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COSMIC-RAY ACCELERATION IN GALACTIC INTERACTIONS AND ITS IMPLICATIONS

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Abstract. It has been shown that galactic interactions and mergers can result in large-scale tidal shocks that propagate through interstellar gas. As a result, this can give rise to a new population of cosmic rays, additional to standard galactic cosmic rays present in star-forming galaxies. We investigate the impact of this tidal cosmic-ray population on the nucleosynthesis of lithium in interacting systems (such is the Small Magellanic clod for example) in the context of the cosmological lithium problem. Moreover we also demonstrate that the presence of these tidal shock-waves and may also have far reaching consequences on our understanding of galactic evolution by affecting the far-infrared radio correlation observed in star-forming galaxies and impacting star formation rates estimates. We discuss how these effects can be further probed through numerical simulations and used to on high-redshift observations of interacting systems.

1. INTRODUCTION

Particle acceleration in astrophysical environments occurs at some level everywhere where there are shock, magnetic fields and charged particles present, through the mechanism called diffusive shock acceleration (Bell 1978). It is generally accepted that the dominant population of cosmic rays in star-forming galaxies are accelerated in strong shocks of supernova remnants, since these sources have sufficient energy to explain observed cosmic-ray fluxes and spectra. For this reason, cosmic rays are perfect probes of galactic star-formation and supernova rates.

Though we can directly detect cosmic rays only at Earth, we can indirectly learn about their current and past fluxes through observing the consequences of their interactions. Specifically, interaction of cosmic-ray protons with ambient hydrogen produces neutral pions which decay into two gamma rays. Most of the diffuse Galactic gamma ray emission from the disk of the Milky Way observed by the Fermi-LAT (Ackermann et al. 2012) is due to this process (Strong et al. 2010). Furthermore, fusion reaction between cosmic-ray alpha particles and ambient helium results in production of lithium nuclei (Reeves 1970). While ^{7}Li is produced in big bang nucleosynthesis and the neutrino process as well as in cosmic-ray interactions, light isotope ^{6}Li is only made by cosmic rays, making it a perfect cosmic-ray dosimeter (Reeves 1970).

Lithium was first observed outside of the Milky Way in the interstellar medium of the Small Magellanic Cloud (Howk et al. 2012). This observation was to test the origin of the long-standing "lithium problem" where pre-galactic ^{7}Li observed in low-metallicity halo stars (Ryan et al. 2000) in the Milky Way is 2-4 times lower than the predicted primordial ^{7}Li abundance (Cyburt et al 2016). However, observation of lithium in the Small Magellanic Cloud showed also that the abundance of ^{6}Li is larger than what would be expected from based on its metallicity, indicating a larger cosmic-ray exposure over its history (Prodanovic et al. 2013). This was furthermore confirmed by predictions of its ^{6}Li abundance (Ciprijanovic 2016, Fields and Prodanovic 2005) based on its observed gamma ray emission (Abdo et al. 2010).

Motivated by the problems related to lithium in both the Milky Way and the SMC, Prodanovic et al. (2012) explored the possibility of existence of another population of cosmic rays in star-forming galaxies that would be in addition to already present galactic cosmic rays (GCRs), and which would result in overall larger ^{6}Li production. These tidal cosmic rays (TCRs) would be accelerated in large-scale tidal shocks that appear the interstellar medium of the host galaxy due to galactic interactions, mergers and close fly-bys (Cox et al. 2006). Extending on the owrk of Murphy (2013), Prodanovic et al. (2012) showed that it would be possible to account for the entire observed ^{6}Li abundance if the entire gas of the SMC was shocked only twice, which would be plausible given that the SMC has experienced close fly-bys with both Milky Way and the Large Magellanic Cloud, evidence of which is a tidal stream of gas seen the between Magellanic clouds (Diaz and Bekki 2011).

In order to further explore the possibility and the impact that this additional cosmic ray population would have on our understanding of star forming galaxies, Donevski and Prodanovic (2015) explored the behavior of the correlation that exist between far infrared and radio emission in star- forming galaxies, during different merger stages of these system. They found that variations found in this correlation, analyzed on a small sample of interacting galaxies, were consistent with additional heating and particle acceleration due to presence of large tidal shocks.

In this work we continue to explore the possible cosmic-ray acceleration in shocks due to galactic mergers and interactions, and present some preliminary results on how this extra TCR population would impact the evolution of the radio emission in star-forming galaxies over redshifts.

