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Report On: SEGUE-1: An Unevolved Fossil Galaxy from the Early Universe - Frebel, Simon & Kirby

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1. BACKGROUND

When studying the early universe scientists commonly seek out stars that were formed early on in the universe. Locked inside these stars are clues about the physical and chemical conditions that led to the formation of the star. With this information scientists can better understand physical and chemical conditions in the early universe as a whole. One way to identify these ancient stars is by their relatively low heavy metal ($Z \geq 24$) content compared to lighter elements, such as α-process elements and hydrogen.

Lighter α-elements are synthesized within massive stars and are released into the interstellar medium (ISM) once these massive stars undergo core-collapse supernova upon running out of helium. The lifetime of these massive stars, from their nucleosynthesis to their core collapse supernova event takes place in a very short time frame, often less than 10^6 yrs. Heavier elements, the paper specifically measures iron (FeI and FeII), strontium, and barium abundance, are synthesized and released later in the universe timeline. Iron is mainly synthesized during Type Ia supernovae events. These events occur when a white dwarf in a binary star system reaches the critical Chandrasekhar limit and explodes into a supernova event. These white dwarf systems have much longer lifetimes of around 10^8 yrs. Strontium and Barium, unlike the α-elements and iron do not form via normal fusion but only during neutron capture nucleosynthesis. Neutron capture nucleosynthesis happens during r-process supernovae and during the nucleosynthesis of population III supermassive stars. During each of these neutron capture nucleosynthesis events approximately $10^{-4}M_{\odot}$ of neutron capture elements are released into the ISM.

The low metallicity of early stars, specifically stars with high [α/Fe] and low [Fe/H] values, indicate that their nucleosynthesis occurred during a period after the first round of core-collapse supernovae but before large numbers of Type Ia supernovae events. For decades scientists looked early stars in the halo of the Milky Way to study the early universe. These Milky Way (MW) Halo stars have [Fe/H] values of < -1.0.

In the past decade efforts such as the Sloan Digital Sky Survey (SDSS) have uncovered a plethora of very dim dwarf spheroidal (dSph) galaxies and ultra faint dwarfs. These dSph and ultra faint dwarfs have total luminosities in the range of $10^5 L_{\odot} \lesssim L \lesssim 10^7 L_{\odot}$ and $L \lesssim 10^5 L_{\odot}$, respectively, which contain stars with [Fe/H] values of ~ -2.5. With the use of medium resolution spectroscopy scientists recently uncovered a moderate population of super low metal stars with [Fe/H] values < -3.0 within ultra fain dwarfs. Within the same systems scientists did not find any stars with [Fe/H] > -1.0. In this population one galaxy, SEGUE-1, stood out from the rest. SEGUE-1's population of stars show increasing metallicity, in the form of α-elements, but do not exhibit decreasing [α/Fe] ratios. This would indicate that the star formation phase in SEGUE-1 occurred before most, if not all, Type Ia supernovae events. This also indicates that there was likely only one star formation phase within the galaxy.

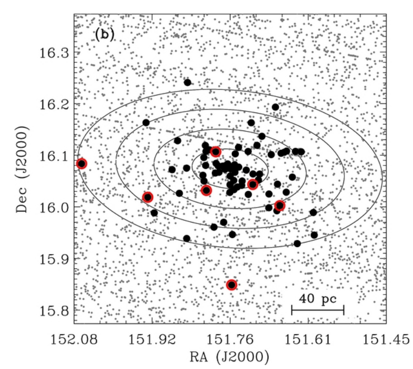

Figure 1. Black dots show the location of surveyed stars within SEGUE-1. The seven dots with red borders indicate the six stars observed in this study as well as one star that was observed in a previous study

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2. NOVELTY AND METHODS

The authors of this paper made new spectrography measurements of six stars within SEGUE-1, highlighted in figure 1, using the Magellan/MIKE and Keck/HIRES spectrographs focusing on the chemical enrichment process to better understand star formation in the very early universe. The six stars that were chosen were the brightest stars in SEGUE-1 which allowed for high resolution spectrography. Using the spectrographs the authors collected data on the abundance of iron (Fe I and Fe II), carbon, α-elements, and neutron-capture elements. The authors then compared this data to stars found in classical dSph galaxies and the Milky Way halo. The detail for the measurements of each of the stars are listed in table 1. Due to the dim nature of the six starts the signal to noise ratio (S/N) was only moderate with values between 20 and 50

