Arp 2 and Terzan 8: a detailed chemical analysis

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ABSTRACT

To compare the globular clusters associated with the Sagittarius Galaxy we report the results obtained from new high resolution spectra of red giant stars in Terzan 8 and Arp 2, collected with the Magellan echelle spectrograph (MIKE) at Las Campanas Observatory. For Ter 8 we find [FeI/H]=-2.37 ± 0.04 and [FeII/H]-2.30 ± 0.07, while for Arp 2 [FeI/H]=-1.77 ± 0.04 and [FeII/H]=-1.89 ± 0.07. Other elements usually of interest show the following results. For oxygen we obtain [O/Fe]=0.71 ± 0.17 for Ter 8 and [O/Fe]=0.21 ± 0.22 for Arp 2. For the α-elements (Mg, Si, Ca, Ti) the mean values are 0.35 ± 0.14 dex for Ter 8 and 0.31 ± 0.11 for Arp 2. These values are not too different from the Galactic globular clusters at a similar [Fe/H] value. Regarding Cu, we find quite underabundant results for both the clusters: -0.96 for Ter 8 and -0.93 for Arp 2. The heavy s-process elements Ba and Nd show no excesses in Ter 8 and in Arp 2. Our only r-process element, Eu, shows an excess of 0.45 dex in Arp 2, based on the only useful line at 6645 Å.

Subject headings: globular clusters: general — globular clusters: individual (Arp 2, Terzan 8)

1. Introduction

The best evidence that nearby dwarf galaxies have contributed significant mass to the Galactic halo is the current on-going capture of the Sagittarius galaxy (Sgr) along with its attendent globular clusters: M54, Terzan 7, Terzan 8, Arp2 and Pal 12. Sgr seems to have been either a dwarf spheroidal galaxy (Ibata et al. 1994) or a dwarf elliptical (Layden & Sarajedini 2000; Monaco et al. 2005) before being distorted by the gravitational field of the Galaxy. Sgr offers an opportunity to study the chemical evolution of a galaxy very different from our own. Detailed chemical composition analysis of the Sgr globular clusters will permit us to define the differences among this dwarf galaxy, the Fornax system and the Milky Way. This would provide a check on current ideas in chemical evolution, place constraints on the star formation rate and IMF in Sgr, and set limits on the accretion of objects similar to Sgr in the construction of the Galactic halo. We will discuss the comparison between Sgr and Fornax in a following paper.

The bulk of the Sgr system shows a wide range of metallicities from about [Fe/H] $=-1.6$ to solar (Smecker-Hane & McWilliam, 2002; McWilliam & Smecker-Hane 2005a; Sbordone et al. 2007).

The globular clusters associated with Sgr are remarkably heterogeneous. Terzan 7 and Pal 12 show metallicities of -0.61 and -0.79 respectively (Tautvaisiene et al. 2004; Sbordone et al. 2005; Cohen 2004). The most populous cluster, M54 (= NGC 6715) was found to show [Fe/H]=-1.55 from an analysis of its brightest giants by Brown, Wallerstein & Gonzalez (1999). This cluster may well have been the nucleus of Sgr. A brief statistical analysis conducted, with the help of Ivan King, on the newest CM diagram of M54 based on HST data (Sarajedini, Dotter & Siegel 2007) shows that the majority of the stars of the lower red giant branch are members of M54, not superimposed Sgr stars. This indicates that the cluster has two populations with significantly differing metallicities. We will tackle this problem in a future paper.

Recently another member has been added to the Sgr system: Whiting 1 (Carraro, Zinn & Moni Bidin, 2007). From its CM diagram they estimate a metallicity of -0.65 dex and an age of 6.5 Gyr. These results place Whiting 1 amoung the young and metal-rich clusters of the Sgr system.

Arp 2 and Terzan 8 are the most metal-poor globular clusters of Sgr and are comparable to the metal-poor globulars of the Galaxy.

Webbink (1985) gave the very first estimate of the metallicity of Arp 2: [Fe/H]=-1.85, based on an unpublished CM diagram by Seitzer and Phillips. A photometric study of this cluster by Buonanno et al. (1995) presented the first CM diagram of this cluster. They found that the slope of the RGB and the overall morphology are consistent with that of a metal-poor cluster with [Fe/H]=-1.84 ± 0.25. Their results also show that Arp 2 is about 1 Gyr older than Ruprecht 106, but since the latter is 3-4 Gyr younger than the metal-poor Galactic clusters, the implied age of Arp 2 is also younger. Another intriguing aspect of this comparison concerns the difference in the morphologies of the horizontal branch (HB) of these two custers. The HB of Ruprecht 106 is entirely red while that of Arp 2 lies predominantly to the blue side of the instability strip. This difference can cast doubt on the usual interpretation of the second parameter effect in the GC, if these clusters have indeed similar metallicity and if both are indeed 2-3 Gyr younger than the typical halo metal-poor globulars. A measurement of the Ca II triplet spectroscopy of 8 stars by Suntzeff et al. (1995) suggests a slightly higher value in the iron content of Arp 2: [Fe/H]=-1.73 ± 0.05. This result agrees very well with the outcome (using the same method) of Da Costa & Armandroff (1995): [Fe/H]=-1.70 ± 0.11.

