UNIVERSITY OF SURREY

BRIDGCE-IReNA 2024: BRIDGING RESEARCH IN DISCIPLINES OF GALACTIC CHEMICAL EVOLUTION AND NUCLEAR ASTROPHYSICS 2024

WORKSHOP PROGRAMME

8-10 July 2024

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INTRODUCTION

The BRIDGCE 2024 annual meeting, at the University of Surrey, couples the themes of nuclear physics and astrophysics to showcase the latest cross-disciplinary across these fields, and exchange knowledge and expertise among BRIDGCE researchers and their collaborators in IReNA and ChETEC. The workshop will give particularly early-career researchers and postdoctoral students an opportunity to present their work and discuss the state-of-the-art of the field with leading UK, US and EU-based collaborators. Key themes include nuclear astrophysics, observational astronomy, stellar populations, stellar explosions and ejecta, and galactic chemical evolution.

Workshop Chair:
Dr Robert Izzard (University of Surrey)

Organising committee:
Dr Payel Das (University of Surrey), Dr Andreea Font (Liverpool John Moores University), Professor Raphael Hirschi (Keele University), Professor Chiaki Kobayashi (University of Hertfordshire), Professor Alison Laird (University of York), Professor Gavin Lotay (University of Surrey), Dr Stuart Sim (Queen's University Belfast) and Dr Matthew Williams (University of Surrey)

Administrative support:
Astha Astha (University of Surrey) and Louise Jones (Institute of Advanced Studies)

PROGRAMME

DAY 1 – MONDAY 8 JULY
Innovation for Health Building, Room 02 IFH 01

(BST)	
10.00 – 11.00	Coffee, Registration and Initial Meet Up
11.00 – 11.15	Welcome - Robert Izzard
	Galaxies 1:
11.15 – 12.00	Investigating the Earliest Galaxies with JWST - Results from the JADES survey - Emma-Curtis Lake (Invited Speaker)
	Stars 1:
12.00 – 12.30	A Model for School Outreach - Andy Brittain
12.30 – 13.30	Lunch
13.45 – 14.30	Understanding Kilonovae Using Radiative Transfer Simulations - Christine Collins (Invited Speaker)
14.30 – 15.00	A New Structure for TŻOs and Implications for GCE: Disagreements in the New Generation of Models - Alex Hackett
15.00 – 15.30	Impact of Newly Measured Nuclear Reaction Rates on 26Al Ejected Yields from Massive Stars - Umberto Battino
15.30 – 16.00	Refreshments
16.00 – 16.30	Models Meet Observations in Supernova 1987A - Mikako Matsuura
16.30 – 17.00	Tertiary Tides with Eccentric Orbits - Yan Gao
17.00 – 17.30	Modelling AGB Stars with MESA - Natalie Rees (online)
From 19.00	Dinner at The March Hare, 2-4 South Hill, Guildford, GU1 3SY

DAY 2 – TUESDAY 9 JULY

Innovation for Health Building, Room 02 IFH 01

(BST)	
	Nuclear and Atomic 1
09.30 – 10.15	Nuclear Uncertainties Impacting the Interpretation of R-Process Observables - Rebecca Surman (Invited Speaker - IReNA)
10.15 – 10.45	Production of Light P-Nuclides in Accreting Neutron Star Common Envelopes - Sophie Abrahms
10.45 – 11.15	Refreshments
11.15 – 11.45	Comprehensive Search for Candidate 'Astromers' Relevant to the Process of Nuclear Excitation by Electron Capture (NEEC) in Terrestrial and Astrophysical Plasmas - Benjamin Wallis
11.45 – 12.30	Extending the Hoyle-State Paradigm to C12+C12 Fusion - David Jenkins (Invited Speaker)
12.30 – 13.30	Lunch
	Galaxies 2
13.45 – 14.15	The Cosmic Metal and Dust Budget of the Universe - Rob Yates
14.15 – 14.45	Near Pristine DLAs and their Chemistry - Louise Amber Welsh
14.45 – 15.15	Chemical Enrichment from the First Stars in Cosmological Simulations - Dyna Ibrahim
15.15 – 15.45	Refreshments
15.45 – 16.15	The Early Chemical Evolution of the Sagittarius Dwarf Galaxy - Federico Sestito
16.15 – 16.45	Chasing the Impact of the Gaia-Sausage-Enceladus Merger on the Formation of the Galactic Disk - Daisuke Kawata
16.45 – 17.15	Reconstructing the Formation Histories of Milky Way-Type Galaxies from the Chemical Abundances of their Tidal Debris - Andreea Font
17.15 – 17.45	Simba-C: Mock Halo X-Ray Observations with Athena X-IFU of the Chemical Abundances - Renier Timothy Hough
From 18.30	Evening Social at Growlers and Cans, 24 Chertsey Street, Guildford. GU1 4HD

DAY 3 – WEDNESDAY 10 JULY

Innovation for Health Building, Room 02 IFH 01

(BST)	
	Nuclear and Atomic 2
09.30 – 10.15	R-Matrix Atomic Data for Applications in Astrophysics - Cathy Ramsbottom (Invited Speaker)
10.15 – 10.45	Constraining the NiCu Cycle in X-Ray Bursts: Spectroscopy of 60Zn - Conner O'Shea
10.45 – 11.15	Refreshments
11.15 – 11.45	NLTE Analysis of Optically Thin Spectral Features - Leo Patrick Mulholland
11.45 – 12.30	Insight to the Explosion Mechanism of Core Collapse Supernovae Through Gamma-Ray Spectroscopy of 46Cr - Chris Cousins
12.30 – 13.30	Lunch
	Stars 2
14.00 – 14.30	Constraining SN Ia Progenitors from the Observed Iron-Peak Elemental Abundances in the Milky Way Dwarf Galaxy Satellites - Ryan Alexander
14.30 – 15.00	The Fate of Massive Stars Across Cosmic Time - Caitlan Chambers
15.00 – 15.30	Refreshments
15.30 – 16.00	The Final Minutes of Silicon Shell Convection in 3D - Vishnu Varma
16.00 – 16.45	Magnetic Field Strength Effects on Nucleosynthesis from Neutron Star Merger Outflows - Kelsey Lund (Invited Speaker - IReNA)
16.45	Workshop summary - Chiaki Kobayashi

