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Gamma-ray luminosity/star-formation rate correlations in the context of the Cherenkov Telescope Array

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Star-forming galaxies (SFGs) are unique γ-ray emitters. The observed correlation between their non-thermal luminosity and their star-formation rate (SFR) strongly suggests that these γ rays result from the interactions of cosmic rays (CRs) injected by phenomena connected with the SFR, such as supernova remnants and massive star winds. These correlations provide insight into how global properties of galaxies like magnetic, velocity or density fields scale with the SFR.

Here we investigate the effect of γ-ray absorption processes and cosmic-ray transport footprints in SFGs at very high energies (VHE) in terms of the luminosity–SFR correlations. With this purpose we extend an existing model that reproduces the non-thermal emission in SFGs from radio to GeV, by including γ-γ absorption process. We predict the correlation between the SFR and the luminosity in the Cherenkov Telescope Array (CTA) energy range, and explore how it is affected by the proton maximum energy and the absorption inside galaxies and en route to Earth.

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1. Introduction

Fourteen SFGs have been detected in γ rays by the *Fermi* telescope. These galaxies show a correlation between their integrated γ-ray luminosity in the 0.1–100 GeV energy range (L_γ) and their SFRs [1, 2]. The radio luminosity at 1.4 GHz of SFGs also features a similar correlation [3]. Such a non-thermal radiation is produced mainly through the interaction of cosmic rays (CRs) with thermal gas, background photons and magnetic fields characterising the interstellar medium (ISM). The CRs are injected by cosmic accelerators, such as supernova remnants [4, 5] or young massive stellar clusters [6], which in turn scale in number with the SFR. The linear relation between CR sources and the SFR is believed to be the origin of the correlations between the SFR and the non-thermal luminosity in different energy bands.

In previous works we modelled the transport of CRs in SFGs and we investigated the associated multi-wavelength emission with the aim of exploring the aforementioned correlations. In particular, we focused on the following energy bands: γ-rays in the GeV band [7], radio [8], and X-ray and MeV [9]. In these works we found that, in general, the γ-ray spectrum of SFGs is dominated by hadronic emission, namely by high-energy photons resulting from the π^0 decay coming from inelastic proton-proton (p-p) interactions. We also showed that SFGs behave calorimetrically at high SFR, whereas at low SFR the importance of CR escape increases. In the case of protons, the mechanism driving the escape is diffusion. Interestingly, the calorimetric behaviour of SFGs with high SFR was confirmed while studying the radio band, where the role of secondary electrons and positrons becomes dominant in shaping the correlation of the radio luminosity with the SFR [8].

The goal of this work is to explore for the first time the γ-ray–SFR correlation in the energy range where CTA will be operative, namely between 100 GeV and 100 TeV. In addition, we plan to analyse the most relevant physical ingredients that could shape the correlation. For this purpose, we extend our model by including external γ–γ absorption. We also explore the impact of the assumed proton maximum energy at injection ($E_{p,max}$) in the predicted correlations.

2. The emission model

We adopt the model developed in [8] and [9] for the CR transport and the associated non-thermal emission from SFGs. In order to carry out a population study, the latter was built to model the non thermal emission coming from a generic SFG, with the SFR as the key parameter.

We solve the transport equation assuming each galaxy as a cylinder of radius $R = 1\,$kpc and height $H = 200\,$pc with homogeneous gas density n and where acceleration sites are uniformly distributed. In this context, CRs are steadily injected, and protons (electrons) can lose energy through different mechanisms such as p-p interactions, ionisation and Coulomb losses (ionization, bremsstrahlung, inverse Compton and synchrotron, see also Fig. 1). Finally CRs escape from the emission region via advection and diffusion. The stationary particle energy distribution is obtained by solving numerically the following form of the transport equation:

$$-\frac{\partial}{\partial E}\left[\sum_j \dot{E}_j N_i(E)\right] + \frac{N_i(E)}{\tau_{\rm esc}(E)} = Q_i(E), \qquad (1)$$

where E is the energy of the particle, $N_i(E)$ is the particle distribution function of specie i (i = e, p represent protons and electrons), the label "j" indicates the sum over all loss mechanisms and $\tau_{\rm esc}(E)$

