

A Globular Cluster in the Dwarf Galaxy Sextans B

M. E. Sharina^{1*}, T. H. Puzia^{2**}, and A. S. Krylatyh³

¹*Special Astrophysical Observatory, Russian Academy of Sciences, Nizhnij Arkhyz, 369167 Russia*

²*Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, BC V9E 2E7 Canada*

³*Astronomy department of the Kazan State University, Kremlevskaya ul., Kazan, 420008 Russia*

Abstract—We present spectroscopic observations of a massive globular cluster in the dwarf irregular galaxy Sextans B, discovered by us on the Hubble Space Telescope Wide Field and Planetary Camera 2 (HST WFPC2) images. Long-slit spectra were obtained with the SCORPIO spectrograph on the 6-m telescope at the Special Astrophysical Observatory of the Russian Academy of Sciences. We determine the age, metallicity and alpha-element abundance ratio for the globular cluster to be 2 ± 1 Gyr, -1.35 ± 0.25 dex, and 0.1 ± 0.1 dex, respectively. Main photometric and structural parameters of it were determined using our surface photometry on the HST images. The mass ($\sim 10^5 M_\odot$), luminosity and structural parameters appear to be typical of the globular clusters in our own Galaxy. Our findings shed new light on the evolutionary history of Sextans B.

PACS numbers : 98.52.Wz, 98.20.Jp

DOI: 10.1134/S1990341307030029

1. INTRODUCTION

Discovery and detailed investigation of GCs in the smallest dwarf galaxies are very important for development of a comprehensive theory of formation and evolution of GCs. Elmegreen & Efremov [1] showed, that massive gravitationally bound stellar clusters are possible progenitors of the present-day old Galactic GCs, born in dense, compact gas clouds in high ambient pressure environments. Such conditions were in place in our Galaxy $\sim 10 \div 13$ Gyr ago, when the density and pressure in interstellar and intergalactic medium were high. Observational studies show, that the formation of the present-day massive gravitationally bound stellar clusters can only happen near the centers of massive galaxies, or in merging and interacting galaxies (e.g. [2]).

Small, low surface brightness galaxies are often considered to be survivors of ancient building blocks of galaxies according to the generally accepted model of hierarchical galaxy formation. Unfortunately, the formation of GCs in dwarf galaxies has not been fully understood up to now. The gas density is low in dwarf galaxies, and star bursts should lead to enormous gas outflows due to shallow galactic gravitational potential wells [3].

Studying of GCs is important for a better understanding of the evolution of their host galaxies. There

are three main morphological types of dwarf galaxies. Irregular galaxies (dIr) are composed mostly of young and intermediate-age stellar populations and are typically found in the field and at a distance of $D > 300$ kpc from a nearby massive galaxy [4]. Spheroidal and elliptical dwarf galaxies (dSph, dE) consist mainly of old stars [4] and concentrate near massive galaxies in groups and clusters [5].

Sextans B is a rather isolated dwarf irregular galaxy, a member of the Antlia-Sextans group near the Local Group [6, 7]. It is a faint galaxy, typical of the population of the Local Group and other nearby poor groups. Its central surface brightness in the filter B of the wide-band Johnson-Cousins system is 22.8 ± 0.2 mag/sq.sec. [8]. The absolute blue magnitude, $M_B = -13.97$, corresponds to the distance 1360 ± 70 kpc [9]. The chemical composition of HII regions and of planetary nebulae in the galaxy has been extensively studied by many authors [10–13]. The star formation history of Sextans B, according to stellar photometry studies was rather complex. According to [14–16], the galaxy experienced a powerful early star formation burst during the first 1–2 Gyr, and an increased SF activity in the last 1–2 Gyr. Dolphin et al. [17] consider the star formation to be active during the whole life of the galaxy. However, all the authors mention that the available color-magnitude diagrams (CMDs) are not very deep to allow determination of the age of the galaxy with an accuracy of $\sim 2 - 3$ Gyr. Kniazev and co-authors [13] discovered that one HII region in the galaxy is twice as metal-rich as others. This

*E-mail: sme@sao.ru

**E-mail: Thomas.Puzia@nrc.ca

Table 1. Fundamental characteristics of the GC in Sextans B determined in our work (see the column content at the end of the section 1)

