'Forging stars and galaxies in the first billion years (ForgingStars)' Abstracts

Talks

A spatially resolved view of stars and ionised gas in Hα emitters at z ~ 6

Authors

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Abstract

H\alpha emission has long been used as a powerful tracer of star formation rate (SFR) within galaxies. The sensitivity and wavelength coverage of JWST now make it possible to extend H\alpha studies back to the Epoch of Reionisation, and the telescope's exquisite resolution provides a view of the clumpy morphology of galaxies at these redshifts. In this talk, I will present the results of spatially resolved SED fitting for deep observations across the rest-frame UV to near-IR for a sample of H\alpha emitters identified by the JWST Emission Line Survey (JELS) using narrowband imaging at z \sim 6.1. I will compare SFRs averaged over \sim 10 and \sim 100 Myr timescales inferred both from H\alpha - and UV-derived measures and through SED modelling. This approach offers insights into recent bursts of star formation driving the hard radiation fields and extreme emission line properties of these galaxies, but also carries challenges and degeneracies due to dust and the biases imposed by uncertain calibrations and priors. By analysing maps of stellar mass, dust, and ongoing star formation on kiloparsec scales, I will establish a picture of when and where these galaxies assembled their stars. In this context, I will discuss the interplay between star formation burstiness and the disordered spatial structures of galaxies in this regime, contributing to the emerging understanding of stochastic star formation in both high-redshift and low-mass systems.

Cosmological simulations of the high-redshift galaxy population adopting a variable IMF

Authors

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Abstract

Recent JWST observations of high-redshift galaxies signal deviations of the stellar initial mass function (IMF) from the form inferred in the Solar neighbourhood. We present large-scale cosmological hydrodynamical simulations of the new COLIBRE galaxy formation model that has been adapted to allow non-universal IMFs, self-consistently adjusting metal yields and feedback energetics. Here we focus on results from simulations in a cosmological volume of (100 cMpc)^3 with a gas and dark matter particle resolution of ~ 10^6 Msolar. We vary the high mass slope of the IMF and choose to make the IMF increasingly top heavy (flatter slope) for stellar populations that form from dense gas. Our model yields an elevated far-UV luminosity in young stellar populations, resulting in high redshift (9 < z < 16) UV luminosity functions that are in stronger agreement with recent data from JWST than current galaxy formation models. One of the advantages of the COLIBRE model is its live dust model, enabling us to track the impact that a variable IMF has on dust formation and evolution in galaxies. The increase in the number of SNII events from the top heavy stellar populations results in higher dust masses per galaxy in our variable IMF simulations than the original COLIBRE model, meaning that a significant fraction of the extra UV photons produced by top heavy stellar populations get extinguished. We compute dust attenuated UV luminosities using the radiative transfer code SKIRT and find that the most luminous galaxies are dimmed via dust by up to 5 magnitudes at z=9, or up to 3 magnitudes at z=12. In fact, accounting for dust attenuation has negligible impact on the shape of the UV luminosity function for 9 < z <16 but limits the attenuated magnitudes to > -20 (> -19 at z=15).

Characterising the Dynamic ISM and the Bursty Star Formation in a Highly Lensed Complex System at z=10.17 with NIRSpec/IFU

Authors

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Abstract

JWST revealed that high-z galaxies exhibit bursty star formation histories regulated by feedback and gas inflows/outflows. According to theoretical models, feedback preferentially removes metal-rich gas, while starbursts are triggered by mergers and metal-poor inflows. Hence, gas-phase metallicity holds key insights about the processes shaping early galaxies.
I will present the first NIRSpec/IFU study of spatially resolved ISM in MACS0647-JD (z=10.17), the brightest system at z>10. The system consists of two stellar components. The main component is substantially more massive and more metal enriched than its companion, suggesting that the former hosts an older stellar population. Intriguingly, the centroid of line emission in this system is spatially offset from the stellar continuum centroid (which coincides with the location of the massive clump). This provides strong evidence for a recent starburst, possibly associated with a merger.
Combining the metallicity and the ionised gas velocity dispersion maps, we infer highly turbulent and metal poor gas between the clumps. Together with the observation of AGN signatures in the inter-clump regions, this could suggest shocked gas accretion. This hypothesis is supported by: 1) a significant spatial correlation between gas dispersion and metallicity in individual spatial pixels (p-value of 1.25e-3) and 2) a morphologically distinct spatial distribution of low ionisation gas (traced by [O II] emission), compared to the high ionisation gas. Our shock modelling analysis implies that, if shock-driven photoionisation are to explain the observed line ratios in the inter-clump regions, extreme pre-shock electron densities would be needed. This may be consistent with a multi-zone ISM, with an inner, high density, high ionisation region and an outer, lower density, lower ionisation region, as suggested by the extended [O II] emission.
The north-eastern region (also between the two clumps) has a high gas dispersion and low metallicity, as well as low stellar mass density and a highly elevated star formation burstiness (given by the SFR10/SFR100 ratio), indicating a recent star formation enhancement driven by a metal-poor gas inflow or a large scale recirculation of the gas originating in the less enriched stellar component. Furthermore, analysing the system on a spaxel-by-spaxel basis, we do not find a significant correlation between the stellar mass density and gas-phase metallicities, revealing that, within the first 500 Myr after the Big Bang, metals have not yet sufficiently mixed to homogenise local chemical variations.
These results highlight the connection between metal-poor inflows, turbulent ISM, and localised starburst episodes in early galaxies. The absence of a resolved mass–metallicity trend suggests that chemical enrichment is highly inhomogeneous on sub-galactic scales. MACS0647-JD provides a unique laboratory for studying stochastic star formation and the complex ISM in the first galaxies.

