RADIOACTIVE ION BEAMS FOR ASTROPHYSICS

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Abstract

The chemical element evolution of galaxies depends on nuclear processes that occur in various types of stellar environments throughout their lifecycle. These processes divide into two generic classes: processes that evolve over millions or billions of years involving reactions between stable nuclei, and processes that evolve explosively within seconds involving reactions between very unstable, short lived exotic nuclei. A major goal of radioactive beam facilities currently in the planning stage, under construction or being operated, is to investigate the role played by exotic nuclei in the chemical element evolution of the initial material that formed the solar system and other stars.

THE YEAR OF ASTRONOMY 2009

The year 2009 has been chosen to be Year of Astronomy because it marks the 400th anniversary of two events that not only changed our view of what lies beyond our world, but also marks a fundamental change in methodology concerning how to question what we see in the world around us and beyond.

In 1609 Kepler published Astronomia Nova in which he presents the results of an analysis of Brahe's planetary observations, and states his first two laws of planetary motion; in 1619 Kepler published his third law. The elegant simplicity of these laws contrasts with the tremendous analytical efforts that lead to them. These laws are based on the heliocentric system rather than the geocentric system that was generally accepted at the time.

Although Galileo did not invent the telescope he was the first to use this instrument to observe the night sky in 1609, and publish systematic observations of the surface of the moon, Jupiter's moons and the phases of Venus; the heliocentric system provided a natural way to understand the illumination phases of the surface of Venus.

The work of Kepler and Galileo can be seen as a turning point in how the world is perceived in relation to the universe, but it can also be seen just as importantly as a turning point in the methods by which natural phenomena should be investigated. Instead of relying on Aristotelian Natural Philosophy, or other authoritarian views to interpret phenomena, Kepler and Galileo started from systematic measurements relating to particular phenomena, and then tried to deduce mathematical relationships between the measured quantities - relationships that were logically consistent and complete within the context – no appeal to a higher authority being necessary or needed. This way of conducting investigations is so familiar to us today that it is difficult to appreciate just how revolutionary this approach was at the beginning of the 17th century. It is therefore very appropriate that we mark the achievements of Kepler and Galileo by this Year of Astronomy, 2009, as not only the start of a new astronomy but also the beginnings of the scientific method that we use today.

FOREFRONT ASTRONOMICAL QUESTIONS

The work of Galileo and Kepler related to the structure of the Solar System - the forefront astronomical question of the day. Our understanding of the universe around us has advanced much since then, but we still have very limited understanding of some very fundamental issues. There can be none more fundamental than the nature of matter that forms the universe. We are very aware of the matter around us in the Earth, the planets, the Sun and the stars beyond, but certain astrophysical measurements relating to the dynamics of individual galaxies and clusters of galaxies indicate that there must be much more matter in these galaxies than can be deduced from the luminous emission from these structures. This matter, called Dark Matter from its non-luminous nature, is the subject of much current research but there is still no understanding as to its nature. However this paper focuses on a seemingly more tangible question concerning the matter that we can see around us i.e. what is the fraction of matter that can be assigned to each of the naturally occurring stable elements? This question can be directed to the Earth, the Solar System, nearest stars, stars across the Galaxy and to stars even in neighbouring galaxies. The stars across the Galaxy will have different ages, so the basic material from which a star formed will depend on the chemical mix at the time of formation.

Our current view of the Universe is that it started as a matter singularity of immensely high density and temperature, which after a few minutes condensed to protons, α particles, a small proportion of light nuclei, neutrinos, electrons and photons. Only much later when stars began to be formed was there any synthesis of the heavier elements. Stars forming with different masses have different efficiencies and ways to evolve the base primordial material p and ^{4}He into the heavy elements. When these early starts came to the end of their life-cycle they ejected a large proportion of the synthesised elements into the interstellar spaces. A new generation of stars formed from this ejected material from earlier stars would have a higher proportion of heavier elements in its core matter, and as a result would evolve on a somewhat different path from the first stars. Since stars of different masses and element compositions, and stars in binary systems, synthesise the elements in different ways, it is in principle possible, if we can measure the current stellar element distribution, to get some clues as to how the stellar structure and chemical evolution evolved over the life of the Galaxy. To do this we need first to measure the chemical composition of stars, and then to measure the nuclear processes that lead to element production at various stellar temperatures and pressures. For this, it is necessary to use sophisticated telescopes and accelerators.

