C. R. Physique 17 (2016) 585–593

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Gamma-ray astronomy / Astronomie des rayons gamma – Volume 2

Starburst galaxies as seen by gamma-ray telescopes

Les galaxies à flambées d'étoiles détectées par les télescopes γ

Stefan Ohm

Deutsches Elektronen Synchrotron DESY, 15738 Zeuthen, Germany

A R T I C L E I N F O

Article history:
Available online 25 April 2016

Keywords:
Cosmic rays
Gamma rays
Star clusters
Starburst galaxies
Ultra luminous infrared galaxies

Mots-clés :
Rayons cosmiques
Rayons gamma
Amas d'étoiles
Galaxies à flambée d'étoiles
Galaxies infrarouges ultralumineuses

A B S T R A C T

Starburst galaxies have a highly increased star-formation rate compared to regular galaxies and inject huge amounts of kinetic power into the interstellar medium via supersonic stellar winds, and supernova explosions. Supernova remnants, which are considered to be the main source of cosmic rays (CRs), form an additional, significant energy and pressure component and might influence the star-formation process in a major way. Observations of starburst galaxies at γ-ray energies give us the unique opportunity to study non-thermal phenomena associated with hadronic CRs and their relation to the star-formation process. In this work, recent observations of starburst galaxies with space and ground-based γ-ray telescopes are being reviewed, and the current state of theoretical work on the γ-ray emission is discussed. A special emphasis is put on the prospects of the next-generation Cherenkov Telescope Array for the study of starburst galaxies in particular and star-forming galaxies in general.

R É S U M É

Les galaxies à flambées d'étoiles se caractérisent par un taux de formation d'étoiles beaucoup plus élevé que ceux des galaxies ordinaires. Les vents stellaires supersoniques et les explosions de supernovæ qui s'y produisent injectent dans le milieu interstellaire une énergie cinétique considérable. De plus, alors que les vestiges de supernovæ sont considérés comme les sources principales de rayons cosmiques, ces derniers augmentent de manière significative la pression et la densité d'énergie du milieu, au point d'influencer fortement le processus de formation d'étoiles. L'observation de galaxies à flambées d'étoiles en astronomie gamma est un moyen unique pour étudier les phénomènes non thermiques dus à des protons et noyaux cosmiques, et leur rôle dans le processus de formation d'étoiles. Cet article passe en revue les observations récentes de galaxies à flambées d'étoiles avec des télescopes à rayons gamma dans l'espace et à partir du sol. Il discute aussi les interprétations théoriques actuelles de l'émission gamma observée. Enfin, un accent particulier est mis sur l'impact des télescopes à effet Tcherenkov atmosphérique

E-mail address: stefan.ohm@desy.de.

http://dx.doi.org/10.1016/j.crhy.2016.04.003
1631-0705/

de la prochaine génération sur l'étude des galaxies à flambée d'étoiles en particulier et, plus généralement, sur la formation d'étoiles dans les galaxies.

1. Introduction

The term "starburst" is often used to describe regions of greatly enhanced star formation within galaxies or to characterise entire galaxies. The starburst phenomenon covers a wide range of physical scales from blue compact starburst galaxies, circumnuclear rings in local barred galaxies to luminous (LIRGs) and ultraluminous infrared galaxies (ULIRGs). The star-formation rate (SFR) in starbursts is considered to be out of equilibrium, with gas-consumption timescales of 1 Gyr or shorter, and typical timescales for the starburst episode of a few 100 Myr (see, e.g., [1,2] and references therein).

Cosmic rays (CRs) are considered to be an important star-formation regulator since they penetrate deep into molecular cloud cores: the seeds of protostars. In fact, they penetrate much deeper into clouds than UV radiation, which is effectively shielded from the most dense cores (see, e.g., [3,4]). CRs initiate complex chemical reactions and are the main driver for gas-phase chemistry in the interstellar medium (ISM) [5,6]. In regions where CR ionisation rates are very high (e.g., starbursts and ULIRGs), CRs might even influence the initial conditions of star formation by preventing low-mass star formation, which leads to a top-heavy initial mass function [7–9]. Interestingly, recent studies also suggest that CRs might play an important role in galaxy formation. CR diffusion leads to galactic-scale winds, which effectively remove material from the disks. When included in detailed 3D hydrodynamical simulations, these CR-driven winds lead to more realistic galaxy rotation curves [10,11].

Although the impact of CRs on their environment is presumably very significant on many spatial scales, their observational study is rather challenging. The vast majority of CRs are charged atomic nuclei, are deflected in interstellar and intergalactic magnetic fields and lose directional information on their way to Earth. The study of CR feedback hence requires indirect detection techniques, including measurements [6] of:

(i) abundances and abundance ratios of certain molecular ions,
(ii) X-ray line emission from electronic de-excitation,
(iii) γ-ray line emission from nuclear de-excitation,
(iv) observation of light-element isotope abundances,
(v) γ-ray emission from π^0-decay (protons), and
(vi) γ-ray emission from inverse Compton (IC), synchrotron and bremsstrahlung processes (electrons).