Star	α (J2000)	δ (J2000)	UT dates	slit	t_{exp} hr	g mag	$E(B-V)$ mag	S/N 5300 Å	S/N 6000 Å
SDSS J100714+160154	10 07 14.6	+16 01 54.5	2011-03-10	1.0″	5.5	18.86	0.027	35	45
SDSS J100710+160623	10 07 10.1	+16 06 23.9	2011-03-13/22	1.0″	7.3	19.20	0.026	28	45
SDSS J100702+155055	10 07 02.5	+15 50 55.3	2011-03-11/12	1.0″	9.2	18.50	0.033	35	46
SDSS J100742+160106	10 07 42.7	+16 01 06.9	2010-04-01	1.15″	3.6	18.60	0.027	20	30
SDSS J100652+160235	10 06 52.3	+16 02 35.8	2010-03-07/08/18/19/23/24	1.0″	15	18.89	0.029	42	50
SDSS J100639+160008	10 06 39.3	+16 00 08.9	2010-03-18/19/22, 2010-05-08/09	0.7″	8	19.48	0.031	26	33

NOTE. — The S/N is measured per $\sim 33\,\mathrm{m\AA}$ pixel (MIKE spectra) and $\sim 20\,\mathrm{m\AA}$ pixel (HIRES spectrum).

Table 1. Observing details for the six measured stars

3. RESULTS AND DISCUSSION

With the high resolution spectrograph data the authors were able to extrapolate the abundances of the various elements inside the stars. In figure 2 the authors plotted the spectra of the 6 stars compared to two other known stars, the ultra low metal $CD-38°245$ and the very bright, and much younger, Arcturus. The plots are listed in ascending order of metallicity from top to bottom.

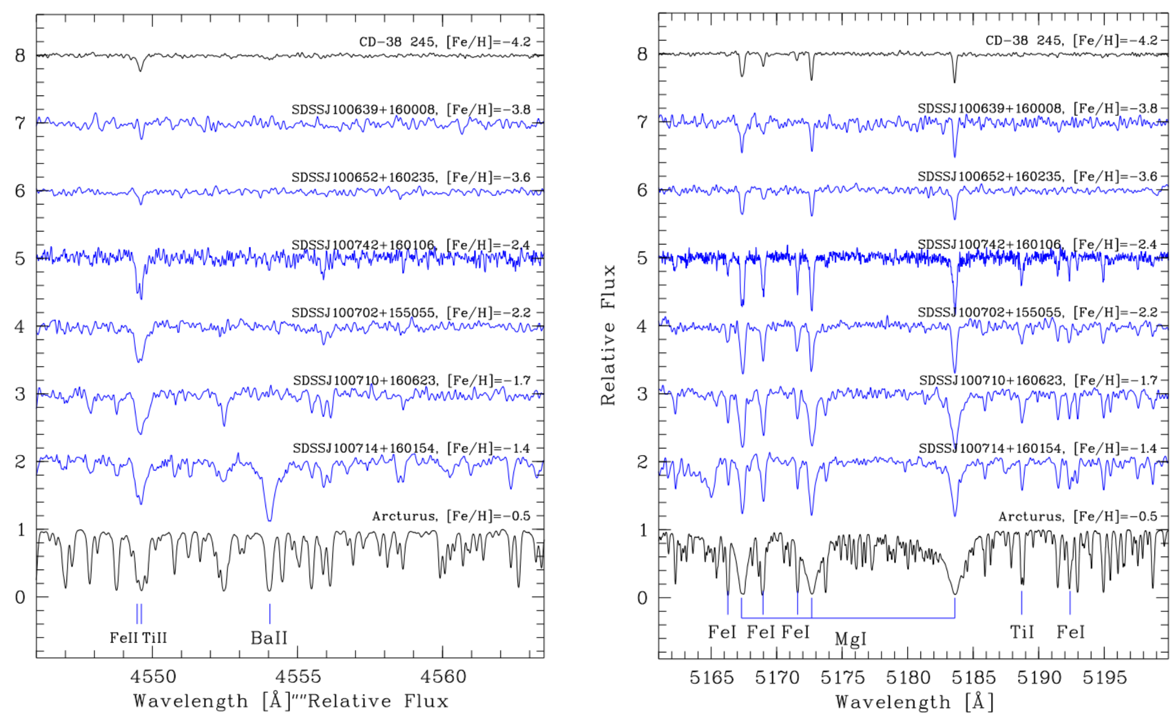


Figure 2. Spectra of the six stars, in blue, bracketed by $CD-38°245$ at the top and Arcturus at the bottom. the spectral lines of the elements are labeled at the bottom with the corresponding ranges of wavelengths.