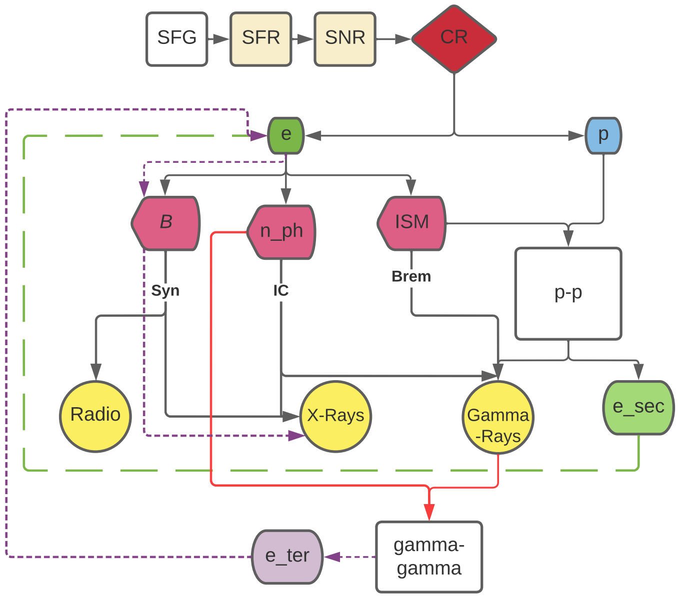

Figure 1: Scheme showing the contribution of each radiative process and generation of particles to the different energy ranges. n_ph: photon field; e_sec: secondary electrons; e_ter: tertiary electrons.

is the compound escape time including diffusion and advection. We adopt a standard injection term $Q_i(E)$ as a falling power law in energy of index $\alpha_{\rm inj}$ with an exponential cut-off at a maximum energy $E_{\rm max}$. We also assume that the main properties of the ISM affecting the CR transport, such as magnetic field (B), advection velocity (v) and gas density (n) are linked with the SFR activity. If we denote s = SFR/1 M$_\odot$ yr^{-1}, the typical values adopted for each constituents scale with s as: $B \approx 50\, s^{0.3}\, \mu$G, $n \approx 30\, s^{0.71}$ cm^{-3}, and $v \approx 50$ km s^{-1} for $s \leq 1$ and $v \approx 400$ km s^{-1} for $s > 1$.

In particular, the scaling of the magnetic field is obtained as a result of equipartition among magnetic and kinetic energy density of gas, the advection velocity scaling is obtained assuming that SFGs have winds that are CR-driven at low SFRs and thermally-driven at intermediate and high SFRs [11]. Finally the gas density is set by using the Kennicutt-Schmid law [10]. We refer the interested reader to [7] and [8] for an extended discussion on the nature of such scaling relations and the exploration of different assumptions.

The extragalactic background light (EBL) and the strong infrared (IR) field inside the galaxies can induce a strong absorption of the γ rays and affect the VHE spectra. Our model included already the internal absorption assuming isotropic diluted black body for the internal IR field [9] and here we implement the external absorption assuming the [12] EBL model. We set the redshift to 0 for the base model and then explore the variation of this parameter.

We finally calculate the photon spectral energy distribution (SED) for a wide range of SFR and we explore how the CRs transport affects the SEDs in the high energy range. We compute the modelled correlations in the CTA energy range by integrating each SED between the corresponding energies. We investigate the absorption and we vary the redshift (z = 0.0, 0.02 and 0.05) to explore the external absorption. We also investigate different values for the $E_{\rm p,max}$ (100 TeV, 1 PeV and 10 PeV) and their effect on the correlation.