Between the Lines: Connecting Star Formation Physics to Burstiness and ISM Structure in High Redshift Galaxies

Authors

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Abstract

Various solutions have been proposed to solve the high-redshift `bright galaxy problem', such as the presence of more efficient star formation, more bursty star formation, and variable initial mass functions. While each will boost the UV flux of a given halo, different star formation scenarios will differ in their characteristic star formation histories and ISM properties -- providing an interesting avenue to constrain such physics using state-of-the-art spectroscopic data from JWST. In this talk, I will provide an overview of results from the MEGATRON suite of high-resolution cosmological radiation hydrodynamics zoom simulations which for the first time feature non-equilibrium chemistry and heating/cooling processes coupled to on-the-fly radiative transfer. Each simulation explores one of these distinct star formation scenarios, coupled to detailed prescriptions for the formation, evolution, and feedback from population II and III stars, including: stellar winds, supernovae, and hypernovae.

Using these simulations, I will discuss the impact that these different star formation scenarios have on high-redshift stellar populations and interstellar gas properties. In particular, I will focus on the nature of bursty star formation histories, on the coupling to and structure of the multi-phase interstellar medium, and on the production and escape of ionizing radiation in the context of cosmic reionization. At each stage, comparisons will be made between synthetic observations of MEGATRON galaxies and JWST observations. Finally, I will touch on ongoing efforts to model the impacts of AGN feedback on the interstellar medium of high-redshift galaxies.

The JWST EXCELS Survey: Spectroscopic constraints on the ionizing properties of star-forming galaxies at 1<z<8

Authors

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Abstract

Accurate estimates of the ionizing-photon production efficiency (xi_ion) are central to determining whether early galaxies supplied the photons that reionized the intergalactic medium, yet robustly linking xi_ion to readily observed galaxy properties remains challenging because of measurement uncertainty, sample diversity and heavy-tailed outliers. Using deep, medium-resolution JWST/NIRSpec spectroscopy from the EXCELS survey (N = 159 star-forming galaxies at 1 < z < 8) we measure Balmer-line luminosities and derive spectroscopic xi_ion for individual objects. To map xi_ion onto observable quantities we implement a Bayesian regression framework that fully marginalises measurement errors, models heavy-tailed scatter, and returns intrinsic variance. Single-variable fits recover clear but scattered correlations with nebular equivalent widths (H-alpha and [O III]) and the UV slope beta. Crucially, a compact multivariate model, with either Halpha or [O III] equivalent width combined with beta and the nebular E(B–V) captures the bulk of galaxy-to-galaxy variation. These three observables permit prediction of xi_ion to =0.15 dex while the population intrinsic scatter is small (sigma_int = 0.035 dex). Dusty, high E(B–V) systems account for most outliers, implying obscured intense star formation or differential attenuation can boost apparent xi_ion. I discuss implications for ionizing budgets and escape fractions, and place these EXCELS results in the context of xi_ion and the role of bursty star-formation directly during the Epoch of Reionization (z~7) using deep imaging from PRIMER and JADES.

Stochastically Sampling Star Clusters: Chemical Enrichment and Ionising Photons

Authors

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Abstract

As observations and simulations probe lower masses at higher redshifts, it becomes increasingly important to accurately model clusters of stars below 10^4 solar masses. At this point the small number of massive stars, which dominate enrichment and ionising photon production, means it is necessary to stochastically sample the initial mass function, as opposed to taking the average.
I am investigating the effect of sampling the IMF over several orders of magnitude in time and a range of cluster masses, looking at the abundance patterns of the ejecta and the ionising photon output.
I apply this methodology to the recently reported high-redshift (z~6.6) object LAP1-B, which has an estimated mass ~2,700 solar masses, and a proposed metallicity 0.4% that of the sun, which would make it the most metal poor galaxy ever observed. I investigate whether the currently cited evidence for population III stars in this galaxy, such as its high C/O ratio and hard ionising spectrum, could also be explained by stochastic IMF sampling of population II stars.
This work will be extended to include as a sub-grid model for star particles in an upcoming cosmological simulation suite, and has implications for the formation of stellar clusters and galaxies, determining their feedback modes, and for confirming or ruling out possible detections of the first stars to form.