N	Parameter	GC
1	RA(2000.0)	10 00 04.64
2	DEC(2000.0)	+05 20 07.4
3	S_n	3.8
4	Age, Gyr	2 ± 1
5	$[Z/H]$, dex	-1.35 ± 0.3
6	$[\alpha/Fe]$, dex	0.1 ± 0.1
7	V_h , km/s	349 ± 5
8	V_0 , mag	17.90 ± 0.02
9	$M_{V,0}$, mag	-7.77 ± 0.02
10	$(V - I)_0$, mag	0.67 ± 0.03
11	Mass ($M_\odot$)	$0.8_{+0.40}^{-0.25} \times 10^5$
12	r_h , pc	4.1 ± 0.2
13	$e = 1 - b/a$	0.05
14	d_{proj} , kpc	0.45
15	$\mu_{V,0}$ mag/sq s	17.89 ± 0.01
16	$\mu_{I,0}$ mag/sq s	17.24 ± 0.02
17	r_c , pc	1.7 ± 0.15
18	r_t , pc	40 ± 2

implies considerable inhomogeneity in the present-day metallicity distribution in Sextans B.

In this paper we report for the first time the discovery and a detailed spectroscopic investigation of a GC in Sextans B with the SCORPIO spectrograph at the SAO RAS 6m telescope. Basic data for the GC obtained in our work are summarized in Table 1: (1), (2) equatorial coordinates, (3) specific frequency of GCs in a galaxy ($S_N = N \times 10^{0.4(M_V + 15)}$), [18], where N is a number of GCs, M_v is the absolute V magnitude of the galaxy), (4)–(6) age, metallicity and alpha-element abundance ratio, (7) heliocentric radial velocity, (8) integrated V magnitude, (9), (10) integrated absolute V magnitude and color, corrected for Galactic extinction, (11) mass in solar masses, (12)–(14) half-light radius, ellipticity, and projected distance to the center of the galaxy; and model parameters obtained by fitting the surface brightness profile by the King law: (15)–(18) central surface brightness in V and I, core and tidal radii.

2. GLOBULAR CLUSTER DETECTION AND PHOTOMETRY

A Hubble Space telescope Wide Field and Planet Camera 2 (HST WFPC2) archive image of the GC in the V band (HST Proposal ID 8601) is shown in the right panel of Figure 1. The cluster is partially resolved into stars with a diffuse envelope. Observations were carried out with the filters F606W and F814W, the band width of which are similar to the filters V and I of the Johnson-Cousins system. The exposure time was 600 seconds in each filter.

The surface photometry and structural parameter determination for the GC on the HST images were carried out using receipts described in detail in our catalog paper of GCs in nearby dwarf galaxies [19]. The photometric results are shown in Figure 2 and summarized in Table 1. The growth curves of integrated light in V and I bands (top) and the distribution of the integrated color in magnitudes along the radius (bottom) are shown in the left panel of the Fig. 2. Surface brightness profiles in mag/sq.sec in V and I (top) and the difference between them (bottom) are shown in the right panel of Fig. 2. The structural parameters obtained by fitting the surface brightness profile by the King law are similar to those of GCs in our own Galaxy. However, the color of the GC in Sextans B is blue, which indicates a younger age. This statement will be tested and quantified in Section 4.

3. SPECTROSCOPIC OBSERVATIONS AND DATA REDUCTION

The long-slit observations were conducted on February 11, 2005 with the SCORPIO spectrograph [20]. The log of the observations is presented in Table 2. We used the grism VPHG1200g, the spectral resolution $5 \text{ \AA}$, the spectral range $3800\text{--}5700 \text{ \AA}$, and the CCD detector EEV42-40. The slit size was $6' \times 1''$. The seeing was about 2 arc seconds during our observations. We observed Lick/IDS and radial velocity standard stars BF23751, HD115043 and HD132142 for proper determination of radial velocities and calibration of our instrumental absorption line measurements to the Lick standard system [21].

The data reduction and analysis were performed using the European Southern Observatory Munich Image Data Analysis System (MIDAS) [22]. Cosmic-ray removal was done with the FILTER/COSMIC program. We used the context LONG for the reduction of our spectroscopic data. For each two-dimensional spectrum the standard procedure of the primary reduction was applied. After wavelength calibration and sky subtraction, the spectra were corrected for extinction and flux-calibrated using the observed spectrophotometric standard GRW