Terzan 8 was studied by Ortolani & Gratton (1990). According to the CM diagram Terzan 8 has an iron content of -1.81 ± 0.10 and shows a strong blue horizontal branch morphology. Its age is similar of that of M92 and NGC 5694. Da Costa & Armandroff (1995) obtained from the Ca II triplet a slightly lower value: [Fe/H]=-1.99 ± 0.08. In a more recent CM diagram study Montegriffo et al. (1998) presented a [Fe/H] value of -2.00 ± 0.10, in agreement with the Da Costa and Armandroff result. Their conclusions on Ter 8's age is that this cluster is coeval with the bulk of the old, metal-poor Galactic GCs.

We undertook a detailed chemical analysis of red giant stars in Ter 8 (3 stars) and Arp 2 (2 stars) to improve the current understanding of the differences between the Sgr GCs and both the Fornax and the Galactic GCs, and the chemical evolution of Sgr, in particular regarding O/Fe and α/Fe ratios but also Fe peak elements, r and s process elements.

The plan of the paper is as follows. In Section 2 we describe the observations and the data-reduction processes; in Section 3 we delineate the steps of the chemical analysis; in Section 4 we discuss our results and in Section 5 we draw our conclusions.

2. Observations and Data Reduction

The observations have been carried out at the Las Campanas Observatory in July 2006 with the Magellan Landon Clay 6.5 m telescope. We collected high-resolution spectra using the Magellan Inamori Kyocera Echelle (MIKE) spectrograph (Bernstein et al. 2003). MIKE is a double echelle spectrograph. We used a 0.5" wide slit, giving a resolving power of 40,000. The spectral range of the blue and red arm combined is between 3400 and 9400 Å, for the configuration we adopted. We binned on-chip in 2x1 pixels, perpendicular to the dispersion.

Program stars were selected among the brightest red giant branch stars from the photometric studies by Ortolani & Gratton (1990) and Buonanno et al. (1995). In Tables 1 and 2 are listed the coordinates (J2000) and the general characteristics of the two clusters and the target stars.

Extraction and wavelength calibration of the spectra were performed with the MIKE pipeline (Kelson 2003). The normalization of the continuum was performend with the IRAF task *continuum*. The 1-D spectra were corrected for heliocentric velocity using *rvcorr* and *dopcor* IRAF tasks. The latter was also used to apply the radial velocity correction, which was derived from 10 unblended narrow lines well spread over the spectrum, selected among Fe I, Fe II and Mg I. The measured signal-to-noise ratio is around 50 at 6000 Å per extracted pixel.

3. Chemical Abundance Analysis

In this section we describe our analysis techniques. We present the line list we used, including hyperfine structure information (HFS) where applicable, and equivalent widths (EWs). We also illustrate how elemental abundances are determined from the stellar parameters and model atmospheres.

3.1. Lines and Equivalent Widths

We assembled our line list using Johnson et al. (2006) list and adding lines from Gratton et al. (2003). Our final list covers a range in wavelenghts from 4200 to 7300 Å. As oscillator strenghts we employed the values taken from Vienna Atomic Line Database (VALD). The EWs were measured using *splot* IRAF task. For the determination of the elemental abundances, we have selected only lines with EWs between 12 and 150 mÅ. The lower limit was chosen to be a fair compromise between the limitatation on accuracy of our data and the need for weak lines for an optimal abundance determination. The upper limit was selected in order to avoid the saturated portion of the curve of growth.

For Ba, Mn, Co and Cu lines (with EWs>30 mÅ) we determined the elemental abundance taking into account the hyperfine structure (hfs). For the Ba II lines we employed the line lists of McWilliam (1998) for solar isotopic composition, generated using the hfs constants of Rutten (1978). The Mn I hfs list was computed by A.M. with the hfs constants of Dembczyński (1979); Goodman et al. (1962); Walther (1962); Woodgate & Martin (1947). Co I hfs line lists were computed from the hfs constants of Guthöhrlein & Keller (1990) and Ibrahim-Rüd (1985). Cu I hfs and isotopic wavelengths listed by Steffen (1985), attributed to Biehl (1976), were employed. The log gf value was taken from Wiese & Martin (1980). The solar isotopic mix was assumed (^{63}Cu : ^{65}Cu of 0.69 : 0.31), taken from NIST database. We used the *blend* routine of the MOOG code (Sneden 1973) to calculate the abundance values for each line.

The line lists of Fe I, Fe II and light and heavy elements with the measured EWs are partially presented in Tables 3 and 4 (the complete line lists are available on-line).

3.2. Model Atmospheres and Stellar Parameters

We used LTE model atmospheres with the new opacity distribution functions (ODFs) computed by Castelli & Kurucz (2003). These models neglect envelope overshooting. We have used a grid of alpha-enhanced models with [Fe/H]=−2.0 dex from which we computed a finer grid with 0.1 dex gravity step and with 50 K temperature steps, by linear interpolation, using a FORTRAN code written by one of us (A.M.). The elemental abundances were computed from the measured EWs using the Kurucz WIDTH9 code (Kurucz 1993; Sbordone et al. 2004; Kurucz 2005).