THE SOLAR SYSTEM ABUNDANCE OF ELEMENTS

Our present understanding of the Solar System formation is that it started about 4.6 billion years ago as a gravitational collapse of a gas cloud of material that probably had been ejected from nova, planetary nebula and supernova from previous generations of stars prior to the collapse. How this initial cloud ultimately led to the structure of the Solar System we see today is obviously a complex issue and one which is still not fully understood. Nevertheless, we can state with some confidence that the chemical composition of the Solar System material has changed little from its initial composition, other than the conversion of hydrogen to helium in the Sun's centre - the source of solar energy. Most of our knowledge about the chemical composition comes from analysis of optical absorption spectra of the Sun's photosphere, although there is also corroborative evidence from certain types of meteorites that survive entry into the Earth's atmosphere. Figure 1 shows the abundance pattern for elements from hydrogen to uranium. The abundance values range over more than 12 orders of magnitude, and show much structure over different regions of low, medium and high atomic number; in addition the abundance of elements with even atomic numbers is higher than those for odd atomic numbers.

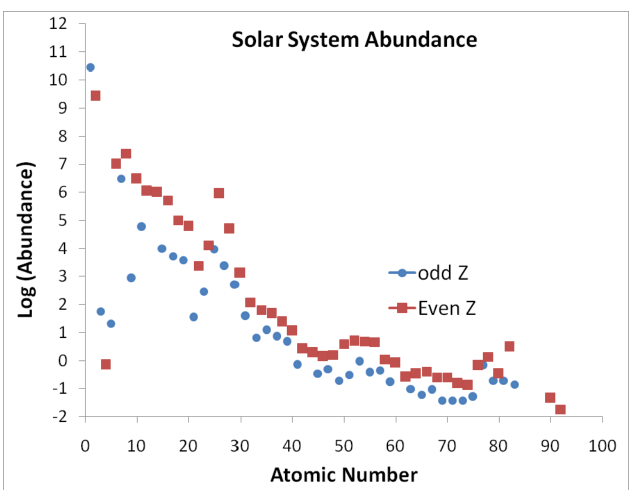

Figure 1: Solar System abundance of the elements (number of atoms normalized to 10^6 atoms of Si). Data correspond to NPL values - see ref. [1]

THE ABUNDANCE PATTERN IN OTHER STARS

With the powerful telescopes available today it is possible to study the optical spectra of stars that are not only in the far reaches of our Galaxy but also in neighbouring dwarf galaxies. To obtain quality spectra good light collection is needed as well as efficient spectrometers with capacity to analyze over a broad range of wavelengths. Indeed, some stars outside the Galaxy disc have been studied in great depth, an example is shown in Fig. 2

A general quantity specifying the heavy element content of a star is the so-called metallicity measure M, which is defined as:

$M=\log_{10}(\{A(Fe)/A(H)\}_{star})-\log_{10}(\{A(Fe)/A(H)\}_{sun})$, where A(Fe) and A(H) denote the abundance (number of atoms) of iron and hydrogen. As a general observation it is found that the metallicity decreases for regions further from the Galactic disc into the halo, and increases in the disc for regions towards the Galactic centre.

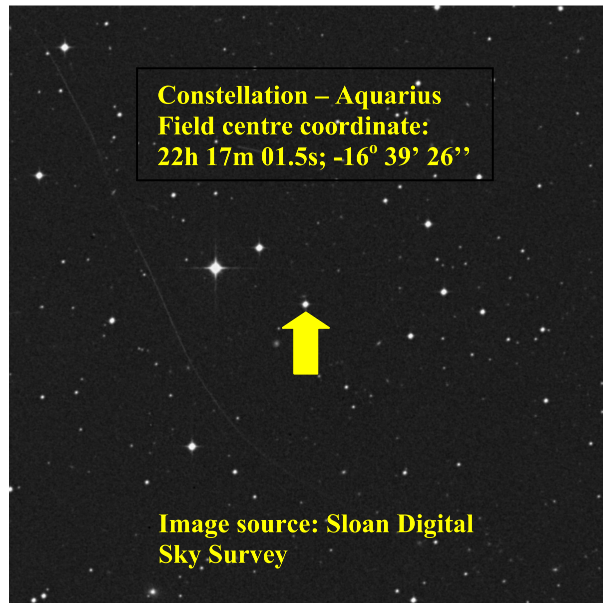

Figure 2: The halo star CS 22892-052 is about 15,000 light years from the earth, and is one of the oldest Galaxy stars. Other than the Sun, it is one of the most studied stars for element abundances - over 50 element abundances have been measured. The metallicity of the star is one of the lowest measured at –3.1. The relative abundance of the heavy elements is substantially different from the Sun – such information gives a clue to the early evolution of the Galaxy, [2].