INVITED SPEAKERS

Christine Collins
North-West University

Dr Christine Collins' research focus is in nuclear physics, specifically in the study of heavy ion collisions. She conducts experiments at GSI to investigate properties of nuclear matter under extreme conditions, such as high temperatures and densities. Her research contributes to our understanding of the fundamental interactions of particles and the behaviour of nuclear matter.

Emma Curtis Lake
University of Hertfordshire

Dr Emma Curtis is an astronomer who studies galaxy formation and evolution in the early universe. They use space telescopes like JWST to find and characterize these galaxies. Dr Emma Curtis is a co-lead on a large survey project to map the properties of galaxies across cosmic time.

David Jenkins
University of York

Professor David Jenkins is a nuclear physicist who studies the structure and evolution of exotic nuclei, with a focus on their role in nuclear astrophysics.

Kelsey Lund
North Carolina State University / Los Alamos National Lab

Dr Kelsey Lund is a graduate student at North Carolina State University. She has given numerous research talks, invited talks, contributed talks, and posters on topics related to nucleosynthesis, kilonova modeling, nuclear physics, and astrophysics.

Cathy Ramsbottom
The Queen's University of Belfast

Dr Catherine Ramsbottom, a leading expert in astrophysical atomic data for over 20 years, now spearheads research on complex atomic data using cutting-edge R-Matrix codes on supercomputers. Her internationally recognized work has garnered funding from prestigious bodies like the STFC, EU, and Leverhulme Trust.

Rebecca Surman
University of Notre Dame

Professor Rebecca Surman is a theoretical nuclear astrophysicist who studies the origins of the heaviest elements forged in extreme events like supernovae and neutron star mergers. Her research focuses on the crucial role of neutrino interactions and nuclear physics in these environments, where conditions create never-before-seen neutron-rich nuclei.

ABSTRACTS

MONDAY 8 JULY
Galaxies 1

Investigating the Earliest Galaxies with JWST - Results from the JADES survey
Dr Emma Curtis Lake, University of Hertfordshire

With a strategy of obtaining deep JWST imaging and following up interesting candidates with NIRSpec spectroscopy, the JADES survey has: broken the highest redshift spectroscopically confirmed record (twice); found possible evidence for the earliest black hole at z~10.6, though other explanations exist; found direct evidence for the stochasticity of star formation in early galaxies with the highest redshift 'mini-quenched' galaxy, and much more besides. I will summarise key results from JADES survey focusing on Chemical evolution and abundances of the earliest galaxies.

Stars 1

A Model for School Outreach
Mr Andy Brittain, Lady Eleanor Holles School

The Window to the Stars (WTTS) software was developed by Rob Izzard to complement the TWIN single/binary stellar evolution code created by Peter Eggleton. This software functions like a web browser for stellar-evolution modelling, providing users with the necessary tools to interpret their own models, guiding them towards an understanding of the physics, and assisting them in predicting stellar behaviour. The WTTS programme enables secondary school students to engage in stellar project work that was previously inaccessible to them. WTTS has been enthusiastically adopted by the author and his students at Lady Eleanor Holles Girls' School (LEH), who have showcased their work at several conferences and contributed to the advancement of the project. LEH now includes the programme as one of its community commitments. Over time, the documentation has been steadily refined, and more schools have been brought on board. Dr Izzard both secured a STFC grant and supported the author's Partnership Grant negotiations with the Royal Society. The Royal Society supports schools with funding, project management and national networking. Several schools around the UK have now adopted WTTS, with more intending to pursue it next year. Additionally, several charitable STEM organisations are promoting WTTS within their resource provisions, some with a global reach. Many teachers at international schools, as well as home-school parents, have expressed interest, and the first WTTS schools symposium has now taken place. In summary, WTTS provides a model for the advancement of outreach projects and collaborative initiatives, offering many valuable lessons for scientific engagement.

Understanding Kilonovae Using Radiative Transfer Simulations
Dr Christine Collins, North-West University

Kilonova observations offer the opportunity to obtain unique constraints on heavy-element r-process nucleosynthesis. The

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detection of the kilonova AT2017gfo has provided us with a wealth of observations, however, interpreting what these observations tell us about the underlying physics requires detailed modelling. I will discuss recent kilonova radiative transfer simulations that are based on hydrodynamical models of neutron star mergers, with detailed r-process nuclear network calculations. The simulated spectra in the polar directions show a remarkably similar evolution to the observations of AT2017gfo. Using these simulations, I will show the importance of accurate atomic data for kilonova modelling, as well as the importance of 3D simulations. By improving radiative transfer simulations and by extending our study to consider a broader range of kilonova models, simulations will be able to connect observations to the underlying merger physics, and place constraints on r-process nucleosynthesis.

