Star-forming galaxies through cosmic time
The impacts and signatures of cosmic rays

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Outline

- Star-forming galaxies in the Universe
- Cosmic rays in star-forming galaxies
- Particle propagation
- Cosmic ray feedback & star-formation histories
- A closer look: star-formation & sub-grid physics
- Signatures (gamma-rays)
Star-forming Galaxies in the Universe

Image of simulated Lyman-alpha emission around a high redshift group of protogalaxies – credit: Geach et al.
Local Starbursts

NGC 253

Arp 220

M 82

\[ \mathcal{R}_{\text{SF}} \sim 10 \, M_\odot \, \text{yr}^{-1} \]

\[ \sim 220 \, M_\odot \, \text{yr}^{-1} \]

\[ \sim 10 \, M_\odot \, \text{yr}^{-1} \]

\[ \mathcal{R}_{\text{SN}} \sim 0.1 \, \text{yr}^{-1} \]

\[ 4 \, \text{yr}^{-1} \]

\[ 0.1 \, \text{yr}^{-1} \]

See e.g. SN Rates: Fenech+2010, Lenc & Tingay 2006, Lonsdale+2006; SF Rate: Varenius+2016, Schreiber+2003, Bolatto+2013
High-redshift starbursts (z~6+)

- Low mass, high SF rates
  - \(10^8\) M\(\odot\)
  - 10s – 100s M\(\odot\) yr\(^{-1}\)
  - SF efficiencies ~ tens of %

- Simulation work suggests possibility of filamentary inflows of gas (cf. works by Keres, Dekel, Birnboim…)

- High supernova event rates
The high-redshift CGM environment

Outflows

Cold inflows (operate mainly at high-redshift)

Birnboim + Dekel 2003; Keres+2005; Dekel 2009

Figure based on Tumlinson+2017
Cosmic rays in star-forming galaxies

Image credit: Crab Nebula, NASA, ESA 2005
Cosmic rays in the Milky Way

Adapted from Gaisser 2007
Starbursts as cosmic ray factories

- Hillas criterion
  \[ E_{\text{max}} \leq qBR \]

- Cosmic rays sources
  - Galactic (internal) in orange

Fig. adapted from Owen 2019 (PhD thesis)
See also Kotera & Olinto 2011; Hillas 1984
Cosmic ray interactions

with radiation fields ($p\gamma$)

Interaction by particles scattering off ambient photons (starlight, CMB…)

**Photopion Interaction**

\[ p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \rightarrow p + 2\gamma \\ n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu \end{cases} \]

+ pion multiplicities at higher energies

**Photopair Interaction**

\[ p + \gamma \rightarrow p + e^+ + e^- \]
Cosmic ray interactions

with matter \((pp)\)

\[
\begin{align*}
p + p &\rightarrow \\
p + \Delta^+ &\rightarrow \\
n + \Delta^{++} &\rightarrow \\
p + p + \pi^0 &
\end{align*}
\]

+ pion multiplicities at higher energies

Neutron and photon interactions produce pions

\[
n + \gamma \rightarrow \pi's
\]

Pions decay to photons, muons, neutrinos, electrons, positrons, antineutrinos

\[
\pi \rightarrow \gamma, \mu, e, \nu \ldots
\]
Cosmic ray interactions

Interactions with typical ISM density fields

Interactions with stellar radiation fields

CMB & cosmological losses

Adapted from Owen+ 2018 (1808.07837)
Particle propagation
The transport equation (hadrons)

- The transport equation for protons (cooling/momentum diffusion assumed negligible)

\[
\frac{\partial n}{\partial t} = \nabla \cdot [D(E, x) \nabla n] + \frac{\partial}{\partial E} [b(E, r) n] - \nabla \cdot [vn] + Q(E, x) - S(E, x)
\]

\[\text{SN rate}\]