In this review, I will focus on the latter two channels and refer the interested reader to the review by [6] and references therein for other possible observational signatures of, e.g., CR ionisation. Another emphasis will be put on the recent developments in γ-ray astronomy in the study of starburst galaxies. The interested reader is referred to the more comprehensive review by [12], which also partly served as a guidance for this work.

High-energy (HE; 100 MeV $\leq E \leq$ 100 GeV) and very high-energy (VHE; 100 GeV $\leq E \leq$ 100 TeV) γ rays are tracers of non-thermal processes of CRs with radiation fields, magnetic fields and gas in the vicinity of particle accelerators. The vast majority of Galactic particle accelerators observed at TeV energies is associated with end products of stellar evolution such as supernovae remnant (SNR) shells, pulsar wind nebulae (PWNe) or γ-ray binary systems. The γ-ray-emitting objects cluster tightly along the Galactic plane and trace regions of dense gas and star formation. With their increased SFR and hence supernova (SN) explosion rate, starburst galaxies are ideal objects to study the physics of CRs and their impact on the ISM and the overall galaxy dynamics with γ rays.

The non-thermal emission from starburst galaxies can be studied at many wavelengths from low-frequency radio, X-rays up to GeV and TeV γ rays. Radio observations probe low-energy electrons and dense gas, and can be used to infer magnetic fields in starburst galaxies (see, e.g., [13] and references therein for magnetic fields in spiral and starburst galaxies). HE and VHE electrons can be probed via synchrotron emission that is radiated at X-ray wavelength. The same population of electrons up-scatters far-infrared photons, which originate from the strong dust-reprocessed stellar radiation, to GeV and TeV energies. X-ray observations in combination with γ-ray measurements therefore provide powerful tools to probe the environment in starburst galaxies. Electrons, however, do not comprise the dominant component of CRs. Hadronic CRs are much harder to probe as, e.g., synchrotron emission is suppressed by a factor $(m_\mathrm{p}/m_\mathrm{e})^4$. Energetic protons and heavier nuclei undergo proton–proton interactions with dense gas particles and produce neutral and charged mesons for proton energies above ~300 MeV. The π^0's instantly decay into two γ rays that can be measured above energies of ~70 MeV. Charged pions decay into electrons and positrons as well as neutrinos.

Observations of starburst galaxies at γ-ray energies provide a multitude of information. They firstly tell us how efficient CRs accelerated in SNRs and other particle accelerators are converted into γ-ray emission in interactions with gas in the starburst region. Secondly, the measured γ-ray luminosity and inferred CR energy densities can be combined with measurements at lower energies to study the ISM conditions in starburst regions. The third question that can be answered with

