Sulphur, zinc and carbon in the Sculptor dwarf spheroidal galaxy

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2016

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

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The Local Group & stellar archaeology

Out of the many millions of galaxies in the Universe, a few dozen are of particular interest, due to their proximity to our Solar system. These galaxies belong to the Local Group, which is dominated in mass, by two giant spiral galaxies, the Milky Way and Andromeda, which are vastly outnumbered by dwarf galaxies of various sizes. The Milky Way has over 30 known dwarf galaxy satellites, see Fig. 1. Recently, there has been a surge in the discovery of new, usually very small and faint, dwarf galaxies, and more are expected to become known over the next few years.

All galaxies are made out of various amounts of dark matter, dust and gas, stars and their remnants. The stars form out of cold gas clouds, and in the course of their evolution create all the chemical elements in the Universe heavier than hydrogen and helium. Over time, many of these heavier elements, referred

Figure 1: All sky view of the Milky Way and some of its known satellite galaxies. Notice Sculptor (Scl) at the bottom of the figure (credit: H. Jerjen & ESO).
to as metals\(^1\), disperse into their surroundings, mostly via energetic supernova explosions. The subsequent generations of stars thus form from “enriched” gas with a fraction of these metals, that increases with time. Low-mass stars can have lifetimes comparable with the age of the Universe. The photospheres of these stars can remain mostly unchanged until the present day, and serve as ancient relics of early star formation, by retaining the chemical composition of their birth environment. Observing stars of different ages, therefore, provides a detailed insight into the chemical enrichment history of the galaxy in which they were formed.

Although photometry can be used to estimate the amount of metals, metallicities, of stars, for detailed and accurate chemical abundance analyses, spectra are needed. Each atomic or molecular species leaves a set of well defined spectral absorption lines in the stellar spectra, and the strengths of the lines depend on the abundance of the relevant elements, as well as the physical conditions of the star.

In our Milky Way and nearby dwarf galaxies, we can obtain high quality spectra for individual stars, of various ages. Thus we can study the chemical evolution in these systems across cosmic time, star by star. The different types of chemical enrichment processes, occurring over the lifetime of a galaxy, all have their unique chemical fingerprint. Studying the detailed chemical abundance patterns and ratios in stars of a galaxy, therefore gives and insight into the time scales and significance of the various physical processes involved in its chemical evolution.

The Local Universe is the only place where the time dependant properties of single galaxies can be measured from their beginnings to the present day. These kind of studies are directly complementary to the study of galaxies at higher redshifts, where it is possible to get large statistical samples with less detailed information available on each galaxy.

**Sculptor**

The main target of this thesis is the low surface brightness Sculptor dwarf spheroidal galaxy (dSph), see Fig. 2. Sculptor was one of the first Milky Way dwarf galaxy satellites to be discovered, in 1938 by the astronomer Harlow Shapley.

This galaxy is located in the southern hemisphere, at high Galactic latitude, see Fig. 1. Sculptor has a total mass of \(M_{\text{tot}} = 3.4 \cdot 10^8 \, M_\odot\) (approximately \(\sim 1/3000\) of the mass of the Milky Way), and is at a distance of \(86 \pm 5\) kpc (\(\sim 280,000\) light years) from the Solar system. At this distance, only the brightest stars, the tip of the red giant branch, are observable with high-resolution

\(^1\) In astronomy, all elements heavier than He are simply called metals.
spectroscopy, which is necessary to measure detailed and accurate chemical abundances in stars.

The stars in Sculptor are predominantly old. The majority of stars was formed more than 10 billion years ago, and no stars have formed recently. Studying stars in this dwarf galaxy therefore gives us a clear view back to early star formation and chemical enrichment processes, in what is one of the most common type of galaxy in the Universe. In stellar archaeology, iron is typically used as a proxy for metallicity, and the typical star in Sculptor has $[\text{Fe}/\text{H}] \approx -2$ which corresponds to $1/100$ of the iron value in the sun. The metallicity distribution of stars in Sculptor extends over a wide range, where the most metal-rich stars have $[\text{Fe}/\text{H}] \approx -1$ ($1/10$ of solar), while the most metal-poor stars observed to date have $[\text{Fe}/\text{H}] \approx -4$ ($1/10,000$ of solar).

