PROCEEDINGS OF SCIENCE

Are Star-forming Galaxies Truly Cosmic-rays Calorimeters? Insights from 15 Years of Fermi-LAT Data

Antonio Ambrosone[a,b,*]

[a] *Gran Sasso Science Institute (GSSI), Viale Francesco Crispi 7, 67100 L'Aquila, Italy*

[b] *INFN-Laboratori Nazionali del Gran Sasso (LNGS), via G. Acitelli 22, 67100 Assergi (AQ), Italy*

Star-forming environments such as star-forming and Starburst Galaxies (SFGs and SBGs) experience intense phases of stellar formation activity. The Fermi-LAT collaboration has found a correlation between the gamma-ray and infrared luminosities for a sample of local SFGs and SBGs. Yet, the nature of cosmic-ray (CR) transport inside these sources is still under debate. I discuss novel and tight constraints between CR transport in these sources and the star formation rate (SFR), exploiting 15 years of public Fermi-LAT data. Firstly, there is an indication at $\sim 4\sigma$ level from other two starburst galaxies, M83 and NGC 1365, strengthening even more the correlation between gamma-rays and SFR. However, sources like NGC 6946 and IC 342 do not show any evidence of gamma-ray emission despite correlating with the most energetic CRs ever observed. Unresolved sources strongly reduce the degree of calorimetry of SBGs, thereby decreasing the contribution of SBGs into the diffuse gamma-ray and neutrino backgrounds. This intrinsically implies that if star-forming activity were able to accelerate ultra-high energy CRs, their corresponding gamma-ray and neutrino emission might be dim.

7th International Symposium on Ultra High Energy Cosmic Rays (UHECR2024)
17-21 November 2024
Malargüe, Mendoza, Argentina

*Speaker

https://pos.sissa.it/

PoS(UHECR2024)014

1. Introduction

SFGs and SBGs have star formation rates (SFRs) much higher than the one measured in the Milky way. Indeed, They are characterised by a high number of supernovae explosions (SNe) [1–3]. SFGs and SBGs are consequently expected to power a high number of CRs, given that SNe are believed to power galactic CRs observed at the Earth position. On this regard, the Fermi-LAT collaboration has found a correlation between the Infrared (IR) Luminosity, which is a tracer of the SFR and the gamma-ray luminosity of a dozen of SFGs and SBGs [4]. The current interpretation is given by CRs losing energy inside the sources colliding with the interstellar gas producing gamma-rays and neutrinos. Furthermore, The Pierre Auger Observatory (PAO) has found a correlation between SBGs and Ultra-High Energy Cosmic Rays (UHECRs) [5]. Indeed, Ref. [6] has studied the possibility for SBGs to power the UHECR spectrum measured by the PAO [7–10]. As a result, SFGs and SBGs are important tools for studying the CR physics. In this contribution, we discuss the updated correlation between gamma-ray and Infrared Luminosities exploiting 15 years of public Fermi-LAT data (see [1] for more details). Moreover, we estimate the calorimetric fraction ($F_{\rm cal}$), namely the fraction of CRs actually losing energy inside SFGs and SBGs producing gamma-rays and neutrinos.

2. Data Analysis and Model Interpretation

We analyse 15.3 years of Fermi-LAT data with the *fermitools*[1] considering an energy range between $1-1000$ GeV. The catalogue analysed consists of 70 sources. 14 sources have been already reported as 5σ excess over the background-only hypothesis, while for the other 56 sources there is still no a clear evidence for a gamma-ray activity. Each source has a galactic latitude $|b| > 10^\circ$ in order to reduce the contribution of galactic photons. We do not find new excesses over 5σ. However, M 83 and NGC 1365 show clear evidence for gamma-ray activity at a level of $\sim 4\sigma$ over the background-only hypothesis. On the other hand, NGC 6946 and IC 342 do not show any gamma ray activity although they correlate with some UHECR events collected by the Telescope Array [11]. Fig. 1 shows the integrated gamma-ray luminosity ($L_\gamma^{1-1000\,\rm GeV}$) between $1-1000$ GeV and the integrated infrared luminosity ($L_{\rm IR}$) between $8-1000\,\mu$m.