We determined the temperatures by minimizing the Fe I abundance vs excitation potential slope. For a first guess we used temperatures derived from color-temperature calibrations of Alonso et al. (1999), using B-V and V-K color from Buonanno et al. (1995); Ortolani & Gratton (1990); Skrutskie et al. (2006) (see Table 2). We converted from 2MASS to CIT (Carpenter 2005) to TCS systems (Alonso et al. 1998) in order to use IR colors with the Alonso calibration. In Table 2 are listed the V−K_{TCS} colors. The microturbulent velocity was determined spectroscopically as well by ensuring that there were no trends in the abundance of Fe I as a function of EW. Our $\log g$ values are calculated from the following relationship:

$$\log g = \log\left(\frac{M}{M_\odot}\right) - 0.4(M^{\odot}_{bol} - M_V - BC) + 4\log\left(\frac{T_{\rm eff}}{T^{\odot}_{\rm eff}}\right) + \log g_\odot \quad (1)$$

where the bolometric correction (BC) was obtained by employing the relation of Alonso et al. (1999). We adopted $T^{\odot}_{\rm eff}$ = 5770 K, $\log g_\odot$=4.44, and $M^{\odot}_{bol}$ = 4.72. We also adopt $\log M/M_\odot$ =

Table 1

Coordinates (J2000) and general characteristcs of the two clusters under study from Harris Database (Harris 2003).

Cluster	R.A.	Dec.	$R_{\odot}$ [Kpc]	R_{gc} [Kpc]	E(B−V)	V_{BH}
Arp 2	19 28 44.1	-30 21 14	28.6	21.4	0.08	18.13
Ter 8	19 41 45.0	-34 00 01	26.0	19.1	0.12	17.95

Table 2

Coordinates (J2000), magnitudes, colors, temperatures from colors and stellar parameters of the program stars.

Cluster	Star	R.A.	Dec.	V	B−V	V−K	T_{BV}	T_{VK}	T_{eff}	v_{turb}	log g
Arp 2	436	19 28 44.1	-30 20 58	15.82	1.25	3.24	4399	4168	4250	1.9	0.8
Arp 2	826	19 28 44.8	-30 21 18	15.51	1.38	3.43	4199	4074	4200	1.8	0.7
Ter 8	305	19 41 37.1	-34 00 37	15.46	1.25	3.16	4450	4231	4450	2.5	1.0
Ter 8	325	19 41 45.3	-34 00 30	15.29	1.33	3.26	4299	4176	4250	2.3	0.8
Ter 8	483	19 41 44.6	-34 00 02	15.50	1.15	2.95	4499	4360	4450	2.0	1.0

Note.—Data from Buonanno et al. (1995), Ortolani & Gratton (1990) and 2MASS All-Sky Survey (Skrutskie et al. 2006). Calculated temperatures and stellar parameters in the last 5 columns.

Table 3

Partial list of Fe I and Fe II lines adopted in our study with the measured EWs.

Wavelenght	Ion	Ter8 305	Ter8 325	Ter8 483	Arp2 436	Arp2 826
4139.94	Fe I	-	99.4	67.3	100.1	-
4143.87	Fe I	-	-	-	-	-
4174.92	Fe I	111.0	150.8	117.6	-	-
4181.75	Fe I	113.6	142.5	107.4	148.9	140.0
4202.04	Fe I	-	-	-	-	-
4216.19	Fe I	-	-	136.5	-	-
4222.22	Fe I	-	130.4	96.1	-	-

Note.—Table 3 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

Table 4

Partial list of light and heavy elements lines adopted in our study with the measured EWs.

Wavelenght	Ion	Ter8 305	Ter8 325	Ter8 483	Arp2 436	Arp2 826
6300.30	O I	13.0	15.0	14.0	16.0	18.0
4730.03	Mg I	-	-	-	27.4	-
5528.42	Mg I	131.2	145.1	129.1	-	-
5711.09	Mg I	28.7	55.5	38.0	79.1	83.8
5665.56	Si I	-	-	-	-	17.3
5684.55	Si I	-	-	17.2	17.5	-
5690.43	Si I	-	-	-	-	17.7

Note.—Table 4 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

−0.097, following the discussion in Kraft & Ivans (2003).

We estimate an uncertainty of 150 K on the effective temperature, of 0.2 km· s^{-1} on the microturbulent velocity and of 0.1 dex on the $\log g$.

4. Results and Discussion

Our results for the elemental abundances of the five stars are presented in Tables 5 and 6. In our study we adopt the solar abundances assembled by Lodders (2003), with the exception of iron for which we adopt the value of 7.51. In the tables are also listed the number of lines (#) measured for each element and the standard deviation from the mean elemental abundance and the uncertainty on the mean value for each element in each cluster (σ_{mean}). This uncertainty is calculated as the square root of the sum of the variance determined for each star, if the number of lines of the element is greater or equal to 5. If the number of lines is less than 5 we adopt as uncertainty on the elemental abundance the mean error detemined for Fe I. The M/Fe ratios have been calculated using Fe I for neutral species and Fe II for ionized species, with the exception of O for which we used Fe II since both Fe II and O I are the dominant ionization species.

In the figures that follow the elemental abundances we obtained for Arp 2 and Ter 8 has been compared with the abundances determined for M54 (Brown, Wallerstein & Gonzalez 1999), Ter 7 (Tautvaisiene et al. 2004), Pal 12 (Cohen 2004), Sgr field stars (Smecker-Hane & McWilliam, 2002; McWilliam et al. 2003; McWilliam & Smecker-Hane 2005a,b; Sbordone et al. 2007). We rescale M 54, Ter 7 and Pal 12 abundances to the solar abundaces we have adopted in order to compare them on the same scale.