Over the last 15 years or so, detailed chemical abundance measurements of individual stars in the Sculptor dSph have been carried out in increasing number and accuracy. This thesis aims to expand on existing work even further, by measuring sulphur (Chapter 3) and zinc (Chapter 4) in a sample of $\sim 90$ stars, as well as detailed chemical abundances of a very unique carbon-enhanced metal-poor (CEMP) star in this galaxy (Chapter 5).

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2 Chemical abundance ratios in astronomy are usually defined on a logarithmic scale where $[X/Y] = \log(N_x/N_y)_\ast - \log(N_x/N_y)_\odot$, and $N$ is the number of atoms for elements $X$ and $Y$ per $M_\odot$. On this scale, $[X/Y] = 0$ corresponds to the same abundance ratio as in the sun, $[X/Y] = -1$ is equal to $1/10$ of the solar ratio, $[X/Y] = -2$ to $1/100$, etc.
Sulphur & Zinc in Sculptor

Both the overall metallicities of stars, [Fe/H], and the more detailed chemical abundance patterns and element ratios are highly dependent of the chemical evolution history of the system in which they were formed. One clear example of this is the ratio of $\alpha$-elements (where the nucleus of the most abundant isotope is made up of $\alpha$-particles, i.e. two protons, and two neutrons) to iron. The $[\alpha/Fe]$ ratios are sensitive to the relative contribution of Supernovae Type II, the deaths of massive stars which explode after $\sim 10$ million years and produce large amount of $\alpha$-elements; and Supernovae Type Ia, which are induced by mass transfer onto a white dwarf, with longer time scales, $\sim 1−2$ billion years, and pollute their environment mostly with iron and other iron-peak elements (such as Cr and Ni).

Early in the chemical evolution of any system, the production and distribution of metals is dominated by Supernovae Type II, since they have relatively short time scales. The abundance ratios of $\alpha$-elements to iron are thus typically higher than in the solar neighbourhood, $[\alpha/Fe] > 0$. After 1-2 Gyr, when the Supernovae Type Ia start to contribute, polluting the environment with a lot of Fe compared to the $\alpha$-elements, the subsequent generations of stars show lower values of $[\alpha/Fe]$.

In Galactic halo stars, sulphur has been shown to behave like other $\alpha$-elements but until now, no comprehensive studies have been made of this element in stars of other galaxies. In this thesis, high-resolution spectra were used to determine sulphur abundances for 85 stars in the Sculptor dwarf spheroidal galaxy, covering the metallicity range $-2.5 \leq [\text{Fe/H}] \leq -0.9$ (see Chapter 3), and the result is shown in Fig. 3.

The sulphur abundances in Sculptor show the same behaviour as other $\alpha$-elements in that galaxy (such as Mg, Si, and Ca). At lower metallicities, $[\text{Fe/H}] \leq -2$ (typically the oldest stars), the abundances are consistent with
a plateau at $[S/Fe] = +0.16$, similar to what is observed in the Galactic halo, $[S/Fe] \approx +0.2$. With increasing $[Fe/H]$, the $[S/Fe]$ ratio declines, reaching negative values at $[Fe/H] > -1.5$. The ratios of $[\alpha/Fe]$ can therefore be used to trace time scales, when the contributions from Supernovae Type Ia start to be come significant, 1-2 billion years after the onset of Supernovae Type II. In the Milky Way, this happens at $[Fe/H] \gtrsim -1$, while in the smaller Sculptor dwarf spheroidal galaxy, star formation is less efficient and the interstellar medium is only enriched up to $[Fe/H] \approx -1.8$, before Supernovae Type Ia start to contribute.

As the star formation died out in Sculptor, the contribution of Supernovae Type Ia started to become more and more significant until negative values of $[\alpha/Fe]$ were reached. In the Milky Way, however, there was a constant supply of Supernovae Type II, counteracting the contribution of Type Ia, so the ratios of $\alpha$-elements to iron do not reach as low values. These subsolar ratios of $[\alpha/Fe]$, are thus typical for nearby dwarf galaxies which had extended star formation that stopped in the past.