Monsters with empty bellies? The first comprehensive view of dense gas in early galaxies

Authors

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Abstract

Monsters with empty bellies? A comprehensive census of dense gas in high-redshift, massive galaxies
Massive galaxies in the early universe have often star-formation rates (SFRs) 100-1000x higher than the Milky Way. However, it has long been unclear what causes these immense SFRs: are high-redshift galaxies forming stars very efficiently, or are they simply more gas-rich than present-day galaxies? Over the last decade, extensive surveys of molecular gas in high-z galaxies (via CO, dust, and [CII] emission) have established that they are indeed very gas-rich. However, a significant fraction of the molecular gas resides in diffuse, extended reservoirs, contributing little to the observed SFR. Maybe high-z galaxies have significantly enhanced star-forming efficiency after all? To answer this question, we need to study the dense gas from which stars form.
As the low-J CO and [CII] emission trace gas down to densities of ~10^2 cm-3, we need to rely on emission lines of HCN, HCO+, and HNC. Unfortunately, as these lines are 10-100x fainter than CO or [CII], they have been detected in only a handful of high-z galaxies. I will showcase PRUSSIC: a comprehensive census of dense gas at high redshift with ALMA, NOEMA, and VLA. We find that high-z galaxies contain surprisingly little dense gas and have an enhanced star-forming efficiency - a direct contradiction to earlier studies. I will outline how these results can inform our understanding of early star formation and next-generation theoretical models.

Cutting the Gordian knot: Revealing the spatially resolved star formation history of a maximally old quiescent galaxy

Authors

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Abstract

High-redshift massive quiescent galaxies are intriguing probes of star formation in the early Universe. Results from JWST suggest that observed quiescent galaxy number densities at z>3 lie above predictions from theoretical models. Moreover, star formation histories of these systems, inferred from SED fitting, indicate very early formation and rapid quenching timescales. These findings might imply tensions with ΛCDM or deviations from standard galaxy formation physics, such as high baryon accretion efficiencies.

An extreme example is ZF-UDS-7329 (henceforth Erigeneia), an ultra-massive (logM*>11) quiescent galaxy (z=3.2) which likely peaked its star formation history and quenched at z~11. While previous studies have focused on the implications of its extremely high formation redshift for ΛCDM or stellar mass build-up efficiency, less attention has been paid to its morphology. From photometry, Erigeneia hosts a central bulge-like component and outer disc. JWST integrated spectroscopy, mostly covering the central bulge, reveals an older stellar population (~1-2 Gyr); however, JWST photometry indicates a colour gradient, suggesting a younger, recently quenched disc (<500 Myr). This raises many open questions about the nature of bulge and disc formation, as well as how this relates to the formation and quenching of massive galaxies in the early Universe. To explore this further, we analyse new ultra-deep (15 hours) high-resolution (R~2700) JWST NIRSpec/IFU observations of Erigeneia, covering the full extent of the galaxy.

We introduce Gordian, a joint photometric-spectroscopic bulge-disc decomposition tool that produces independent bulge and disc spectra. Gordian combines the excellent spatial resolution of NIRCam imaging with the spectral coverage of IFU data to decompose a galaxy into bulge and disc components and extract their respective spectra. By fitting the SEDs of each component with self-consistent α-enhanced stellar population models, motivated by the likely α-enhancement of Erigeneia ([α/Fe]≈0.2-0.5), we robustly constrain the ages, chemical enrichment, and quenching timescales of the bulge and disc separately. We find evidence for a more recently quenched disc, with an extended star formation history, and an older quiescent bulge – results that are indicative of inside-out quenching. We also explore the influence of factors such as galaxy mergers, environment and variations of the initial mass function as possible explanations for Erigeneia's early and complex formation.

Our spatially resolved analysis offers new insight into whether rapid early bulge formation and more extended disc quenching are required to explain one of the most extreme massive quiescent galaxies known. This provides direct constraints on the formation channels and chemical enrichment pathways that govern the assembly and quenching of massive systems in the early Universe.

JWST's N-emitters, ALMA's F-emitters, and intermittent star formation

Authors

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Abstract

The James Webb Space Telescope (JWST) is expected to find the first galaxies - those hosting metal-free stars. Surprisingly, though, galaxies with strong metal lines have been detected indicating unusual chemical composition (e.g. high N/O ratio). Nitrogen can be enhanced not only by asymptotic giant branch (AGB) stars but also Wolf-Rayet stars. I show galactic chemical evolution models that can naturally reproduce N emitters with intermittent star formation. This does not require changing the initial mass function (IMF). I will then discuss how other elements (C and Ar) can be used to constrain the IMF. Finally, as Wolf-Rayet stars are expected to enhance Fluorine as well, I will show two cases hunting for `F-emitters' with Atacama Large Millimeter/submillimeter Array (ALMA); one submillimeter galaxy at z=4.4 indicated a high F abundance, while another at z=6.0 did not show the F enhancement, which further supports the intermittent star formation in high-redshift galaxies.