NUCLEAR PROCESSES FOR THE CHEMICAL EVOLUTION OF THE GALAXIES

For interpretation of the chemical abundances of our Sun, other stars in our Galaxy and beyond, it is necessary to understand the stellar environments and the nuclear reactions that led to the measured values. Our present understanding is that there are several different types of stars which evolve chemically over many millions of years through nuclear reactions between stable atomic nuclei. In addition there are types of stars that at certain times in their life undergo explosive behaviour, rapidly changing their chemical composition in seconds through nuclear reactions involving very unstable exotic nuclei. At the end of a star's life, much of the chemical material produced over its life span will be dispersed into interstellar space – and will have a chemical fingerprint that relates to general characteristics of the parent star. Material that is mixed in the interstellar medium from several previous stars will therefore have traces of different chemical fingerprints; so determining the chemical distribution of a new star that is formed from this material can give hints to previous stellar history. To do this, the basic nuclear reactions that lead to the chemical fingerprints must be determined. The stellar explosive events involve reactions with short lived exotic nuclei, however very little is known about these exotic nuclei, so one of the main missions of radioactive beam facilities is to produce pure beams of these short lived nuclei and study their properties and interactions.

PRODUCTION OF RADIOACTIVE ION BEAMS

There are two basic ways to produce Radioactive Ion Beams (RIB): the ISOL (Isotope Separation On Line) method and the in-flight method. For the ISOL method, high-energy light nuclei projectiles bombard a thick target, exciting target nuclei to high energy which subsequently de-excite by rapid emission of nucleons so yielding a broad range of radioactive residual nuclei. Since the target is thick these residual nuclei will rapidly stop within it. However if the target is heated to a high temperature many of these residual nuclei diffuse rapidly out where they can be ionized, selected through a mass spectrometer and either studied at low energy or accelerated through a post-accelerator for further study.

The in-flight method involves fragmenting a high-energy heavy ion beam by passing it through a thin target-thin enough for the broad spectrum of fragments to be emitted in the forward direction. A fragment separator then selects out the nuclear fragment species of interest, either to be used at high energy, or stopped and then re-accelerated in a post-accelerator for low energy experiments.

Today there is a sizable number of RIB facilities operating around the world – too many to be comprehensively reviewed in this short article so only a few will be mentioned here. The ISOL facility at CERN, ISOLDE, [3], has a long and distinguished history of producing RIB. Currently it utilizes the 1.4 GeV proton beam from the PS Booster as the driver beam to irradiate thick targets. There are two such target stations, one where residual nuclei can be separated to a single mass value, and another where the residual nuclei can be selected over a broader mass range. Recent developments have added a post linear accelerator to the facility. The ISOL facility at TRIUMF, ISAC [4], uses the 500 MeV cyclotron proton beam to produce some of the most intense RIB in the world - ISAC is currently the highest powered ISOL facility, Fig. 3.

The GANIL laboratory utilizes a cascade of cyclotrons to produce driver beams either for in-flight or ISOL production of RIB; there is a further post-accelerator (cyclotron) for acceleration of ISOL beams [5].

THE NUCLEAR ASTROPHYSICS CHALLENGE

From an astrophysical viewpoint, some of the investigations needed with radioactive beams involve charged particle or neutron induced reaction investigations. Similar types of such reactions have been studied for many years with stable beams, but from an experimental point of view there are major differences: stable beams are much more intense than RIB so the event rate for RIB experiments is low, and since the beams are radioactive the experimental backgrounds are high, i.e. the signal to noise ratio is very poor. To address this issue there needs to be considerable innovation in areas such as more intense driver beams, developing targets capable of absorbing high beam powers, and experimental techniques to cope with high radiation backgrounds.