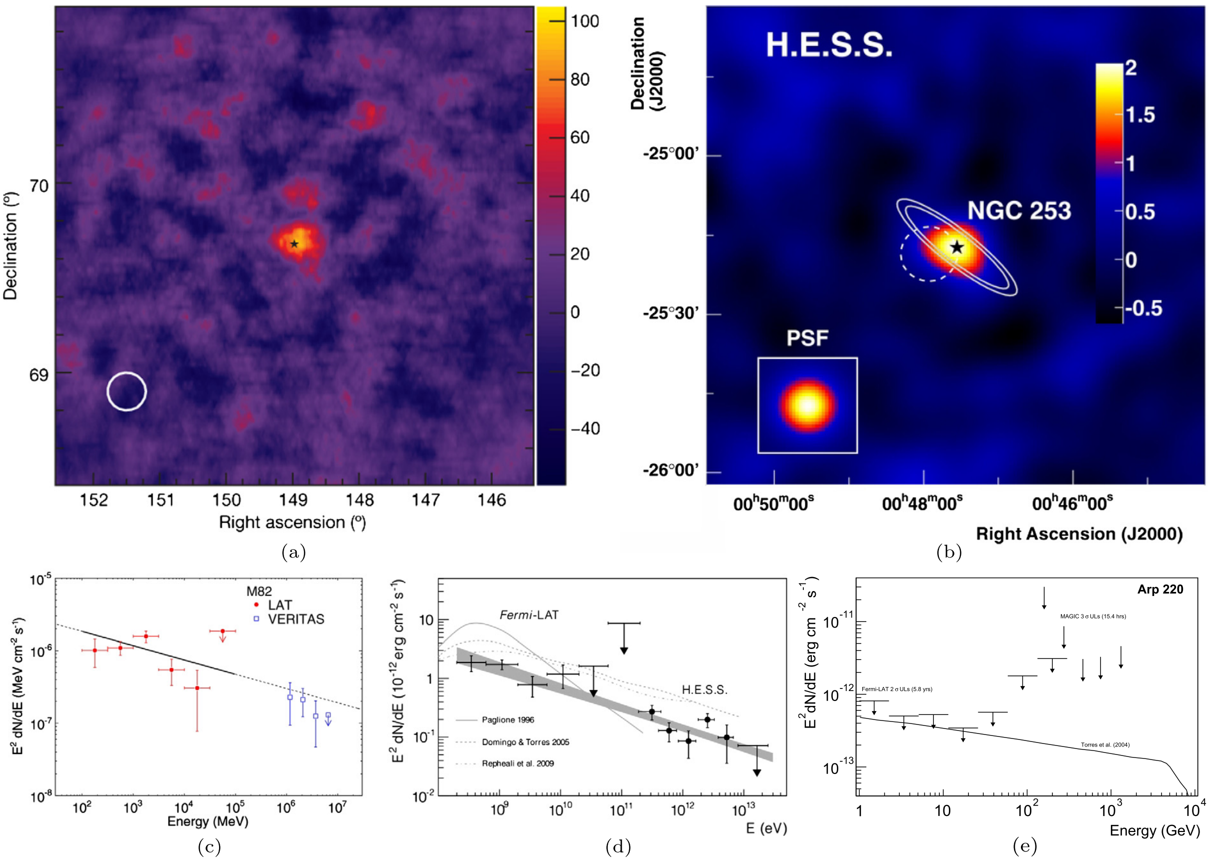

Fig. 1. Sky maps of M82 (a, [20]) and NGC 253 (b, [23]), and their combined GeV and TeV γ-ray spectra (c, [22]; d, [23]). e) Arp 220: γ-ray flux upper limits from 5.8 years of Fermi-LAT data along with the MAGIC data and model predictions (full line, [24]). Note the conversion of energy flux into SI units is $1\ \mathrm{W{\cdot}m^{-2}} = 10^3\ \mathrm{erg{\cdot}cm^{-2}{\cdot}s^{-1}} = 6.24 \times 10^8\ \mathrm{MeV{\cdot}cm^{-2}{\cdot}s^{-1}}$.

γ-ray observations is whether or not equipartition between CRs, magnetic fields and radiation fields hold in the extreme environments of starburst galaxies. With their greatly enhanced SFR and SN rate, starburst galaxies offer an independent probe for the SNR paradigm for CR origin.

2. γ-Ray emission from starburst galaxies – observations

2.1. GeV and TeV observations of starburst galaxies

Given the expected CR energy input from SN explosions and the dense gas present in starburst nuclei, the nearby starburst galaxies M82 and NGC 253 have long been predicted to emit γ rays at a detectable level (e.g., [14–16]). The previous generation of satellite-based instruments such as EGRET, and ground-based imaging atmospheric Cherenkov telescopes like HEGRA were, however, not quite sensitive enough to detect this γ-ray emission and only reported upper limits [17,18].

It was the currently operating generation of γ-ray instruments that finally allowed us to detect NGC 253 and M82. The H.E.S.S. and VERITAS collaborations reported on the detection of both objects in VHE γ rays in 2009 [19,20]. Shortly after the TeV discoveries, the Fermi collaboration reported on the detection of both starbursts at GeV energies with the Large Area Telescope (LAT) in 2010 [21]. Since then, the Fermi-LAT GeV data sets increased compared to the original publication [22] and H.E.S.S. published a detailed spectral and morphological study of NGC 253 [23].

Fig. 1 shows the sky maps of M82 and NGC 253 for γ rays with energies $\gtrsim$200 GeV and the γ-ray spectra over almost five orders of magnitude in energy from ~100 MeV to ~10 TeV. The γ-ray emission from both starbursts appears to be point-like with a limit on the possible extension comparable to the size of the central starburst in the case of NGC 253. The γ-ray emission is spatially coincident with the starburst nuclei of NGC 253 and M82. On a qualitative basis, this observation supports the idea that the regions of enhanced star formation and supernova activity are also the regions where the bulk of CRs are being produced, interact with the dense gas, and produce the observed γ-ray emission. The γ-ray signals are also not time-variable, suggesting that a buried central active galactic nucleus is not significantly contributing to the γ-ray emission. The γ-ray spectra of M82 and NGC 253 look surprisingly similar and can both be described by a single power-law in energy $F(E) = F_0 E^{-\Gamma}$, with $\Gamma \sim 2.2 \pm 0.1$. Although statistics is limited, there is no indication of a spectral break or cutoff feature apparent in the data, which suggests that energy-independent transport and/or losses dominate in these systems. The measured γ-ray flux level further suggests that (in the most simplistic picture; see below) only a fraction of CRs produced in SN explosions in these two starbursts interact and produce γ-ray emission in proton–proton interactions. In the next section I will briefly review the interpretation of these results and what they tell us about the properties of non-thermal particles in starburst galaxies and their impact on the ISM. But let us briefly look at other galaxies that can potentially be detected at γ-ray energies.

