The secret agent of galaxy evolution

Ellis Owen discusses how cosmic rays can shape galaxy evolution, and the exciting opportunities to study their effects

1 (main image) *Stephan's Quintet, a compact group of galaxies experiencing forced interactions and successive bursts of star formation. Composite image with JWST NIRCam-MIRI.* (NASA, ESA, CSA, STScI)
(inset top) *The galaxy Arp 220, undergoing a huge burst of star-forming activity in the aftermath of a collision between two galaxies, around 700 million years ago.* (NASA, ESA, the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/ Stony Brook University)).
(inset bottom) *The two interacting neighbouring galaxies M81 (left) and M82 (right) shown in UV as a tracer for star formation activity. The starburst episodes in M82 are driven by successive tidal interactions between the galaxies, with M82's starburst driven superwind visible above and below the galactic plane.* (Dietmar Hager and Torsten Großmann)

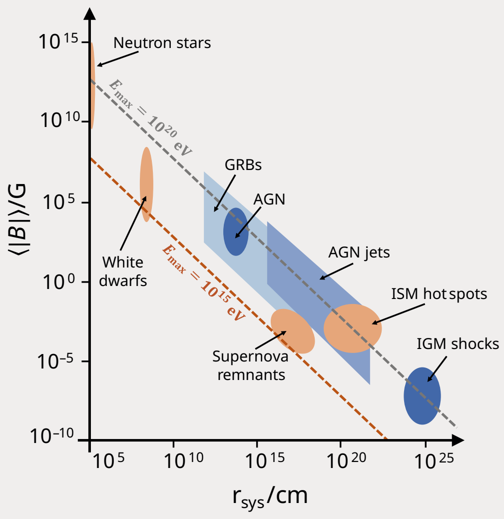
Energetic supernova explosions shape the evolution of galaxies and the intergalactic medium over cosmic time. There is a consensus that they deliver energy to their surroundings both through mechanical processes and via energetic particles, providing two pathways for feedback. The mechanical component can be measured and has already been well studied. However, the influence of energetic particles is more challenging to observe. These so-called cosmic rays (CRs) essentially serve as a 'hidden' form of energy feedback. Their precise effects locally and globally in galaxies are not yet clearly established, and we are yet to settle on a sensible picture of how this hidden feedback agent operates.

Galaxy evolution is an important topic. Our physical understanding of the processes at work needs to be correct to develop a thorough understanding, and this includes our treatment of feedback. Galaxy dynamics are currently modelled mechanically, with occasional consideration of chemical processes. This treatment is incomplete, with crucial outstanding questions remaining. Why does star-formation decline after the cosmic noon? Why do abundance-matching relations between halo and stellar masses turn-over around the 'golden mass' of 300 billion $M_{\odot}$? And what causes long periods of quenching in isolated high redshift primordial galaxies? CRs are powerful energy carriers in galaxy ecosystems and there are hints that they may provide answers to some of these pressing issues. There is also unmistakable evidence of their activity and engagement within galaxies, including signatures in γ-rays, sub-millimeter and radio. New observatories and instruments such as the Cherenkov Telescope Array (CTA) and the Pacific Ocean Neutrino Experiment (P-ONE) will soon come online, expanding our multi-wavelength and multi-messenger capability to detect CR processes in galaxies. These facilities will bring exciting new opportunities to study CRs, and probe their hidden influence on galaxy evolution.

In this article, I will discuss CRs as an energy-carrying agent, and how they would shape galaxy evolution throughout cosmic time. I will elaborate the current view of their influence across the hierarchy of structures in and around galaxies. Then I will consider the potential to explore their impacts using new and near-future facilities, and identify the astrophysical systems we can target to test predictions of their effects.

1. Charged particle acceleration in galaxies

The Hillas (1984) criterion indicates the maximum energy to which an astrophysical environment can accelerate charged particles. Higher energies can be reached in more strongly magnetised environments, or in systems larger in physical scale. Figure 2 shows the maximum CR energy that can be achieved in a selection of cosmic accelerators. In order to contribute significantly to production within star-forming galaxies, accelerators need to be both smaller than a typical galaxy, and abundant in starburst environments. Hence, supernova remnants are a clear candidate.



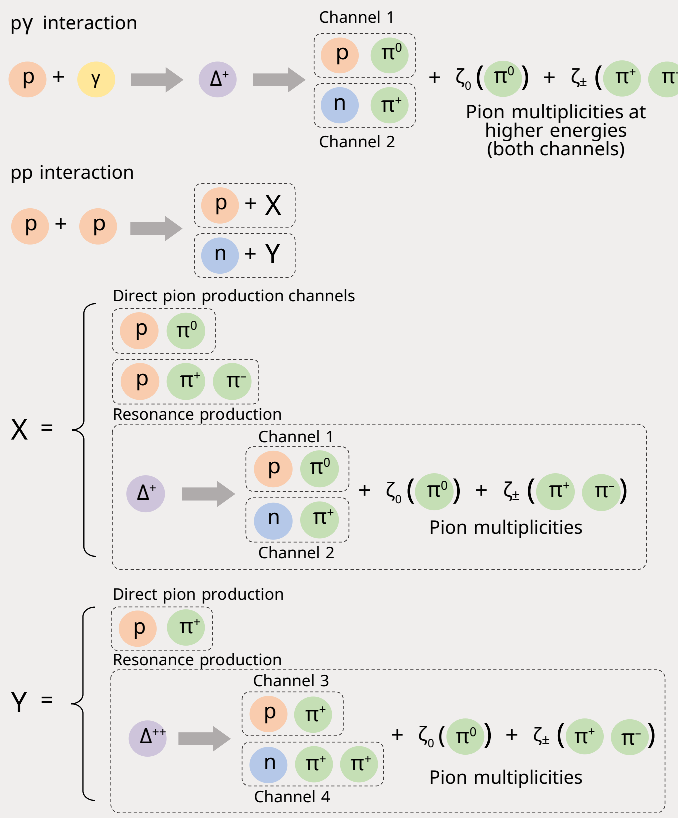
2 *The Hillas plot, indicating the maximum energy that protons can reach in different astrophysical environments.* (Reproduced from Owen (2019))