A New Structure for TŻOs and Implications for GCE: Disagreements in the New Generation of Models

Dr Alex Hackett, CEICO, Institute of Physics of the Czech Academy of Sciences

Thorne-Żytkow Objects are a class of hybrid stars (Thorne & Żytkow 1977), consisting of a neutron star, surrounded by a diffuse convective envelope. The formation rates of TŻOs are not well constrained but the presence of a modest population of such objects in the Galaxy could have a significant effect on Galactic Chemical Evolution. Optimistically, a large fraction of X-ray binaries end up as TŻOs, contributing to the abundance of p-process elements. Farmer et al. (2023) placed a central boundary condition at ~600km above the centre of the star whereas we instead opt to place this at the surface of the neutron star and make use of an accretion prescription set by the opacity at the base of the envelope to model the release of gravitational energy. We construct a series of models that show differences from those of Cannon and Farmer. Our models' structures show an analogue of the supergiant-like solutions from TŻ and Cannon et al., these solutions being found across a wide range of masses, including where TŻ found a different, giant-like structure. We find that the deviation from the Cannon et al. series can be explained by our prescriptions for neutrino generation, while the more significant differences to Farmer et al. are likely a function of the differences in boundary conditions. We discuss the implications of the possible existence of differing series of structures for TŻOs. We also discuss the implications of our structures for nucleosynthetic pathways, and the further effects on GCE.

Impact of Newly Measured Nuclear Reaction Rates on 26Al Ejected Yields from Massive Stars

Dr Umberto Battino, Keele University

Over the last three years, the rates of all the main nuclear reactions involving the destruction and production of 26Al in stars (26Al(n, p)26Mg, 26Al(n, α)23Na, 26Al(p, γ)27Si and 25Mg(p, γ)26Al) have been re-evaluated thanks to new high-precision experimental measurements of their cross sections at energies of astrophysical interest, considerably reducing the uncertainties in the nuclear physics affecting their nucleosynthesis. We computed the nucleosynthetic yields ejected by the explosion of a high-mass

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star (20 M⊙, Z = 0.0134) using the FRANEC stellar code, considering two explosion energies, 1.2 × 10^51 erg and 3 × 10^51 erg. We quantify the change in the ejected amount of 26Al and other key species that is predicted when the new rate selection is adopted instead of the reaction rates from the STARLIB nuclear library. Additionally, the ratio of our ejected yields of 26Al to those of 14 other short-lived radionuclides (36Cl, 41Ca, 53Mn, 60Fe, 92Nb, 97Tc, 98Tc, 107Pd, 126Sn, 129I, 36Cs, 146Sm, 182Hf, 205Pb) are compared to early solar system isotopic ratios, inferred from meteorite measurements. The total ejected 26Al yields vary by a factor of ~3 when adopting the new rates or the STARLIB rates. Additionally, the new nuclear reaction rates also impact the predicted abundances of short-lived radionuclides in the early solar system relative to 26Al. However, it is not possible to reproduce all the short lived radionuclide isotopic ratios with our massive star model alone, unless a second stellar source could be invoked, which must have been active in polluting the pristine solar nebula at a similar time of a core-collapse supernova.

Models Meet Observations in Supernova 1987A

Dr Mikako Matsuura, University of Cardiff

Recent developments of hydrodynamic models of supernova explosions are remarkable. The models predict asymmetric distributions of elements, triggered by Reyleigh-Taylor instabilities developed after the supernova explosion. We present comparisons of spatial distributions of elemental predicted by hydrodynamic models with ALMA observations of SiO, CO and HCO+.

Tertiary Tides with Eccentric Orbits

Dr Yan Gao, University of Birmingham

Within hierarchical triple stellar systems, there exists a tidal process unique to them, known as tertiary tides. In this process, the tidal deformation of a tertiary in a hierarchical triple drains energy from the inner binary, causing the inner binary's orbit to shrink. Previous work has uncovered the rate at which tertiary tides drain energy from inner binaries, as a function of orbital and tidal parameters, for hierarchical triples in which the orbits are all circular and coplanar. However, not all hierarchical triples have orbits which are circular and coplanar, which requires an understanding of what happens when this condition is relaxed. In this paper, we study how eccentricities affect tertiary tides, and their influence on the subsequent dynamical evolution of the host hierarchical triple. We find that eccentricities in the outer orbit undergo tidal circularisation quickly, and are therefore trivial, but that eccentricities in the inner binary completely change the behaviour of tertiary tides, draining energy from the outer orbit as well as the inner orbit. Empirical functions that approximate this behaviour are provided for ease of implementing this process in other stellar evolution codes, and the implications of these results are discussed.

Modelling AGB Stars with MESA

Miss Natalie Rees, University of Surrey

Stellar evolution codes, such as the widely-used MESA, are essential tools for the astrophysical community to compute stellar structure and nucleosynthesis. These computations reveal the chemical

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and mechanical feedback of stars on galaxies, which is crucial for the BRIDGCE consortium. In this talk, I will discuss how MESA models the evolution of most stars during the final phase of stellar evolution: the thermally pulsing asymptotic giant branch (TP-AGB) stage. This phase is characterized by thermal pulses, where degenerate helium periodically ignites, playing a critical role in the creation of elements like carbon and nitrogen, as well as heavy metals such as barium and lead. Severe mass loss at the end of the AGB phase returns these metals to the interstellar medium. Unfortunately, accurately computing these thermal pulses and the potentially unstable stellar envelope during the TP-AGB stage is a challenging and computationally expensive task. Codes like MESA often encounter difficulties, leading to uncertain nucleosynthesis yields and the inability to model subsequent phases, such as the post-AGB. To address this, I adapt MESA to evolve stars through thermal pulses with a reduced envelope mass and tackle two major instabilities: the hydrogen recombination instability and the Fe-peak instability. I will present methods to avoid the numerical instabilities that typically hinder MESA and other codes. Using this newly-developed approach, I investigate how varying the envelope mass of a star influences its thermal pulses and chemical yields, thereby assessing the contribution of binary AGB stars to galactic chemical evolution.

