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High-energy emission from star-forming galaxies

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Summary. — Adopting the convection-diffusion model for energetic electron and proton propagation, and accounting for all the relevant hadronic and leptonic processes, the steady-state energy distributions of these particles in the starburst galaxies M 82 and NGC 253 can be determined with a detailed numerical treatment. The electron distribution is directly normalized by the measured synchrotron radio emission from the central starburst region; a commonly expected theoretical relation is then used to normalize the proton spectrum in this region, and a radial profile is assumed for the magnetic field. The resulting radiative yields of electrons and protons are calculated: the predicted $> 100\,\mathrm{MeV}$ and $> 100\,\mathrm{GeV}$ fluxes are in agreement with the corresponding quantities measured with the orbiting *Fermi* telescope and the ground-based VERITAS and HESS Cherenkov telescopes. The cosmic-ray energy densities in central regions of starburst galaxies, as inferred from the radio and γ-ray measurements of (respectively) non-thermal synchrotron and π^0-decay emission, are $U_{\mathrm{p}} = \mathcal{O}(100)\,\mathrm{eV\,cm^{-3}}$, *i.e.* at least an order of magnitude larger than near the Galactic center and in other non–very-actively star-forming galaxies. These very different energy density levels reflect a similar disparity in the respective supernova rates in the two environments. A $L_\gamma \propto SFR^{1.4}$ relationship is then predicted, in agreement with preliminary observational evidence.

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PACS `98.54.Ep` – Starburst galaxies and infrared excess galaxies.
PACS `98.56.Ne` – Spiral galaxies (M 31 and M 33).
PACS `98.56.Si` – Magellanic Clouds and other irregular galaxies.

1. – Introduction

In the nuclear regions of starburst (SB) galaxies, active star formation (SF) powers emission of radiation directly by supernova (SN) explosions and indirectly by SN-shock heating of interstellar gas and dust, as well as from radiative processes involving SNR-accelerated cosmic-ray electrons (CRe) and protons (CRp).

Some basic considerations suggest that the timescales required for CRp to be accelerated (by SN shocks) and lose energy (via pion decay into photons and e^+e^- pairs, or via advection) are shorter than timescales of SB activity in galaxies, that are themselves comparable to galactic dynamical timescales. A consequence is that in a SB region a balance can roughly be achieved between energy gains and losses for galactic CRs during a typical burst of SF [1]. Under basic hydrostatic and virial equilibrium conditions in a galaxy, a minimum-energy configuration of the field and the CRs may be attained. This implies that energy densities of particles and magnetic fields can be in approximate equipartition [2].

The equipartition assumption enables deduction of the CRp energy density, $U_{\rm p}$, from the measured synchrotron radio emission (which can be observed relatively easily) and a theoretically motivated injection p/e ratio. Alternatively, $U_{\rm p}$ can be estimated also from SN rates and the fraction of SN energy that is channeled into particle acceleration. Knowledge of $U_{\rm p}$ enables prediction of γ-ray emission (either at high energies (HE: $\geq 100\,$MeV) or at very high energies (VHE: $\geq 100\,$GeV)), which is mostly due to CRp interactions with ambient gas protons, via π^0 decay.

2. – HE emission from star-forming galaxies

In this section we will review some basic features of SB modeling, notably applied to the local galaxies M 82 and NGC 253, and the status of observations of star-forming galaxies in the HE/VHE γ-ray domain.

2·1. *Modeling*. – In both nearby SB galaxies, M 82 and NGC 253, the central SB region (which will also referred to as the source region) with a radius of $\sim 300\,$pc and height of 300 pc is identified as the main site of particle acceleration. Here, the injection particle spectrum is assumed to have a non-relativistic strong-shock index $q = 2$. A theoretical $N_{\rm p}/N_{\rm e}$ ratio, predicted from charge neutrality of the injected CRs, is likely to hold in this source region—as is also the assumption of equipartition.

Due to the implicit dependences in the expression for the synchrotron flux, CR/field equipartition is implemented iteratively to solve for $N_{\rm e}$ (primaries plus secondaries), $N_{\rm p}$, and B. For both M 82 and NGC 253, central values $B_0 \sim 200\ \mu$G have been obtained in detailed models (M 82: [3, 4]; NGC 253: [5-7]).

Adopting the convection-diffusion model for energetic electron and proton propagation, and accounting for all the relevant hadronic and leptonic processes, the steady-state energy distributions of these particles in the galaxies M 82 and NGC 253, in both the SB nucleus and the disk, can be determined with a detailed numerical treatment. In particular, to numerically follow particle energy losses and propagation outside the source region, one needs to know the HI and HII densities and their profiles, as well as the spatial variation of the mean strength of the magnetic field. (*E.g.*, assuming magnetic flux freezing in the ionized gas, then $B \propto n_{\rm HII}^{2/3}$ [8].)