Cosmic rays in galaxies

The main sources of CRs in galaxies without strong active galactic nucleus (AGN) activities are the remnants of violent supernova explosions. These begin to emerge shortly after the onset of star-formation, suggesting starburst galaxies like Arp 220 (figure 1), and galaxies engaged in tidal inter-galaxy interactions with elevated star formation (e.g. the M82/M81 pair, and in compact groups like Stephan's Quintet; figure 1) would likely be significant CR factories. In supernova remnants, diffusive

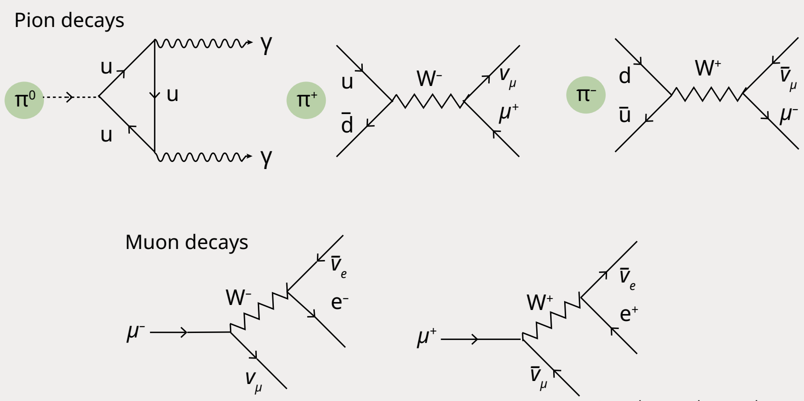
2. Electron, neutrino and γ-ray photon production by hadronic interactions

CRs undergo hadronic interactions when they interact with photons (proton-photon, or pγ interactions) or with low-energy nuclei in interstellar gases (proton-proton, or pp interactions). The pp interaction is usually the most important of these two processes in a typical galaxy interstellar medium (ISM). Hadronic interaction rates have been investigated experimentally, and detailed parametrisations for their various channels have been developed using data from ground-based laboratory experiments (for example, Kelner *et al.* 2006; Kafexhiu *et al.* 2014). The formation mechanisms of pion intermediates in pp and pγ interactions are shown below, where ζ_0 and $\zeta_\pm$ denote their increased production (multiplicities) at higher interaction energies. Below ~2 GeV, direct single pion production channels dominate, but multi-pion production can occur through baryonic resonances (e.g. Δ^+, Δ^{++}) or other mechanisms at higher energies.



3 *Pion production channels in pp and pγ hadronic CR interactions*

Upon their formation, pions decay rapidly as outlined in figure 4. Neutral pions decay into γ-rays within ~10^{-16} s, whereas charged pions decay into muons and neutrinos over ~10^{-8} s. Muons decay further into electrons, positrons, and neutrinos.



4 *Pion decay channels to form electrons, γ-ray photons and neutrinos*

shock acceleration processes produce CRs (e.g. via Fermi acceleration; Fermi (1949) and Box 1) by boosting hadrons and leptons to relativistic energies. These CRs then are scattered and deflected through their host galaxy's magnetic fields. This prevents their free escape into intergalactic space, and establishes a diffusive regime of CR propagation within a galaxy. After star formation begins in a galaxy, CRs build up until a steady state is reached when the injection of CRs is balanced against their slow diffusive leakage into circumgalactic space. This produces a magnetic containment effect, where the abundance of CRs in a galaxy can be enhanced by a factor of 10^5–10^6 (see Owen *et al.* 2018). By refocusing their feedback potential back into the interstellar ecosystem, this magnetic containment is able to enforce a powerful CR feedback effect that could modify a galaxy's evolution. This may, for example, be able to quench star formation, or could even modify the types of stars a galaxy can form. Recent simulation work also suggests energy deposition by CRs could fundamentally change the hydrodynamic properties and long-term evolution of galaxy ecosystems (Hopkins *et al.* 2021), and they could have an important influence in regulating the early thermodynamics of primordial galaxies (Owen *et al.* 2018).

The mechanism by which CRs deposit energy and momentum is not always easy to discern and their precise astrophysical impacts are challenging to predict. Their engagement can be placed into one of two categories. First are the dynamical effects of CR pressure gradients. These can gradually produce a force capable of driving galactic outflows over long timescales and large distances (for example, Samui *et al.* 2010; Yu *et al.* 2020) or regulate the gas supply and re-circulation in the wider circumgalactic environment (Owen *et al.* 2019a). Second are collisional interaction effects, which operate to deposit energy and momentum throughout a galaxy. These deliver feedback energy much more directly and locally than dynamical processes, and can have more immediate and targeted consequences for a galaxy's star formation.

Energy deposition and feedback

Most energy deposition channels available to CRs within a galaxy depend on hadronic collisions with interstellar gas nuclei, although a sub-dominant channel via collisions with photons is also possible (Box 2). Proton-proton (pp) interactions dominate above a threshold energy of about ~0.3 GeV, leading to the production of electrons, γ-rays and neutrinos (Box 2). Of these products, γ-rays and neutrinos escape from the production location with minimal losses, while the electrons engage more strongly with their immediate environment. This means electrons tend to mediate local CR energy deposition, while γ-rays and neutrinos are the messengers of CR interactions.

The electrons released by hadronic interactions regulate the thermalisation and astrophysical feedback of CRs within a galaxy. This typically proceeds through Coulomb collisions of energetic secondary CRs and thermal ions in interstellar plasma, or in the semi-ionised gas of diffuse molecular clouds. This powers a heating effect which can dominate across an ISM (Owen *et al.* 2018). When considering a multi-phase ISM configuration, the regions most strongly affected by hadronic interactions and the release of electrons are the dense molecular clouds, i.e. the sites of star-formation. Here, the feedback effects of CRs would be particularly severe and their heating impact could far exceed the ISM average.

