COSMIC RAY NUCLEOSYNTHESIS IN GALACTIC INTERACTIONS

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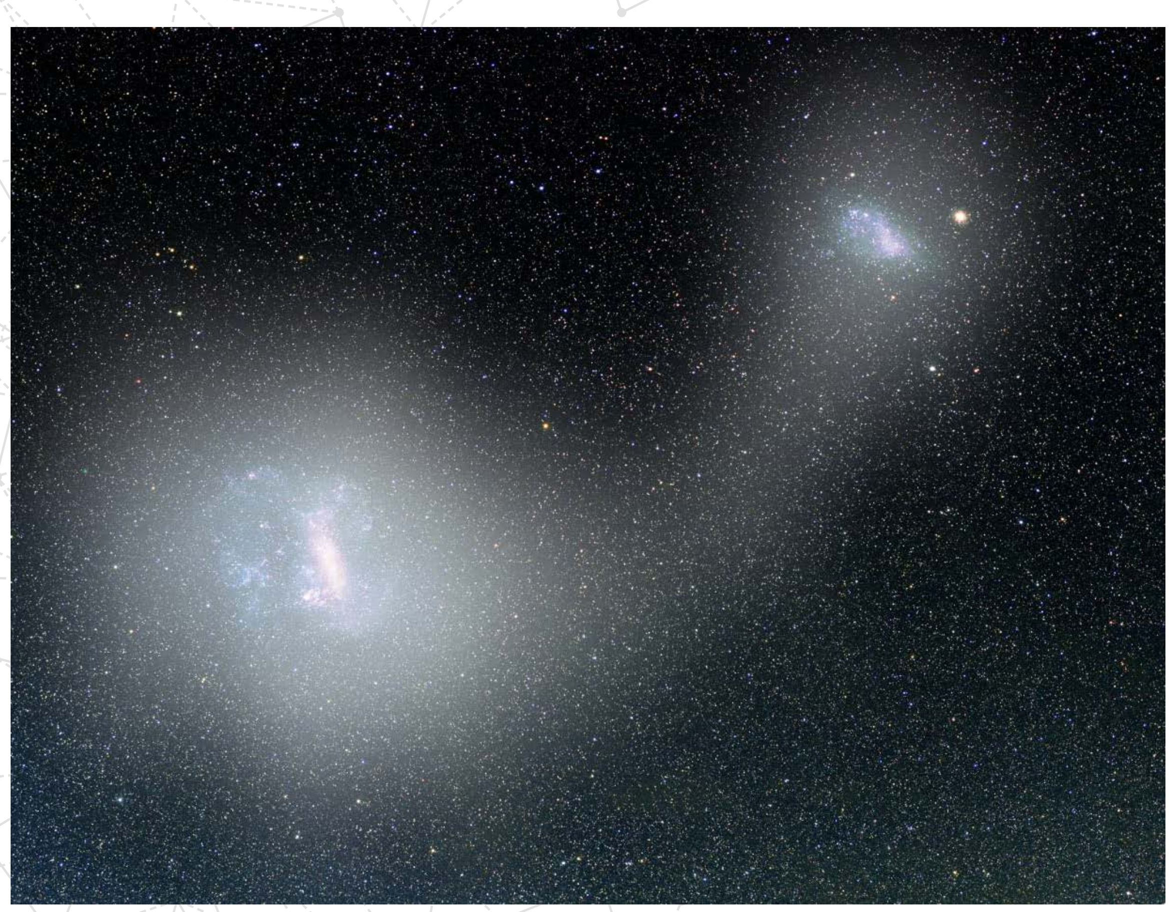
Introduction

- **Galactic interactions** result in large-scale tidal shock waves that impact interstellar medium (ISM), affect evolution of galaxies and trigger star-formation [1].
- A new cosmic ray (CR) population can be accelerated in galactic tidal shocks – **tidal cosmic rays** (TCRs) [2]
- Tidal cosmic rays in a galaxy could [3]:
  - **Increase light element** abundance without accompanying increase in metallicity
  - Cause enhanced non-thermal radio emission of the galaxy
  - Cause enhanced dust temperature
  - Affect far-infrared – radio correlation
  - Affect estimates of star-formation rate (SFR)
- Though both **Li isotopes are made in CR interactions** in the ratio varying between ^{7}Li /^{6}Li=1.3-2 depending on the CR spectrum, elements like ^{6}Li that are made only through CR nucleosynthesis would most be affected
- **Li observations in ISM of Small Magellanic Cloud and M82 could reveal and quantify TCR presence**



The Large and Small Magellanic Clouds.
Image credit: V. Belokurov / D. Erkal / A. Mellinger.

Small Magellanic Cloud "Smoke"

- Small Magellanic Cloud (SMC) has suffered galaxy harassment by the Milky Way and Large Magellanic Cloud
- Li was observed in SMC at the metallicity ~20% of Solar with $(^7\mathrm{Li/H})_{SMC} = 4.8\times10^{-10}$ and isotopic ratio ^{6}Li/^{7}Li=0.13±0.05 that is higher than at solar metallicity ^{6}Li/^{7}Li=0.08 [4].
- Prodanovic et al. 2013 [2] showed that it would be sufficient to shock the entire SMC gas twice to account entire Li abundance and explain high isotopic ratio.