Constraining the bursty star formation cycle of early rejuvenating galaxies using JWST

Authors

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Abstract

The bursty nature of much of early star formation, particularly in dwarf galaxies, has become somewhat established through simulations and recent high-redshift observations carried out by JWST. These bursty star formation histories (SFHs) have significant implications for the evolution of the star-forming main sequence, explaining the luminosity function at high-redshift, and deriving accurate parameters from SED fitting. Bursty SFHs are thought to be caused by feedback with an associated duty cycle. Many early quiescent galaxies have already been identified at redshifts as high as $z \sim$ 5, with authors finding signs of potentially temporary quiescence or lulls in star formation from SED fitting. We identify a sample of 11 galaxies from JADES DR4 spectra at redshift 2 $< z <$ 4, sometimes on the upper mass limit of dwarf galaxies ($\sim10^9 M_\odot$), which appear to have recently restarted star formation after a lull. These objects are characterised by continua reminiscent of A and F stars with large Balmer breaks and an indicative bend in the UV but display booming emission lines with no detectable broad component. We estimate the age of the original stellar population using the Balmer break and introduce a new age diagnostic based on the UV bend which is calibrated with single stellar population spectra. Using diagnostic line ratios and SED fitting carried out with BAGPIPES, BEAGLE, and PROSPECTOR to refine our estimates and to constrain duty cycles, we identify a consistency in the duration of the star-formation lull, around $\sim$0.2-0.4 Gyr. We further investigate the equivalent width of lines and their correlation with the Balmer break strength and UV bend strength diagnostics of these galaxies. The morphology and resolved SEDs of the objects show strong variation, suggesting several mechanisms may be at play.

The ultraviolet continuum slopes of galaxies at $z \geq 12$ selected from 0.5 sq. deg of JWST imaging

Authors

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Abstract

The shape of the UV continuum SED (parameterised by the UV continuum slope, β) is an excellent probe of young stellar populations and dust attenuation in galaxies. With deep JWST/NIRCam imaging, accurate measurements of the continuum slope out to the highest confirmed redshifts (z =14.5) are now possible, yielding crucial insights into both properties at the earliest cosmic epochs. In recent years, several JWST studies have investigated the UV continuum slopes of galaxies up to z=12. Consistently, these studies have shown that the slope becomes, on average, very blue by z = 11 ($\beta \sim -2.6$). The most straight-forward interpretation of this is that galaxies become dust (attenuation) free, with correspondingly large escape fraction at the highest redshifts. The fact that the UV SEDs of galaxies appear to be completely unattenuated can also, in part, help to explain the abundance of UV-bright galaxies at z > 10.

However, due to the wide areas needed to obtain large enough sample sizes, little is currently known about the average UV continuum properties of the galaxy population at z > 11. In my talk, I will present the largest ever sample of photometrically-selected galaxies at z > 12 from a wide-area (0.5 sq. deg) search across all publicly available NIRCam imaging. I will demonstrate that the average UV-continuum slope at these redshifts remain consistent with the attenuation-free limit of -2.6, continuing the trend seen in previous studies. We also find that at the highest redshifts (z > 13.5), the average UV slope may even be bluer. Our results suggest that above z=11 the galaxy population is, on average, unattenuated by dust, and may also have a high average escape fraction (> 20%). These findings have important implications for the physics of early galaxy growth and timeline of cosmic reionization.

The High Redshift Frontier with JWST - spectroscopic results from JADES

Authors

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Abstract

I will give an overview of results on the highest redshift galaxies from the Guaranteed Time Observations of the NIRSpec Instrument Science Team, including those co-ordinated with the NIRCam Team as part of the JWST Advanced Deep Extragalactic Survey (JADES). We have used the multi-object microshutters on NIRSpec to target several thousand galaxies in the GOODS fields, including several hundred at redshifts beyond 6 (within the epoch of reionization) and have spectroscopically confirmed galaxies beyond redshift 14 for the first time.

NIRSpec spectroscopy at 1-5microns is sensitive to rest-optical emission lines over a wide range of redshifts and means that we can study the evolution of dust attenuation, star formation rates, metallicity, chemical abundances, ionization and excitation mechanism in galaxies out to high redshifts. Our observations have revealed low metallicities, large ionization parameters and high ISM temperatures for galaxies at redshifts beyond 6, indicating dramatic changes in the stellar populations compared with low redshift. These include a very UV-luminous galaxy at z=14, where bursty star formation or potentially a top-heavy initial mass function may be brightening the UV. In another galaxy within the epoch of reionization we have evidence of a Balmer jump due to nebular continuum, and hot enough stars to produce enough ionizing photons such that the two-photon emission becomes visible, again hinting at a top-heavy IMF. A z=10.6 galaxy (GN-z11) unexpectedly has Lyman-alpha in emission, and a super-solar N/O ratio is inferred from rarely-seen high-ionization lines of nitrogen.