Within molecular clouds, filamentary structures, semi-ionised clumps, and dense cores are arranged hierarchically (Box 3). CR heating effects in these systems are therefore highly inhomogeneous, and can vary greatly in different parts of a cloud's internal structure. As thermalisation relies on Coulomb scattering, it can be very inefficient in dense, neutral cores. Clumps would instead experience much higher CR heating rates than cores, because of their higher ionisation fraction. Although this does not support the claim that CR heating can affect the exact locations of star formation (which usually occurs in dense cores), it does suggest that CRs are capable of driving considerable heating that could modify the initial conditions of star formation, particularly within the clumps from which star-forming cores would later emerge.

The implications this CR heating has for star formation remains a subject of investigation, with possibilities ranging from rapid quenching to more subtle effects – for example an increased tendency for clumpy star formation, or a modified stellar initial mass function (IMF). The minimum temperature of dense gas deep within molecular clouds can be raised from ~10 K (typical of the dense phase of the Galactic ISM) to ~ 50–100 K at CR energy densities of ~ 10^3–10^4 times those of the Galaxy (Papadopoulos *et al.* 2011). Similar temperatures can be achieved for clouds in environments representative of the ISM of the nearby starburst galaxies M82, NGC 253 and Arp 220 when considering a CR heating scenario (Owen *et al.* 2021). The emergence of a 'top-heavy' stellar IMF (which favours more massive star formation) in galaxies with CR energy densities greater than around five times that of the Milky Way may also be possible due to this raised cloud temperature (Papadopoulos *et al.* 2011). This would suggest that highly star-forming galaxies are inclined to produce more massive, short-lived stars. The boost in CR production arising from an increasingly top-heavy IMF could then trigger a runaway feedback scenario which could ultimately quench a galaxy. A significant resurgence of star formation would then not take place until cooling could once again restore the appropriate conditions.

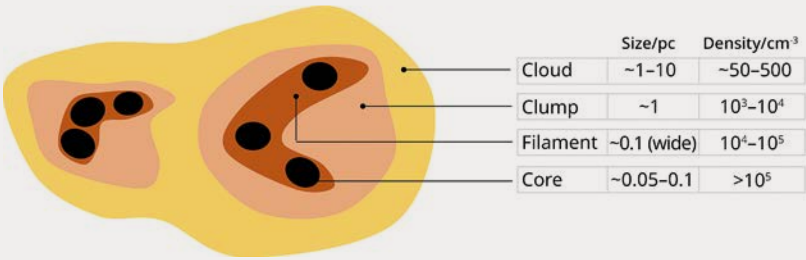
Signatures of cosmic ray interactions

CRs become more prevalent as the supernova remnant population increases. This means that their abundance tracks the star formation of a galaxy, and their effects will be more pronounced in massive, highly star-forming young galaxies that were ubiquitous when the universe was around 2–3 billion years old (Box 4), as well as in protogalaxies in the primordial universe. These distant systems are difficult to observe, and even our most advanced telescopes are not able to detect them easily, or need to rely on gravitational lensing to bring them into practical observational reach. However, probing such distant galaxies in detail may not actually be necessary: the elevated star formation rates of nearby starbursts like M82, Arp 220 and galaxies undergoing interaction-driven starbursts in e.g. tight compact groups like Stephan's Quintet mean they will also be rich in CRs. Being much closer at hand, they are within relatively easy observational reach and can offer insights as analogues of their primordial counterparts.

The high energy emission from CR interactions in nearby starburst galaxies serve as a useful laboratory for tuning and testing models of CR engagement in a galaxy ecosystem, and their close proximity means they are accessible to high-energy γ-ray observatories

3. The complex structure of molecular clouds

Molecular clouds in galaxies have a complicated, hierarchical structure (figure 5). Their temperature typically ranges from a few K in cores to a few 10s of K in the diffuse intra-cloud medium. They are permeated by complex magnetic fields that have dynamical impacts of their own: anisotropic support can be provided by magnetic pressure during the collapse phase of a molecular cloud, changing its morphology and fragmentation. There is an interplay of different effects that are competing locally in different cloud regions, which result in complex magnetic fields and gas structures. Thermal, turbulent or magnetic support against gravitational collapse lead to different local configurations, depending on which processes dominate locally throughout the cloud.

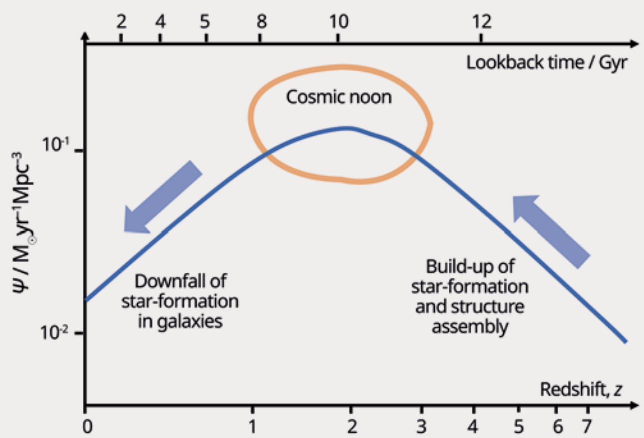


5 *The hierarchical density structure of molecular clouds, from the diffuse cloud to small dense cores (Bergin & Tafalla 2007). Cores are the site of star formation, however it is not guaranteed that all cores will form stars (those which do not host young stellar/pre-stellar objects or show signs of star-forming activities are known as 'starless cores').*

4. The 'high noon' of cosmic star formation

The growth of galaxies in the young universe is driven by gravity, where gas accretion fuels their star formation and builds up their stellar mass. The process of galaxy assembly after the epoch of reionisation was moderated by radiative feedback from starlight and mechanical feedback from supernovae. Over time, galaxies accumulated mass, which strengthened their gravitational fields. This led to ever more efficient star formation, until about 2–3 billion years after the Big Bang (about z~2–3). It was during this time that most stars in galaxies formed, and many key properties of galaxies were established – for example, the formation of their discs.