Discovered sources, namely sources for which the significance is above 5σ level are indicated with cyan points, while sources which clearly indicate an activity ($\sim 4\sigma$ excess) are reported as orange points. Finally, for other sources, we report the 95% CL upper limits considering a fixed $E^{-2.3}$ flux. Fig. 1 shows a clear relation between IR and gamma-ray luminosities. SFR is tightly correlated to $L_{\rm IR}$ because interstellar material re-emits the UV light emitted by stars in the IR range. Indeed, we have [1]

$$\mathrm{SFR} = 1.36 \cdot 10^{-10} \left(\frac{\mathrm{L_{IR}}}{\mathrm{L_\odot}}\right)\left(1 + \sqrt{\frac{10^9\,\mathrm{L_\odot}}{\mathrm{L_{IR}}}}\right) \mathrm{yr}^{-1} \tag{1}$$

Therefore, there is a clear correlation between the SFRs and the gamma-ray fluxes of these sources. In order to interpret these results, we introduce a physical model with which calculate the

[1] Please see https://fermi.gsfc.nasa.gov/ssc/data/analysis/software/

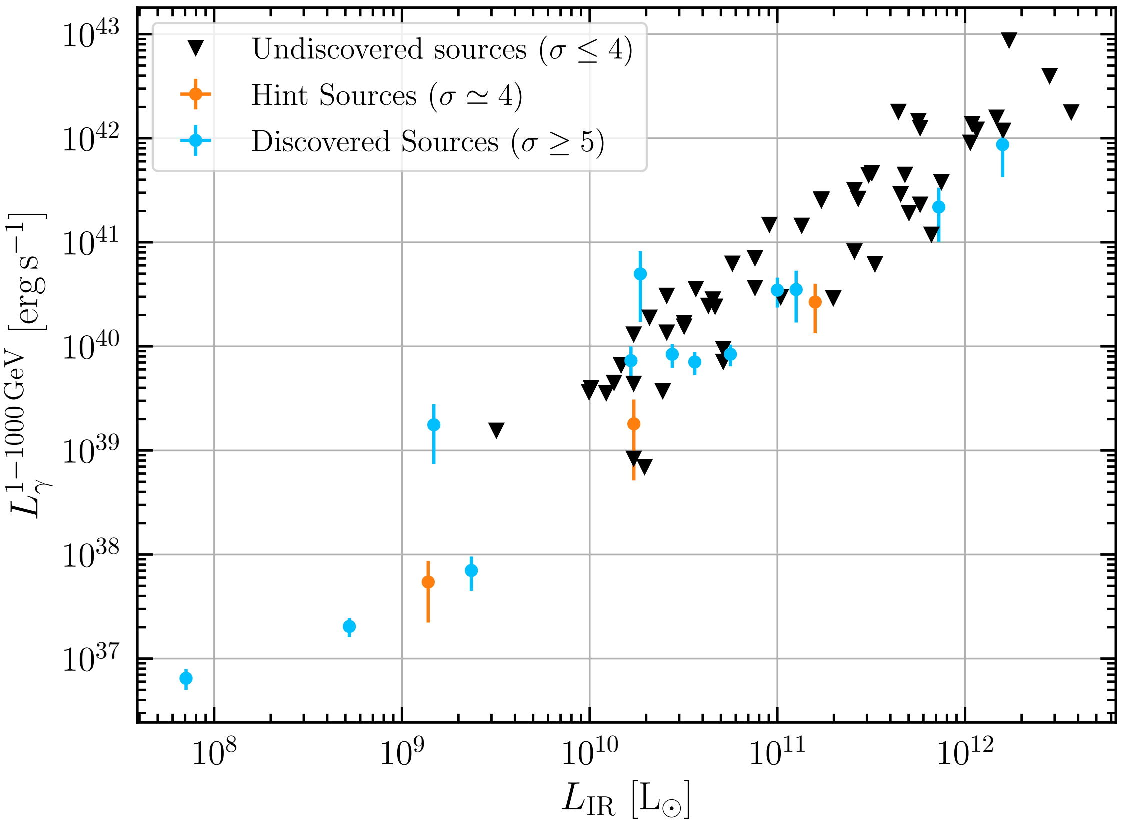

Figure 1: $L_\gamma^{1-1000\,\mathrm{GeV}}$ vs L_{IR} for the 70 catalogue analysed. Sources with a significance above 5σ are reported as cyan points, while sources which evidence of gamma-ray activity ($\sim 4\sigma$ excess) are reported as orange points. Finally, we report 95% CL upper limits for other sources as black triangles. Image taken from [1]

gamma-ray emission of SFGs and SBGs. To this purpose, we estimate the CR numer density as

$$N_{\mathrm{CR}}(E) = F_{\mathrm{cal}} \cdot \frac{\tau_{\mathrm{loss}}}{E} \int_E^{+\infty} Q(E')\mathrm{d}E' \tag{2}$$

where $Q(E)$ is the power-law injection CR flux normalised using the SFR. F_{cal} is the fraction of CRs that actually lose their energy in the system that produces gamma rays. We emphasise that F_{cal} is generally energy-dependent. However, given that Fermi-LAT is not able to probe more complicated spectra than a simple power-law (above 1 GeV), for the following, we are going to assume F_{cal} to be constant representing an average fraction. The theoretical gamma-ray flux predicted by our model is calculated using the analytical prediction of Ref. [12]. We estimated the F_{cal} value for each source by matching the theoretical predictions with the gamma-ray flux of each source. We study if F_{cal} correlates with the SFR using

