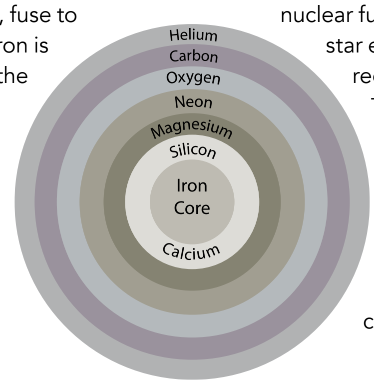
Galactic nucleosynthesis: the onset of element production in our galaxy

"Kepler's supernova" was the last exploding supernova seen in our Milky Way galaxy - Johannes Kepler, among others, observed it with the naked eye in 1604

In an extended study investigating how elements are formed and galaxies chemically evolve, **Dr Christopher Sneden** from the University of Texas, along with his team, look at stars within our own galaxy for vital clues. There are many diverse populations of stars located throughout the galaxy, from the galactic centre and spiral arms, through to a diffuse, random spread of stellar objects in an area that cocoons the Milky Way, called the galactic halo. Dr Sneden's research specifically concentrates on ancient, metal-poor halo objects to discover how primordial elements, such as hydrogen and helium, grow to form heavier elements that populate our surroundings.

We are all aware of the range of substances that makes up the periodic table. From hydrogen, the lightest, most abundant substance in the universe, through to commonly used elements such as copper, iron and uranium. All are familiar, but how are they produced? Apart from hydrogen, helium and lithium, which together make up the three lightest elements forged during the big bang, nearly all elements in the periodic table, known as metals, are forged in nuclear fusion processes throughout a star's lifetime. This ongoing chemical evolution is what Dr Sneden and his team have dedicated their research to, with particular attention being paid to metal-poor halo objects. This is critical to the research programme, as these ancient objects act as an intermediate source of information linking past stellar activity with current chemical abundancies.

During a star's lengthy participation on the galactic stage it will go through various phases of chemical evolution as lighter elements, such as hydrogen, fuse to eventually form iron. Once iron is formed within a stellar core the end of its life is imminent. Once this stage has been reached reactions in the core become endothermic, meaning more energy is put in to fusion processes than is released. This situation is unsustainable and inevitably leads to a core collapse supernova. During the following high energy explosion, as the star obliterates, heavier elements are formed via a process of neutron capture. For this reason, iron and neutron capture are important players within nucleosynthesis, and are elements Dr Sneden pays particular attention to within his research.



NEUTRON CAPTURE AS A PATHWAY TO HEAVIER ELEMENTS

Due to core reactions becoming endothermic once iron has formed, all heavier elements in the periodic table are formed during a star's post main-sequence phase or violent supernovae events. Neutron capture is split between two time-variant mechanisms, called the slow (s) and rapid (r) processes.

S-PROCESS

The s-process occurs mainly in stars that range in size from 1 to 8 solar masses. When hydrogen to helium reactions (hydrogen burning) cease to be the dominant source of nuclear fusion within a stellar core, the star expands and moves into the red giant phase of evolution. This particular period sees hydrogen burning continue, although in a shell formation enclosing the core. Helium burning now becomes the star's primary fusion source in the dense central region, with helium

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moving up in the atomic weight scale to form carbon – the next producible element in nucleosynthesis. It is this particular area that Dr Sneden has targeted for exploration, as carbon is by far the main by-product of s-process reactions within the core and any surrounding envelopes. During this stage neutrons are captured by atomic nuclei in the interior stellar fusion zones. Due to their neutral charge this can occur relatively easily. Once a neutron has been captured it can then go through a beta-minus decay, where the neutron decays under the weak nuclear force into a proton to increase the atomic number and form heavier elements. This is known as the 'slow' process because the neutron capture takes a relatively long time compared to the beta decay processes.

R-PROCESS

In stark contrast, the r-process occurs in very different circumstances and timescales. Although the nuclear processes are the same in principle, neutron capture is realised during violent supernovae events of massive stars greater than about 8 solar masses. Once iron is produced deep within the interior, core-collapse is triggered. The following explosion causes the release of an extreme number of free neutrons, which are then rapidly captured by existing atoms within the debris. Time per reaction is believed to be in seconds rather than thousands of years, therefore heavier elements are produced very quickly. Dr Sneden points out that many ancient, metal-poor stars within the halo show greatly enhanced r-process elements, which he states were produced by high-mass, rapidly evolving stars that existed prior to the formation of any halo stars we observe today.

Light echo around V838 Monocerotis

HOW OLD IS THE MILKY WAY?