New physical effects began to take hold of galaxy evolution after the first few billion years. It has been found that star formation was impeded after a 'high-noon' around 10 billion years ago (figure 6), with quenching leading to a downturn in cosmic star formation. This quenching process seems to be especially important in galaxies above the 'golden mass', around 300 billion $M_\odot$, which shut-down their star-formation particularly quickly. Quenching is linked to the emergence of elliptical galaxies, which lack gas to support ongoing star formation. However this is not true of all quenched galaxies, and the exact processes responsible for bringing about the downfall of star formation after the cosmic noon remain unsettled. CRs are regarded as one possible agent able to fulfil this role.



6 *Evolution of the cosmic star formation rate density of the universe Ψ, obtained empirically by Madau & Dickinson (2014). The 'high noon' of cosmic star formation is the peak around 10 billion years ago (at z~2).*

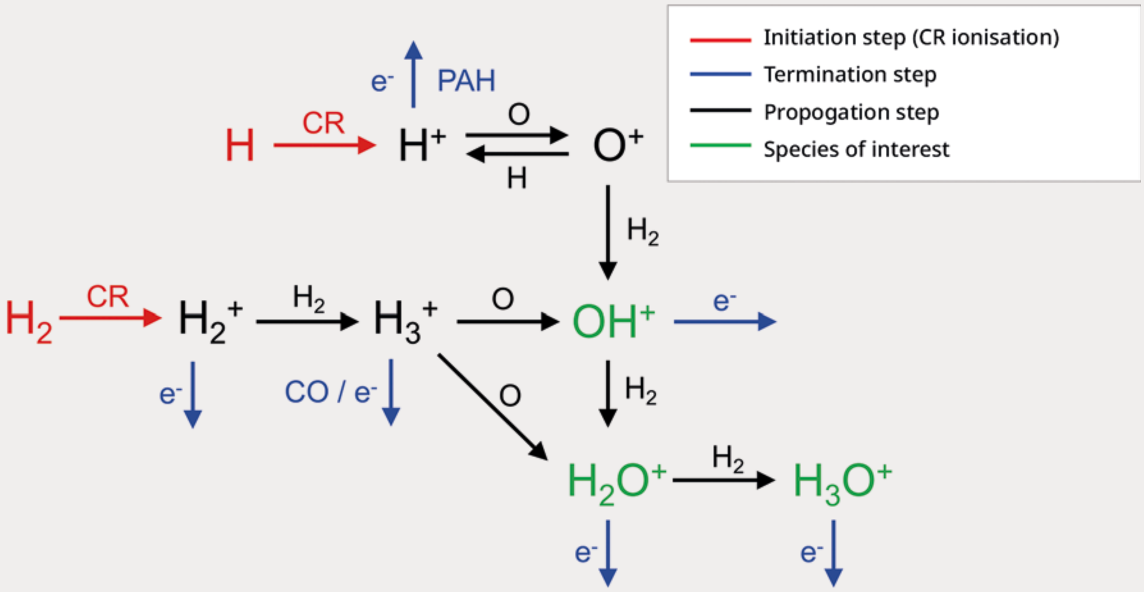
7 (left) *The prototype Large-Sized Telescope (LST-1) of CTA in La Palma, Spain. Completed in 2018, it is foreseen to become the first LST telescope of CTA and is currently undergoing commissioning.* (CTAO (2019)) (right) *ALMA antennas at night, with the Galactic centre in the background.* (S. Otarola, ALMA (ESO/- NAOJ/NRAO))

and may be bright enough to be detected as neutrino sources. In GeV γ-rays, the Fermi Large Area Telescope (LAT) has already resolved more than a dozen nearby starbursts and also some main sequence galaxies like M31 (Ajello *et al.* 2020). Follow-up observations with ground-based Cherenkov Telescopes have also confirmed that their emission persists above TeV γ-ray energies in some cases (e.g. Abramowski *et al.* 2012), with star formation activity (probed via infrared luminosity) being well-correlated with high-energy γ-ray luminosity (Ackermann *et al.* 2012). These are clear signs of active CR engagement in these systems.

We will soon be able to probe the non-thermal astroparticle processes of these galaxies in greater detail and out to larger distances, thanks to a new generation of γ-ray observatories. Compared to current capabilities, instruments like CTA (figure 7) will allow us to obtain even more robust constraints on the γ-ray emission properties of nearby galaxies between 100s of GeV to 100s of TeV (Ambrosone *et al.* 2022). Together with complementary new and in-development instruments such as the Large High Altitude Air Shower Observatory (LHAASO) experiment, and the Southern Widefield Gamma-ray Observatory (SWGO; Huentemeyer *et al.* 2019), we will be able to reach substantially improved sensitivities and spatial and spectral resolution capabilities in the next few years (Cao *et al.* 2019). This will support efforts to improve our knowledge of particle propagation in galaxies, test high energy emission scenarios from CRs in nearby galaxies, and determine the exact relationship between CR engagement in a galaxy, energy deposition, γ-ray emission and star formation (Tibaldo *et al.* 2021).

5. CR-driven Oxygen chemistry in diffuse molecular clouds

The formation of OH+ and H_2O+ in cold (T<300 K), dense molecular clouds can be driven by the CR ionisation of atomic or molecular hydrogen. The CR ionisation rate is determined by balancing the formation and destruction rates of these molecules, if other sources of ionisation in the cloud have been eliminated. The formation of these species (together with the closely chemically-related species H_3O+) can be modelled with an oxygen chemical network (Hollenbach *et al.* 2012). Figure 8 shows a simplified network summarising the main formation channels for these species.