4.1. The Iron abundance

In Tables 5 and 6 are listed the Fe I and the Fe II values with their uncertainties. It shows that, for Ter 8, the mean Fe I is 0.07 dex less than the mean Fe II abundance, while for Arp 2 we find a slightly higher difference, <[FeI/H]> − <[FeII/H]> is 0.12 dex. We adopt as metallicity of the clusters the average of the mean values of the neutral and ionized iron obtained for the stars under study. For Arp 2 we found [Fe/H]=−1.83±0.07 dex, Ter 8 is more metal-poor with [Fe/H]=−2.34±0.07 dex.

Comparing our results with previous studies we found, for Arp 2, a good agreement with Buonanno et al. (1995) value [Fe/H]=−1.84±0.25, while Da Costa & Armandroff (1995) value, [Fe/H]=−1.70±0.11, is more metal-rich. In the case of Ter 8, our value is much lower than Or-

Table 5
Elemental abundances of two stars in Arp 2.

[M/H]	Arp2 436	#	σ	Arp2 826	#	σ	<[M/H]>	<[M/Fe]>	σ_{mean}
$[O/H]$	-1.68	1	-	-1.67	1	-	-1.68	0.21	0.22
$[Mg/H]$	-1.28	2	0.03	-1.49	2	0.28	-1.39	0.38	0.22
$[Si/H]$	-1.51	6	0.06	-1.45	5	0.05	-1.48	0.29	0.08
$[Ca/H]$	-1.43	18	0.05	-1.39	16	0.06	-1.41	0.36	0.08
$[Ti/H]$	-1.63	31	0.03	-1.47	29	0.03	-1.55	0.22	0.04
$[TiII/H]$	-1.59	13	0.04	-1.51	18	0.05	-1.55	0.34	0.06
$[Cr/H]$	-1.93	4	0.04	-1.79	5	0.09	-1.86	-0.09	0.22
$[Mn/H]$	-2.31	4	0.15	-2.19	3	0.15	-2.25	-0.48	0.22
$[Fe/H]$	-1.79	83	0.02	-1.74	68	0.03	-1.77	-	0.04
$[FeII/H]$	-1.87	16	0.06	-1.91	9	0.03	-1.89	-	0.07
$[Co/H]$	-2.02	4	0.24	-1.80	6	0.25	-1.91	-0.14	0.22
$[Ni/H]$	-1.93	15	0.04	-1.68	13	0.04	-1.81	-0.04	0.06
$[Cu/H]$	-2.88	1	-	-2.51	2	0.23	-2.70	-0.93	0.22
$[YII/H]$	-2.03	2	0.09	-1.95	4	0.14	-1.99	-0.10	0.22
$[BaII/H]$	-1.68	1	-	-1.68	1	-	-1.68	0.21	0.22
$[LaII/H]$	-1.75	3	0.07	-1.67	3	0.09	-1.71	0.18	0.22
$[NdII/H]$	-1.89	3	0.10	-1.83	2	0.03	-1.86	0.03	0.22
$[EuII/H]$	-1.50	1	-	-1.38	1	-	-1.44	0.45	0.22

tolani & Gratton (1990) result, [Fe/H]=-1.81 ± 0.10, Montegriffo et al. (1998), -2.00 ± 0.10, and Da Costa & Armandroff (1995), -1.99 ± 0.08, values. These two clusters are the most metal-poor in the Sgr system and they both present a blue horizontal branch.

4.2. O and light elements

The oxygen abundances have been determined using the [O I] 6300.31 line. The oxygen abundances in the two clusters show similar differences. [O/Fe] values for our two Arp2 stars are 0.19 dex and 0.24 dex, while for Ter 8 stars they vary between [O/Fe]=0.44 dex and [O/Fe]=0.79 dex. In Figure 1 is shown the oxygen trend with the metallicity of the Sgr globular clusters (filled circles) and field stars from different studies: Smecker-Hane & McWilliam, (2002); McWilliam & Smecker-Hane (2005a) abundances are the open circles, while Sbordone et al. (2007) values are the open squares. As we can see four clusters and the field stars oxygen abundances present a decreasing trend with increasing metallicity. The Ter 8 oxygen value is overabundant, [O/Fe]=0.71 dex, compared to the other clusters, however considering its uncertainty of 0.17 dex this result is not so far above the oxygen plateau around 0.3 dex in the metallicity range between -2.5 dex and -1 dex.

We used the average of Mg, Si, Ca and Ti abundances as α-elements abundance. We obtained for Arp 2 a value of [α/Fe]=0.31 ± 0.11 dex, while for Ter 8 [α/Fe]=0.37 ± 0.14 dex. The α-elements abundance trend with the metallicity is shown in Fig. 2, where the Sgr globulars are the filled circles, the Sgr field star abundances from Smecker-Hane & McWilliam, (2002); McWilliam & Smecker-Hane (2005a) are the open circles and the ones from Sbordone et al. (2007) are the open squares. The α/Fe ratio decreases as the metallicity increases from a plateau around 0.3 dex to -0.2 dex. This is in agreement with what is shown by Gratton et al. (2004) in their figure 4, for the Galactic globular clusters and field stars.

4.3. Iron-peak elements

The Fe-peak elements we observed in Arp 2 and Ter 8 are Cr, Mn, Co, Ni and Cu. Ni, Co and Cr have abundances around the solar value while Mn

Table 6

Elemental abundances of three stars in Terzan 8.