A measured radio index of ~ 0.7 in the central disk implies $q \sim 2.4$ there. This implies a substantial steepening of the CRe spectrum from the injection value, $q = 2$. The steady-state electron and proton spectra in the SB region of NGC 253 are shown in fig. 1. At low energies both spectra are flat, whereas at $E \gg 1\,$GeV the stronger electron losses result in steeper electron (than proton) spectra.

Electron emissions by bremsstrahlung and Compton scattering are shown in fig. 2; the γ-ray emission from π^0 decay (following pp collisions) is also shown. As expected, the losses due to bremsstrahlung dominate the lower energy regime, whereas losses due to π^0 decay dominate at higher energies. (While synchrotron emission extends to the

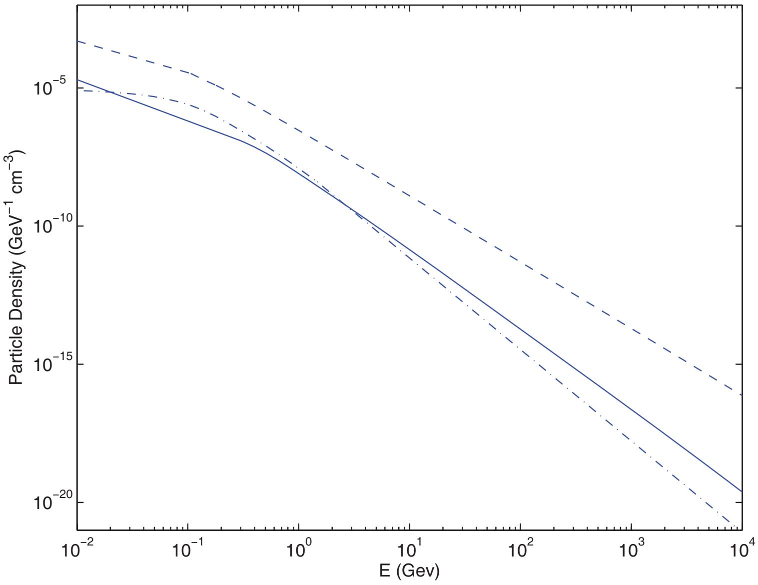

Fig. 1. – Properties of the emitting particles in the central SB region of NGC 253 [7]: steady-state spectra of primary (solid line) and secondary (dot-dashed line) electrons and protons (dashed line).

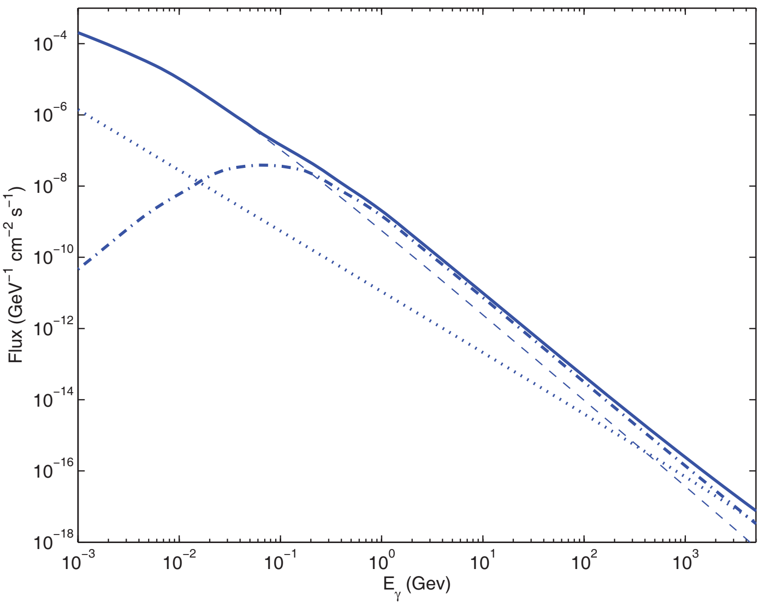

Fig. 2. – Properties of the emitted radiation in the central SB region of NGC 253 [7]: radiative yields from electron Compton scattering off the FIR radiation field (dotted line), electron bremsstrahlung off ambient protons (dashed line), π^0 decay following pp collisions (dash-dotted line), and their sum (solid line).

X-ray region, it is negligible at much higher energies.) Our main interest here is the VHE emission, which—as anticipated—is mainly from the latter process.

It is interesting to note that the numerically predicted VHE γ-ray flux is a factor ~ 6 lower than that obtained in an approximate treatment where the impact of radial energy losses and propagation mode of the CRp is ignored [3]. This simplified approach results in an unrealistically high contribution of the main disk (exterior to the SB region) to the total TeV emission: in fact even the slight steepening of the CRp spectrum, occurring in the disk because of energy losses, significantly lowers the TeV emissivity [9] and hence the predicted source flux.