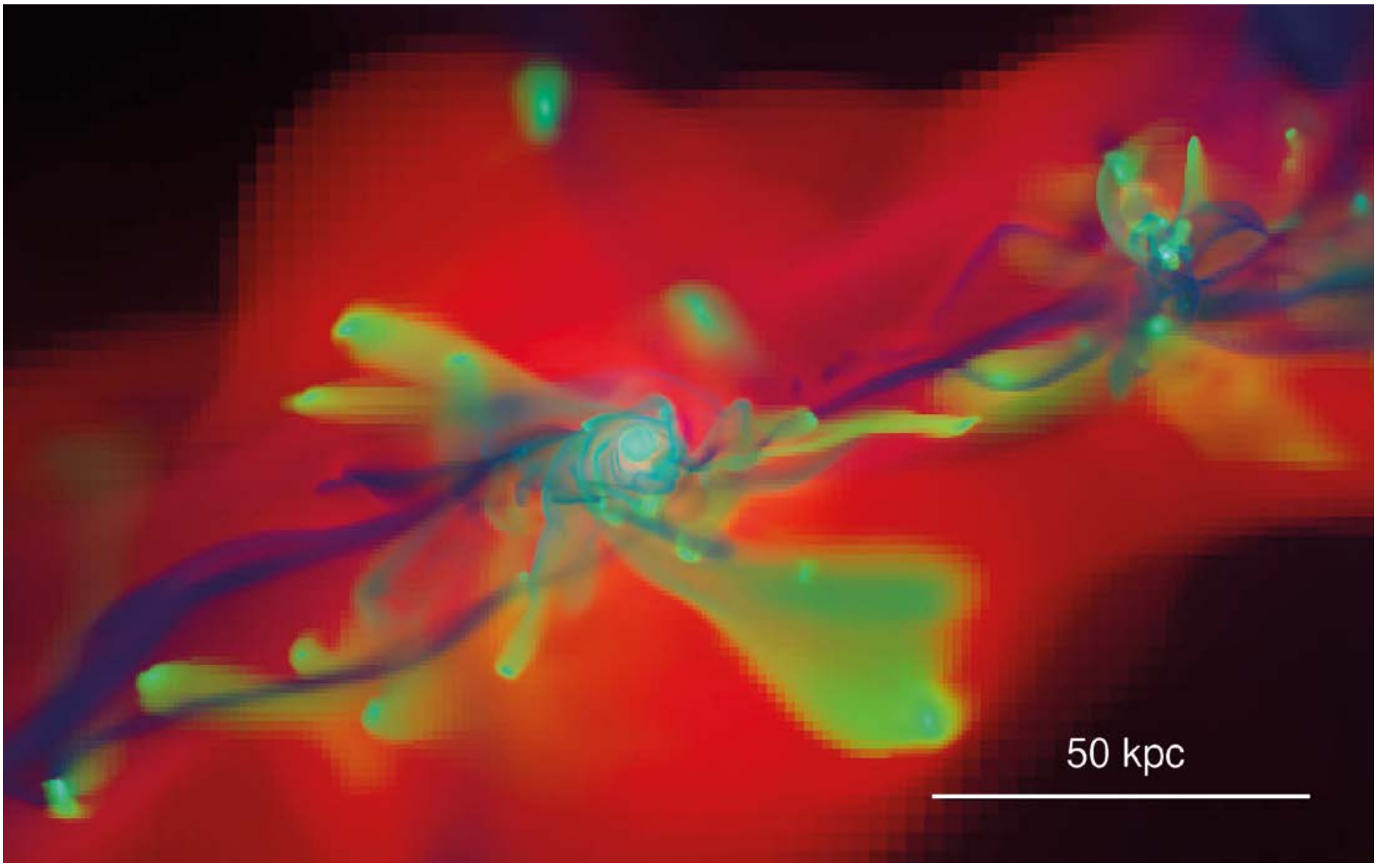


8 *Standard chemical network for the CR-driven ionisation of H and H_2 in a molecular cloud, leading to the formation of OH^+, H_2O^+ and H_3O^+. Termination steps are caused by neutralisation with electrons (which may be ambient free electrons, or even low-energy CRs) within the cloud are indicated in blue. It is also possible for polyaromatic hydrocarbons (PAHs) or carbon monoxide (CO) to facilitate some termination processes, as marked.*

Complementary efforts across the electromagnetic spectrum provide a broader view of how CRs are engaging through different components of an ISM. In the submillimetre band, the Atacama Large Millimetre/submillimetre Array (ALMA; figure 7) is already accumulating high-fidelity data on the density, temperature, and ionisation level of the interstellar material within nearby γ-ray starburst galaxy sources (CTA Consortium 2019), which will be crucial to properly resolve the efficiency of CR energy deposition processes (Owen *et al.* 2018). For more distant galaxies, multi-wavelength efforts can also be informative. Astrochemical signatures of CR engagement can, for example, be determined during the cosmic noon for lensed and dusty galaxies. In dense and neutral H and H_2 gas, chemical reaction chains are driven by the ionising effects of CRs in molecular clouds: H^+ and H_2^+ are formed by CR ionisation, which then leads to the production of species such as OH^+ and H_2O^+ (Box 5). These are relatively direct chemical tracers of CR ionisation, and cosmological redshift from the cosmic noon ($z \sim 2$–3) brings some of their transition lines into submillimetre wavelengths accessible with ALMA. Bright, lensed submillimetre galaxies are strong continuum sources, and can be used to detect the presence of these species in absorption, allowing the CR ionisation rate within a galaxy to be obtained in the dense molecular cloud ISM phase, where impacts of feedback are likely to be most severe (Indriolo *et al.* 2018).

While astrochemical and γ-ray signatures can be useful probes of CR activity in galaxies, astrochemical tracers are only sensitive to the effects of low-energy CRs (which do not always robustly track their high-energy counterparts that dominate CR energy densities), while photon attenuation by extragalactic background radiation limits the maximum distance to which we can access individual sources in γ-rays to just ~ 10–20 Mpc above ~100 TeV. Multi-messenger studies can provide the complementary information that is otherwise missing at these higher energies: neutrinos will soon instead provide a window to access CR processes in starburst galaxies above 100s of TeV. According to current modelling, most nearby starburst galaxies will even be detectable within several years using current neutrino observatories like IceCube or the Cubic Kilometre Neutrino Telescope, KM3NeT (Ambrosone *et al.* 2021). Even before this, the success of atmospheric and astrophysical neutrino separation methods (e.g. using muons produced in atmospheric showers as vetoes at energies above a few 10s of TeV; Ahlers *et al.* 2018) mean that diffuse extragalactic background neutrino fluxes are even easier to access than individual sources (Palladino *et al.* 2019). These backgrounds can already provide important insights into CRs in some galaxy populations, e.g. for testing CR transport models (Ambrosone *et al.* 2022).