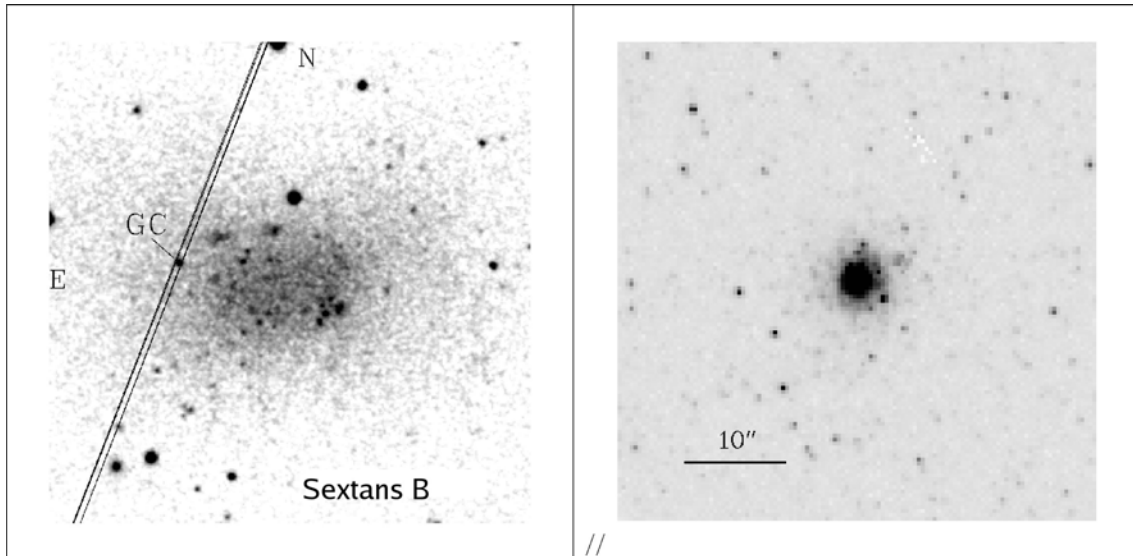


Fig. 1. DSS2-R 5x5 arcsec image of Sextans B with marked the long slit position (left); WFPC2 HST image of the GC (right).

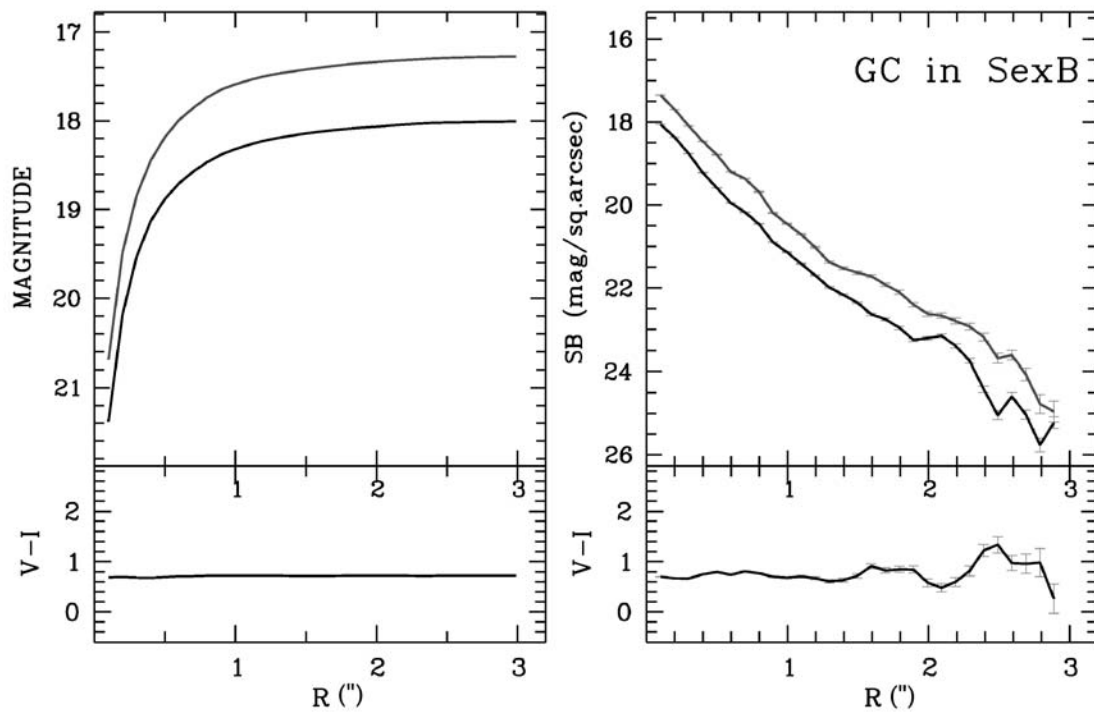


Fig. 2. Surface photometry results for the GC in Sextans B on the HST WFPC2 images.