*M82 in H\(\alpha\) (WIYN) and optical (HST)*

*Smith+ 2005*
Secondary electrons

- Injection by the pp attenuation process

\[ \text{pp} \rightarrow \{ \pi^0, \pi^+, \pi^- \} \]

- Transport equation (electrons)

\[
\frac{\partial n_e}{\partial t} = \nabla \cdot [D(E, x)\nabla n_e] + \frac{\partial}{\partial E} [b(E, r) n_e] - \nabla \cdot [v n_e] + Q_e(E, x) - S_e(E, x)
\]
The transport equation (hadrons)

\[
\frac{\partial n}{\partial t} = \nabla \cdot \left[ D(E, x) \nabla n \right] + \frac{\partial}{\partial E} \left[ b(E, r) n \right] - \nabla \cdot [\mathbf{v} n] + Q(E, x) - S(E, x)
\]

- Approximate ISM as a sphere
- Absorption depends on
  - density of CRs
  - density of ISM gas
  - interaction cross section (dominated by pp process)
- CR injection as a BC (for now)
  - restate problem as individual linearly independent events \((t' \text{ since inj. event})\)

\[
n = \frac{n_0}{[4\pi D(E, r')t']^{3/2}} \exp \left\{ - \int_0^{t'} \text{c} \, dt \hat{\sigma}_{p\pi} n_{\text{ISM}} \right\} \exp \left\{ - \frac{r'^2}{4D(E, r')t'} \right\}
\]
Cosmic ray distribution in ‘stationary’ ISM
Cosmic ray feedback

Image credit: National Bunsen Burner Day (March 31st), McGill University 2016
Timescales

- Estimate by considering condition for them to no longer be gravitationally bound – upper-limit (a very crude approximation → details later)

\[ \tau_Q = \tau_{\text{mag}} + \tau_{\text{heat}} \]

- Magnetic containment time; required for CR effects to develop
- \( \tau_{\text{mag}} \propto \text{SFR}^{-1} \)
- Time for region of gas to exceed \( T_{\text{vir}} \) due to CR heating
Inferred behavior of MACS1149-JD1

• Spectroscopic z=9.11 (t = 550 Myr)
  $\mathcal{R}_{\text{SF}} \approx 4.2^{+0.8}_{-1.1} \, M_\odot \, \text{yr}^{-1}$

• Two populations of stars
  – One from observed SF activity
  – Other from activity ~100 Myr earlier

• Earlier burst of Star-formation at z=15.4; t=260 Myr (Hashimoto+2018)

• Quenched fairly quickly
  – distinct inferred age of older stellar population – SED, size of Balmer break

Can CRs account for the rapid 100 Myr quenching after initial burst?
Can CRs do the job? – half an answer…

- Hashimoto+ 2018 star-formation burst models (intense, medium, slow).
- Schober+ 2013 magnetic field growth, traces cosmic ray containment.
- Consistent with CR mechanisms (or mechanical mechanisms)
  - Radiative heating timescales not consistent with rapid ‘quenching’ (need a delay, then fast action)
Why not other mechanisms?

Owen+ 2019b (1905.00338)

But what about the detail…?

- Clear trend, not predominantly sudden/stochastic (i.e. not mechanical hypernovae, etc)
  - Progressive heating (e.g. by CRs) consistent here too
- Dependence on only intrinsic (internal) parameters
  - Internal feedback not external trigger
A closer look…

Image credit: HST image of N90 Star forming region in SMC, NASA/ESA 2007
IC 5146 star-forming region in Cygnus

Herschel 250 micro-m (Arzoumanian+ 2011)

Dense star-forming filaments

Dust polarization (of background starlight)

Lines show orientation of magnetic field vector
Evolution of magnetic fields in clouds

Initial collapse from ISM (drags hourglass field)

Collapses along field (pancake/filament)

Collapse injects turbulence, some fragmentation & magnetic support (messy small-scale magnetic field)