Abundance measurements (and upper limits) were also measured for Zn in $\sim100$ individual red giant branch stars in the Sculptor dwarf spheroidal galaxy, covering the metallicity range $-2.7 \leq [Fe/H] \leq -0.9$ (see Chapter 4). This is the largest available sample of Zn abundance measurements within a stellar system beyond the Milky Way. These results are consistent with previous observations of a limited number of stars in Sculptor and in other dwarf galaxies, Zn shows an $\alpha$-element-like behaviour, see Fig. 4. That is, super solar values at low metallicities, and decreasing $[Zn/Fe]$ with increasing $[Fe/H]$. At higher metallicities in Sculptor, $[Fe/H] > -1.8$, we find very low values of Zn and a significant scatter, $-0.8 < [Zn/Fe] < 0.4$. These results suggest that Zinc has a complicated nucleosynthetic origin in Sculptor, neither completely being an $\alpha$- nor an iron peak element, and possibly having several production sites.
Figure 5: The ratios of carbon to iron as a function of [Fe/H] in dwarf galaxies (in various colours from the smallest dwarf galaxies in red, to the largest in magenta), and in the Milky Way halo (gray and black squares). Filled black and coloured symbols are CEMP-no stars, filled gray stars are unclassified CEMP stars. Note the first CEMP-no star in Sculptor (blue triangle at [Fe/H] $= -2$). For references and more detail see Fig. 6.1.

CEMP stars in Sculptor and other dwarf galaxies

The very first stars in the Universe formed out of pristine material containing only H, He and some Li. Because of the absence of metals, cooling and fragmentation in primordial gas clouds was inefficient, and these first stars are thus predicted to be typically more massive than present-day stars. The majority of these first stars would have been short-lived, and therefore not still observable in the Local Universe. No direct observation of a zero-metallicity star has yet been confirmed.

The properties of the first stars can be observed indirectly, through the chemical elements they left behind. The gas that was polluted by these primordial stars can still be observed today in the low-mass, long-lived stars which were subsequently formed. The chemical abundance pattern that these zero-metallicity stars left behind, should therefore be detectable in the photospheres of ancient metal-poor stars.

All surveys for metal-poor stars in the Milky Way halo have found that a significant fraction of stars with [Fe/H] $\leq -2.0$ exhibit over-abundances of carbon, (i.e. [C/Fe] $\geq +0.7$), see Fig. 5. These stars are referred to as carbon-enhanced metal-poor (CEMP) stars.

These CEMP stars are divided into subcategories, depending on their heavy element abundances (of elements such as Ba and Eu). Out of these subcategories
CEMP-no stars are of particular interest since their frequency and carbon-excess is found to increase with decreasing [Fe/H], becoming most extreme in the most iron-poor objects, see Fig. 5. These results have led to the suggestion that the chemical abundance pattern of CEMP-no stars indicates the original chemical composition of their birth environment, possibly polluted by the first generation of stars.

The first CEMP-no star discovered in Sculptor is presented in this thesis. This star is consistent with forming out of a gas cloud that had previously been polluted by a mixture of the first stars, and later generation stars. In addition to its carbon-enhancement, this star also has other abundance anomalies (see Chapter 5). The discovery of this CEMP-no star at an unusually high [Fe/H] = −2, led to the modelling of the frequency of CEMP-no stars in dwarf galaxies in general (see Chapter 6), revealing that the probability to observe CEMP-no stars is different between dwarf galaxies, depending on their star formation histories.

Conclusions

The Local Group of galaxies provides the unique opportunity to study individual stars in extraordinary detail. Thus, we gain valuable insight into various processes of galactic formation and evolution. In particular, ancient low-mass stars in the Milky Way and its satellites are import relics of the chemical enrichment processes in the early Universe, and can even reveal the properties of the very first generation of stars. The Sculptor dwarf spheroidal galaxy is one of the ideal targets to study the entire chemical evolution of a single system, due to its relatively large number of stars, and simple star formation history. In the upcoming years, more Milky Way satellites are expected to be revealed, which along with more surveys of metal-poor stars will bring us an even clearer picture of how the various chemical elements were built up in the Universe.