+70°5824 [23]. The dispersion solution provides an accuracy of the wavelength calibration of $\sim 0.08 \text{ \AA}$. All one-dimensional spectra of each object were summed up to increase the S/N ratio. The spectrum of the GC in Sextans B is shown in Fig.3. The radial velocity of

the cluster was determined via cross-correlation with the radial velocity standard stars. We used several radial velocity standards and division on few regions of spectra for the determination of the radial velocity error. The derived heliocentric radial velocity is listed

in Table 1. The signal-to-noise ratio per pixel in the spectrum of the cluster measured at 5000 Å is ~ 40 . The quality of the spectrum allows us to accurately measure the absorption line indices and determine the age, metallicity, and alpha-element abundance ratio ($[\alpha/Fe]$) of the cluster by comparison of the measured values with predictions of the population synthesis model.

A detailed description of the Lick index measuring technique and of the Lick/IDS system itself, as well as the demonstration of our tests on the correspondence of our instrumental Lick index system to the standard one are given in our methodological paper [24]. In Table 3 the averaged differences between the measured indices and the corresponding indices in the Lick system, ‘c’, are shown. We obtain zero points of transformations of our index measurements to the Lick/IDS system by averaging the values of ‘c’ for each index using all observed standard stars. Note, that the calculated zero-point transformations to the Lick/IDS system agree well with those given in our methodological paper [24] for the multislit variant of observations with the same instrument. Absorption-line indices for the GC in Sextans B, measured by the GONZO program [25] and transformed into the Lick system are listed in the last column of Table 3.

4. AGE, METALLICITY AND ALPHA ELEMENT ABUNDANCE RATIO

We determine the age, $[Z/H]$ and $[\alpha/Fe]$ for the GC in Sextans B using our procedure of three-dimensional linear interpolation and χ^2 minimization described in detail in [26]. This program minimizes the difference between the measured Lick indices and the model predictions [27] normalized to the index measurement uncertainty. The program was extensively tested by comparison of ages, $[Z/H]$ and $[\alpha/Fe]$ obtained by the routine with the same values available in the literature for 12 Galactic and 46 M31 GCs [26]. The total Lick index measurement errors are determined using the GONZO routine [25] from bootstrapping the object spectrum. The errors include the Poisson errors and the radial velocity measurement uncertainties. Note, that not only random index uncertainties, but also errors of the transformations to the Lick system can alter the measured ages, $[Z/H]$ and $[\alpha/Fe]$ ratios. Therefore, as many Lick standard stars as possible should be observed to minimize the systematic errors.

We determine the age, metallicity, and $[\alpha/Fe]$ of the GC: 2 ± 1 Gyr, $[Z/H] = -1.35 \pm 0.25$ dex, $[\alpha/Fe] = 0.1 \pm 0.1$ dex.

A visual representation of how the Lick indices help to divide age and metallicity effects can be obtained from the so-called age–metallicity diagnostic

Table 2. Log of spectroscopic observations

Object	Data	Exposure
GC in Sex B	11.03.2005	4x1200 s.
GRW+70d5824	11.03.2005	3x60
HD115043	11.03.2005	10,20
HD132142	11.03.2005	2x20
HD2665	18.01.2007	21
BF23751	11.03.2005	120

Table 3. Correction terms of the transformation to the Lick/IDS standard system [21]: $I_{\text{Lick}} = I_{\text{measured}} + c$. In the last column the GC indices corrected for the zero points of transformations into the standard system are presented