On smaller and more local scales, theoretical studies have also examined non-thermal emission signatures from CRs in individual molecular clouds using radio observations (Dogiel *et al.* 2021) and γ-rays (Dogiel *et al.* 2018). Radio studies provide complementary information about cloud magnetic fields, but γ-rays will be especially promising to assess how CRs penetrate into clouds and to test propagation models. Galactic molecular clouds are considered to be useful tracers of the Milky Way's CR density and the variation of the CR 'sea level' (Peron *et al.* 2021). These have shown that the CR distribution varies throughout the Galactic disc, with regions near likely CR sources harbouring an excess of CRs. Thus, cloud complexes located near more CR source environments (for example, those associated with Pulsar Wind Nebulae; Mitchell *et al.*



9 *Red-Green-Blue image of simulated filamentary inflows around 11.5 billion years ago (z~3), showing a galaxy disc and an accretion region. Here, red is gas temperature, green are metals and blue is density. Streams of dense, cold, pristine filamentary gas extend for more than 100 kpc, supply gas to the central galaxy and connect directly to the edge of its disc.* (Reproduced from Agertz *et al.* (2009))

2021) would be more strongly irradiated. Such clouds are close at hand and can be studied in far greater depth and with higher resolution than those located in external galaxies. As such, they are useful 'backyard' analogues to provide insights into CR feedback in the multi-phase ISM of more distant CR-rich galaxies.

Galaxy thermodynamics and inflows

While some of the impacts of CRs in galaxies at high redshift can be extrapolated from local analogues, other feedback effects in primordial systems are unique to the specific processes driving galaxy growth in the early universe. In primordial galaxies, cold filamentary inflows directly from the cosmic web (figure 9) are thought to be a major driver of star formation, particularly in massive galaxies (Dekel *et al.* 2009). This contrasts with galaxies in the local, more evolved universe, where star formation is instead driven by instabilities in gas reservoirs triggered primarily by mergers (including cosmic collisions like Arp 220 in figure 1) and tidal inter-galaxy interactions (as in the case of M82 and its interacting neighbouring galaxy M81, or in compact groups of galaxies, like Stephan's Quintet).

At early times, when the universe was only around 7% of its current age (above redshifts z ~ 6), young galaxies have been observed to exhibit perplexing, bursty star formation histories reaching back to the very earliest stages of the cosmic dawn. One such example is the lensed galaxy MACS1149-JD1 (Box 6). In this galaxy, the observed star-formation was considered to be driven by cold filamentary inflows (Hashimoto *et al.* 2018), and tentative indications of their presence were even reported in support of this scenario (via blue-shifted Lyα emission compared to the [OIII] emission in the galaxy's rest-frame).

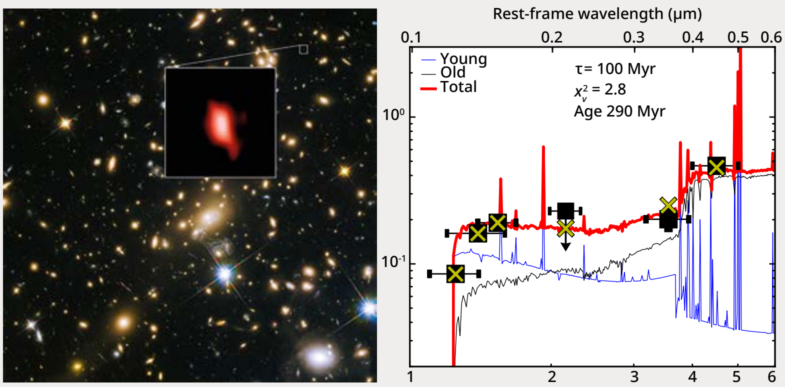
When inflows of gas supplying a galaxy can either be physically prevented, or modified such that the gas they supply is no longer suitable to sustain star formation in the host, temporary quenching, or 'stunning' can arise. A resurgence of star formation would then occur some hundreds of Myr later, if the fuelling inflows are able to resume. CRs may modify these inflows by heating or evaporating them (Owen *et al.* 2019b), and could sufficiently irradiate and heat the flows that they would be unable to support star formation in the galaxy they are supplying. On application to MACS1149-JD1, it was found that CR-induced stunning timescales were consistent with the inferred star formation history of this galaxy. Moreover, the cooling of inflowing gas after star formation had ceased (and CR feedback processes had stopped) would then allow for a delayed, moderate resurgence of star formation after a few hundred Myr – also consistent with the inferred history of this galaxy.

CRs have been shown to be a plausible agent able to account for the behaviour of this one particular high-redshift galaxy (Owen *et al.* 2019a). This leads our attention to other systems, to investigate how this picture can be extended. Other feedback processes could produce bursty star formation behaviour, and it is possible primordial galaxies could instead be stunned by hypernova/supernova activity, through vast galactic outflows evacuating interstellar gases, or by stellar heating. This raises two key questions: how can different feedback mechanisms be distinguished? and how prevalent is CR-driven stunning in protogalaxies?