There are several new developments concerning driver accelerators. At GANIL, SPIRAL 2, [6], is a new facility comprising a superconducting linear accelerator to accelerate an intense beam of deuterons to 40 MeV, conversion of this beam to an intense flux of neutrons, which in turn will be used to produce intense beams of fission fragments, which will be mass separated and accelerated as required for experiments. At RIKEN, the new Radioactive Beam Factory, [7] was commissioned in 2007 and utilises a cascade of three cyclotrons with K=570, 980 and 2500 MeV, this last accelerator being superconducting; the design goal is to accelerate light ions up to 440 MeV/u and 350 MeV/u for heavy ions at beam intensities up to 10^{13} pps for in-flight fragmentation. The FAIR facility of GSI, [8], now under construction, will use synchrotrons to produce intense beams of heavy ions at 1.5 GeV, 10^{12} pps for in-flight production of RIB. With improvements in the fragment separator design, it is estimated that increases of up to 10^4 for RIB intensities can be expected over current values. The recently announced FRIB facility at MSU, [9], will use a superconducting linear accelerator to accelerate heavy ions up to uranium with energy 200 MeV/u and beam power up to 400 kW; following in-flight production of RIB, fragments will be separated in a new superconducting separator. Finally, but by no means least, there is a proposal in Europe to build a superconducting proton linear accelerator to irradiate directly ISOL targets at 100 kW, or to use this proton beam at 4 MW power to produce intense beams of neutrons that through the fission reaction will produce exotic neutron rich nuclei.

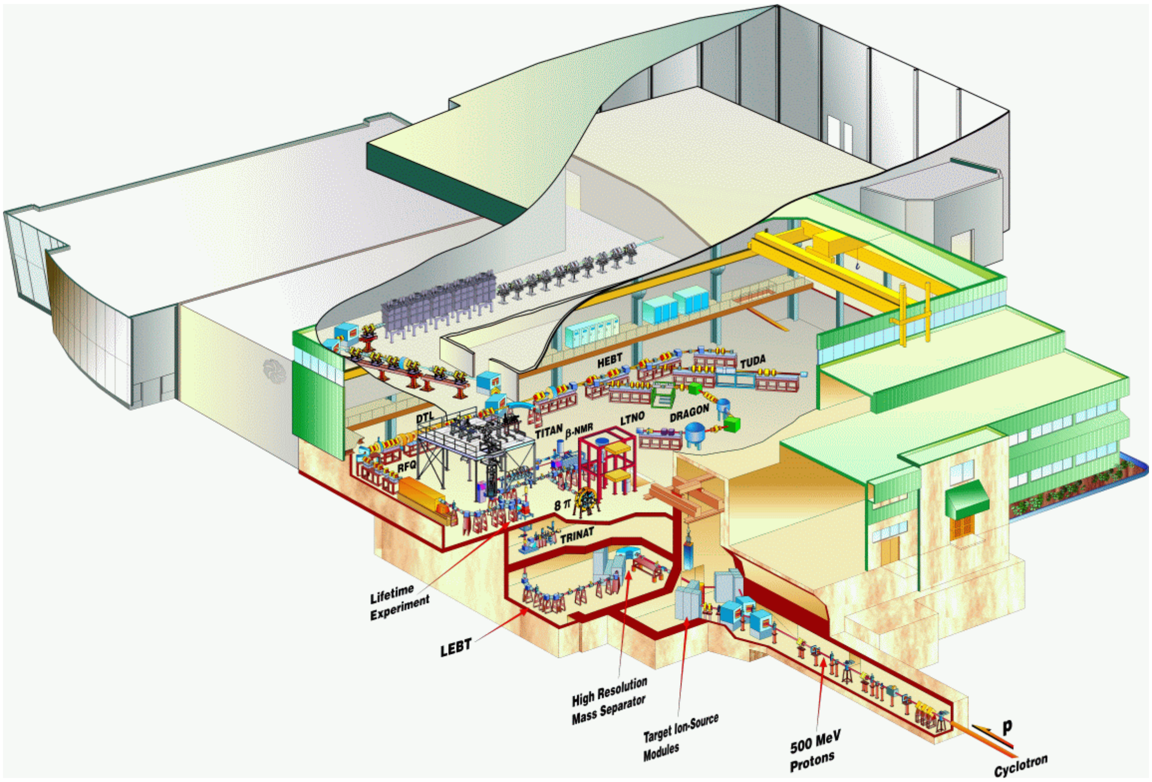

Figure 3: The RIB facility at TRIUMF uses the 500 MeV cyclotron 100 μA proton beam to irradiate ISOL targets.