Index	c	rms error	Units	Indices for GC in Sex B
CN1	-0.020	0.002	mag	-0.192 ± 0.001
CN2	-0.019	0.006	mag	-0.165 ± 0.001
Ca4227	0.033	0.121	Å	0.410 ± 0.052
G4300	0.786	0.720	Å	0.084 ± 0.057
Fe4384	0.598	0.300	Å	0.040 ± 0.066
Ca4455	0.288	0.030	Å	0.046 ± 0.068
Fe4531	-0.043	0.020	Å	1.718 ± 0.075
Fe4668	-0.163	0.210	Å	0.107 ± 0.085
H β	-0.909	0.270	Å	4.609 ± 0.085
Fe5015	0.498	0.169	Å	2.692 ± 0.091
Mg ₁	-0.035	0.013	mag	0.020 ± 0.002
Mg ₂	-0.019	0.007	mag	0.024 ± 0.002
Mg _b	0.202	0.348	Å	0.336 ± 0.096
Fe5270	0.554	0.358	Å	0.909 ± 0.098
Fe5335	0.066	0.370	Å	0.312 ± 0.099
Fe5406	0.001	0.010	Å	0.547 ± 0.100
H δ_A	0.152	0.060	Å	7.897 ± 0.103
H γ_A	-1.508	0.340	Å	5.931 ± 0.106
H δ_F	-0.345	0.360	Å	5.590 ± 0.107
H γ_F	-0.069	0.142	Å	4.864 ± 0.108

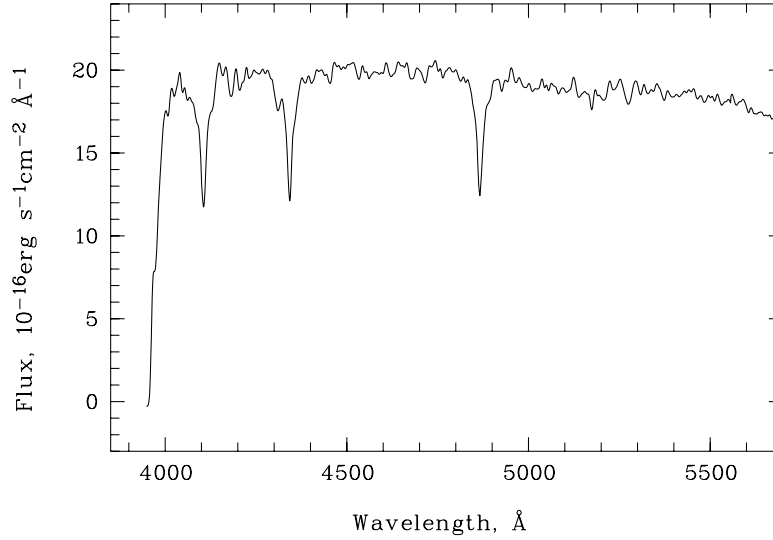


Fig. 3. The spectrum of the GC in Sextans B obtained with the SCORPIO spectrograph.

plots [28] (see Figure 4). Lines in Figure 4 represent the model predictions by Thomas et al. [27]. The indices for the GC are shown by black dots. The rms errors of zero points of the transformations to the Lick system are shown in the corners of the panels. The plots show the dependence of age-sensitive $H\beta$, $H\delta_A$, $H\gamma_A$, $H\delta_F$, $H\gamma_F$ on the $[\alpha/Fe]$ insensitive index

$$[MgFe]' =$$

$$\{Mg b \times (0.72 \times Fe5270 + 0.28 \times Fe5335)\}^{1/2}.$$

To explore the Mg/Fe abundance ratio, the metal-abundance sensitive index

$$\langle Fe \rangle = (Fe5335 + Fe5270)/2$$

is compared with the index Mg_2 .

5. DISCUSSION

It is interesting to compare the metallicities of different stellar populations in Sextans B. The metallicity of old stars, $[Fe/H] = -2.1$ dex, was obtained by Grebel et al. [4] via a comparison of the red giant branch (RGB) with globular cluster fiducials. Star formation history studies led to $[Fe/H] \sim -1.2 \div -1.3$ ([14, 17]). Our estimate of the GC metallicity agree well with the last value. We suggest that the time of the GC birth coincides with the strongest star burst in the galaxy. However, the derived $[\alpha/Fe] = 0.1$ likely implies that there was a significant contribution from type-Ia SNe over the past ~ 3 Gyr. However, star formation was never so intense as in giant elliptical galaxies, where $[\alpha/Fe]$ ratios for GCs can be significantly higher up to ~ 0.5 dex [29]. It is not excluded, that the age of the parent galaxy

is much higher than the age of the GC. The color-magnitude diagram of Sextans B is deep enough to clearly indicate the presence of red giants and a considerable number of intermediate-age stars [9]. However, the age of red giants is not determined, and the presence of older stars was not proved. Dolphin et al. [30] pointed out, that the color of 13 Gyr old metal-poor RGB stars is actually the same as that of 2 Gyr old stars having metallicity higher by $0.4 \div 0.8$ dex.