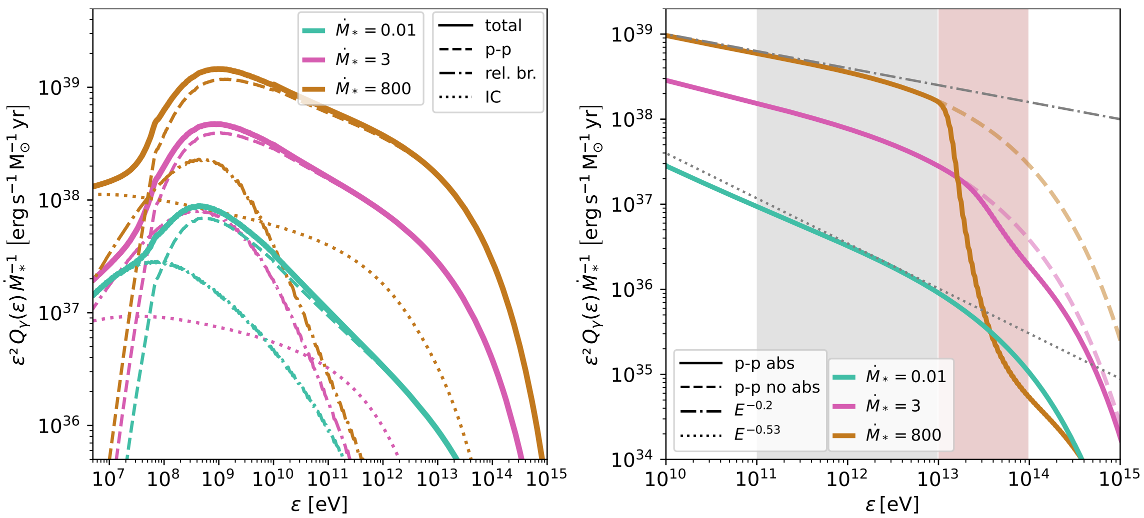

Figure 2: Normalised SED for three different SFR values: $\dot{M}_* = 0.01\, M_\odot/\mathrm{yr}$ (green), $\dot{M}_* = 3\, M_\odot/\mathrm{yr}$ (pink) and $\dot{M}_* = 800\, M_\odot/\mathrm{yr}$ (brown). *Left panel*: the unabsorbed leptonic (IC and bremsstrahlung) and hadronic (p-p) emission components, and their sum, are shown with different linestyles. *Right panel*: absorbed (solid line) and unabsorbed (dashed line) p-p contributions. The shaded regions correspond to two energy ranges of CTA (0.1–10 TeV in grey and 10–100 TeV in brown). The grey lines mark the characteristic slope of the γ-ray emission under two different conditions: when proton transport is dominated by advection/p-p cooling, which preserves the injection index $\alpha_{\mathrm{inj}} = -2.2$ (dot-dashed line), and a scenario dominated by diffusion with a coefficient $D_{\mathrm{diff}} \propto E^{\delta}$, with $\delta = -1/3$, which softens the distribution to $\alpha_{\mathrm{inj}} + \delta = -2.53$ (dotted line).

3. Results

We find that for the whole range of SFRs considered the p-p emission dominates the SED for photon energies $\epsilon > 0.1$ GeV, as shown in Fig. 2 (left panel). In Fig. 2 (right panel) we also show the impact of the γ - γ absorption in the p-p spectrum depending on the SFR of the galaxy. In addition, this figure illustrates how the CR transport determines the slope of the γ-ray spectrum at VHE. At low SFRs the diffusion is more relevant and steepens the spectrum, whereas at high SFR the diffusion only affects the SED at $\epsilon > 10$ TeV, where the effects of absorption starts dominating. We compare these three different SFR scenarios with the asymptotic behaviour of γ-ray emission produced by two populations of protons: the first is characterised by advection-cooling dominated transport ($N(E) \sim E^{-\alpha_{\mathrm{inj}}}$) and a scenario dominated by diffusion ($N(E) \sim E^{-\alpha_{\mathrm{inj}}-\delta}$). In turn, the SED at VHE is also affected by the assumed $E_{\mathrm{p,max}}$ (which is 1 PeV) and the γ-γ absorption.

We finally build the luminosity - SFR correlation by integrating the SED in a wide range of SFR in three energy bands, the *Fermi* band (0.1–100 GeV) and two bands that will be accessible to CTA: 0.1–10 TeV and 10–100 TeV. The first one shows that our model fits well the observed correlation (top left panel of Fig. 3). Regarding the predicted correlations in the CTA energy band (top right and bottom panels of Fig. 3), we explore the dominant physical processes. We find that internal absorption is significant in the 10–100 TeV energy range at SFRs > 10 $\mathrm{M_\odot yr^{-1}}$ (due to the stronger IR field), which leads to a flattening of the $L_{10-100\mathrm{TeV}}$–SFR correlation (bottom left panel of Fig. 3). The external (EBL) absorption and the $E_{\mathrm{p,max}}$ can also affect the $L_{10-100\mathrm{TeV}}$ luminosity; as they do not depend on the SFR, their net effect is to shift the normalization of the whole correlation. The Bottom panels show the impact of different $E_{p,max}$ and external absorption respectively. Interestingly, none of these effects are noticeable in the lower energy range of CTA (top right panel).

4. Discussions and conclusions

In this work we explored the TeV luminosity–to–SFR correlation by extending a one-zone model we previously adopted for studying such correlations at other wavelengths. We find that the internal absorption and the change in the maximum energy substantially impact the correlation in the highest energy range. The impact of the external absorption is strong at higher redshift. Nevertheless, we do not expect to observe galaxies with CTA with a redshift greater than 0.02 due to sensitivity limitation. In addition, it provides key information on particle transport because of the possible strong footprints of particle diffusion. The 0.1–10 TeV CTA energy range is not affected by the absorption process, nor the proton maximum proton energy. Thus, the aforementioned range is a promising window to study the CRs transport because any possible deviation from our prediction would be probably due to different transport conditions.

We conclude that the luminosity–SFR correlation in the VHE band can provide information on the CR transport, the absorption and $E_{p,max}$. It can also guide us in improving our understanding of CR transport and radiative processes in SFGs.