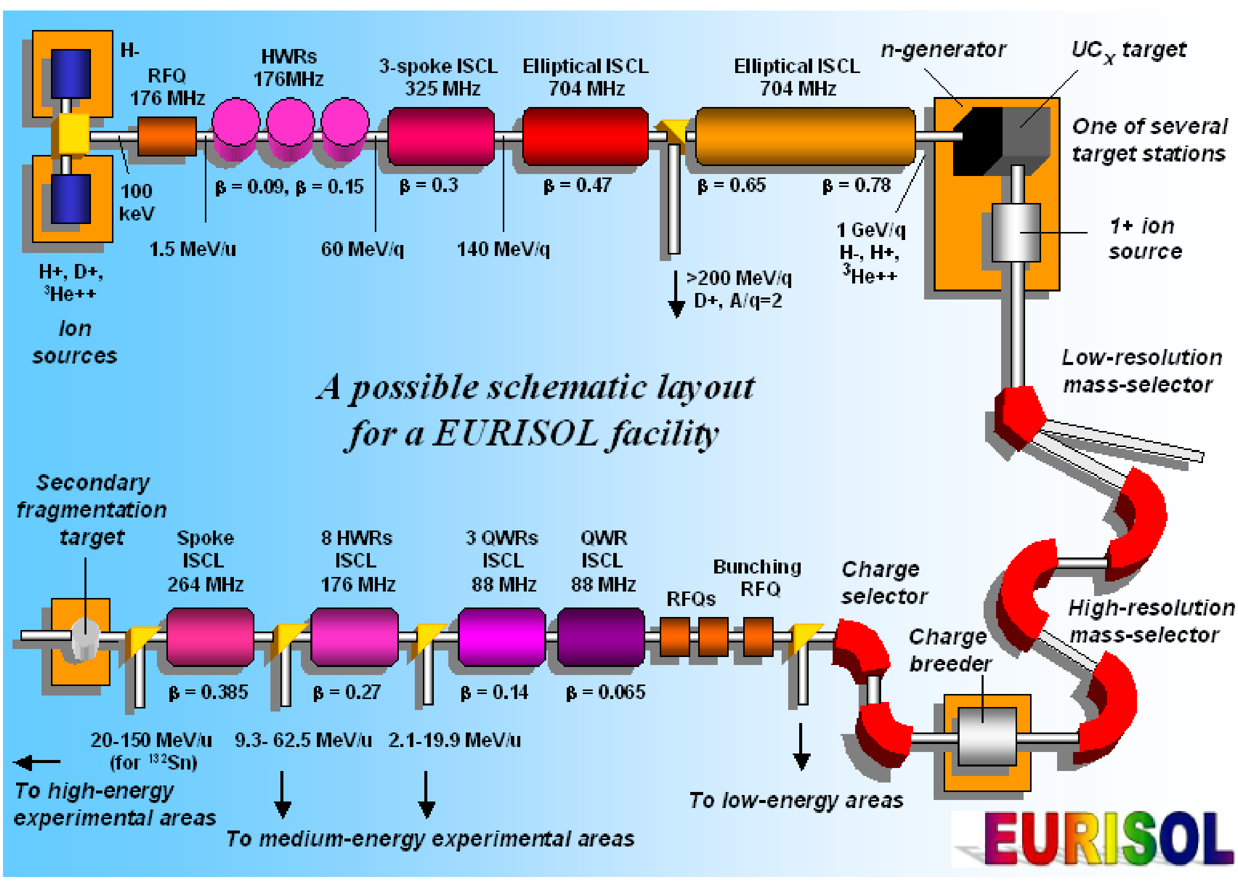

Figure 4: The EURISOL Facility

This facility, named EURISOL, is illustrated in Fig. 4, [10]

As indicated above there is a lot of innovation concerning driver accelerators, but much innovation also is needed to produce RIB targets that are capable of sustaining high beam powers for considerable lengths of time; innovation is also needed to design experiments that can efficiently exploit RIB.