We convert the $[Fe/H]$ value determined for stars and the GC in Sextans B to $[O/H]$, assuming $[Fe/O] \sim 0$ [11] and $12 + \log(O/H)_\odot = 8.66$ [31]. The obtained value agrees well with the one for most HII regions in Sextans B [13]. Thus, the metallicity of the GC and of young stellar populations in Sextans B appear to be similar. This fact does not contradict the previous findings of star formation history studies which indicate a low initial star formation activity. Additionally, Sextans B could lose metals through stellar winds due to a shallow gravitational potential well.

We can estimate the mass of the GC using the obtained age, metallicity, luminosity, simple stellar population models of Bruzual and Charloft [32], and an assumed Salpeter initial mass function. The obtained mass, $0.8_{-0.25}^{+0.40} \times 10^5$, and structural parameters, tidal and core radii (see table 1), are typical of GC population of our Galaxy.

The specific frequency, $S_N \sim 3.8$, is much higher than the expected one, if GCs form in direct proportion to the mass of the galaxy [33]: $S_N \simeq \epsilon(1 + M_{gas}/M_*) \simeq 0$, where M_{gas} is the mass of gas, M_* is the mass of stars, and $\epsilon = 0.0025$ is the ratio

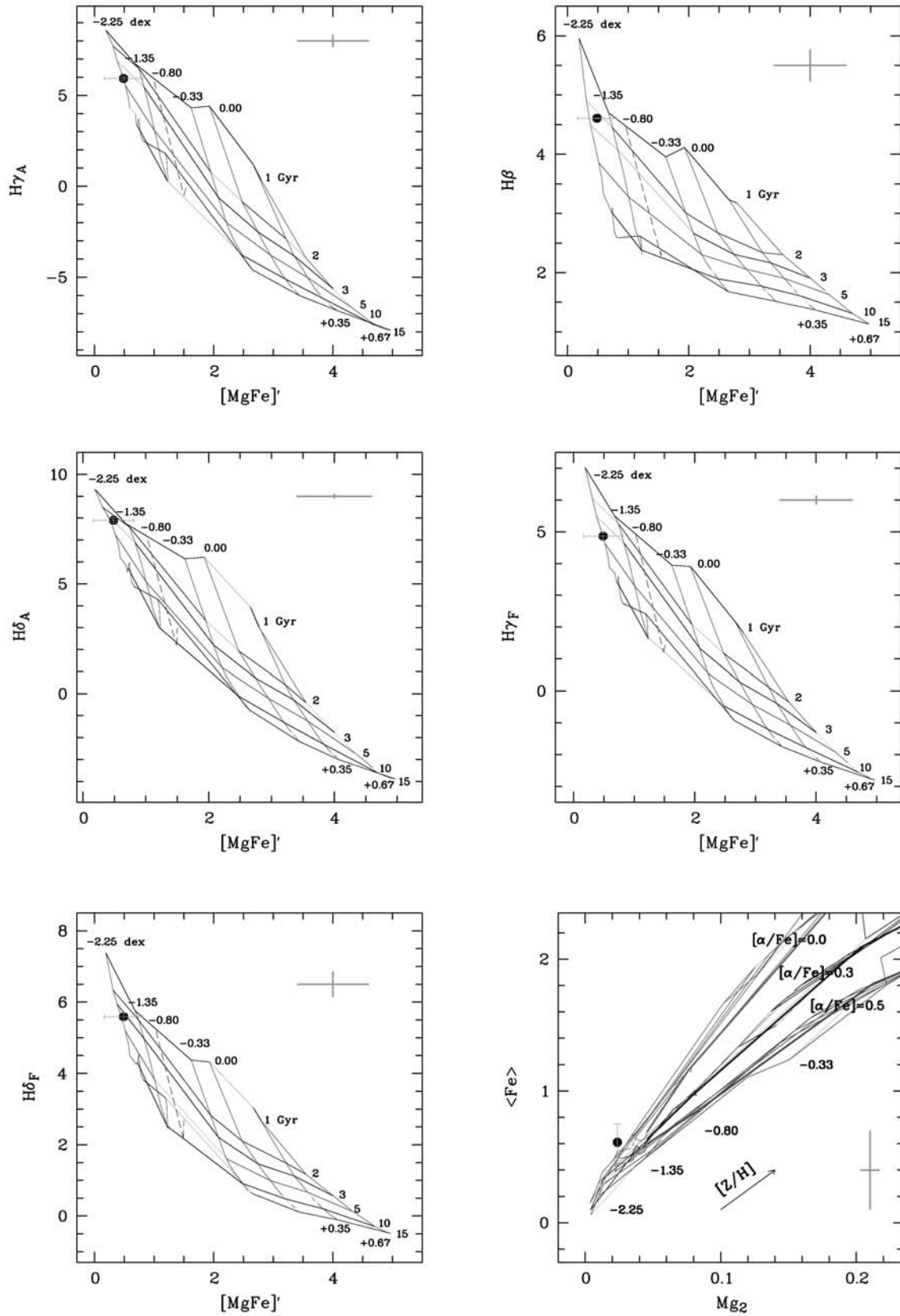


Fig. 4. Age–metallicity diagnostic plots for the GC in Sextans B. The SSP model predictions from [27] are overplotted by lines.

of GC mass to the summary mass of gas and stars. The relation $M_{gas}/M_* \sim 0.9$ for Sextans B can be estimated using the hydrogen mass-to-luminosity ratio, $M_{HI}/L_B \sim 1.5$ [34, 35], the stellar mass-to-luminosity ratio, $M_*/L_B \sim 1.58$ [36], and integrated color of the galaxy, corrected for the Galactic reddening $(B - V)_0 \sim 0.5$. The $S_N \sim 3.8$ is slightly lower than the expected one in the case of mass loss by stellar winds [3, 37].

Sextans B is often compared in the literature with Sextans A, the galaxy similar in structure, size, luminosity and distance to neighbors, which is also a member of the Antlia-Sextans group (e.g. [13]). It is interesting to note that we did not find GCs in the central part of this galaxy on the HST images.