As with any form of research, alternative verification methods are always sought to confirm a theory. Using a distance-independent process called nucleocosmochronometry, Dr Sneden's team have also been able to provide, utilising their research, an alternative method of ageing the Milky Way. Utilising observed radioactive isotopes, such as thorium and uranium, age constraints on the galaxy, and subsequently the universe, have been obtained. When compared to alternative estimates already calculated from a diverse number of sources (from thorium/uranium ratios in meteorites to satellite and ground-based sky surveys) the new method provides a galactic age of 12–14 billion years. As Dr Sneden states: *'Nucleocosmochronology offers promise as an independent dating technique. The chronometric results are generally in agreement with other age estimates such as globular cluster ages and cosmological age estimates.'*

FUTURE ADVANCES

To date, research has advanced well. In his recent paper investigating iron group elements within the halo star HD84937, Dr Sneden points out that observed chemical abundance levels do not always agree with prior abundance results for these elements (scandium through zinc) and *'when carefully analyzed can be excellent measures of prior nucleosynthesis events'*. This confirms metal-poor halo objects as perfect starting points for the development of galactic chemical evolution (GCE) theories.

For this reason, further detailed investigations into metal-poor stars are required. This should be realised as results from large-scale observation surveys are obtained. As Dr Sneden concludes: *'additional precise abundance determinations in metal-poor halo stars should be undertaken; such studies may help to identify the nature of the first stars as well as to discover additional r-process-rich, ultra-metal-poor stars.'*

The vast majority of elements in the periodic table, known as metals, are forged in nuclear fusion processes throughout a star's lifetime

Q&A

More data is required to fine tune our understanding. What current, or forthcoming, sky surveys are planned for this purpose?

The Gaia/ESO large spectroscopic survey will be a major step in the right direction, gathering more than 100,000 high resolution spectra of stars that will have very good parallaxes from the Gaia astrometric parallax mission. There are also several other current spectroscopic very large-sample studies that can take advantage of the Gaia database: e.g., APOGEE, a dedicated near-infrared (thus able to penetrate Galactic dust) survey, and GALAH, a wide wavelength-coverage spectroscopic survey of the Galactic disk and halo.

What type of laboratory experiments are used in conjunction with astronomical observations?

Abundances of elements in stellar atmospheres can be no more accurate than the input atomic transition data, particularly transition probabilities, for absorption lines that are seen in stellar spectra. We need these transition data for work on all kinds of stars, from metal-poor halo stars to metal-rich disk stars. Fortunately, the efforts of several laboratory atomic physics groups (in Wisconsin, London, Mons, and Lund, for example) have been rewarded in recent years with heightened accuracy in the basic lab data – which have instantly improved the stellar abundance results.

How do chemical abundance levels vary between the outer halo region and the galactic plane?

The dominant effect is the overall greatly diminished bulk levels of heavy elements in outer halo stars. Even though our Sun is composed of about 90% hydrogen and 9% helium, and the other 1% comprising the entire set of heavy elements, our Sun qualifies as "metal-rich". Stars in the outer halo are more pristine H and He objects, with the heavy elements making up 1/10% down to about 1/1,000,000%. It is often difficult to detect the presence of any heavy elements in the spectra of halo stars. Just as interestingly, the relative abundances are often decidedly non-solar. For example we have detected r-process-rich and s-process-rich halos stars, ones with more lithium than our Sun has, and ones that are anomalously enhanced in carbon.

Is chemical evolution witnessed when we observe entire galaxies back through time, at different cosmological epochs?

Yes (see previous answer). Since the halo stars are so metal-weak, we believe that sometimes the elements in a halo-star's atmosphere might be the product of the lives and deaths of just a few (maybe even one) stars. This gives us direct insight into the nucleosynthetic process.

We can look back in time but not forward. How do you expect the Milky Way to evolve into the future, and what will its final chemical state look like?

The overall heavy element content will grow with time. It is a bit difficult to distinguish "super metal-rich stars" (those with larger heavy-element contents than our Sun) because the present solar chemical composition is the product of many prior stellar generations of element donors – one additional contribution won't change things that much. Nevertheless, there are several ongoing efforts to identify stars more metal-rich than our Sun, and to see if their relative abundance ratios are different than the Sun.

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Detail

RESEARCH OBJECTIVES

Dr Sneden's research focuses on observational astronomy with an emphasis on ground-based stellar spectroscopy. His work is helping to inform our knowledge of how the chemical elements that make up our world came into being.

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COLLABORATORS

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BIO

After a BA in Astronomy from Haverford College, Dr Chris Sneden completed his PhD in Astronomy at the University of Texas at Austin, where he is now Rex G. Baker, Jr. and McDonald Observatory Centennial Research Professor of Astronomy. He has published about 260 peer-reviewed articles with nearly 22,000 citations from these.

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