2. EVOLUTION OF THE FAR-INFRARED RADIO CORRELATION

Observation have established that there is a strong correlation between radio and far infrared (FIR) emission in star-forming galaxies (van der Kruit 1971). It is understood that the origin of this correlation is in the star-formation itself where the FIR emission is coming from dust heated by the UV radiation of young stars, while radio emission is dominantly due to synchrotron emission of electrons accelerated in supernova remnants. This FIR-radio correlation is often represented through parameter

$$q_{\rm FIR} = \log\left(\frac{F_{\rm FIR}}{3.75\times 10^{12}{\rm Wm^{-2}}}\right) - \log\left(\frac{S_{1.4}}{\rm Wm^{-2}Hz^{-1}}\right) \qquad (1)$$

where $F_{\rm FIR}$ and $S_{1.4}$ dust emission flux and radio emission flux at 1.4 GHz respectively (Helou et al. 1985). The value of this parameter analyzed on the sample of 1800 star-forming galaxies including interacting was found to be $q_{\rm FIR} = 2.34 \pm 0.01$ (Yun et al. 2001). Though Murphy (2009) that the value of this parameter should increase going to higher redshifts due to increased importance of inverse Compton energy losses of electrons onto increasing density cosmic microwave background photons, results of numerous studies showed that this correlation parameter was relatively stable and unchanging over redshifts (Sargent et al. 2010). However, the infrared-radio correlation has recently been investigated on a large sample containing more that 12000 star-forming galaxies up to redshift $z < 6$ in the COSMOS field (Delhaize et al. 2017). They found that, contrary to previous predictions, the FIR-radio parameter decreases with redshift as (Delhaize et al. 2017):

$$q_{\rm FIR}(z) = (2.52 \pm 0.03)^{-0.21 \pm 0.01}. \tag{2}$$

In the light of results of Donevski and Prodanovic (2015) we can say that the presence of interacting systems in this sample is guaranteed to add to the scatter in $q_{\rm FIR}$ values in the observed sample at some level. Here we explore how would the determined FIR-radio parameter change if analysis was done on a sample of star-forming galaxies that contains some fraction of interacting systems and we allow that the value of this parameter changes over different merger stages as was shown in Donevski and Prodanovic (2015). Assume that at any epoch, a sample of analyzed star-forming galaxies contains a fraction of interacting galaxies where that fraction is a function of redshift. Interacting galaxies in that sample will be in different merger stages, where each stage will have different characteristic value of the $q_{\rm FIR}$ parameter: early interaction stages will be shortest and characterized by extra shock heating causing the increase in $q_{\rm FIR}$ value, later stages will be longer and characterized by additional particle acceleration and dominance of the TCR population and decrease in the $q_{\rm FIR}$ value, while in final stages the FIR-radio parameter should return back to its "‘unperturbed"’ value (Donevski and Prodanovci 2015). Thus due to different timescales of these interaction stages, overall effect should be systematic decrease in the $q_{\rm FIR}$ determined from a sample of interacting galaxies. And the larger the fraction of interacting systems is in the sample, the more prominent would this decrease be, and we assume that this fraction evolves as $f_m = 0.008(1+z)^3$ (Bluck 2011). On the other hand, as star-formation rate also evolves, galactic cosmic ray flux will evolve as well, and as tidal cosmic-ray population is competing with it, this will result in lessening the decrease in the $q_{\rm FIR}$ due to interactions as star-formation rate increases, and strengthening the decrease in the $q_{\rm FIR}$ as it decreases. To include the effects of star-formation we adopt cosmic star formation rate from Madau and Dickinson (2014). Finally, we also take into account the expected increase in $q_{\rm FIR}$ due to decrease of synchrotron emission as a result of increased inverse Compton losses on the cosmic microwave background photons (Murphy 2009).

One example of our results is presented on Figure 1. The bottom magenta curve is the FIR-radio correlation parameter evolution found in Delhaize et al. (2017), while the blue curve above is the evolution that follows from our assumption that interacting galaxies introduce an overall decrease of the $q_{\rm FIR}$ and modeled evolution of the fraction of interacting galaxies, where we also include the effects of cosmic star-formation rate evolution and increase in cosmic microwave background photon density which will impact relative importance between inverse Compton an synchrotron energy losses. The last effect is sensitive to the choice of galactic magnetic field which was for the purpose of demonstration here taken to be 500μG. Though the exact behavior does depend on model details like choice of evolution of interaction fraction, choice of cosmic star-formation rate, galactic magnetic field, timescales of interaction phases as well as the magnitude of deviation of $q_{\rm FIR}$ value from its nominal, non-interacting value, we see that the observed decrease in $q_{\rm FIR}$ can be modeled.