TUESDAY 9 JULY

Nuclear and Atomic 1

Nuclear Uncertainties Impacting the Interpretation of R-Process Observables

Professor Rebecca Surman, University of Notre Dame

The astrophysical origins of the heaviest elements via rapid neutron capture remain unresolved, even with exciting recent progress in gravitational wave and astronomical observations. One key barrier to elucidating r-process origins using these new observables are the uncertainties that arise from the unknown properties of the thousands of nuclear species that participate in the r process. Here we consider the role played by nuclear physics uncertainties in our interpretations of r-process observables such as light curves, abundance patterns, and isotopic ratios. We will discuss the prospects for reducing these uncertainties via advances in nuclear theory and experiment and point out potential observables that may rise above current uncertainties.

Production of Light P-Nuclides in Accreting Neutron Star Common Envelopes

Ms Sophie Abrahms, University of York

In massive-star binary systems, upon reaching later stages of stellar evolution one star can expand as a giant and envelope its companion in what is called a common envelope phase. The enveloped companion, here a neutron star, begins to accrete matter. The angular momentum of the accreting material results in the formation of an accretion disk. Accretion of hydrogen rich onto common-envelope- phase neutron stars can result in material ejected from the accretion disk having undergone burning near

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the neutron star's surface [1]. Not much is understood about what nucleosynthesis occurs in this system. However, Keegans (2019) found that accreting neutron star common envelopes have the potential to impact galactic chemical evolution (GCE) [1]. Our preliminary results show that this astrophysical scenario can produce large amounts of light p-nuclides 92Mo, 96Ru and 98Ru - upwards of one order of magnitude more than their initial abundances in our simulations. This is significant as these isotopes are all underproduced in current p-process models and their origins are not known [2, 3]. The presented work builds on Keegans et al. (2019), which modelled accreting neutron star common envelopes without the inclusion of angular momentum, and Abrahams et al. (2023), which presented initial results on updated models which included the impact of angular momentum [1,4]. We will present yields from our common envelope simulations and discuss the nucleosynthesis which leads to high production of particular light p-nuclides.

[1] Keegans J., Fryer C.L., Jones S.W., Côte B., Belczynski K., Herwig F., Pignatari M., et al., 2019, MNRAS, 485, 620. doi:10.1093/mnras/stz368
[2] Roberti L., Pignatari M., Psaltis A., Sieverding A., Mohr P., Fulop Z., Lugaro M., 2023, A&A, 677, A22. doi:10.1051/0004-6361/202346556
[3] Role of Core-collapse Supernovae in Explaining Solar System Abundances of p Nuclides, C. Travaglio, T. Rauscher, A. Heger, M. Pignatari, C. West
[4] Abrahams S.E.D., Fryer C., Hall-Smith A., Laird A., Diget C., 2023, EPJWC, 279, 10002. doi:10.1051/epjconf/202327910002

Comprehensive Search for Candidate 'Astromers' Relevant to the Process of Nuclear Excitation by Electron Capture (NEEC) in Terrestrial and Astrophysical Plasmas

Dr Benjamin Wallis, University of York

The population of isomeric (metastable) excited states in nuclei within astrophysical environments associated with R-process freezeout can affect the final abundance of stable isotopes; these astrophysically relevant isomers are known as 'astromers'. Astromers can be populated/depopulated via various electromagnetic mechanisms, generally via low excitation energy, short-lived states above the isomer. The population of these 'astromers' has recently received theoretical attention using the Planckian photon bath, in which a multistep network of photo-nuclear excited states and subsequent relaxations is considered during the population of an astromer from its associated nuclear ground state. Similarly, an isomer can be depopulated/populated with a much lower, yet albeit comparable electron flux via single-step inelastic electron-scattering processes, which will necessarily also affect the astromer population. One such electromagnetic process is `nuclear excitation by electron capture' (NEEC), which is the inverse of internal conversion, reported in Nature 2018 to deplete isomers terrestrially with excitation probability per nucleus of P-exc= 0.010(3) in a radioactive ion-beam scenario. Despite multiple iterations of state-of-the-art theory and repeats of the same experiment at different facilities, the excitation probability is still calculated to be over 7 orders of magnitude smaller than this. The presentation focuses around encouraging the development hot-dense-plasma

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experiments using the photon and electron flux available at current or in-development Peta-Watt (PW) laser facilities, which allow experimentation into separating the electromagnetic mechanisms at play in depleting/ populating isomers. This will allow us to readily challenge the relevance of astromers in calculating the final abundances of isotopes in the cosmos. Similarly, an isomer can be depopulated [2] with a much lower, yet albeit comparable electron flux via inelastic electron-scattering processes, which will necessarily also deplete the astrophysical isomer [3]. One such electromagnetic process is `nuclear excitation by electron capture' (NEEC), which is the inverse of internal conversion, recently reported to deplete isomers terrestrially with a high [4], yet still refuted [5], excitation probability in a radioactive ion-beam scenario.This presentation focuses around encouraging the development hot-dense-plasma experiments using the photon and electron flux available at current or in-development peta-Watt (PW) laser facilities, which allow experimentation into separating the electromagnetic mechanisms at play in depleting isomers. This will allow us to readily challenge the relevance of astromers in calculating the final abundance of isotopes in the cosmos.