We note that the related neutrino flux ($\pi^{\pm}$ eventually produce $e^{\pm} + \nu_e + \bar{\nu}_{\rm e} + \nu_\mu + \bar{\nu}_\mu$) at energies higher than 100 GeV is about a third of the corresponding photon flux [3].

2·2. *γ-ray detections.* – The two local SB galaxies M 82 and NGC 253 are the only non-AGN extragalactic sources that, up to now, have been detected in both the GeV [10] and TeV [11, 12] domains. The measured fluxes and spectra of both galaxies in the two bands agree with predictions of recent numerical models (M 82: [3, 4]; NGC 253: [5-7]). The highest-SFR galaxy in the nearby universe, Arp 220, was undetected by MAGIC [13].

HE γ-ray detections were obtained for a number of low SFR galaxies: the Large Magellanic Cloud (LMC: [14]), the Small Magellanic Cloud (SMC: [15]), the Andromeda galaxy (M 31: [16]), and the composite Sy2/SB galaxies NGC 1068 and NGC 4945 [17]. The scenario of mostly hadronic HE γ-ray emission is generally confirmed for these galaxies, except for NGC 1068 where emission from the active nucleus may be dominant. Only flux upper limits exist for the Triangulum galaxy (M 33: [16]).

3. – CRs in star-forming galaxies

The CRp energy density in galaxies can be either i) measured directly if the GeV-TeV spectral flux is known, or ii) evaluated indirectly if source size, distance, and radio spectral index and flux are known, and particles/field equipartition and a p/e ratio are assumed, or iii) estimated if the SN rate, the CRp residence timescale, the energy per SN going into CRs, and the size of the SF region are known.

i) *CRs and GeV-TeV emission.* The detection of M 82 and NGC 253 confirmed the values $U_{\rm p} = \mathcal{O}(100)\,{\rm eV\,cm^{-3}}$, resulting from accurate numerical treatments based on the solution of the diffusion-loss equation for the accelerated particles (see refs. above). In the ~ 200 pc region of the Galactic center $U_{\rm p} \sim 5\,{\rm eV\,cm^{-3}}$ based on HESS observations [18]. For the comparable environment of the Andromeda galaxy, the *Fermi*-LAT detection implies an average $U_{\rm p}$ at a level of ≈ 0.35 the average Galactic value [16]. For the even more quiet environments of the LMC and the SMC), actual *Fermi*-LAT GeV detections imply, respectively, $U_{\rm p} \sim (0.2 - 0.3)$ and $\sim 0.1\,{\rm eV\,cm^{-3}}$ [14, 15].

ii) *CRs and radio emission.* Based on method ii) above, for the central SB regions of NGC 253, M 82, and Arp 220, respectively, [1] evaluate $U_{\rm p} \approx 75$, 97, and $520\,{\rm eV\,cm^{-3}}$. These radio-based estimates match, to within a factor of ≈ 2, those derived from GeV-TeV-based measurements.

iii) *CRs and supernova rates.* The CRp residence timescale is given by $\tau_{\rm res}^{-1} = \tau_{\rm pp}^{-1} + \tau_{\rm out}^{-1}$, where the pp interaction timescale $\tau_{\rm pp}$ is a function of the ambient gas density n, and the advection timescale $\tau_{\rm out}$ is a function of the speed of the outflowing gas ($v_{\rm out}$) and of the size (radius) of the SB region ($r_{\rm s}$). Typically, $\tau_{\rm pp} \sim 10^4$ y and $\sim 10^5$ y for the central SB regions of Arp 220 and, respectively, the M 82 and NGC 253 [1]. If, however, a fast SB-driven wind advects the energetic particles out of the disk plane, then possibly $\tau_{\rm out} \ll \tau_{\rm pp}$. For M 82, $v_{\rm out} \sim 2500\,{\rm km\,s^{-1}}$ [19]. Assuming a homogeneous distribution of SNe within the SB nucleus of radius $r_{\rm SB}$, the outflow timescale is then $\tau_{\rm out} \sim 3 \times 10^4$ y. So in some SB galaxies $\tau_{\rm res} \sim \tau_{\rm out}$. During $\tau_{\rm res}$ a number $\nu_{\rm SN}\tau_{\rm res}$ of SNs explode and deposit the kinetic energy of their ejecta, $E_{\rm ej} = 10^5$ erg, into the interstellar medium. The Galactic CR energy budget and SN statistics suggest that $\eta \sim 0.05$ of this energy may go into accelerating particles. The CRp energy density in the central SB region is then $U_{\rm p} = \frac{1}{4}\nu_{\rm SN}\tau_{\rm res}\eta E_{\rm ej} r_{\rm SB}^{-3}$. A substantial agreement with the equipartition estimates is reached for NGC 253, M 82, Arp 220, Milky Way, LMC: $U_{\rm p} \sim 75, 95, 505, 5.7, 0.2\,{\rm eV\,cm^{-3}}$, respectively [1]. Summarizing, the CR energy densities estimated in five galactic nuclei of similar size (three SB galaxies, the central Galactic region, and the LMC), appear to be largely correlated with key features of the ongoing SF: SN rate and CRp residence time (the latter being, in turn, a function of the local gas density and of the galactic superwind speed). In fact, in these environments, for same $\eta E_{\rm ej}$ (by assumption) and similar $r_{\rm s}$ (from observations), the CRp energy density seems to be well described just as a function of the number of SN explosions during the CRp residence timescale,