[M/H]	Ter8 305	#	σ	Ter8 325	#	σ	Ter8 483	#	σ	<[M/H]>	<[M/Fe]>	σ_{mean}
$[O/H]$	−1.65	1	-	−1.72	1	-	−1.61	1	-	−1.66	0.71	0.17
$[Mg/H]$	−1.78	2	0.08	−1.87	1	-	−1.62	2	0.08	−1.76	0.61	0.17
$[Si/H]$	−1.85	2	0.02	−2.08	3	0.05	−1.84	4	0.25	−1.92	0.45	0.17
$[Ca/H]$	−2.05	13	0.05	−2.08	18	0.05	−2.09	15	0.04	−2.07	0.30	0.08
$[Ti/H]$	−2.25	4	0.10	−2.17	17	0.06	−2.33	4	0.16	−2.25	0.12	0.17
$[TiII/H]$	−2.02	13	0.03	−1.87	19	0.03	−2.03	18	0.05	−1.97	0.40	0.07
$[Cr/H]$	-	-	-	−2.52	2	0.11	-	-	-	−2.52	−0.15	0.17
$[Mn/H]$	−2.79	1	-	−2.66	2	0.01	−2.60	1	-	−2.68	−0.31	0.17
$[Fe/H]$	−2.44	48	0.03	−2.26	78	0.02	−2.42	54	0.02	−2.37	-	0.04
$[FeII/H]$	−2.44	13	0.04	−2.16	15	0.04	−2.31	14	0.04	−2.30	-	0.07
$[Co/H]$	−2.25	1	-	−2.31	5	0.11	-	-	-	−2.28	0.09	0.17
$[Ni/H]$	−2.45	8	0.04	−2.33	15	0.04	−2.52	5	0.09	−2.43	−0.06	0.11
$[Cu/H]$	−3.27	1	-	-	-	-	−3.38	1	-	−3.33	−0.96	0.17
$[YII/H]$	−2.77	4	0.16	−2.57	5	0.07	−2.45	3	0.04	−2.59	−0.29	0.17
$[BaII/H]$	−2.46	2	0.02	−2.38	2	0.03	−2.34	1	-	−2.39	−0.09	0.17
$[LaII/H]$	-	-	-	−2.19	1	-	-	-	-	−2.19	0.11	0.17
$[NdII/H]$	-	-	-	−2.20	3	0.12	−2.09	3	0.05	−2.15	0.15	0.17
$[EuII/H]$	<-0.70	-	-	<-0.85	-	-	<-0.85	-	-	<-0.80	<1.48	

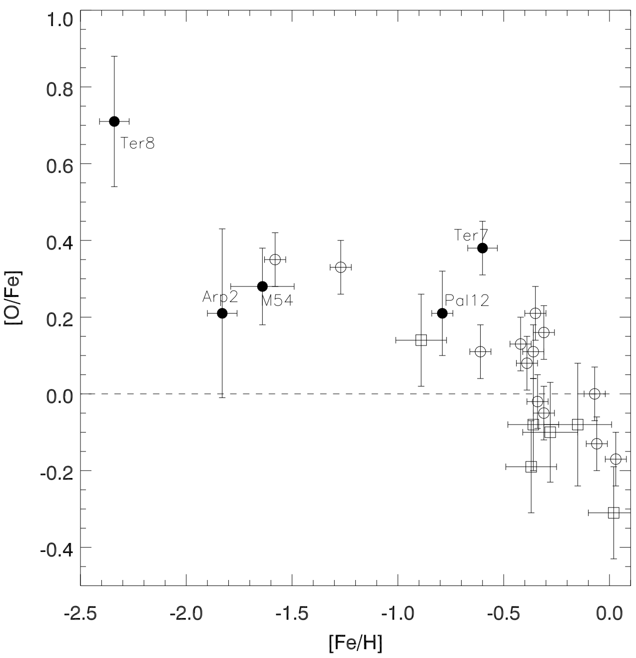


Fig. 1.— Oxygen trend with metallicity of the Sgr globular clusters, filled circles, and Sgr field stars from Smecker-Hane & McWilliam, (2002); McWilliam & Smecker-Hane (2005a), open circle, and from Sbordone et al. (2007), open squares.

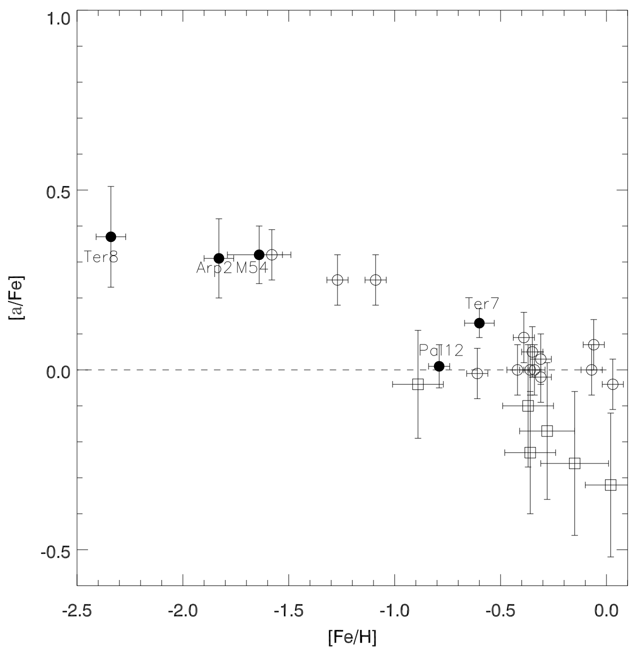


Fig. 2.— α-elements trend with metallicity of the Sgr globular clusters, filled circles, and Sgr field stars from Smecker-Hane & McWilliam, (2002); McWilliam & Smecker-Hane (2005a), open circle, and from Sbordone et al. (2007), open squares .

and Cu are underabundant with average values [Mn/Fe]=-0.48 and [Cu/Fe]=-0.93 dex for Arp 2 and [Mn/Fe]-0.31 and [Cu/Fe]=-0.96 dex for Ter 8.