It is unlikely, that the galaxy was influenced by ram pressure, tidal stripping, and/or encounters with neighbors because of its rather isolated location. Hence, the star formation in Sextans B was regulated by internal mechanisms. Deep CMD studies and the detailed chemical evolutionary modelling would help to elucidate the nature of SF activity and the GC formation mechanisms in the galaxy.

6. CONCLUSIONS

In this paper we report on the discovery and determination of fundamental, evolutionary, photometric, and structural parameters of a massive GC in the nearby dwarf irregular galaxy Sextans B.

From a comparison of population synthesis models [27] with the measured Lick absorption line indices we obtain the age, metallicity and $[\alpha/Fe]$: 2 ± 1 Gyr, $[Z/H] = -1.35 \pm 0.25$ dex, and $[\alpha/Fe] = 0.1 \pm 0.1$ dex. The metallicity of the GC agrees well with that known in the literature for stars, HII regions and planetary nebulae in the galaxy. The age of the GC coincides with the epoch of the most powerful star formation activity in Sextans B according to the literature photometric studies. The alpha-element abundance ratio implies a significant contribution of type-Ia SNe over the past ~ 3 Gyr.

The structural parameters and luminosity of the GC are typical of Milky Way GCs. The mass of the GC is $0.8_{-0.25}^{+0.40} \times 10^5 M_\odot$, the core radius is $r_c = 1.7 \pm 0.15$ pc, and the tidal radius is $r_t = 40 \pm 2$ pc.

The number of GCs in Sextans B per unit luminosity is much higher than the expected one if we assume that GCs form in direct proportion to the parent galaxy mass.

The results of this work are important for solving the problem of the origin of GCs in dwarf galaxies. Our data indicate that massive GCs can form in extremely shallow potential wells and isolated field environments.

ACKNOWLEDGMENTS

We thank Dr. S. N. Dodonov for supervision of our observations, and Dr. S.A. Pustilnik for helpful discussions. T.H.P. gratefully acknowledges the financial support through the Plaskett Research Fellowship from National Research Council of Canada at the Herzberg Institute of Astrophysics.