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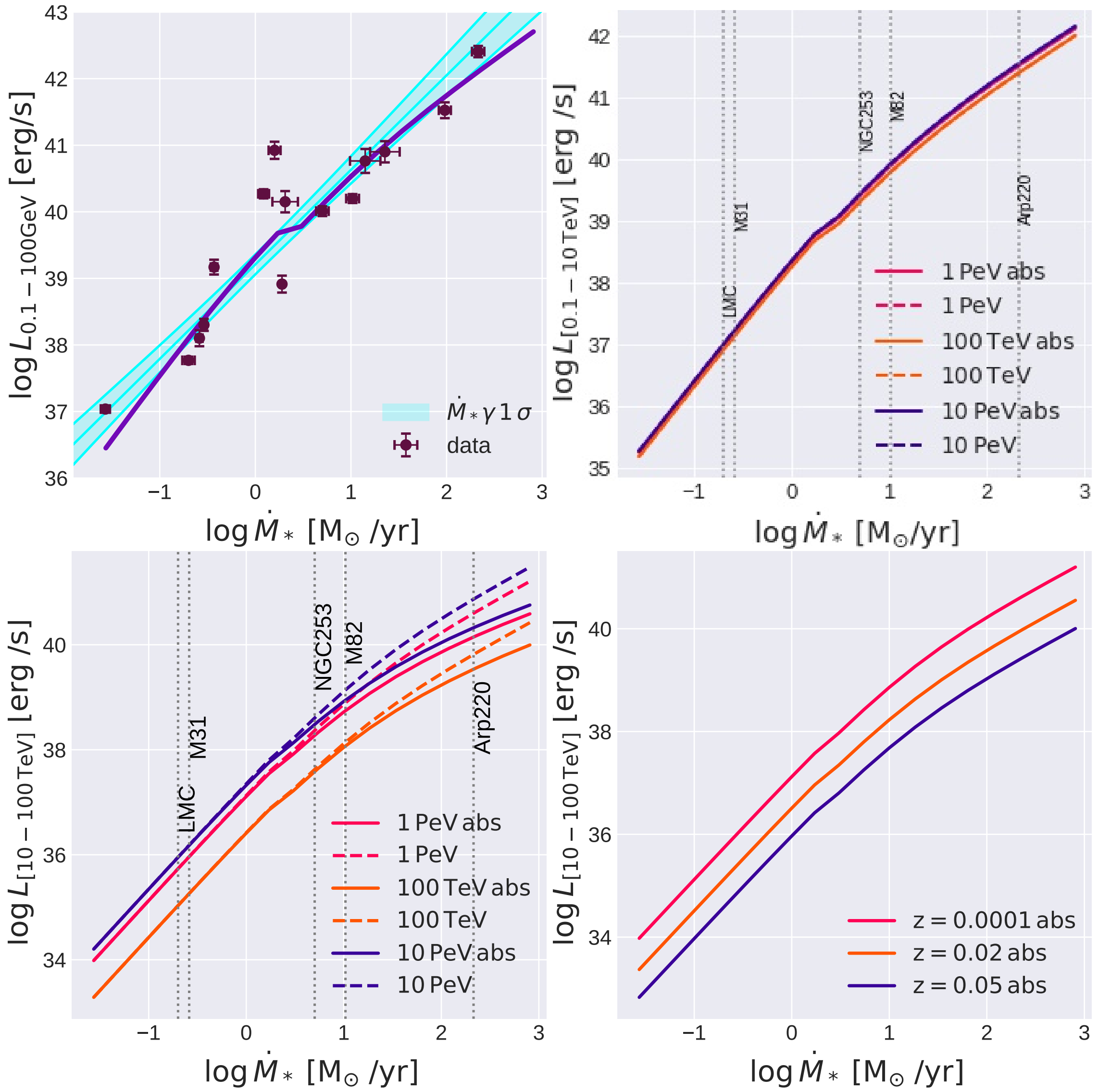

Figure 3: L_γ–SFR correlations. *Top left panel*: Correlation in the *Fermi* energy range (adapted from [8]); the violet line is the model, and the cyan line and shaded band are the best fit to the data (purple circles) and its 1-σ confidence interval, respectively. *Top right panel:* Predicted correlation in the CTA low energy range for different proton maximum energies and with or without the inclusion of the internal absorption (solid and dashed lines, respectively); hereafter the dashed vertical lines show the targets proposed for observations in the CTA key science project. *Lower left panel:* Predicted correlation in the CTA high energy range for different proton maximum energies and with or without the inclusion of the internal absorption. The effect of internal absorption is non-negligible at high SFRs. *Lower right panel:* Predicted correlation in the CTA high energy range for different redshifts.