$$F_{\mathrm{cal}} = A \left(\frac{R_{\mathrm{SN}}}{\mathrm{yr}^{-1}}\right)^{\beta} \left(1 + A \left(\frac{R_{\mathrm{SN}}}{\mathrm{yr}^{-1}}\right)^{\beta}\right)^{-1} \tag{3}$$

where $R_{\mathrm{SN}} = \frac{1}{83 M_\odot}$SFR is the expected SNe rate for each source.

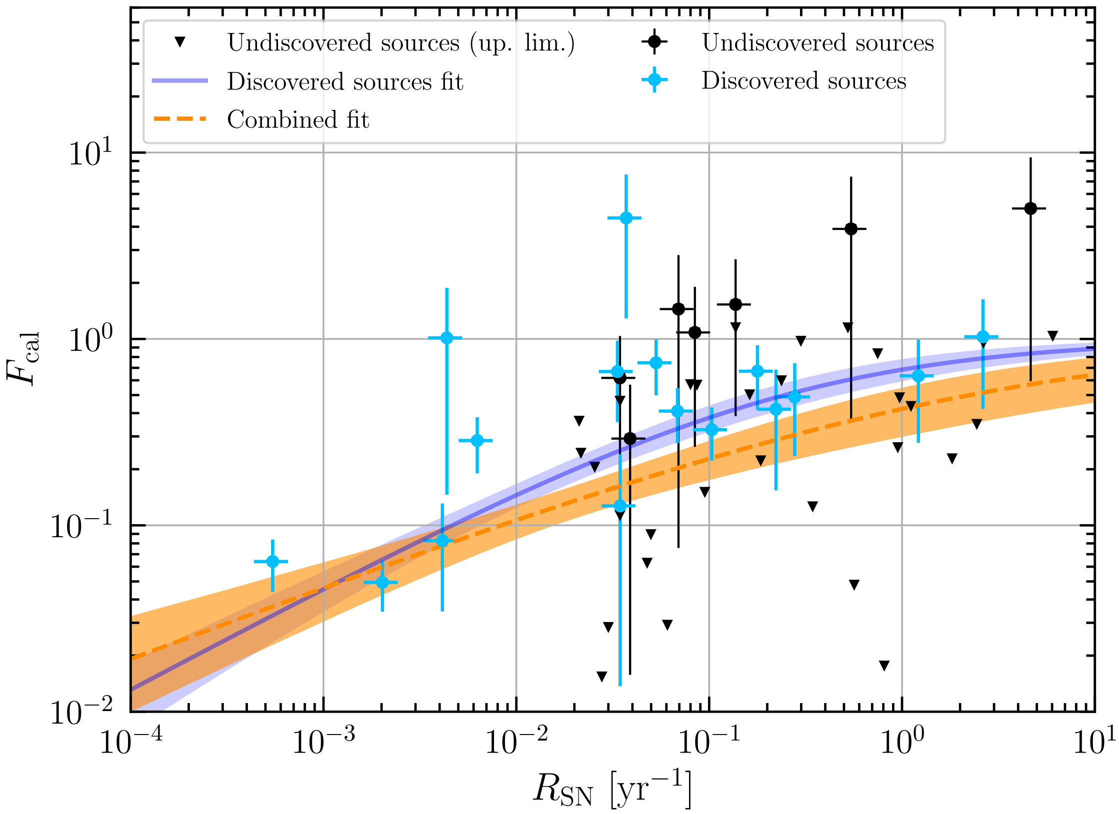

Figure 2: $F_{\rm cal}$ vs $R_{\rm SN}$ for the 70 source catalogue analysed. Discovered and excess sources are reported as cyan points while the other sources are reported as black points. The purple and orange lines respectively represent the fit consider only discovered sources and the whole catalogue. The bands refer to the 2σ uncertainty. Image taken from [1].

Fig. 2 reports the fit for Eq. 3. The purple line refer only to the discovered sources while the orange line considers the whole catalogue. Interestingly, sources which show no gamma-ray activity constrain $F_{\rm cal}$ almost of a factor ~ 2 at the best-fit scenario, leading to a reduced capacity of SFGs and SBGs of trapping CRs inside their systems. This might reduce the degree calorimetry of these sources which have been considered in previous articles.