In the three lowest metallicity stars (The top 3 blue lines) the abundance of iron (both Fe I and Fe II) is mostly indistinguishable from the noise in the measurements. In the 3 stars with observable amounts of iron there was no correlation between increasing iron abundance and increasing metallicity, indicated by the appearance of more spectral lines as the metallicity increases. This indicated that there was at most one or maybe two Type Ia supernova that enriched SEGUE-1's birth cloud. This contrasts the trend found in younger galaxies where there would be a clear trend in increasing metallicity and increasing iron abundance in the stellar population as they evolve alongside energetic supernovae events.

Using the spectrography data the authors also plotted in figure 3 the abundance ratios [X/Fe] relative to the iron abundance [Fe/H] for the elements that were measured. The dashed line at [X/Fe] = 0 indicates the ratio of the element in our Sun with positive values meaning higher abundance and lower values indicating lower abundance, on a log scale. Notice that in all of the SEGUE-1 stars the abundance of α-elements such as Mg, Si, Ca, and Ti, are all above that of the Sun. Elements that are synthesized by other processes that occur later in the timeline such as Al, Cr, and Mn, have consistent abundances lower than that of the Sun.

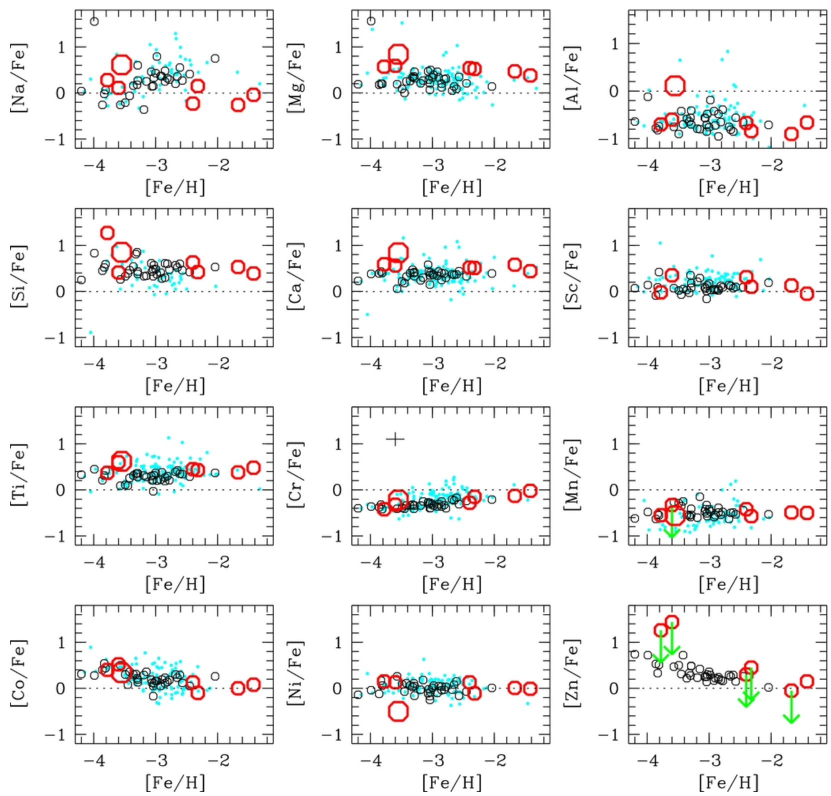


Figure 3. The abundance ratios [X/Fe] compared to the metallicity [Fe/H] of each of the elements that were measured with the spectroscopes. The six small red circles represent the SEGUE-1 stars measured in this article. The larger red circle is a SEGUE-1 star measured in a previous paper. The small black and blue circles represent MW halo stars measured from previous papers.