Diffusion until further fragmentation & collapse into clumps/cores/stars

Harvard-Smithsonian Center for Astrophysics (2006)
Multi-scale structure

ZONE 1

ZONE 3
Dense clumps/cores

ZONE 1

ZONE 2
Diffuse inter-clump region

Incoming CRs from ISM

Owen+2020 (submitted)
Cosmic ray propagation

Revisit the transport equation:

\[ \frac{\partial n}{\partial t} - \nabla \cdot [D(E) \nabla n] + \nabla \cdot [v n] + \frac{\partial}{\partial E} [b(E, s)n] = Q(E, s) - S(E, s) \]

 Depends on local-scale structure and strength of the magnetic field

- **Strength:**
  - Direct (Zeeman splitting)
  - Indirect (DFC method via structure function AKA dispersion function)

- **Structure:**
  - Via power spectrum (fluctuation analysis); quantifies CR ‘tangling’

\[ D \propto \frac{1}{P(k)} \quad P(k) = \frac{1}{2} \mathcal{F} [S_2(\ell)] \]

Wiener-Khinchin theorem
Dispersion function

- Quantify polarization angle (B field) fluctuations
- Dispersion function of all possible pairs of PAs
- Indicates structure over length-scales (separations)

\[ S_n(\ell) = \frac{1}{N_{\text{pair}}} \sum_{i=1}^{N_{\text{pair}}} [\phi_i(x + \ell) - \phi_i(x)]^n \]

\( n=2 \)
Heating and ionization

Owen+2020 (submitted)
Temperature

- Milky Way → no substantial heating in the inner parts of the cloud

- Starburst galaxies: CRs much more important
- Increase Jeans mass of cloud by ~1 order of magnitude (Arp 220)
- Implications:
  - larger ISM clumps
  - more bursty star-formation
  - quenching (longer to accumulate sufficient mass)
Signatures

Image credit: Gamma-ray Sky with Fermi - NASA/DOE/Fermi-LAT Collaboration
Gamma-ray emission from starburst galaxies

\[ \pi^0 \rightarrow 2\gamma \]

Cosmic ray interactions with matter \((pp)\)

\[
\begin{align*}
p + p &\rightarrow \left\{ \begin{array}{l}
p + \Delta^+ \\
p + p + \pi^0
\end{array} \right. \\
n + \Delta^{++} &\rightarrow \left\{ \begin{array}{l}
n + p + \pi^+ \\
n + n + 2(\pi^+) 
\end{array} \right.
\end{align*}
\]

Neutron and photon interactions produce pions
\(n + \gamma \rightarrow \pi^0\)

Pions decay to photons, muons, neutrinos, electrons, positrons, antineutrinos
\(\pi \rightarrow \gamma, \mu, e, \nu \ldots\)

+ pion multiplicities at higher energies
**Signatures: spatial anisotropies**

Imprints signature at preferred (peak) scale

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Planck 2018

Redshift (cosmology) dependent
Signatures: spatial anisotropies

Different populations peak at different redshifts

→ Leaves signatures on different scales

Madau & Dickinson 2014

Silverman 2008; Jacobsen 2015
Future work and considerations

- Modelling intrinsic emission from populations
  - SB intrinsic emission can be parametrized (density, SFR, dust fraction, clumpiness…)

- Probable limitations from EBL attenuation/reprocessing
  - How far in z will populations be detectable with CTA?
  - Could IGM B fields smear-out signal?

- Data: Fermi-LAT; CTA KSP 8 ~25% of the EG sky over 3 years
Summary

• Cosmic rays are presumably abundant in high redshift starbursts (high supernova event rates)

• Can deposit energy into ISM with implications for star-formation and quenching

• May be able to account for the “bursty” star-formation histories in high-z starburst/post-starbursts

• Gamma-ray emission is associated with cosmic ray interactions in starburst galaxies
  – May leave signatures in extragalactic diffuse gamma-ray background (anisotropies)