[1] G. Wendell Misch et al. "Astromers: Nuclear Isomers in Astrophysics". In: The Astrophysical Journal Supplement Series 252.1 (Dec. 2020), p. 2. doi: 10.3847/ 1538-4365/abc41d
[2] G. Wendell Misch, T. M. Sprouse, and M. R. Mumpower. "Astromers in the Radioactive Decay of r-process Nuclei". In: The Astrophysical Journal Letters 913.1 (May 2021), p. L2. doi: 10.3847/2041- 8213/abfb74
[3] J. Carroll and C. Chiara. "Isomer depletion". In: The European Physical Journal Special Topics (Apr. 2024). doi: 10.1140/epjs/s11734-024-01149-8
[4] C. Chiara et al. "Isomer depletion as experimental evidence of nuclear excitation by electron capture". In: Nature Publishing Group 554.7691 (2018), pp. 216–218. doi: 10.1038/nature25483.
[5] Y. Wu, C. H. Keitel, and A. P´alffy. "93mMo isomer depletion via beam-based nuclear excitation by electron capture"

Extending the Hoyle-State Paradigm to C12+C12 Fusion

Professor David Jenkins, University of York

Carbon burning is a key step in the evolution of massive stars, Type 1a supernovae and superbursts in x-ray binary systems. Nevertheless, our understanding of this critical fusion reaction is not as complete as might be desirable to fully constrain astrophysical models. This limitation centres of the difficulty in determining the ^{12}C+^{12}C fusion cross section at energies corresponding to the Gamow window for these different scenarios as it relies on extrapolation of direct measurements made at higher energies. Such direct fusion measurements are complicated by the presence of resonances at and below the Coulomb barrier. These resonances have traditionally been associated with the formation of short-lived molecular states based on ^{12}C+^{12}C or similar alpha-conjugate systems. Despite study of these resonances over many years, a comprehensive theoretical model accounting for their existence and structure is presently lacking. Given the difficulties associated with direct fusion studies of the ^{12}C+^{12}C reaction, indirect studies which can identify potential resonances within the respective Gamow windows are of high value. In this respect

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, a study of the ^{24}Mg(α,α')^{24}Mg reaction has identified several 0^{+} states in ^{24}Mg, close to the ^{12}C+^{12}C threshold, which predominantly decay to ^{20}Ne(ground state) + α [1]. Not only were these states newly identified but surprisingly they were not observed in previously well-studied ^{20}Ne(α,α_0)^{20}Ne resonance scattering, potentially suggesting that they have a dominant ^{12}C+^{12}C cluster structure. Given the very low angular momentum associated with sub-barrier fusion, these states, which sit in the Gamow window for massive stars, may play a decisive role in ^{12}C+^{12}C fusion. We present estimates of updated ^{12}C+^{12}C fusion reaction rates based on likely parameters for such resonances [1]. A fascinating aspect of the identification of these potential 0$^+$ cluster states in ^{24}Mg close to the break-up threshold for ^{12}C+^{12}C and similar channels such as ^{16}O+^{8}Be is the circumstantial similarity to the situation in ^{12}C with the Hoyle state at the break-up threshold and the critical role that it plays in in helium burning.

Galaxies 2

The Cosmic Metal and Dust Budget of the Universe

Dr Rob Yates, University of Hertfordshire

In this talk, I will present results from the latest version of L-GALAXIES, a galaxy evolution simulation which now includes binary stellar evolution (using binary_c) and dust production & destruction. Through its sophisticated galactic chemical evolution modelling, L-GALAXIES can provide a comprehensive overview of the total metal and dust content in the Universe, separated into various astrophysical ""phases"" (e.g. stars, molecular clouds, neutral interstellar medium, and diffuse circumgalactic medium). By comparing this to observations, we can help provide constraints on the small-scale models used in simulations for stellar nucleosynthesis, stellar feedback, and dust production (including supernovae, binary-star phenomena, and grain growth). First, I will present the evolution of the cosmic metal density in L-GALAXIES back to z~6, compared to observations of the neutral ISM from damped Lyman-alpha (DLA) systems. Second, I will show the complimentary evolution of the cosmic dust mass density in L-GALAXIES across the same period, compared to dust observations from SED fitting and DLA absorption-line spectra. Third, I will combine these to provide an overall census of the dust and metal content in various phases of galaxies as a function of their stellar mass. These analyses reveal three key findings: (a) simulations must allow significant ejection of metals and dust out of galaxies via supernova-driven winds, (b) simulations may also need to be recalibrated at high redshift to account for the dust-obscured star formation now observed, and (c) DLA observations may over-estimate the metal and dust budget of the Universe due to biased sampling.

Near Pristine DLAs and their Chemistry
Dr Louise Amber Welsh, INAF OATs

The properties of the first (Pop. III) stars remain a mystery. The chemistry of relic environments, enriched only by the supernovae of these first stars, offer an exciting avenue to study this population. Stellar relics are often found in the local Universe while gaseous relics probe the chemistry of low density structures at earlier epochs (z>2). I will discuss the complementary nature of these searches and how they can be used together to understand early chemical evolution and structure formation. Particularly, I will focus on the most metal-poor DLAs found at z~3 and the associated high-precision abundance determinations. This will include an updated view, provided by new data, on both the [O/Fe] enhancement seen at the lowest metallicities and the 12C/13C isotope ratio. Uniquely, this isotope ratio can be used to probe the existence of low-mass (i.e. 1M_sun) Pop III stars and the enrichment timescale of these near-pristine DLAs.