The Clumpy Fraction of Galaxies at z~3–9 with JADES: A Transition from Major merger-driven to Disk-instability-driven Formation

Authors

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Abstract

The stellar mass growth history of galaxies over cosmic time is governed by the combination of star formation and the accretion of satellites, and with recent observations of JWST revealing a large number of clumpy systems at z>3, a natural question arises regarding the in-situ or ex-situ origin of these substructures, particularly as a function of redshift and stellar mass. I investigate the formation mechanisms of star-forming clumps in log(M/Msol)=8–10 galaxies at redshifts z=3−9 using JADES NIRCam imaging. I develop a self-consistent clump detection algorithm that uses dendrograms, clump-to-galaxy flux fraction, and galactocentric selection criteria to extract clumps from rest-frame UV and optical images. By applying completeness corrections, I measure the fraction of clumpy galaxies and compare it with major merger fractions to distinguish between formation channels. At lower stellar masses, we find that the clumpy fraction remains flat with redshift at ∼13%, while for higher-mass galaxies it declines from ∼51% (z∼3) toward higher-z. We uncover a key wavelength dependence: clumps in low-mass galaxies are more prominent in the rest-frame optical (implying higher mass, lower SFR), while clumps in higher-mass galaxies are brighter in UV (lower mass, higher SFR). By comparing these trends with merger rates, we conclude that major mergers are the primary driver of clump formation at high-z and low stellar mass. As the host galaxy's stellar mass increases, in-situ mechanisms, such as violent disk instabilities, become the dominant channel at >10^9 Msol. Our findings demonstrate that the dominant clump-formation pathway depends on both galaxy mass and cosmic epoch, with mergers playing a critical role in early galaxy evolution.

Let There Be Light: UV Luminosity Functions at z=7-15 from the new COLIBRE Simulations

Authors

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Abstract

COLIBRE is a new suite of large-volume cosmological simulations that, for the first time, explicitly models the multi-phase ISM and follows the formation and evolution of dust self-consistently in cosmological volumes. At low redshift, we have already shown that COLIBRE reproduces the observed galaxy luminosity functions (LFs) from the far-UV to the sub-millimetre with unprecedented success. In this talk, I will present predictions for the UVLFs of COLIBRE galaxies at z = 7-15, computed with the SKIRT radiative transfer code, and compare them with current observational constraints, including recent JWST results. I will show that, although COLIBRE broadly reproduces the observed evolution of the stellar mass function up to z ~ 12, its predicted UVLFs remain systematically too low at the bright end. To test whether this discrepancy could be driven by observational effects, we explore the impact of redshift binning, Eddington bias, and photometric redshift errors. These effects reduce the discrepancy, but do not remove it. The results suggest that, despite its strong success at low redshift, additional physics may still be required to reproduce the UV luminosities of the earliest galaxies, for example a top-heavy IMF.

Metal Mayhem at z~7-10: Diversity and Evolution of Gas-Phase Metallicity Gradients

Authors

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Abstract

The first billion years of cosmic history mark a crucial phase in galaxy evolution, when metal enrichment, feedback, and the circumgalactic medium (CGM) were rapidly taking shape. With JWST now providing spatially resolved spectroscopy at unprecedented redshifts, we can directly probe the distribution of metals from the interstellar medium out to the interface with the surrounding gaseous environment. I present my study of gas-phase metallicity gradients at z = 7-10, based on NIRSpec IFU observations of seven low-metallicity galaxies, directly addressing the gas-galaxy connection in the era of reionisation. Our analysis reveals a wide diversity of metallicity gradients, with values ranging from mildly negative to flat or positive, and substantial scatter across the sample. This contrasts with the uniformly negative gradients observed at $z \approx 0$ and the flattened gradients at cosmic noon, pointing to a three-phase evolutionary sequence. The scatter likely reflects the stochastic nature of high-redshift star formation, driven by the shifting interplay between pristine gas accretion, bursty feedback, and turbulent internal mixing. To place these gradients in a broader chemical context, we also examine the mass–metallicity relation (MZR), star-forming main sequence (SFMS), and the fundamental metallicity relation (FMR) and its offsets from the local relation. Our sample lies systematically below the z∼0 baseline, consistent with rapid pristine gas inflow from the CGM and inefficient metal retention.

Finally, we identify three low-metallicity satellites around two hosts, which exhibit flattened gradients suggesting efficient radial mixing. Crucially, in one system, we detect a gaseous bridge, mainly consisting of [OIII], directly connecting the satellite to the host galaxy. This gaseous link provides a clear signature of ongoing tidal interaction and gas exchange, demonstrating how mergers and environment shape the chemical landscape of the early Universe. Taken together, these observations provide new constraints on the early baryon cycle and the mechanisms regulating galaxy formation in the first billion years.