As an example of target innovation, the planned EURISOL 4 MW target, [11], will stop the 1 GeV 4 mA proton beam in a fast moving liquid Hg target, producing neutrons, which in turn will produce fission fragments in six uranium outlying pellets, see Fig. 5. The total fission power is 200 kW, which is similar to some research reactors; safe handling of such a system will be a challenge.

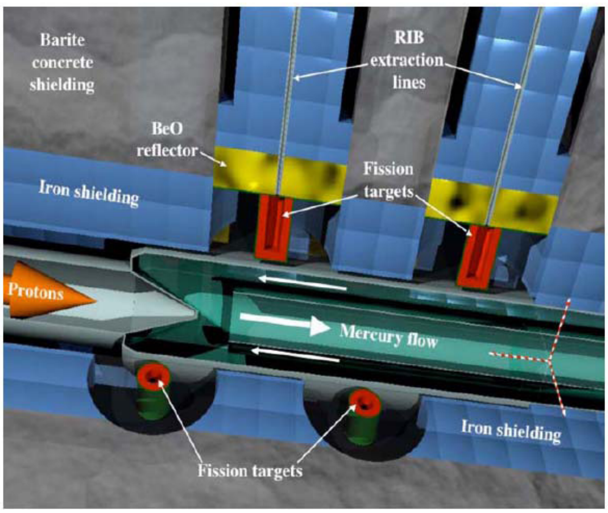

Figure 5: The EURISOL 4MW target

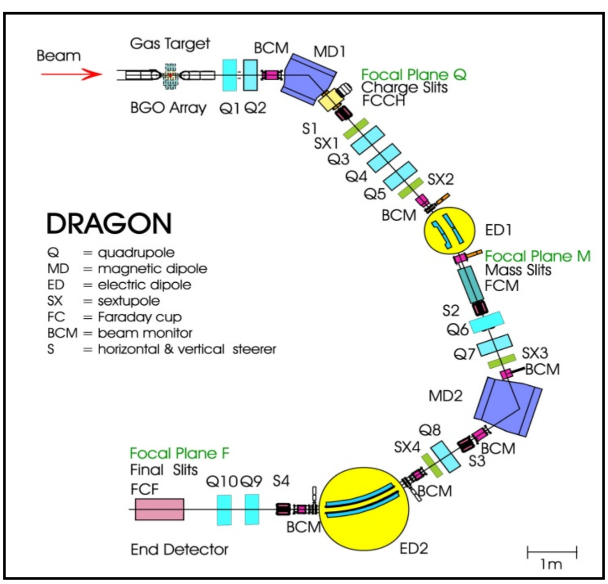

Figure 6: The DRAGON spectrometer. This is designed to study low energy charge particle capture reactions at energies relevant to astrophysical situations. The spectrometer detects the rare capture events and strongly suppresses the intense radiation background effects from the incident RIB.

Innovation is also needed with the design of experimental equipment to undertake research with radioactive beams. With stable beam experiments there is normally a high event rate so detectors do not have to be 100% efficient. In contrast, experiments with RIB due to much lower beam intensities, will have a low experimental event rate. In addition the scattering of radioactive beams in the experimental environment will generally mean that detectors record a high level of background radiation events. Therefore there is a requirement to develop detector systems that have the highest experimental event efficiencies, but low sensitivity to background radiation. Examples of such detectors at TRIUMF are the DRAGON Spectrometer (Fig. 6, [12]), TIGRESS γ-ray spectrometer and the TITAN system [4].

CONCLUSIONS

The chemical evolution of the galaxies comes about through nuclear reaction processes that are associated with certain stellar environments. Some stellar systems primarily evolve by nuclear reactions with stable nuclei that can extend over many millions of years, while others evolve by reactions between very unstable nuclei in stellar explosive scenarios. The chemical fingerprint left by these different stellar scenarios on the distribution of elements in the interstellar medium will be unique. So by first determining the element distribution in different stars it may be possible to ascribe this distribution to different contributions from previous stellar events that produced the material from which the star was formed; such studies can reveal important clues as to how the galaxies evolved.

These studies not only need the development of large telescopes and spectrometers to measure the element distributions of far distant stars, they also require the development of powerful RIB facilities to determine the chemical element fingerprint for explosive stellar events. With new developments in both astronomical and accelerator technology, the next decade should see exciting new insights into galactic chemical evolution, which in turn could provide a valuable insight into the macroscopic dynamical evolution of galaxies.

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