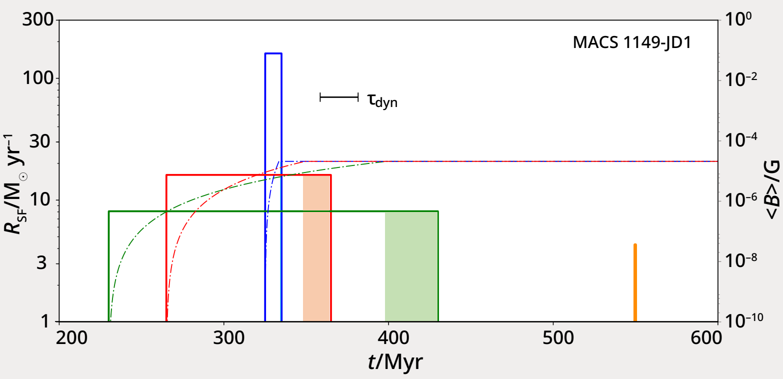
Based on the observation of a class of objects that show similarities in their star formation behaviours to MACS1149-JD1, it has been demonstrated how both of these questions could be addressed together (Owen *et al.* 2019b). Post-starburst galaxies, also known as E+A galaxies, recently stopped forming stars. They exhibit strong Balmer absorption lines (associated with young populations of stars), but lack the optical emission features that would be expected for a currently star-forming galaxy. Additionally, they show strong metallic absorption lines (e.g. Ca, H, and K), attributed to an older population of stars, suggesting that these galaxies experienced at least two prior bursts of star formation – one having been shut down relatively recently, and one being more historic: these galaxies may therefore represent a class similar to MACS1149-JD1, which have evolved beyond a second resurgence of

6. The curious case of MACS1149-JD1

MACS1149-JD1, a gravitationally lensed galaxy around 500 million years after the Big Bang (z=9.11), was found to be forming stars at a rate of 4.2 $M_\odot$ yr^{-1} (Hashimoto *et al.* 2018). This was a secondary resurgent star-formation episode after a much earlier starburst (figure 10), which may have occurred as long as 13.5 billion years ago (z≈15). This raises questions about the cause of the quenching epoch prior to the resurgence of star formation. It is possible that CRs delivered feedback into the galactic ecosystem during the initial starburst period (figure 11).



10 (above left) *Inset shows oxygen distribution observed with ALMA for MACS1149-JD1 in context with the Hubble Space Telescope (HST) image of the MACS J1149.5+2223 galaxy cluster. (ALMA (ESO/NAOJ/NRAO), NASA/ESA Hubble Space Telescope, W. Zheng (JHU), M. Postman (STScI), the CLASH Team, Hashimoto et al. (2018))* (above right) *The spectral energy distribution of MACS1149-JD1 with emission models from an old and young stellar population indicated (figure 11) required to reproduce the excess 4.5μm flux. The dominant old stellar component is required to reproduce the Balmer break. The young component is further constrained by both the Lya and [OIII] 88-μm emission (not shown).* (Data from HST, VLT/HAWK-I and Spitzer/IRAC. Reproduced with permission by Springer Nature, from Hashimoto et al. (2018))



11 *The range of star formation histories (solid lines) required to reproduce the observed spectrum and the size of the Balmer break (Hashimoto et al. 2018). This is compared to the time for the magnetic field of the galaxy to be amplified (according to a turbulent dynamo treatment from Schober et al. 2013; dashed lines), which sets the CR containment time after which CR effects would be refocused into the galactic ecosystem (shaded region). This follows the underlying star formation history for this system, even though the precise timescales of the starbursts could not be uniquely determined with present data.* (Reproduced from Owen et al. (2019a))

star formation to return to a quenched state. Their behaviour is especially intriguing given their abundance of interstellar molecular gas (French *et al.* 2015), which would normally support vigorous star formation.

Certain population behaviours can be expected if CRs are responsible for this quenching. CR feedback via any mechanism is controlled by their supernovae over time. This would result in a progressive feedback effect with a delayed onset, which would be discernible in a population of post-starbursts by a proportionality between star-forming activity during their burst phase and the duration of their quenched phase, as well as an inverse relation between the star formation rate during their burst phase and the duration of the burst (Owen *et al.* 2019b). A population of E+A galaxies should therefore exhibit these trends with minimum scatter if CR feedback has a dominant role in controlling their evolution. By contrast, these trends would not arise under a more stochastic feedback mechanism, such as energetic hypernova events: feedback would instead be delivered suddenly and randomly, yielding scattered timescales without any clear intrinsic dependency on galaxy properties. Other mechanical feedback mechanisms are easier to rule out in E+A systems – for instance, the presence of considerable gas reservoirs suggests outflows evacuating gas is unlikely to be an important quenching mechanism. Additionally, while they may be present, AGN have been found not to play a major role in shaping E+A galaxy evolution (Lanz *et al.* 2022).

Searching for a 'smoking gun'

Timescales for star formation and quenching can provide insights into how CR feedback affects primordial galaxies, even if the precise mechanism of such feedback is as yet unknown. Information about the stellar populations within a particular galaxy, as well as its observed rate of star formation, is necessary to access these timescales. At 88μm, the forbidden [OIII] emission line flux can be used to estimate the star formation rate of a galaxy. For primordial systems at high redshift, this line is accessible to ALMA (Inoue *et al.* 2016). The spectral energy distribution (SED) can be used to determine the characteristics of a galaxy's stellar population. In particular, the Balmer break reveals evidence of recent star formation activity, and can be observed using the NIRSpec instrument on JWST. The Balmer break results from populations of hot stars (e.g. A-type stars) which survive for only a short time after they are formed. As star formation activities end, the number of these hot stars will start to decline, such that a constraint on the stellar population age can be obtained based on the strength of this break (this was found to be true for most plausible choices of stellar IMF; Binggeli *et al.* 2019).

A variety of existing and new-generation instruments can be used to obtain suitable UV and dust continuum data for galaxies at high redshifts. While the lensed high-redshift proto-galaxy MACS1149-JD1 was a valuable demonstration case (Hashimoto *et al.* 2018), it was not possible to unambiguously determine the timescales involved in the two phases of star formation in this galaxy. However, it did provide a clear procedure that can be applied to high quality spectral observations of primordial galaxies, which are now possible with JWST. With these new capabilities, the opportunity is now within reach to measure SEDs for larger numbers of primordial galaxies in detail, and evaluate their star formation histories. This opens up the exciting prospect of soon being able to discern a 'smoking gun' of CR feedback in young proto-galaxy populations for the first time, and firmly establishing the role of CRs in the structural evolution of the universe.