Another indication of SEGUE-1's age is the enhanced [α/Fe] values found in all the measured stars that are consistent with each other and the initial birth cloud. Figure 4 shows enrichment behavior plots, [Fe/H] vs. [α/Fe], for MW Halo stars, classical dSph galaxy stars, and SEGUE-1 stars. The top left plot in fig. 4 shows the general trend of how classical dSph galaxies and MW Halo stars will appear on the enrichment behavior plot. The top right plot shows the spread of MW Halo stars which have a plateau in the [α/Fe] until [Fe/H] ≈ -1 at which point the [α/Fe] approaches 0 where [Fe/H] is almost at 0. The bottom plot of fig. 4 shows the enrichment behavior plot for dSph galaxy stars (small black circles), the measured stars from SEGUE-1 (large red filled in circles from this article, and red crosshair from previous papers), and some other candidate stars (blue square, green circles, and magenta circles). In this bottom plot we can see that the classical dSph stars and some of the other candidate stars have a plateau but do slope down towards the [α/Fe] = 0 line. On the other hand, the 6 measured stars from SEGUE-1 all reside around the [α/Fe] =

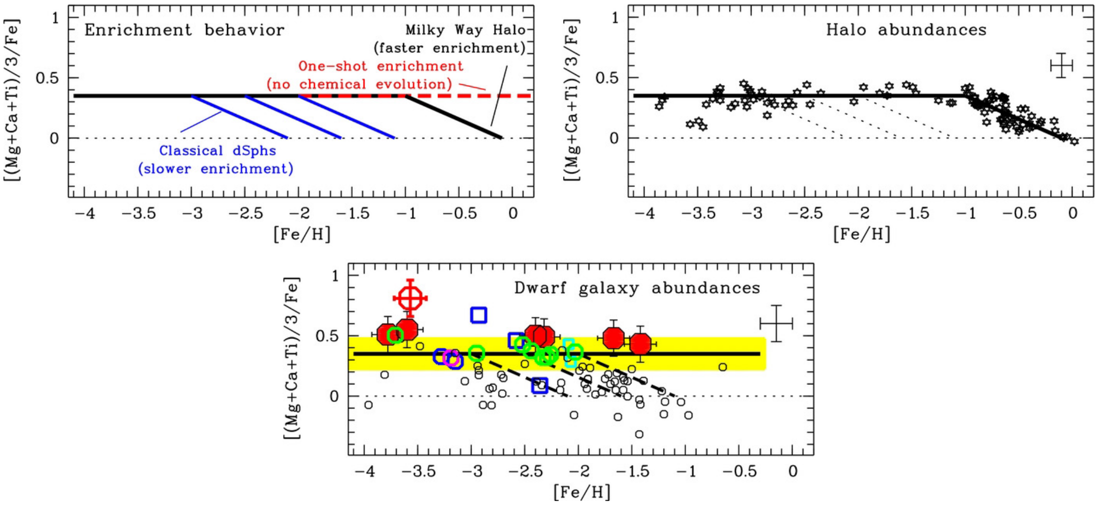


Figure 4. Enrichment Behavior plots for MW Halo stars, the six measured SEGUE-1 stars, a previously measured SEGUE-1 star, and stars from other classical dSph galaxies. These plots show the relationship between α-element abundance (specifically Mg, Ca & Ti) ratios [α/Fe] and the metallicity [Fe/H] within the stars.

0.5 line, even past the point where MW Halo starts to slope down on the [Fe/H] axis. The consistent [α/Fe] values in SEGUE-1 stars suggest that after the initial enrichment of the birth cloud there were no other enrichment events, such as type Ia supernovae, in SEGUE-1.

The final indicator of SEGUE-1's old age is the low abundance of neutron-capture elements in SEGUE's non-binary system stars. Outside of binary star systems neutron-capture elements are synthesized in events such as r-process events and population III supermassive stars undergoing s-processes nucleosynthesis Truran et al. (2002). Population III stars are believed to exist in the very early universe but have not been directly observed while r-process events can be observed from mergers of neutron stars or type II supernovae Truran et al. (2002). The authors looked specifically at Sr and Ba for neutron capture elements. In figure 5 we see neutron-capture element abundances [Sr/H] and [Ba/H] for MW Halo stars, classical dSph galaxy stars, and SEGUE-1 stars. The spread is quite wide with a number of stars having neutron-capture element abundances equal to, and even greater, than the Sun as well as stars with neutron-capture element abundances almost to [X/H] = -6. We can see that one of the SEGUE-1 stars observed in this study has a neutron-capture element abundance within [X/H] $\pm$0.5 of our Sun while the other five observed in this study, as well as the one observed in a previous study, much lower at around [Sr/H] ≈ -5 and [Ba/H] ≈ -4.5. The total abundance of neutron capture elements within the lower six SEGUE-1 stars, five from this study plus one from the previous study, total to less than $\sim 10^{-7} M_{\odot}$ for each element, which is orders of magnitude lower than the $\sim 10^{-4} M_{\odot}$ released by a single neutron-capture element producing event. This low abundance indicates that aside from the neutron-capture elements released in the very early universe no other neutron-capture element synthesis occurred within SEGUE-1.

