Star-forming Galaxies at High Redshift

The feedback impact of energetic cosmic rays

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Outline

• Star-forming galaxies in the Universe
• Cosmic rays in star-forming galaxies
• Particle propagation
• Energy deposition and heating by particles and radiation
• Implications for star-formation and feedback
• Summary
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

$R_{\text{SF}} \sim 10 \, \text{M}_\odot \, \text{yr}^{-1}$

$R_{\text{SN}} \sim 0.1 \, \text{yr}^{-1}$

$\sim 220 \, \text{M}_\odot \, \text{yr}^{-1}$

$4 \, \text{yr}^{-1}$

$\sim 10 \, \text{M}_\odot \, \text{yr}^{-1}$

$0.1 \, \text{yr}^{-1}$

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
  - $10^8 \, M_\odot$
  - $10\, s - 100\, s \, M_\odot \, yr^{-1}$
  - SF efficiencies ~ tens of %

- Some known to host Lyman-\(\alpha\) haloes
  - Multi-phase CGM…

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

MACS1149-JD1 (HST/ALMA) – NASA/ESA, Hashimoto+ 2018
EGSY8p7 (Hubble/Spitzer) – NASA, Labbe+ 2015
GN-z11 (HST) – NASA, Oesch+ 2015
EGS-zs8-1 (Hubble/Spitzer) – NASA/ESA, Oesch & Momcheva 2015
The high-redshift CGM environment

Outflows

Cold inflows
(operate mainly at high-redshift)

ISM

Figure based on Tumlinson+2017

Birnboim + Dekel 2003;
Keres+2005; Dekel 2009
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 acceleration

- Shocks, e.g. SNR
  - First order Fermi acceleration

- Each pass through the shock increases the energy

- After $n$ crossings, energy is $E = E_0 \langle \xi \rangle^n$
Cosmic ray acceleration

- Some particles will escape after a crossing – take $P$ as probability of remain, so number remaining after each crossing

- Eliminate $n$ and rearrange

- Result is CRs accelerated to high energies, $\sim$GeV and above, following a power-law

$$\Gamma \approx 2.1$$

$$\frac{N}{N_0} = \left( \frac{E}{E_0} \right)^{\frac{\log P}{\log \langle \xi \rangle}}$$

$$= \left( \frac{E}{E_0} \right)^{-\Gamma}$$
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)

\[ p + p \rightarrow \begin{cases} 
  p + \Delta^+ \\
  n + \Delta^{++} 
\end{cases} \rightarrow \begin{cases} 
  p + p + \pi^0 \\
  p + p + \pi^+ \\
  p + n + \pi^+ \\
  n + p + \pi^+ \\
  n + n + 2(\pi^+) 
\end{cases} \]

+ 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

Image credit: M25 Motorway, Carillion UK Transport
The transport equation (hadrons)

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

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

- Diffusion dominated, i.e. \( v = 0 \)
- Advection dominated, i.e. \( D(E, x) = 0 \)
The diffusion zone (‘stationary’ ISM)

\[
\frac{\partial n}{\partial t} = \nabla \cdot [D(E, x)\nabla n] + \frac{\partial}{\partial E} [b(E, r)n] - \nabla \cdot [vn] + Q(E, x) - S(E, x)
\]
The diffusion zone (‘stationary’ ISM)

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

- 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 \((t’\) since inj. event)

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

- Solution for steady-state from continuous injection from single source (time integral)
- Numerically convolve with a source ensemble (MC distribution)
  - Follows ISM gas profile
The diffusion zone (‘stationary’ ISM)

- Solution for steady-state from continuous injection from single source (time integral)
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Secondary electrons

- Injection by the pp attenuation process

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

\[ \begin{align*}
\pi^- &\rightarrow e^- + \bar{\nu}_e + \nu_{\mu} + \bar{\nu}_{\mu} \\
\pi^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_{\mu} + \nu_{\mu}
\end{align*} \]