3. Discussion and Conclusions

In this contribution, we have revised the correlation between gamma-ray and IR luminosities for SFGs and SBGs. In doing so, we exploit 15 years of public Fermi-LAT data. We analyse a catalogue of 70 sources. While, we do not find compelling evidence for new sources, we find that M 83 and NGC 1365 indicate strong gamma-ray activity at level of $\sim 4\sigma$. We interprete these results in terms of diffuse hadronic emissions due to CRs losing their energy into the system and estimate the calorimetric fraction for each source. Moreover, we study the correlation of $F_{\rm cal}$ in terms of the SFR. We find that our model can fairly represents the data and that $F_{\rm cal}$ increases with SFR. However, undiscovered sources reduces $F_{\rm cal}$, leading us to the conclusion that while some

SBGs are able to strongly confine CRs inside their system, in general the population might not be as calorimetric as previously considered. As a result, if SBGs are able to power UHECRs might be dimmer in gamma-ray as previously consideres, as recently pointed out by Ref. [13]. Finally, with these results, the SFG and SBG population cannot saturate the isotropic gamma-ray background (IGRB) measured by Fermi-LAT while being consistent with a 20% contribution to the 6-year Cascade diffuse neutrino flux measured by the IceCube Neutrino Observatory [1].

Acknowledgments

The author acknowledges the support of the project "NUSES- A pathfinder for studying astrophysical neutrinos and electromagnetic signals of seismic origin from space (Cod. id. Ugov: NUSES; CUP: D12F19000040003). The author is also supported by the research project TAsP (Theoretical Astroparticle Physics) funded by the Istituto Nazionale di Fisica Nucleare (INFN). This research has made use of the *fermitools* and the Fermi-LAT data which are publicly available.

References

[1] Antonio Ambrosone, Marco Chianese, and Antonio Marinelli. Constraining the hadronic properties of star-forming galaxies above 1 GeV with 15-years Fermi-LAT data. *JCAP*, 08:040, 2024.

[2] Antonio Ambrosone, Marco Chianese, Damiano F. G. Fiorillo, Antonio Marinelli, Gennaro Miele, and Ofelia Pisanti. Starburst galaxies strike back: a multi-messenger analysis with Fermi-LAT and IceCube data. *Mon. Not. Roy. Astron. Soc.*, 503(3):4032–4049, 2021.

[3] Antonio Ambrosone, Marco Chianese, Damiano F. G. Fiorillo, Antonio Marinelli, and Gennaro Miele. Could Nearby Star-forming Galaxies Light Up the Pointlike Neutrino Sky? *Astrophys. J. Lett.*, 919(2):L32, 2021.

[4] M. Ackermann and Others. Gev observations of star-forming galaxies with the fermi large area telescope. *The Astrophysical Journal*, 755(2):164, August 2012.

[5] A. Abdul Halim et al. Constraining models for the origin of ultra-high-energy cosmic rays with a novel combined analysis of arrival directions, spectrum, and composition data measured at the Pierre Auger Observatory. *JCAP*, 01:022, 2024.

[6] Antonio Condorelli, Denise Boncioli, Enrico Peretti, and Sergio Petrera. Testing hadronic and photohadronic interactions as responsible for ultrahigh energy cosmic rays and neutrino fluxes from starburst galaxies. *Phys. Rev. D*, 107(8):083009, 2023.

[7] P. Abreu et al. The energy spectrum of cosmic rays beyond the turn-down around 10^{17} eV as measured with the surface detector of the Pierre Auger Observatory. *Eur. Phys. J. C*, 81(11):966, 2021.

[8] Alexander Aab et al. Measurement of the cosmic-ray energy spectrum above 2.5×10^{18} eV using the Pierre Auger Observatory. *Phys. Rev. D*, 102(6):062005, 2020.

[9] A. Abdul Halim et al. Constraining the sources of ultra-high-energy cosmic rays across and above the ankle with the spectrum and composition data measured at the Pierre Auger Observatory. *JCAP*, 05:024, 2023.

[10] Francesco Fenu. The cosmic ray energy spectrum measured with the Pierre Auger Observatory. *Adv. Space Res.*, 72:3531–3537, 2023.

[11] R. U. Abbasi et al. An extremely energetic cosmic ray observed by a surface detector array. *Science*, 382(6673):abo5095, 2023.

[12] S. R. Kelner, Felex A. Aharonian, and V. V. Bugayov. Energy spectra of gamma-rays, electrons and neutrinos produced at proton-proton interactions in the very high energy regime. *Phys. Rev. D*, 74:034018, 2006. [Erratum: Phys.Rev.D 79, 039901 (2009)].

[13] Angelina Partenheimer, Ke Fang, Rafael Alves Batista, and Rogerio Menezes de Almeida. Ultra-high-energy Cosmic-Ray Sources Can Be Gamma-Ray Dim. *Astrophys. J. Lett.*, 967(1):L15, 2024.