REFERENCES

1. B. G. Elmegreen, Yu. N. Efremov, *Astrophys. J.* **480**, 235 (1997).
2. S. Larsen, T. Richtler, *Astronom. and Astrophys.* **354**, 836 (2000).
3. A. Dekel, J. Silk, *Astrophys. J.* **303**, 39 (1986).
4. E. K. Grebel, J. S. Gallagher III, D. Harbeck, *Astronom. J.* **125**, 1926 (2003).
5. J. Einasto, E. Saar, A. Kaasik, A. D. Chernin, *Nature* **252**, 111, (1974).
6. S. van den Bergh, *Astrophys. J.* **517**, L97 (1999).
7. R. B. Tully, R. S. Somerville, N. Trentham, M. A. Verheijen, *Astrophys. J.* **569**, 573 (2002).
8. M. E. Sharina, I. D. Karachentsev, A. E. Dolphin, et al., *Monthly Notices Roy. Astronom. Soc.* (in prep.) (2007).
9. I. D. Karachentsev, M. E. Sharina, D. I. Makarov, A. E. Dolphin, et al., *Astronom. and Astrophys.* **389**, 812 (2002).
10. G. Stasinska, G. Comte, L. Vigroux, *Astronom. and Astrophys.* **154**, 352 (1986).
11. E. D. Skillman, R. C. Kennicutt, P. W. Hodge, *Astrophys. J.* **347**, 875 (1989).
12. M. Moles, A. Aparicio, J. Masegosa, *Astronom. and Astrophys.* **228**, 310 (1990).
13. A. Y. Kniazev, E. K. Grebel, S. A. Pustilnik, A. G. Pramskij, D. B. Zucker, *Astronom. J.* **130**, 1558 (2005).
14. M. Tosi, L. Gregio, G. Marconi, P. Focardi, *Astronom. J.* **102**, 951 (1991).
15. S. Sakai, B. F. Madore, W. L. Freedman, *Astrophys. J.* **480**, 589 (1997).
16. M. Mateo, *ARA&A* **36**, 435 (1998).
17. A. E. Dolphin, D. R. Weisz, E. D. Skillman, J. A. Holtzman, *astro-ph/0506430*.
18. W. E. Harris, S. van den Bergh, *Astronom. J.* **86**, 1627 (1981).
19. M. E. Sharina, T. H. Puzia, D. I. Makarov, *Astronom. and Astrophys.* **442**, 85 (2005).
20. V. L. Afanasiev, A. V. Moiseev, *Astron. Lett.* **31**, 194 (2005).
21. G. Worthey, *Astrophys. J. Suppl.* **95**, 107 (1994).
22. K. Banse, Ph. Crane, Ch. Ounnas, D. Ponz, MIDAS, in *Proc. of DECUS* (Zurich, 1983), p. 87.
23. J. Oke, *Astronom. J.* **99**, 1621 (1990).
24. M. E. Sharina, V. L. Afanasiev, T. H. Puzia, *Astron. Lett.* **32**, 185 (2006).
25. T. H. Puzia, R. P. Saglia, M. Kissler-Patig, et al., *Astronom. and Astrophys.* **395**, 45 (2002).
26. M. E. Sharina, V. L. Afanasiev, T. H. Puzia, *Monthly Notices Roy. Astronom. Soc.* **372**, 1259 (2006).

27. D. Thomas, C. Maraston, R. Bender, *Monthly Notices Roy. Astronom. Soc.* **339**, 897 (2003).
28. T. H. Puzia, M. Kissler-Patig, D. Thomas, et al., *Astronom. and Astrophys.* **439**, 997 (2005).
29. T. H. Puzia, M. Kissler-Patig, P. Goudfrooij, *Astrophys. J.* **648**, 383 (2006),
30. A. E. Dolphin, A. Saha, E. D. Skillman, R. C. Dohm-Palmer, E. Tolstoy, A. A. Cole, J. S. Gallagher, J. G. Hoessel, M. Mateo, *Astronom. J.* **126**, 187 (2003).
31. M. Asplund, N. Grevesse, A. J. Sauval, C. Allende Prieto, D. Kiselman, *Astronom. and Astrophys.* **417**, 751 (2004).
32. G. Bruzual, S. Charlot, *Monthly Notices Roy. Astronom. Soc.* **344**, 1000 (2003).
33. D. E. McLaughlin, *Astronom. J.* **117**, 2398 (1999).
34. C. M. Springob, M. P. Haynes, R. Giovanelli, B. R. Kent, *Astrophys. J. Suppl.* **160**, 149 (2005).
35. I. D. Karachentsev, V. E. Karachentseva, W. H. Huchtmeier, D. I. Makarov, *Astronom. J.* **127**, 2031 (2004).
36. E. F. Bell, R. S. de Jong, *Astrophys. J.* **550**, 212, (2001)
37. W. E. Harris, in *Star Clusters, Saas-Fee Advanced Course 28. Lecture Notes 1998*, Swiss Society for Astrophysics and Astronomy, Ed. by L. Labhardt and B. Binggeli (Springer-Verlag, Berlin, 2001).