Chemical Enrichment from the First Stars in Cosmological Simulations
Ms Dyna Ibrahim, University of Hertfordshire

The first stars can be constrained by the chemical composition of distant galaxies. It is crucial to understand how and when the first stars formed to understand the formation and evolution of our Universe. The latest observational data reveal unprecedented information about the chemical enrichment of the early Universe, which seems to behave differently from the local Universe. The first stars, being very massive, enrich their metal-poor environment in an uncertain way. To predict the abundances of the first galaxies, we include nucleosynthesis yields from Population III stars up to 300Msun, including faint supernovae, Wolf Rayet and Pair Instability Supernovae into our state-of-the-art hydrodynamical cosmological simulations. Our code (based on Gadget-3) also includes the latest nucleosynthesis yields from population II stars (from Kobayashi et al. 2020) for all stellar mass ranges. We predict the chemical abundance evolution of galaxies for different elements from the early Universe to the local Universe. For example, we find that the N/O abundance gives a systematically larger value with nucleosynthesis yields from Population III stars, which is comparable with observational data of the GN-z11 galaxy. I also discuss the evolution of metallicity gradients and elemental abundances of the intergalactic medium. We constrain our model by comparing it with observational data from the James Web Space Telescope (JWST) and the Atacama Large Millimeter/submillimeter Array (ALMA).

The Early Chemical Evolution of the Sagittarius Dwarf Galaxy
Dr Federico Sestito, University of Victoria

The most metal-poor stars offer a unique opportunity to understand early chemical enrichment in galaxies, carrying imprints of the first supernovae (SNe). The Sagittarius (Sgr) dwarf galaxy is ideal for testing chemical evolution and hierarchical accretion models. However, its most metal-poor region remains unexplored. I will summarize findings from the Pristine Inner Galaxy Survey (PIGS), which hunts the most metal-poor stars in the inner Galaxy and Sgr. I will present results from

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the largest detailed chemical abundance analysis of very metal-poor stars ([Fe/H]−2.0, as suggested by [Co/Fe] in this range. In the second part, I will discuss the chemo-dynamical properties of Sgr using a sample of ~350 metal-poor ([Fe/H]+0.7) underestimates the fraction of these stars in dwarf galaxies. We propose adjusting this threshold to [C/Fe]~+0.35 for Sgr, leading to a similar fraction of CEMP stars between the Milky Way and Sgr.

Chasing the Impact of the Gaia-Sausage-Enceladus Merger on the Formation of the Galactic Disk
Professor Daisuke Kawata, MSSL, UCL

We measure stellar age for APOGEE giants using our Bayesian Machine Learning framework BINGO (Bayesian INference for Galactic archaeOlogy, Ciuca et al. 2024). After de-noising the data, we found a drop in metallicity with an increase in [Mg/Fe] at an early epoch, followed by a rapid chemical enrichment with increasing [Fe/H] and decreasing [Mg/Fe]. Comparing with the Milky Way-like zoom-in cosmological simulation Auriga, we discuss that this could be due to the early epoch of gas-rich merger. We further argue that this could be associated with the last massive merger of our Galaxy, the Gaia-Sausage-Enceladus merger, and discuss how it impacted the formation of the Galactic thick and thin disks and also the Galactic bar. We will also briefly introduce Japan Astrometry Satellite Mission for INfrared Exploration (JASMINE), which will reveal the Milky Way's central core structure and its formation history with Gaia-level (~25 uas) astrometry in the NIR Hw-band, (1.0-1.6 um), Galactic centre archaeology survey.

Reconstructing the Formation Histories of Milky Way-Type Galaxies from the Chemical Abundances of their Tidal Debris
Dr Andreea Font, Astrophysics Research Institute, Liverpool John Moores University

From the chemodynamical properties of tidal debris in the Milky Way (MW), it has been inferred that disrupted dwarf satellites had different chemical abundances at their time of accretion compared with similar-mass dwarf satellites which survive at present day. Specifically, disrupted satellites appear to have had lower [Fe/H] and higher [Mg/Fe] at fixed stellar mass than the surviving ones. In a recent study (Grimozzi, Font & De Rossi 2024), we have used the ARTEMIS simulations to investigate this problem, and determine the evolution of chemical abundances (e.g., the stellar mass-metallicity relation, MZR) with redshift. We have found a strong correlation between the scatter in the MZR of the disrupted dwarfs and their accretion redshift (zacc), as well as with their cold gas fractions at accretion. The slopes of the MZRs of disrupted dwarf satellites are fairly similar at different accretion redshifts and are comparable with the MZR slope of surviving satellites in the MW today (≈ 0.32). These findings constrain some of the physical processes that regulate the chemical enrichment of dwarf galaxies (for example, the stellar feedback). The simulations also predict strong correlations between averaged properties of the disrupted dwarf populations, such as between «zacc», «[Fe/H]» and «[Mg/Fe]»), which suggests that the chemical abundances of the entire disrupted dwarf population can be used to constrain the

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merger history of its host. More specifically for the MW, the ARTEMIS simulations predict that the bulk of the disrupted population was accreted at «zacc» ≈ 2, to match the averaged «[Fe/H]» and «[Mg/Fe]». More broadly, our results suggest that one can gain an insight into the formation histories of other MW 'analogues', such as M31 or other massive galaxies nearby, provided that chemical abundances ([Fe/H] and [alpha/Fe]) of their debris from disrupted satellites become available.