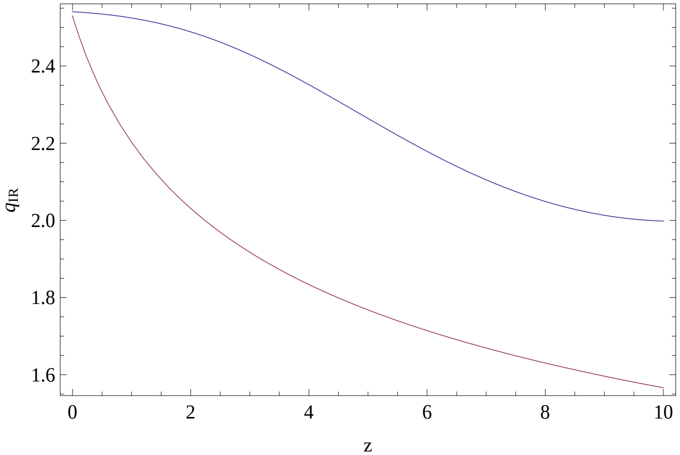

Figure 1: Evolution of the $q_{\rm FIR}$ over redshift. The bottom magenta curve is the evolution found from the sample of star-forming galaxies in the COSMOS filed (Delhaize et al. 2017. The top blue curve is the evolution expected if we assume that sample contains some fraction of interacting galaxies where the value of the $q_{\rm FIR}$ is systematically lower compared to non- interacting galaxies (Donevski and Prodanovic 2015).

3. DISCUSSION

Following the results of Donevski and Prodanovic (2015) where it was found that the FIR-radio correlation parameter varies across merger stages for interacting galaxies, and motivated by the recent findings of Delhaize et al. (2017) that this parameter decreases with redshift, we have explored how this parameter would change when analyzed sample includes an evolving fraction of interacting systems. Our preliminary results indicate that, when effects of galactic interactions are taken into account, specifically when cosmic rays are allowed to be accelerated in tidal shocks that arise in interactions, the FIR-radio correlation parameter can decrease in a manner similar to what was observed. Though the results are indeed strongly model dependent, it is clear that presence of interacting systems will not only add to the scatter in the observed sample, but that it can also have observable effect, which will be better quantified in publication to follow.

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Galactic Cosmic Rays (GCR) are the slowly varying, highly energetic background source of energetic particles that constantly bombard Earth. GCR originate outside the solar system and are likely formed by explosive events such as supernova. These highly energetic particles consist of essentially every element ranging from hydrogen, accounting for approximately 89% of the GCR spectrum, to uranium, which is found in trace amounts only. For galactic cosmic rays, energies up to the knee: âˆ¼1015 eV For extragalactic cosmic rays, energies beyond the ankle: âˆ¼1020 eV. Elemental abundances of cosmic rays similar to interstellar/circumstellar abundances. General principles of acceleration.Â Open questions on galactic cosmic rays. Why does the energy spectrum change its slope at âˆ¼1015 eV? How are cosmic rays accelerated to âˆ¼1017â€“1018 eV? Are cosmic rays between the knee and ankle: galactic, extragalactic, or a combination?Â Fraction of energy lost in each interaction is small so effective interaction distance remains large: âˆ¼ 600 Mpc At energies above âˆ¼1020, pion production becomes possible. p + Î³CMB â†' p + Ï€0 p + Î³CMB â†' n + Ï€+. (46) (47). â€¢ The evolution and interaction of turbulence and cosmic rays determines how the cos-mic rays will eventually be released by the SNR, which has an impact on the amplitude and frequency of variations of the cosmic-ray flux near Earth and at other locations in the Galaxy [4]. The study of diffuse Galactic gamma-ray emis-sion is important for a number of reasons. â€¢ It provides direct information on the cosmic-ray spectrum in various locations in the Galaxy, which is needed to understand the origin of cosmic rays near and beyond the knee.Â This is a prin-cipal goal that will elucidate our understanding of plasma shocks, generation of magnetic turbu-lence and cosmic ray acceleration in the cosmos. 1.2.2 Diffuse galactic emission.