$$U_{\rm p} \propto \nu_{\rm SN}\tau_{\rm res}\,. \tag{1}$$

4. – HE/VHE γ-ray emission and SFR

The Schmidt-Kennicutt (SK) law of SF, $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^N$ (where gas comprises both HI and H_2), states that projected SFR varies as a power law the projected gas density. This is true piecewise: both locally and disk-averaged, it is $N \sim 2.5$ for $\Sigma_{\rm gas} < 10\,M_\odot\,{\rm pc^{-2}}$ and $N \sim 1.4$ for higher densities [20]. If disk thicknesses do not vary much among galaxies, then the SK law can be written in deprojected units with the same index N.

For a source with gas number density n, proton energy density $U_{\rm p}$, and volume V, the integrated hadronic γ-ray photon luminosity above some photon energy ϵ is

$$L_{\geq\epsilon} = \int_V g_{\geq\epsilon}\, n\, U_{\rm p}\, {\rm d}V\,{\rm s^{-1}} \tag{2}$$

with the integral emissivity $g_{\geq\epsilon}$ in units of photon ${\rm s^{-1}(H\text{-}atom)^{-1}(eV/cm^3)^{-1}}$ [9]. Using volume-averaged quantities and setting $\epsilon = 100$ MeV, from eqs. (1), (2) we can write

$$L_{\geq 100\,{\rm MeV}} \propto M_{\rm gas}\,\nu_{\rm SN}\,. \tag{3}$$

This is in agreement with the observational luminosity *vs.* (gas mass)×(SN rate) correlation [16], which evidently describes the γ-ray luminosity arising from π^0 decay.

Owing to the SK law, the above equation transforms into $L_{\geq\epsilon} \propto {\rm SFR}^{1+1/N}$: if $N = 2.5$ as appropriate for our sample galaxies with $\Sigma_{\rm gas} < 10\,M_\odot\,{\rm pc^{-2}}$ [20], then

$$L_{\geq 100\,{\rm MeV}} \propto {\rm SFR}^{1.4}\,. \tag{4}$$

Within limited statistics, this prediction agrees with observations [16].

So the observational non-linear L_γ-SFR correlation [16] stems from the GeV luminosity being (mostly) hadronic in origin, from CRs being linked with SF (through SN explosions), and from the *Fermi*-LAT–detected galaxies being located in the steep wing (*i.e.*, low-$\Sigma_{\rm gas}$ regime) of the SK law of SF.

5. – Conclusion

The link between SF and CR particles was suggested long ago [21]. It is based on the recognition that the CRe's, responsible for diffuse non-thermal synchrotron emission, are produced in the sites of SN explosions. The rough agreement between the relatively short lifetime ($\lesssim 3 \times 10^7$ y) of massive stars, and the similarly short synchrotron energy loss time of high-energy electrons, led to the expectation that the non-thermal radio emission of a galaxy is a measure of its SF activity on scales much shorter than the Hubble time.

HE/VHE γ-ray detections (with, respectively, the orbiting *Fermi* telescope and ground-based IACTs) of some nearby star-forming (SB and normal) galaxies, that span a large range of SFR, have provided direct $U_{\rm p}$ measurements. These are consistent with theoretical predictions based on radio measurements, and with estimates based on SN rates and local CRp residence times. Should the match between measured and predicted $U_{\rm p}$ be confirmed, some immediate implications would be:

i) star-forming galaxies can be powerful particle accelerators, able to achieve CRp energy densities orders of magnitude higher than the Galactic value;

ii) SNe, both in quietly star-forming galaxies and in very actively star-forming galaxies, probably have a common universal CR acceleration efficiency;

iii) CR energy densities and equipartition magnetic fields derived from radio measurements can be used as proxies for the quantities characterizing the full particle energy distributions (derived from accurate spectral fits of the GeV-TeV emission): this could be particularly useful in the case of galaxies that are too far away for their (umbeamed) γ-ray emission to be measured.

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