Tracing bursty star formation and star-formation efficiency in the first billion years: Bayesian SED fitting of JADES NIRSpec + NIRCam observations

Authors

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Abstract

Understanding star formation in the first billion years of cosmic history requires robust constraints on how galaxies form their stars, whether through smooth, steady accretion or through intense, short-lived bursts. Disentangling these modes observationally demands both broad wavelength coverage to anchor the stellar continuum and spectroscopic measurements to probe the instantaneous star-formation rate through nebular emission. JWST now provides both simultaneously for statistically significant samples at high redshift. We present a Bayesian SED fitting analysis of approximately 3000 spectroscopically confirmed galaxies from the JADES survey, spanning $1<z<14$. Our framework, built on Prospector, jointly fits JWST NIRCam broadband photometry across 20 filters and 34 different NIRSpec emission line fluxes. The model incorporates a non-parametric star-formation history with 8 time bins, a flexible dust attenuation law (Calzetti with a free power-law slope and a separate birth-cloud component), self-consistent nebular emission with free gas-phase metallicity and ionization parameter, and IGM absorption. We explore 36 model configurations, varying the star-formation history prescription, the treatment of ionizing photon escape, and the inclusion of an emission line scaling parameter, and compare them using their relative Bayesian evidence.

We focus on what these fits reveal about the burstiness of star formation at high redshift. By comparing SFR indicators sensitive to different timescales like the UV continuum (tracing star formation averaged over ~100 Myr), the SED-derived SFR from the non-parametric SFH (sensitive to the most recent ~10-30 Myr), and the H-alpha luminosity (tracing the instantaneous rate over ~5 Myr) we quantify the prevalence and amplitude of recent bursts. We examine how burstiness correlates with stellar mass, specific star-formation rate, and position relative to the star-forming main sequence, and assess whether the scatter in the main sequence at high redshift can be attributed to stochastic star-formation histories. We also present constraints on the gas-phase metallicity and its co-evolution with stellar mass and star-formation rate, providing an independent probe of the efficiency with which these early galaxies convert gas into stars and enrich their surroundings. Finally, we discuss how the inferred escape fractions of ionizing photons connect bursty star formation to the process of reionization.

Improved initial conditions in ΛCDM: consequences for galaxy formation in the first billion years after the Big Bang

Authors

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Abstract

ΛCDM predicts that baryons and CDM emerge from recombination with distinct density fields, resulting in compensated spatial variations in the local baryon-to-CDM ratio. Analytic predictions show that overdense regions are baryon deficient, which may be important for galaxy formation in the early Universe. Yet most cosmological simulations neglect this effect in their initial conditions (ICs).

In this talk I will present results from cosmological simulations, including those using the FLAMINGO galaxy formation model, that compare standard ICs with physically consistent two-fluid ICs. I will show that the baryon deficiency in overdense regions imprinted at recombination persists through non-linear collapse and can be predicted by an analytic model. This deficiency leads to systematic reductions in star formation rates, stellar masses, and black hole growth, which are largest at early times and become negligible by the present day. As JWST and upcoming facilities increasingly probe the early Universe, incorporating two-fluid ICs into cosmological simulations will be essential for producing unbiased predictions of early galaxy formation and black hole growth.

Interpreting the stellar IMF at early times - Impact of the pre-main sequence on chemical enrichment and stellar population synthesis.

Authors
Elizabeth Stanway (1)

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Abstract
Communities working on individual stars and those modelling stellar populations have historically had different interpretations of the term 'stellar mass'. These are built on assumptions designed for use in the local Universe, and not always appropriate to high redshift galaxies. Here we consider the impact of including the hitherto-neglected stellar pre-main sequence delay timescale on the interpretation of composite stellar populations at ages of <1 Gyr. We find that the impact on the inferred stellar mass and mass-to-light ratios is significant (a factor of 2 or more), depending on how those properties are defined. We find that the short time scales for star formation in the distant Universe require a clearer definition for the stellar mass in a population, and will impact assumptions about the inferred shape of the stellar initial mass function from observations and also the interpretation of chemical enrichment in low mass stars.

Star formation rate density as a function of stellar mass: A more complete mass function for star-forming dwarf galaxies and high redshift line emitters

Authors

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Abstract

Detecting and characterizing the low-mass galaxy population remains a major challenge in astrophysics, particularly at high redshift where galaxies are intrinsically faint and often selected through line emission. Traditional measurements of the galaxy stellar mass function (GSMF) suffer from severe incompleteness in this regime due to the difficulty of detecting low-surface-brightness dwarf galaxies. This limits our ability to probe the halo mass function and to test models of galaxy formation and cosmology. In contrast, the star formation rate density as a function of stellar mass, SFRD(M∗), provides a more direct and observationally less susceptible metric for probing the star-forming galaxy population. Because galaxies with higher star-formation rates are more readily detected—especially in emission-line surveys—SFRD(M∗) offers a less biased view of the low-mass population as it is dominated by galaxies with high star formation rate. SFRD(M∗) is analytically linked to the GSMF, enabling predictions of its slope even where direct mass measurements are incomplete.