In Fig. 3 (top) is shown the Ni trend with the metallicity for the Sgr. The Ni abundances are around the solar value for the globular clusters, while Sbordone et al. (2007) results for the Sgr field stars are distributed on a plateau around -0.4 dex. There is no clear indication of a trend. In the bottom panel are presented Cu abundances for four of the Sgr clusters, filled circles, and the Sgr field stars from McWilliam & Smecker-Hane (2005b); Sbordone et al. (2007), open circles and open squares, respectively. The value for M 54 wasn't available in the literature. All the clusters show an underabundant value of Cu, but Ter 8 and Arp 2 values are particularly low. There is no clear indicaton of a trend with metallicity but it seems to follow the results of Simmerer et al. (2003) for the Galactic globulars and of Mishenina et al. (2002) for the Galactic field stars. We also compare the Sgr Cu abundances with the following relation for Galactic globulars and field stars: [Cu/Fe]=0.38[Fe/H]+0.15 (McWilliam 1997). Ter 8 abundance lies at 1.5σ from the curve, while Arp2 and Pal 12 values are at 2.5σ. All the abundances obtained by Sbordone et al. (2007) for the Sgr field stars are beyond 3σ from the curve along with half of the stars analysed by McWilliam & Smecker-Hane (2005b). We also note that, comparing Ni with Cu abundances, Ter 7 is the only cluster that show similar values while for the others Cu has always lower value, with differences between 0.3 and 0.9 dex.

Our Mn results for Arp 2 and Ter 8 (-0.48 dex and -0.31 dex, respectively), along with the values of the other Sgr clusters and the Sgr field stars from McWilliam et al. (2003), are in good agreement with the trend shown by Gratton et al. (2004) in their figure 3 for the Galactic globulars and field stars.

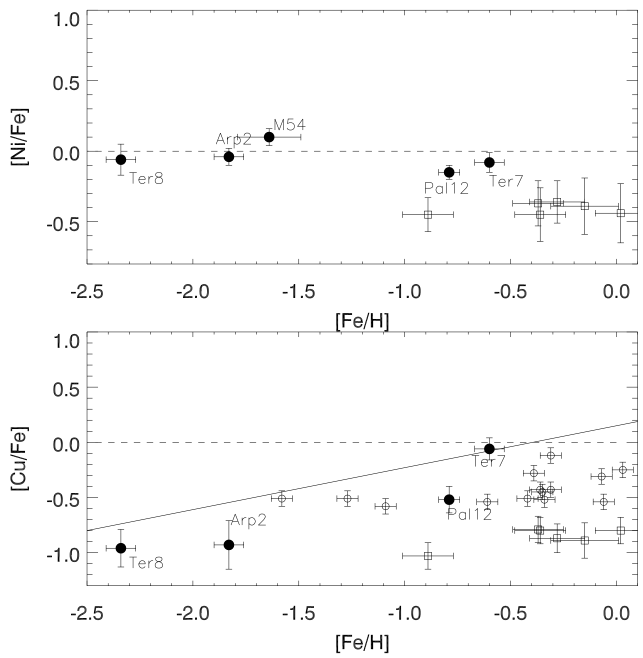


Fig. 3.— Nickel (top) and Copper (bottom) trends with metallicity of the Sgr globular clusters, filled circles, and Sgr field stars from McWilliam & Smecker-Hane (2005b), open circle, and from Sbordone et al. (2007), open squares. The long-dashed line is the relation from McWilliam (1997) for Galactic globulars and field stars.

4.4. Heavy elements

The s-process elements we observed are Y, La, Ba and Nd, while our only r-process element is Eu. In the case of Ter 8 we obtained the La abundances for only one star (325) with only one line, while we estimate an upper limit for Eu, since it was not possible to estimate an abundance because the 6645.13 line was too weak in the spectrum of all three stars. The Eu/Fe and Eu/La+Ba ratios for the Sgr GCs are plotted in Fig. 4 (filled circles), along with the results from Smecker-Hane & McWilliam, (2002); McWilliam & Smecker-Hane (2005a) for the Sgr field stars (open circles).

The Y abundances are below the solar value for Arp 2 and Ter 8, and, considering also the other Sgr clusters and the Sgr field stars, they do not present a clear trend with metallicity. They seem to be in agreement with Pritzl et al. (2005) results for Galactic globulars and field stars. On the other hand, Ba+La abundance is overabundant for Arp 2, reaching a value of [Ba+La/Fe]=0.20 dex, while Ter 8 Ba/Fe ratio is just above zero. Considering the whole system of globular in the Sgr galaxy, it seems that there is a slightly increasing trend with increasing metallicity. The metal-poor clusters abundances are in agreement with the results found by Pritzl et al. (2005).

The Nd/Fe ratios are slightly above the solar value with result of 0.03 dex for Arp 2, and 0.15 dex for Ter 8.