- Transport equation (electrons)

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

- Negligible advection
- No absorption
- Diffusion coefficient same as for protons (depends on charge)
Cosmic ray distribution in ‘stationary’ ISM

- **Electrons** calculated for each proton injection diffusion profile (MC distribution)
- Then convolved across proton source distribution (i.e. the SN events)
The advection zone (outflows)

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

M82 in H\(\alpha\) (WIYN) and optical (HST)
Smith+ 2005
The advection zone (outflows)

Hydrodynamical outflow model

Owen+ 2019a; Samui+ 2010
The advection zone (outflows)

Particle propagation

- Steady state solutions to transport equation, i.e. \( \frac{\partial n}{\partial t} = 0 \)

Owen+ 2019a
Energy deposition and heating

*Image credit: National Bunsen Burner Day (March 31st), McGill University 2016*
Heating mechanisms & global impacts

- **Direct Coulomb (DC)**
  
  "quenching"

  Also operates in magnetized CGM via CR streaming instability + Alfvén wave dissipation (similar rate)

- **Indirect Inverse Compton X-rays (IX)**
  
  "strangulation"

  Also advected CRs may also slow inflows, or heat filaments in CGM by DC, Alfvén dissipation…

Figure based on Tumlinson+ 2017
Direct Coulomb heating

Zone comparisons

Adapted from Owen+ 2019a (1901.01411)
Indirect heating
ISM reference case

CGM minimum shown here: value in inflow filaments would be higher (proportional to density)

Owen+ 2019b
(1905.00338)
CGM structure and implications

Strangulation vs. quenching

- Scaling relation to deal with filaments
- Effective heating power ~1-2 orders of magnitude lower than ISM value

Owen+ 2019b (1905.00338)
Timescales

- Estimate by considering condition for them to no longer be gravitationally bound – upper-limit

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

\[ \tau_S = \tau_{\text{mag}} + \tau_{\text{IX}} \]

\( \tau_{\text{mag}} \propto \text{SFR}^{-1} \)

Time for ISM to exceed \( T_{\text{vir}} \) due to DC heating

Time for filament region to exceed \( T_{\text{vir}} \) due to IX heating

Application to real galaxies…
Feedback and star-formation

Image credit: HST image of N90 Star forming region in SMC, NASA/ESA 2007
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 $\sim$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?

- Hashimoto+ 2018 star-formation burst models (intense, medium, slow).
- Schober+ 2013 magnetic field growth, traces cosmic ray containment.
- Consistent with CR strangulation + quenching working together.
  - Radiative heating timescales not consistent with rapid ‘quenching’

\[ \frac{\dot{R}_{\text{SF}}}{M_\odot \text{yr}^{-1}} \]

\[ \langle B \rangle / \text{G} \]

\[ t/\text{Myr} \]

\[ t_{\text{dyn}} \]
Why not other mechanisms?

Intrinsic parameters

No clear correlation

- 11 more systems selected from literature, post-SB with relatively high stellar mass, but low SFR (plus availability of measured quantities…)
  - Indicative of being in a quiescent stage of their evolution

- Dependence on only intrinsic (internal) parameters
  - Internal feedback not external trigger
Why not other mechanisms?

Extrinsic parameters

Owen+ 2019b (1905.00338)

- Clear trend, not predominantly sudden/stochastic (i.e. mechanical hypernovae, etc)
  - Progressive heating (e.g. by CRs) consistent here too
Summary and outlook

• Cosmic rays are presumably abundant in high redshift starbursts
• Can deposit energy into ISM and multi-component CGM with implications for star-formation quenching/strangulation
• Able to account for the “bursty” star-formation histories in high-z starburst/post-starbursts
• Next steps: sub-galactic and super-galactic scales
  – Detail of internal feedback in molecular clouds/observable signatures
  – Impacts on CGM and flows of matter/energy
  – Impacts on external environment (e.g. cosmic reionisation, gamma-ray background)

• Selected publications: