Cosmic Rays: A View Into Galactic Interactions and the New Physics

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Introduction

- Galactic interactions result in large-scale shock waves that impact the interstellar medium[1], affect the evolution of galaxies[2] and trigger star-formation[3].
  - They can be a new source of cosmic rays accelerated in large-scale tidal shocks – tidal cosmic rays (TCRs)[4].
  - TCRs would impact light element abundances[5] and non-thermal radio emission[6] of interacting galaxy. It would be sufficient for the entire gas of the Small Magellanic Cloud to be shocked only twice[4], to accelerate enough TCRs to produce as much lithium as galactic cosmic-rays (GCRs) have made throughout its history.
- Star-forming galaxies
  - Far-infrared (FIR) emission - dust heated by the UV radiation from young massive stars
  - Diffuse radio emission - non-thermal synchrotron emission of GCR electrons accelerated in supernova remnants.
- FIR-radio correlation of star-forming galaxies[6]
  - Powerful tool[7] for determining star-formation rates of galaxies[8].

Tidal shocks will affect the FIR-radio correlation in interacting galaxies and estimates of star-formation rates. Here we explore these effects.

FIR-radio Correlation

Far-infrared--radio correlation is defined with parameter

$$q_{\mathrm{IR}} = \log\left(\frac{F_{\mathrm{FIR}}}{3.75\times10^{12}\,\mathrm{W\,m^{-2}}}\right) - \log\left(\frac{S_{1.4}}{\mathrm{W\,m^{-2}\,Hz^{-1}}}\right)$$

- $S_{1.4}$ is radio continuum flux at 1.4 GHz with index α.
- F_{FIR} is rest-frame far-infrared dust emission flux.

If there was significant impact of tidal shocks on the ISM:

- Early merger - additional heating (increasing q_{IR}),
- Mid merger - increase in non-thermal radiation as TCRs get accelerated (decreasing q_{IR})
- Later merger - star-formation triggered (increasing q_{IR})

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Results

- We have analyzed 43 available,[9,10,11] interacting galaxies in various merger stages, and explored possible differences in their radio and FIR emission spectra and luminosities.
- **FIR and radio observations indicate that a new cosmic-ray population is potentially present in interacting galaxies.**
- Dashed line is the typical value[6] of the q_{IR}=2.34 ±0.21, with mean deviation denoted with dotted lines. Mean FIR-radio parameter was also determined for each merger stage separately and presented as filled (red) symbols with blue error bars.

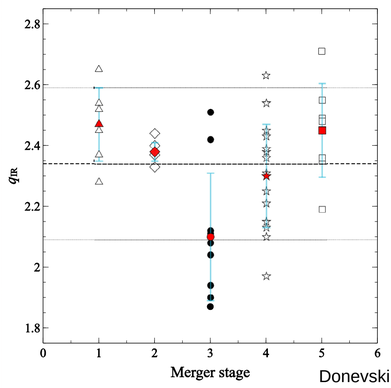

Fig. 1: The FIR-radio correlation parameter vs. merger stage. q_{IR} varies across different merger stages in a manner that would be expected under the hypothesis of tidal shock heating and particle acceleration[5].

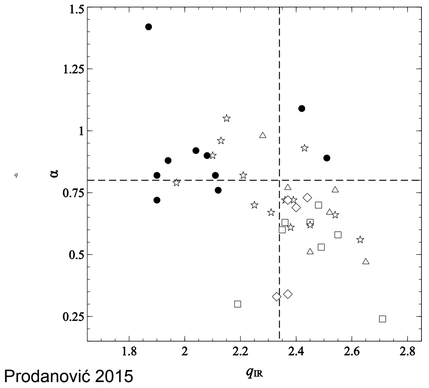

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Fig. 2: Spectral index vs. FIR-radio parameter. Most of merger stage 3 systems (filled circles) cluster in the upper left quadrant of the plot corresponding to spectral index values larger (more non-thermal) than the typical value.

Merger stage	Symbol	Description
0	None	Non-merger
1	Δ	Pre-merger: separate galaxies, non tidal tails
2	◊	Ongoing merger, early: progenitor galaxies distinguishable
3	●	Ongoing merger: progenitors sharing an envelope
4	★	Ongoing merger, late: one galaxy with double nuclei and a tidal tail
5	□	Post-merger: one galaxy with single (disturbed) nucleus and prominent tails
6	None	Post-merger, late: one galaxy with single nucleus and weak tail

Star-Formation Rates

- If FIR-radio correlation is affected so will be the star-formation rates (SFR) determined from it.
- SFR determined from radio and infrared observation will be different than the one determined from UV and Hα that should be unaffected.

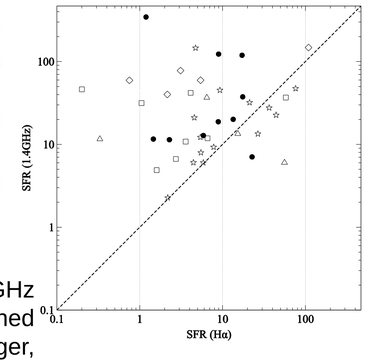

Fig 3: SFR determined from 1.4 GHz emission vs. Hα SFR. SFR determined from radio flux is systematically larger, especially in the case of merger stage 3.

Discussion

- FIR-radio parameter varies across different galactic interaction stages.
- We hypothesize that this is due to effects of tidal shock (heating and particle acceleration), causing a dispersion in the FIR-radio correlation of star-forming galaxies.
- This could result in the overestimate of the star-formation rate of interacting system.
- To further quantify these effect a larger sample of interacting galaxies would have to be analyzed, smaller interacting components would have to be observed and numerical models built.

The effects of tidal interactions between galaxies could prove to be important for detecting interacting galaxies at high redshifts.

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