Eu abundances show a flat trend with metallicity around 0.5 dex for the Sgr system, well in agreement with the values presented by Gratton et al. (2004) in their figure 6 for the Galactic globulars. We observe also an increasing and then decreasing trend with increasing metallicity for the Eu/Ba,La ratio, in agreement as well with Gratton et al. (2004) results. This may be due to an increasing contribution by the r-process to Ba and La at low metallicity.

4.5. Elemental trends with age

In Fig. 5, 6 and 7 are shown the trends with age of iron, oxygen and α-elements, light and heavy s-process elements and europium. The globular clusters and the field stars of the Sgr system in Fig. 6 and 7 are represented as follow: Ter 8 with open stars, M 54 with filled circles, Arp 2 with filled stars, Ter 7 with filled triangles, Pal 12 with upside-down triangles and Sgr field stars with filled squares. We adopted as ages of the clusters the results presented in: Carraro, Zinn & Moni Bidin, (2007) for Whiting 1, Harris (2003) for the other clusters.

The metallicity increases as the age decreases, as can be seen in Fig. 5. The globular clusters in the Sgr system can be divided in two distinct groups: young and relatively metal-rich (Ter 7, Pal 12 and Whiting 1) and old and metal-poor (M 54, Arp 2, Ter 8).

Figure 6 shows the trends of oxygen and α-elements abundances with age. The α/Fe ratios decreases with decreasing age from a plateau around 0.3 dex for the globular clusters to a value slightly below solar for the Sgr field stars. Oxygen abundances have a behaviour similar to the α-elements, i.e. decreasing with a decreasing age and reaching a solar value for the field stars, but

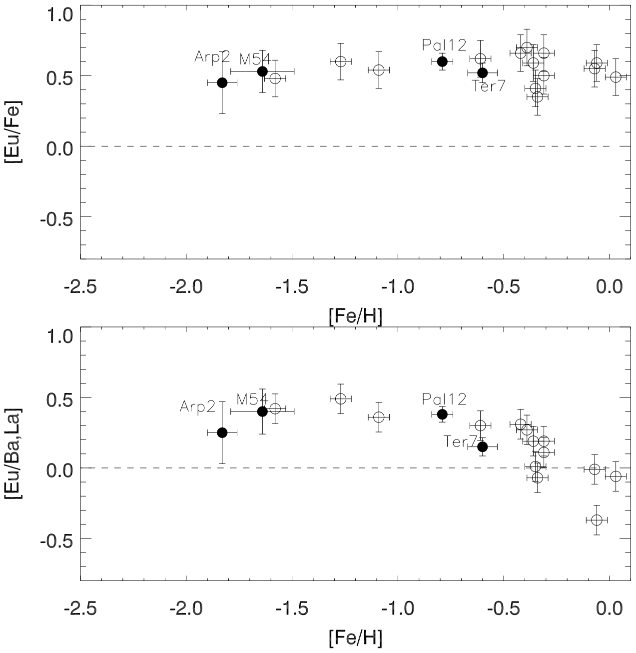


Fig. 4.— Europium (top) and Europium/heavy s-process elements (bottom) trends with metallicity of the Sgr globular clusters, filled circles, and the Sgr field stars from Sbordone et al. (2007), open circles. We didn't include the maximum limit determined for Ter 8, since being really overabundant is not particularly meaningful.

for Ter 8 value which present a difference from the plateau of +0.3 dex.

In Fig. 7 are show the trends of s-process and r-process elements, divided as follow: light s-process elements Y and Zr (ls), heavy s-process elements La and Ba (hs) and Eu, as the only r-process elements (R). The ls abundances present a flat trend around −0.2 dex with age, with the exception of Ter 7, which has a higher value at 0.02 dex. On the other hand, hs abundances show a flat trend around 0.3 dex with increasing age until 11 Gyr (Arp 2), after we can see a drop in the abundance, with the two oldest clusters in Sgr presenting values around solar. Eu abundances show a plateau around 0.5 dex, but we cannot say anything about Ter 8 since it was not possible to measure Eu in any of its stars.

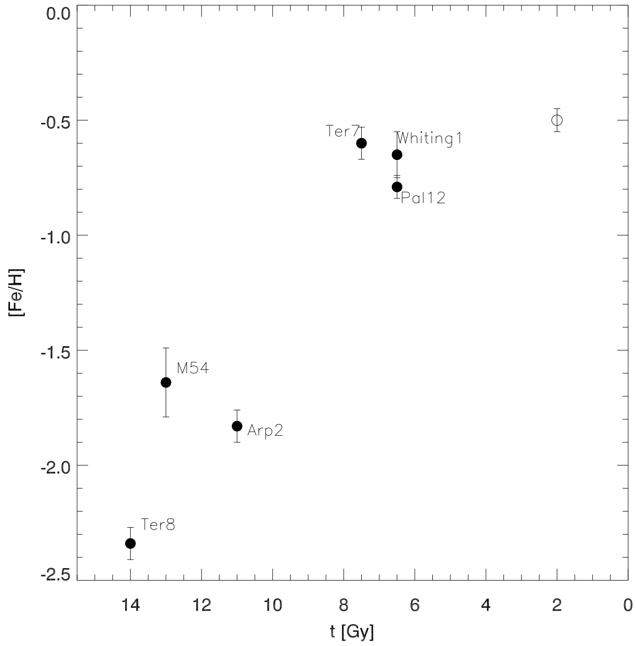
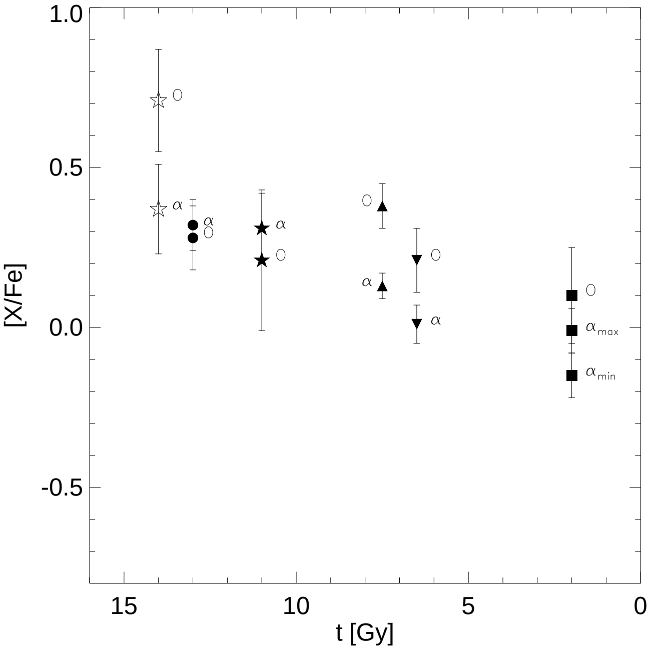


Fig. 5.— Iron abundance trend with the age of the Sgr globular clusters, filled circles, and Sgr metal-rich field stars, open circle.

5. Summary and Conclusions

We extended the inventory of metallicity and other elemental abundances of the Sgr globular clusters, analysing, for the first time, high resolution spectra of red giant stars in Ter 8 and Arp 2. We find for Arp 2 [Fe/H]=-1.83 ± 0.07, while for Ter 8 [Fe/H]=-2.34 ± 0.07. Arp 2 result is in good agreement with previous studies that estimate the metallicity of this cluster from CM diagrams and Ca II triplet, while Ter 8 is more metal-poor than previously determined. Other elements usually of interest show the following results. For oxygen we obtain [O/Fe]=0.71 ± 0.17 for Ter 8 and [O/Fe]=0.21 ± 0.22 for Arp 2. For the α-elements (Mg, Si, Ca, Ti) the mean values are 0.37 ± 0.14 dex for Ter 8 and 0.31 ± 0.11 for Arp 2. These values are not too different from the Galactic globular clusters at a similar [Fe/H] value. The heavy s-process elements Ba, La and Nd show no excesses in Ter 8 and in Arp 2. Our only r-process element, Eu, shows an excess of 0.45 dex in Arp 2, in agreement with the results found for the other Sgr clusters. We were not able to determine an



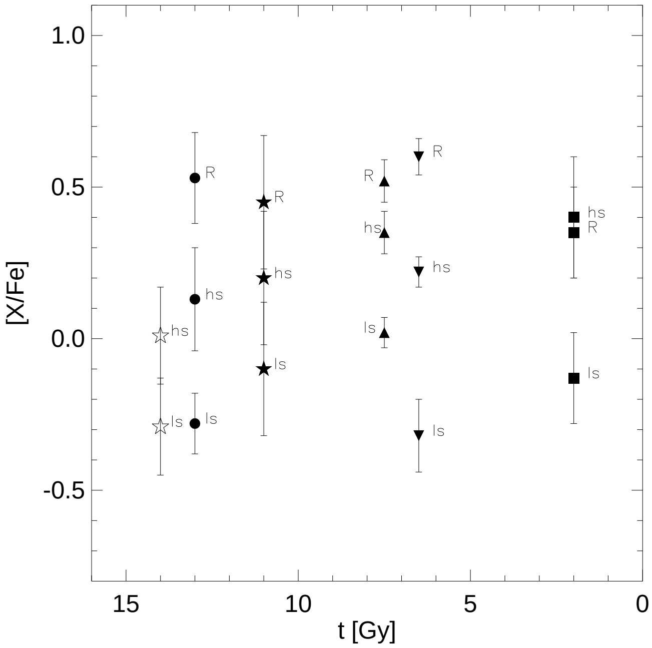


Fig. 6.— Light element abundances (O, α) trends with the age of the Sgr globular clusters and field stars. Symbols: open stars (Ter 8), filled circles (M 54), filled stars (Arp 2), filled triangles (Ter 7), upside-down triangles (Pal 12) and filled squares (Sgr field stars).

Fig. 7.— Heavy element abundances (ls=Y+Zr, hs=La+Ba, R=Eu) trends with the age of the Sgr globular clusters and field stars. Symbols: open stars (Ter 8), filled circles (M 54), filled stars (Arp 2), filled triangles (Ter 7), upside-down triangles (Pal 12) and filled squares (Sgr field stars).

abundance of Eu for Ter 8.

Considering all the globular clusters in the Sgr system and also young field stars, we find a trend with age for Fe, O and the α-elements. While iron increases with decreasing age, both oxygen and α-elements, relative to iron, decrease with decreasing age. Light s-process elements, heavy s-process elements and Eu present, on average, a flat trend with age around -0.2 dex, 0.3 dex and 0.5 dex, respectively. Although the La-Ba trend shows a drop to values around solar for the two oldest clusters of the system.

Our elemental abundances along with the results from previous studies of the other Sgr globular clusters show that there are similarities with the Galactic globulars (α-elements, Ni, Cu, Mn, s-process elements and Eu). We will further discuss the comparison with an analogous system, the Fornax dwarf galaxy, in a following paper.

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