In this work, we use the EAGLE and TNG50 cosmological simulations to investigate the behaviour of SFRD(M∗) across cosmic time, with particular emphasis on the high-redshift regime where observational limitations are most acute. At present-day redshift, we compare the simulations to measurements from GAMA, MUSE, and SDSS, demonstrating that SFRD(M∗) provides a robust and consistent description of the star-forming population down to stellar masses of 10^5.5M⊙, with no evidence for a turnover in the GSMF at the low-mass end. We show how SFRD evolves in the high-redshift regime accompanied by the GSMF and the mean SFR curve and how these functions are connected and affect each other. We further show that the slope of SFRD(M∗) varies with mass range and with the underlying physics prescriptions, highlighting its sensitivity to both galaxy evolution processes and cosmological context. Together, these results establish SFRD(M∗) as a powerful and observationally less susceptible probe of the low-mass galaxy population—particularly for high-redshift, line-emitter–selected samples—and as a complementary tool for constraining the GSMF and testing models of dark matter and galaxy evolution.

Panchromatic modelling of resolved high-z galaxy observations using Bayesian Neural Networks

Authors

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Abstract

Galaxy growth has traditionally been explored through two complementary perspectives: the build-up of stellar mass inferred from galaxy integrated SED modelling, and the growth in size captured by high-resolution imaging. While these approaches have driven major advances in our understanding of galaxy evolution, both tend to gloss over the fact that both dust attenuation and stellar populations may vary spatially, which has been known to influence colour gradients in galaxies since the Hubble Space Telescope era and therefore limiting the physical realism of inferred properties. Meanwhile, deep multi-wavelength surveys on high-redshift galaxies provide increasingly rich datasets across the UV to mm, but the data exhibits different spatial resolutions, resulting in a mixture of highly resolved, marginally resolved and unresolved data. To address these limitations, we developed a novel modelling technique aimed at maximally exploiting all of this rich yet varied information without sacrificing unresolved or poorly resolved bands, and without sacrificing resolution where available. Our modelling approach simultaneously and self-consistently models a galaxy's spectral energy distribution and its spectral distributions of global structural parameters: the wavelength dependent galaxy size, light profile and projected axis ratio using a computationally efficient machine learning emulator trained on a large library of toy model galaxies processed with 3D dust radiative transfer and mock observed under a range of viewing angles. The toy models vary in their stellar and dust geometries, and include radial stellar population gradients allowing for informative extraction of these properties during inference (i.e., what are stellar age gradients within galaxies, if any? How is the dust distributed with respect to the stars?). The emulator reproduces the spectral distributions at an accuracy of ~ 0.05 dex or less across the dynamic range of input parameters, and across the rest-frame UVJ colour space spanned by observed galaxies out to $z = 3.5$. This framework enables physically realistic inference for galaxies around cosmic noon, and we demonstrate its application to TNG50 star forming galaxies and observations from the COSMOS and GOODS-South fields.

Cosmological simulations of dust formation and evolution including Population III stars

Authors

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Abstract

At very high redshifts, galaxies observed with JWST are blue monsters with little dust attenuation but by z~7 ALMA observes higher dust masses than can be explained by production in supernovae alone. Carbonaceous dust has also been observed at high redshifts, despite models expecting most carbonaceous dust to be produced on longer timescales by AGB stars. To follow the evolution of dust species in the early Universe, we include the production, growth and destruction of dust into our cosmological hydrodynamical simulations together with the latest nucleosynthesis yields. We robustly trace the mass of ten different dust species in the ISM from initial conditions: a variety of silicates, as well as carbonaceous, iron and alumina dust. Into this model, we introduce also dust formation in Population III stars. We then compare results from a dust model both with and without Population III dust yields, and investigate to what extent each version of the model is able to reproduce observations at high redshift.

Clustered Star Formation, Radiative Feedback, and the Ionising Budget of a z = 6 Galaxy from Cosmological Radiation-Hydrodynamics Simulations

Authors

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Abstract

Star formation in the first billion years is expected to be stochastic, bursty, and dominated by clustered processes in low-metallicity, high-density environments — yet the physics governing early cluster formation and its consequences for chemical enrichment and reionization remain among the largest uncertainties in modelling early galaxy assembly. We present novel cosmological zoom-in radiation-hydrodynamics simulations of a dark matter halo reaching $10^{10} M_\odot$ at $z = 6$ (Thompson et al., in prep.), which resolve individual star cluster formation and directly track the production and transport of ionising radiation.

Star clusters form via a sink-particle framework with individually tracked sub-grid stellar populations that self-consistently regulate their surroundings through radiative feedback and supernova explosions. Convergence is demonstrated across three resolution levels reaching 2.8 pc, with control simulations isolating the decisive impact of pre-supernova radiative feedback.