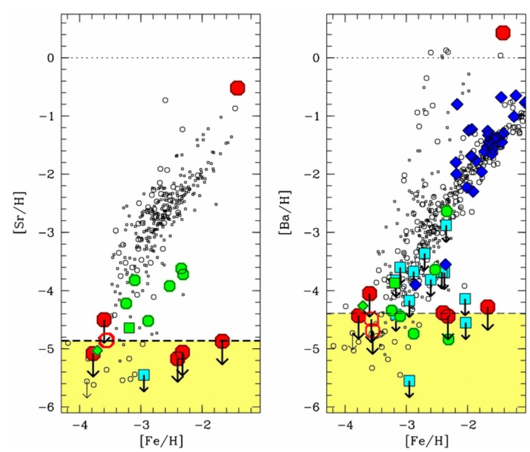


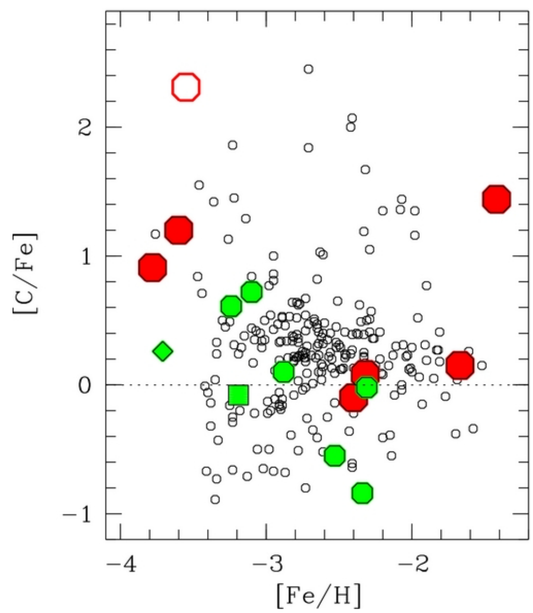
Figure 5. Neutron-capture element abundance [Sr/H] and [Ba/H] within the six observed SEGUE-1 stars in this study (filled in red circles), one previously studied SEGUE-1 star (empty red circle), MW Halo stars (small black dots), and the other candidate stars (cyan, green, and blue markers). The light dotted line at [X/H] = 0 represents the abundance of the respective element within the sun and the bold dashed line represents the average abundance of the respective element within the observed SEGUE-1 stars.

In addition to confirming the age of the SEGUE-1 galaxy the authors also made some discoveries regarding chemical composition of early stars. Figure 6 shows the carbon abundance [C/H] for the observed SEGUE-1 stars as well as other candidate stars and MW Halo stars. We can see that 3 of the SEGUE-1 stars observed in this paper, as well as the one observed previously show enhanced levels of carbon. These carbon enhanced stars are observed to be the the four lowest mass stars out of the seven SEGUE-1 stars and indicates the importance of carbon in the enrichment process of early stars.

Additionally the authors observed a large range of iron abundance within the SEGUE-1 stars spanning over two orders of magnitude between [Fe/H] = -1.4 to [Fe/H] = -3.8. this large range in combination with the relative consistency in metallicity of the stars indicates that the distribution of iron within the intergalactic and interstellar medium was inhomogeneous in the early universe, around the time of star formation within SEGUE-1

4. FUTURE WORK

Future research points to observing a larger portion of SEGUE 1 stars. The six stars that were observed in this paper, plus the star observed in a previous study, were deemed to be the brightest in the ultra faint dwarf galaxy with magnitudes of $\sim$ 19 mag. These seven SEGUE-1 stars were the only ones that scientists were able to capture sufficiently high resolution spectra for. These seven only represent a small sample



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