Future opportunities

Efforts to establish the role of CRs as an active agent shaping the evolution of galaxies has been gaining traction in recent years. As modelling of CR physics on small scales has become more sophisticated with modern theoretical and computational advances, our understanding of their physical effects in complex astrophysical media has been refined. In particular, hadronic interaction models informed by data obtained from major particle experiments (e.g. Fedynitch *et al.* 2019) have been able to provide a stronger foundation for modelling astrophysical CR microphysics.

The maturing capabilities of ground-based γ-ray telescope arrays will also continue to unlock new CR astrophysics at the highest of photon energies. The next generation of high-energy instruments will also open up the multi-messenger domain – particularly with neutrino observations. IceCube upgrades and new facilities (e.g. KM3NeT and P-ONE) will, for the first time, make the multi-messenger astronomy of galaxies a reality within the next decade. Additional capabilities and upgraded facilities across the electromagnetic spectrum (most importantly ALMA and JWST) offer scope to study external galaxies in unprecedented detail, providing further means to pin down the feedback effects of CRs across the hierarchical structure of media. Together, these efforts and exciting new observational opportunities will soon allow us to begin to confidently pull back the shroud of mystery surrounding one of galaxies' best-kept secrets. ●

ACKNOWLEDGEMENTS

The author thanks the NTHU Center for Informatics and Computation in Astronomy for supporting this research, via a grant from the Ministry of Education of Taiwan (R.O.C.). Figure 1, main and inset top panels, are reproduced in accordance with STScI/NASA content use policy, and the lower-right panel is reproduced by permission of the copyright holders, Dietmar Hager and Torsten Großmann. Figure 7 (left) is provided by the CTAO (2019) and reproduced under the terms of the CC BY-NC-ND 2.0. Figure 7 (right) is provided by S. Otarola – ALMA (ESO/NAOJ/NRAO) and reproduced under the terms of the CC BY 4.0 licence. Figure 9 is reproduced from Agertz *et al.* (2009), Figure 1, under the *Monthly Notices of the Royal Astronomical Society: Letters* rights and permissions for academic, educational or non-commercial research. Figure 10 is reproduced under the terms of the CC BY 4.0 licence (left panel), and by permission of Springer Nature from Hashimoto *et al.* (2018) (right panel). Figure 11 is reproduced from Owen *et al.* (2019a) under the *Monthly Notices of the Royal Astronomical Society* rights and permissions for academic, educational or non-commercial research.

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REFERENCES

Abramowski A *et al.* 2012 *Astrophys. J.* **757** 158
Ackermann M *et al.* 2012 *Astrophys. J.* **755** 164
Agertz O *et al.* 2009 *Mon. Not. R. Astron. Soc.* **397** L64
Ahlers M *et al.* 2018 *Euro. Phys. J. C* **78** 924
Ajello M *et al.* 2020 *Astrophys. J.* **894** 88
Ambrosone A *et al.* 2021 *Astrophys. J.* **919** L32
Ambrosone A *et al.* 2022 *Mon. Not. R. Astron. Soc.* **515** 5389
Bergin EA & Tafalla M 2007 *Ann. Rev. Astron. Astrophys.* **45** 339
Binggeli C *et al.* 2019 *Mon. Not. R. Astron. Soc.* **489** 3827
Cao Z *et al.* 2019 *The LHAASO Science Book*, arXiv:1905.02773
CTA Consortium 2019 *Science with the Cherenkov Telescope Array*, ISBN 9789813270084
Dekel A *et al.* 2009 *Nature* **457** 451
Dogiel VA *et al.* 2018 *Astrophys. J.* **868** 114
Dogiel VA *et al.* 2021 *Astrophys. J.* **921** 43
Fedynitch A *et al.* 2019 *Phys. Rev. D* **100** 103018
Fermi E 1949 *Phys. Rev.* **75** 1169
French KD *et al.* 2015 *Astrophys. J.* **801** 1
Hashimoto T *et al.* 2018 *Nature* **557** 392
Hillas AM 1984 *Ann. Rev. Astron. Astrophys.* **22** 425
Hollenbach D *et al.* 2012 *Astrophys. J.* **754** 105
Hopkins PF *et al.* 2021 *Mon. Not. R. Astron. Soc.* **501** 3663
Huentemeyer P *et al.* 2019 *Bull. Am. Astron. Soc.* **51** 109
Indriolo N *et al.* 2018 *Astrophys. J.* **865** 127
Inoue AK *et al.* 2016 *Science* **352** 1559
Kafexhiu E *et al.* 2014 *Phys. Rev. D* **90** 123014
Kelner SR *et al.* 2006 *Phys. Rev. D* **74** 034018
Lanz L *et al.* 2022 *Astrophys. J.* **935** 29
Madau P & Dickinson M 2014 *Ann. Rev. Astron. Astrophys.* **52** 415
Mitchell AMW *et al.* 2021 *Mon. Not. R. Astron. Soc.* **503** 3522
Owen ER *et al.* 2018 *Mon. Not. R. Astron. Soc.* **481** 666
Owen ER 2019 *Ph.D. Thesis, UCL*
Owen ER *et al.* 2019a *Mon. Not. R. Astron. Soc.* **484** 1645
Owen ER *et al.* 2019b *Astron. & Astrophys.* **626** A85
Owen ER *et al.* 2021 *Astrophys. J.* **913** 52
Palladino A *et al.* 2019 *J. Cosmol. Astropart. Phys.* **2019** 004
Papadopoulos PP *et al.* 2011 *Mon. Not. R. Astron. Soc.* **414** 1705
Peron G *et al.* 2021 *Astrophys. J.* **907** L11
Samui S *et al.* 2010 *Mon. Not. R. Astron. Soc.* **402** 2778
Schober J *et al.* 2013 *Astron. & Astrophys.* **560** A87
Tibaldo L *et al.* 2021 *Universe* **7** 141
Yu BPB *et al.* 2020 *Mon. Not. R. Astron. Soc.* **492** 3179