We recover the initial cluster mass function (ICMF) and demonstrate its strong sensitivity to early radiative processes, with direct consequences for the ionising photon budget. Exploiting the native radiation transport in our simulations, we quantify the ionising photon production efficiency and Lyman-continuum escape fractions from individual clusters and the galaxy as a whole, providing physically grounded predictions for the contribution of clustered star formation to reionization. We characterise the star formation rate variability across timescales, confirming the bursty, stochastic nature of high-redshift star formation in our simulations. We track the evolving metallicity distribution function and place our simulated galaxy on the mass–metallicity relation at $z \sim 6$, comparing directly with JWST spectroscopic constraints to test whether our feedback-regulated cluster formation model reproduces the enrichment patterns now observed in the early Universe.

In our highest-resolution runs, we resolve the hierarchical assembly of star clusters within individual giant molecular clouds, with cluster formation timescales and gas accretion histories quantified at every timestep — revealing how local gas conditions and feedback set the pace of clustered star formation at cosmic dawn.

Together, these results connect the small-scale physics of clustered star formation to the global ionising output, chemical enrichment, and UV properties of an early galaxy, providing new theoretical context for JWST photometric and spectroscopic observations at $z > 6$.

A view from the HIGHLANDS: The impact of local Lyman-Werner radiation on star and early galaxy formation (Online)

Authors
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Abstract
The mismatch between the number of massive galaxies (and their properties) observed by JWST at high-z and predictions from current theoretical and numerical models highlights a shortcoming in our understanding of star formation physics at this early epoch. It implies that baryonic physics models might be missing crucial physical dependencies or that star formation physics might change across cosmic time. These results highlight the need for improved physics models in numerical simulations, in order to provide a better framework for the interpretation of current and future observations.
I will present detailed analysis of the HIGHLANDS suite of cosmological zoom-in simulations, comprising galaxies across a range of halo masses (from ~1e9 to 1e12 Msun) evolved until z=5. The fiducial physics of HIGHLANDS include a star formation model that depends on the turbulent properties of the gas, on-the-fly treatment for the Lyman-Werner radiation emitted by massive young stars, and a model for population III stars. Non-equilibrium chemistry for hydrogen (including molecular hydrogen) and helium, new metal yield tables, metal line cooling for the interstellar medium down to 10K, as well as early and supernova stellar feedback are also included. Additionally, each galaxy has been simulated again with changes in the key physics, e.g. switching off local Lyman-Werner radiation, making this an ideal testbed for the impact of these physics on the formation of the earliest galaxies.
I will discuss the complex interplay between Lyman-Werner radiation and star formation and their impact on galaxy properties at z=5, as well as their evolution across cosmic time. I will show that the total stellar mass and star formation rates at z=5 differ significantly between runs with and without local Lyman-Werner radiation, a direct consequence of Lyman-Werner radiation inhibiting further popIII star formation following the formation of the first stars. This results in different star formation histories (and dramatically different gas fraction evolution) and highlights the importance of capturing this effect on the thermo-chemical evolution of the gas at runtime. Furthermore, the natal properties of stars (e.g. birth density, metallicity) are significantly affected as well.
These results present an important step towards a better understanding of the physics of star formation and the impact these small-scale processes have on galaxy formation and evolution in the early universe.

The formation of Population III stars across Cosmic Dawn

Authors

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Abstract

With the advent of JWST, we are now able to probe some of the earliest star-forming regions at Cosmic Dawn. Some of these regions might be hosts of the first (Population III) stars, which formed from primordial and metal-free gas. Although many such systems have been put forward as Population III candidates in the past few years, no robust detection has yet to be made. We therefore require complex numerical simulations to infer the properties of Population III systems, if they are observable, and where to find them.
In this talk, I will present results of Population III formation in the MEGATRON suite of simulations, which self-consistently follows radiation and non-equilibrium chemistry, and resolves gas at near-pc resolution in a Milky Way-mass progenitor at Cosmic Dawn. While the very first Pop~III stars form in halos with masses well below the atomic cooling limit, the majority of Pop~III stars form in more massive systems above the 10^4~K atomic cooling threshold as a Lyman-Werner (LW) background of $10^{-21}\,\rm erg\,s^{-1}\,cm^{-2}\,Hz^{-1}\,sr^{-1}$ is rapidly established. I find that the global Pop~III star formation rate stabilizes to a value of $10^{-3}\,\rm M_\odot\,yr^{-1}$ at $z=20$. Among the three processes that quench Pop~III star formation in mini-halos, the LW background, gas starvation, and external chemical enrichment, the LW background is most important. A small fraction of halos undergo multiple episodes of Pop~III star formation when the earlier forming stars all directly collapse to black holes. If the halos become massive enough, they can form up to ~100 Pop~III stars in a single burst, which may be observable by JWST with moderate gravitational lensing. Pop~III stars form at a wide range of distances from UV-bright galaxies, with only $0.06\,$\% of Pop~III stars forming within the virial radius of galaxies with $M_{\rm UV}<-17$. Finally, by tracking Pop~III star remnants down to $z=0$, I find that $75-80\,$\% reside in the stellar halo of our simulated Milky Way analogue, while the remainder are gravitationally bound to lower-mass systems, including satellite halos.