Simba-C: Mock Halo X-Ray Observations with Athena X-IFU of the Chemical Abundances

Dr Renier Timothy Hough, North-West University

We use the (100 Mpc/h)3 Simba-C simulation to examine the chemical abundances in hot intragroup and intracluster gas, by extracting and fitting mock X-ray spectra using the MOXHA pipeline from Jennings & Dave'. As part of our initial testing phase, we used XSPEC to extract the inner-core chemical abundances of O, Ne, Mg, Al, Si, S, Ar, Fe, and Ni from our simulated MOXHA X-ray spectra for seven clusters, seven warm groups, and seven cooler groups. We found increasing chemical abundances for most elements as a function of the halo temperature above kT>1 keV (corresponding to the warmer groups), with exceptions observed for Al, S, and Ar. We also found decreasing [α/Fe] abundance ratios as a function of the halo temperatures. We are in the process of extending the number of haloes to include all simulated haloes within Simba-C with sufficient M500 halo mass and sufficient hot gas for Athena X-IFU 0.5-3.0 keV detections at R500, as well as using the Bayesian X-ray Analysis MCMC simulation to maximise the best-fit likelihood.

WEDNESDAY 10 JULY

Nuclear and Atomic 2

R-Matrix Atomic Data for Applications in Astrophysics

Professor Cathy Ramsbottom, The Queen's University of Belfast

The spectra currently emerging from ground- and space-based facilities are of exceptional resolution and cover a broad range of wavelengths. To meaningfully analyse these spectra, astronomers utilise complex modelling codes to simulate the astrophysical observations. The main inputs to these codes are radiative and collisional atomic data to include energy levels, transition probabilities, collision rates for electron-impact excitation/ionisation, photoionisation and recombination. While some of the data can be obtained experimentally, they are usually of insufficient accuracy or limited to a small number of transitions. The R-Matrix approach is credited as one of the most powerful and reliable tools in calculating these atomic data. Recent and ongoing developments of the relativistic parallel DARC codes have enabled an order of magnitude advance in the accuracy of the atomic structure and subsequent collision calculations that are now feasible for lowly ionised high Z ions. In 2017 the first gravitational wave from a binary neutron star merger (NSM) was detected and the ejected matter created a bright glow called a Kilonova via r-process nucleosynthesis. Disentangling r-process abundances from the broad spectra of NSM is a challenging

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task that demands a high degree of rigour in calculations of the ejecta opacity and the atomic calculations that underpin them. Recent publications by the group at QUB report on extensive relativistic atomic structure and electron-impact excitation collision calculations for the species Au I-III, Pt I-III, Sr II, Y II and Te I-III, which were subsequently used in collisional-radiative models to investigate line ratio diagnostics in NSM environments

Constraining the NiCu Cycle in X-Ray Bursts: Spectroscopy of 60Zn

Mr Conner O'Shea, University of Surrey

Type-I X-ray bursts are interpreted as thermonuclear explosions in the atmospheres of accreting neutron stars in close binary systems. During these bursts, sufficiently high temperatures are achieved such that "breakout" from the hot CNO cycle occurs. This results in a whole new set of thermonuclear reactions known as the rp process. This process involves a series of rapid proton captures resulting in the synthesis of very proton-rich nuclei up to the Sn – Te (A ~ 100) mass region. Various sensitivity studies have highlighted the 59Cu(p,γ)60Zn reaction as significant in its impact on energy generation along the rp -process path within X-ray bursts, and hence, the resultant light curve and final isotopic burnt ashes composition. In particular, competition between the 59Cu(p,α)56Ni and 59Cu(p,γ)60Zn reactions within the NiCu cycle directly determines whether the pathway of nucleosynthesis flows towards higher mass regions. At present, stellar reaction rates for both of these astrophysical processes are based entirely on statistical-model calculations. Recently, however, an indirect study of the nucleus 60Zn has surprisingly shown a plateau in the level-density of states in the region of interest, contrary to the usual expectation of exponential growth with increasing excitation energy. As a result, a statistical-model approach of the 59Cu(p,γ) reaction rate may be insufficient, and it is therefore now essential to explore the properties of excited states in 60Zn that influence the astrophysical 59Cu(p,γ)60Zn reaction. Specifically, the 59Cu(p,γ) reaction is expected to be dominated by resonant capture to excited states above the proton-emission threshold in 60Zn, Sp = 5105.0(4) keV, that lie within the Gamow energy window, Ecm ~ 0.7 – 1.5 MeV. In this work, we aim to utilise the 59Cu(d,n) reaction in inverse kinematics at the Facility for Rare Isotope Beams (FRIB) to obtain the first measurement of single-particle properties of resonances in the 59Cu(p,γ) reaction. Specifically, 60Zn ions separated within the S800 spectrometer and identified prompt with respect to γ-rays detected by the GRETINA array will be used to determine the energy and angle-integrated cross sections of key resonance states, while neutrons detected by the LENDA array will be used to constrain the distribution of spin-parity assignments across the relevant excitation energy region of Type-I X-ray burst nucleosynthesis

NLTE Analysis of Optically Thin Spectral Features

Mr Leo Patrick Mulholland, The Queen's University of Belfast

The AT2017gfo has added to the growing interest in r-process elements, which are expected to be particularly abundant in the nucleosynthesis trajectories of neutron star

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mergers. With the choice of elements guided by nuclear physics at particular values of Y_e, our group calculates atomic data catered for modelling of the astrophysical objects without the use of local-thermodynamic-equilbirum using collisional radiative modelling. By enforcing observed luminosities, we are then able to make mass estimates of the candidate ions. This serves particularly as a test of the calculated atomic data and, based on the feasibility of the mass estimate, also the underlying nucleosynthesis theory. This event, as well as the GRB230307A last year sport features consistent with the fine structure lines of Te and W, which are particularly interesting to atomic and nuclear physicists likes - as these species lie at the second and third peaks respectively of the r-process abundance. These features also occur at the late stage collisionally dominated regime of the events, making an optically thin model suitable for their analysis. Collisional radiative modelling, and particularly mass estimation of these species in and out of LTE will be discussed.

