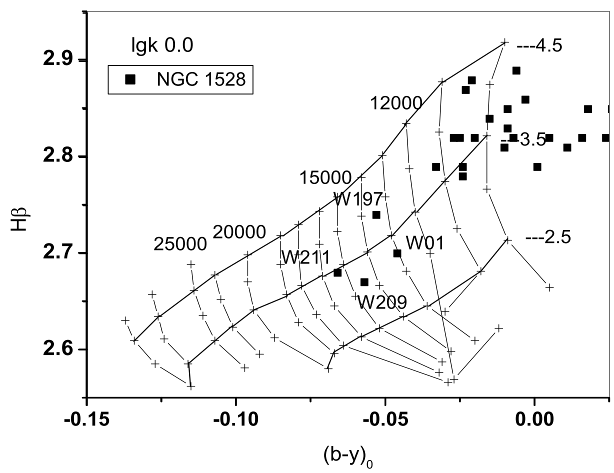

Fig. 3. Location of the unreddened points (filled squares) in the LGK86 grids. Values of the effective temperature and surface gravity are indicated.

3.5 respectively. Furthermore, W197 has log g of 4 and an effective temperature of 13500 K ($\log T$e of 4.13). Once the membership and effective temperature of the hottest star are established, an age for NGC 1528 can be determined through the calibrations of Meynet, Mermilliod & Maeder (1993) from the relation $\log(age) = -3.611 \times (\log T\mathrm{e}) + 22.956$ valid in the range $\log T$e within the limits [3.98, 4.25]. The results is $\log(age) = 8.04$. All these quantities are summarized in Table 5.

6. DISCUSSION

With the procedures we have described we obtained distances for stars of spectral types B, A and F. Membership was assigned in the histogram for those stars within one sigma of the distance mean value. Out of our sample of sixty-five stars, thirty-four were considered to be members in this fashion, six to be marginally members and nine non-members. Eleven were late type stars and no distance was determined for them. A mean reddening value was calculated for the member stars. The age was fixed from the temperature of the hottest star which, by the way, is considered to be a member of the cluster both in the literature and in our findings. This age is in agreement with its spectral type, B5V.

7. CONCLUSIONS

The physical characteristics we determined in the present study coarsely agree with the previously determined ones. As was mentioned at the beginning, the distance was fixed at 776 pc. Our value

TABLE 5

CHARACTERISTICS OF THE OPEN CLUSTER NGC 1528

	WEBDA	Lynga (1987)	Present Paper
Distance [pc]	776	776	954 ± 154
Reddening [mag]$E(B-V)$	0.258	0.258	0.251 ± 0.069
Reddening [mag]$E(b-y)$		0.145	0.196 ± 0.054
Distance modulus [mag]	10.25		9.87 ± 0.35
Log age	8.568	8.57	8.04
[Fe/H]		−0.10	-0.31 ± 0.08

is 954 ± 154 pc. Of the 65 stars studied 14 are early type stars, 16 A type stars, and only two are of spectral type F with a mean [Fe/H] of -0.310 ± 0.079; the reddening $E(B-V)$ was 0.258 mag, whereas our value for $E(b-y)$ of 0.196 ± 0.054 gives an $E(B-V)$ of 0.251 ± 0.069 if the well-known relation of $E(b-y) = 0.78E(B-V)$ is applied. The reported age is $\log(age) = 8.568$, whereas our determined value is 8.04. However, the values from the $uvby-\beta$ photoelectric photometry were determined on a star-by-star basis whereas the literature values were determined by the main sequence fitting method, which does not consider the membership probability of each star, but rather the overall behavior of the all stars in a coarse statistical manner.

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