- Here we demonstrate that if isotopic ratio is due to enhanced star-formation phases and GCR nucleosynthesis, **mean SFR of SMC would have to be almost twice as high as mean Milky Way SFR**:

$$\frac{^7\mathrm{Li}}{^6\mathrm{Li}} = \frac{^7\mathrm{Li}_\mathrm{p}+{}^7\mathrm{Li}_\mathrm{CR}}{^6\mathrm{Li}_\mathrm{CR}} = \frac{^7\mathrm{Li}_\mathrm{p}}{^6\mathrm{Li}_\mathrm{CR}} + 1.3 \qquad (1)$$

where we have neglected stellar ^{7}Li sources.

$^7\mathrm{Li}_\mathrm{p}$ – primordial
Li_CR – produced in cosmic-ray nucleosynthesis
$^7\mathrm{Li}_\mathrm{CR}/{}^6\mathrm{Li}_\mathrm{CR} = 1.3$

- CR nucleosynthesis yields are proportional to CR fluxes and timescales so assuming that fusion channel dominates we have $\mathrm{Li} \sim \tau\sigma_{\alpha\alpha} y_\alpha \phi_{CR,\alpha}$
- If supernovae are the only source of CRs then fluxes ϕ_{CR} are proportional to star-formation rates ψ thus we have

$$\frac{\langle\phi_{CR}\rangle_{SMC}}{\langle\phi_{CR}\rangle_{MW}} = \frac{(^7\mathrm{Li}/^6\mathrm{Li})_{MW}-1.3}{(^7\mathrm{Li}/^6\mathrm{Li})_{SMC}-1.3} = \frac{\langle\psi_{SMC}\rangle}{\langle\psi_{MW}\rangle} \qquad (2)$$

- Taking mean "quiescent" SFRs of MW and SMC to be $\langle\psi_{MW}\rangle = 1M_{sun}/\mathrm{yr}$ and $\langle\psi_{SMC}\rangle = 0.1M_{sun}/\mathrm{yr}$ we find mean SFR ration over entire time to be $\boldsymbol{\langle\psi_{SMC}\rangle/\langle\psi_{MW}\rangle = 1.6}$
- Harris & Zaritsky 2004 [5] showed SMC had 3 recent bursts of star-formation lasting in total ~2 Gyr with the most intense one being at the level of 0.2 M_{sun}/yr.
- **To account for observed isotopic ratio mean SFR in "burst" phase would have to be $\langle\psi_{SMC}\rangle_*$ ~ 7 M_{sun}/yr which is about 35x higher than observations suggest.**

"Smoke" from Cigar Galaxy

- M82 is a dwarf, starburst galaxy that has experienced interaction with M81 [6]
- At metallicity ~0.5 of solar, lithium has been observed in M82 gas phase to have ~2x higher abundance than solar $(\mathrm{Li/H})_{M82} = 3.98\times10^{-9}$.
- Li abundance should scale with metallicity but starburst phase can result in diluting the metal content due to intense gas inflow
- **Comparing observed Li abundances between M82 and MW,** and assuming that their primordial and stellar (at same metallicity) contributions are same one finds that **$^7\mathrm{Li}_{M82}$ / $^7\mathrm{Li}_{MW}$ ~10**
- This translates to the ratio of mean star-formation or supernova rates $\boldsymbol{\langle R_{SN,M82}\rangle/\langle R_{SN,MW}\rangle \sim 10}$
- We can estimate mean supernova rate of M82 from observed supernova rates taking that current starburst phase lasts for ~ 0.3 Gyr with current $\langle \boldsymbol{R_{SN,M82}}\rangle_* \sim 10\boldsymbol{R_{SN,MW}}$ while quiescent phase had $\langle\boldsymbol{R_{SN,M82}}\rangle_\mathrm{q} \sim \boldsymbol{0.3R_{SN,MW}}$ [6]

$$\langle R_{SN,M82}\rangle = \frac{\langle R_{SN,M82}\rangle_q \times \tau_q + \langle R_{SN,M82}\rangle_* \times \tau_*}{\tau_q + \tau_*} \sim R_{SN,MW} \qquad (3)$$

M81 versus M82.
Image credit: Rainer Zmaritsch & Alexander Gross

Results and Conclusions

- Close fly-bys between galaxies can result in large scale tidal shocks in the galactic gas which would accelerate tidal cosmic rays.
- This hypothetic CR population can be tested in systems like the SMC and M82 which have experienced recent galaxy harassment
- Light element abundances, especially for cosmic-ray dosimeters like 6Li, would especially be affected by presence of additional CRs
- SMC and M82 are only extragalactic systems where lithium abundance has been observed in their ISM
- We find that
  - **High isotopic ratio of SMC inconsistent with SMC's star-forming history and requires additional CR component** that would result in nucleosynthesis equivalent to SFR ~ 7 M_{sun}/yr
  - **High observed Li abundance in M82 requires that mean supernova rate in M82 is about the current**, starburst phase rate, which is ~10x larger than observations give
  - **Observed lithium abundances indicate that additional CR population is present in interacting systems.**

References

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