Insight to the Explosion Mechanism of Core Collapse Supernovae Through Gamma-Ray Spectroscopy of 46Cr

Mr Chris Cousins, University of Surrey

Currently, the explanation behind the explosion mechanism of core collapse supernovae is yet to be fully understood. New insight to this phenomena may come through observations of 44Ti cosmic gamma rays; this technique compares the observed flux of cosmic 44Ti gamma rays to that predicted by state-of-the-art models of supernova explosions. In doing so, the mass cut point of the star can be found. However, a road block in this procedure comes from a lack of precision in the nuclear reactions that destroy 44Ti in supernovae, most notably the reactions 44T(alpha,p)47V and 45V(p,gamma)46Cr. Therefore, this study aims to better understand the 45V(p,gamma)46Cr reaction by performing gamma-ray spectroscopy of 46Cr with the aim of identifying proton-unbound resonant states. The experiment was conducted at the ATLAS facility at Argonne National Laboratory, using the GRETINA+FMA setup, where 46Cr was produced via the fusion-evaporation reaction 12C(36Ar,2n). The cross section for producing 46Cr, in this reaction, is estimated to be in the mu b range. Nevertheless, with the power of the GRETINA+FMA setup, we show that it is possible to cleanly identify gamma rays in 46Cr. These include decays from previously unidentified states above the proton-emission threshold, corresponding to resonances in the 45V + p system.

Stars 2

Constraining SN Ia Progenitors from the Observed Iron-Peak Elemental Abundances in the Milky Way Dwarf Galaxy Satellites

Mr Ryan Alexander, University of Hull

Nucleosynthesis yields from sub-Chandrasekhar (sub M-ch) and Chandrasekhar (M-ch) SN Ia progenitors have been discussed and debated for decades on their contributions to iron peak elements in the cosmos. Investigating SNe Ia in ultra-faint dwarf galaxies (UFDs) and dwarf spheroidal galaxies (dSphs) with different star formation and chemical enrichment histories may shed light on the progenitors in different environments. To this end, we incorporate metallicity dependent SN Ia yields from different progenitors within our novel inhomogeneous chemical evolution model, i-GEtool, and compare the predicted chemical abundances to observations in different UFD and dSph galaxies. While the observed [Mn/Mg] ratios increase towards higher metallicities both within single galaxies and when considering galaxies with different metallicity distributions, the observed [Ni/Mg] ratios show a weaker correlation. In my talk, I will show that our models for UFD and dSph can reproduce the observed trends along with their scatter without invoking any contribution from sub M-ch SN Ia progenitors, at variance with previous studies in the literature. I will discuss the implications of our findings for the observed iron peak elemental abundances in the Milky Way halo and disks, outlining our future plan.

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The Fate of Massive Stars Across Cosmic Time

Miss Caitlan Chambers, Keele University

Massive stars have a profound impact on the universe, particularly through how they end their lives. The fate of massive stars, including the type of supernova and remnant they produce, is dependant on both their CO core mass and the composition of their envelope. Both of these properties depend heavily on mass loss, and so are also dependent on metallicity. Rotating models experience an increase in mixing in radiative zones, leading to larger CO core masses. Additionally, rotation can increase mass loss both directly and indirectly, through mechanical mass loss and increased luminosity. We present analysis of the fate of massive stars using existing grids of rotating and non-rotating GENEC stellar evolution models with initial masses from 9-500 solar masses, and metallicities across extremely metal poor, SMC, LMC, solar and supersolar values. We find that metallicity and rotation have a significant impact on both the remnant and supernova type of massive stars. Finally, the results are combined with an initial mass function (IMF) to determine the fraction of massive stars per fate, and a comparison between the Salpeter IMF and a top-heavy IMF is given. In particular, the types of pair-instability supernovae are discussed alongside the location of the pair-instability mass gap.

The Final Minutes of Silicon Shell Convection in 3D

Dr Vishnu Varma, Keele University

The workhorse of understanding stellar evolution has been in 1D stellar evolution modelling, where simplified prescriptions of physical processes are implemented to evolve a star over its entire lifetime. While stellar evolution modelling has improved over the decades, their results are still limited by uncertainties in the physics due to complex multi-dimensional processes in stellar interiors. To better understand, and hopefully improve some of these uncertainties, we have run 3D hydrodynamic simulations of the final hour of silicon shell convection of a 14M_solar star prior to core-collapse. I will present these results, and compare them to what was found in 1D stellar evolution calculations. I will discuss how the presence of realistic turbulent mixing affects nuclear burning and how choices of convective overshooting in 1D can affect the final structure of the massive star.

Magnetic Field Strength Effects on Nucleosynthesis from Neutron Star Merger Outflows

Dr Kelsey Lund, North Carolina State University / Los Alamos National Lab

The merging of two neutron stars can provide the conditions necessary for the production of the heaviest elements in the universe via the rapid neutron capture process (r-process). When this occurs, an abundance of material is produced lying far from nuclear stability, and the decays of these nuclei produce the electromagnetic signal: the kilonova. Modeling these kilonova signals, and indeed the entire merger system, remains subject to uncertainties stemming from both nuclear properties far from stability as well as from incomplete information regarding the evolution of the extreme astrophysical environment in which this occurs. I will discuss current work aimed at approaching this problem from both an astrophysical perspective with magnetohydrodynamic simulations of the post-merger disk with neutrino transport, as well as from a nuclear perspective with detailed nucleosynthesis studies.

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