2.2. GeV and TeV observations of other star-forming galaxies

The link between star formation and CR acceleration and subsequent γ-ray production is not unique to starburst galaxies or the Milky Way, but applies to any star-forming galaxy. The Fermi-LAT collaboration searched for GeV γ-ray emission from a sample of 69 nearby star-forming galaxies (dwarfs, spirals, LIRGs and ULIRGs) and studied the connection with star-formation tracers such as radio and far-infrared emission over five orders of magnitude in SFR [22]. Apart from γ-ray emission from M82 and NGC 253, the LAT detected *diffuse* GeV emission from the Milky Way, its satellite galaxies the Large and Small Magellanic Clouds (LMC, SMC), and the Andromeda galaxy (M31). GeV γ rays were also observed from the LIRG NGC 2146 [25] and the Seyfert-II galaxies NGC 1068 and NGC 4945 [26]. For the latter two, however, the contribution associated with star-forming activity is hard to disentangle from the central (active) black hole. Even with almost six years of Fermi-LAT data, the most active star-forming galaxy in the local universe, the ULIRG Arp 220 is not detected in GeV γ rays. The derived upper limits are close to theoretical model predictions and start to probe the fraction of CRs that interact in Arp 220's starburst region (see Fig. 1).

At TeV energies, H.E.S.S. reported the detection of diffuse emission from the Milky Way [27] and discovered the first population of particle accelerators at TeV energies in an external galaxy: the LMC [28]. Among the discovered sources are the PWN associated with the most energetic pulsar known, the prominent SNR N 132D and the largest non-thermal X-ray shell, the 30 Dor C superbubble – the first of its kind seen at TeV energies. However, no diffuse emission from CRs interacting with the ISM were detected in these observations. For Andromeda, the VERITAS collaboration reported upper limits on the TeV γ-ray emission using a limited data set and not-yet optimised/final analysis [29]. All these discoveries have been made over the past five years, demonstrating that current γ-ray instrument have now reached the sensitivity to probe CRs in external galaxies. In the following I will briefly discuss the interpretation of the γ-ray results and give a short overview of current theoretical work.

3. Gamma-ray emission from starburst galaxies – interpretation

3.1. The physical conditions in starburst regions

In order to study the production, propagation and interaction of non-thermal particles in starbursts, it is important to look at the physical conditions in star-forming regions. The ISM in a starburst region differs significantly from the conditions in the typical Milky Way ISM. Gas densities in starbursts are much higher than in the Galactic ISM and the rate at which new stars form is greatly enhanced. The large number of massive stars leads to a high number density of stellar (mainly UV) photons that are absorbed by dust, which re-emits at infrared wavelength. Magnetic fields are also enhanced by a similar factor. As a result, non-thermal particles experience stronger losses and cool faster. The dense gas in the starburst region is heated by stellar winds and SNe and the additional energy input can not be compensated for by radiative cooling. As a result, a starburst wind (or "superwind") develops, which effectively removes gas and non-thermal particles from the core and enriches the galactic halo. At the same time, the role of particle diffusion relative to advection is diminished due to nonlinear effects caused by the increased energy flux density of CRs and the magnetic field fluctuations they drive (see, e.g., [23]). For the typical dimensions of starburst regions in M82 or NGC 253 for instance, the advection time in the superwind is $\sim 10^5$ years — much shorter than the starburst lifetime of $\gtrsim 10^7$ years. This implies that accelerated particles spend only a limited time in the starburst region and that the non-thermal particle spectrum reaches an equilibrium after a few 10^5 years.

Fig. 2a shows the cooling times of electrons and protons computed for the starburst nuclei of NGC 253 and Arp 220. Also shown is the typical advection timescale of the gas to leave the starburst region in the central molecular outflow. In a typical starburst galaxy like NGC 253, the advection timescale is comparable to the proton–proton cooling time, but much longer than the electron cooling time. This implies that electrons predominantly stay and cool in the starburst environment, whereas protons either interact with the dense gas or leave in the superwind. The situation in Arp 220 is even more extreme, as basically *all* accelerated protons and electrons cool in the starburst region. The cooling time of TeV electrons is as short as one year (due to efficient synchrotron and IC cooling) and still only ~ 100 years at 1 GeV energies, where bremsstrahlung dominates. At electron energies below 1 GeV, Coulomb losses become increasingly important and limit the cooling time again to less than 100 years. These short cooling timescales are important when considering the sources of non-thermal particles and comparing them to HE and VHE γ-ray sources and source populations in the Milky Way, as discussed in the next section.

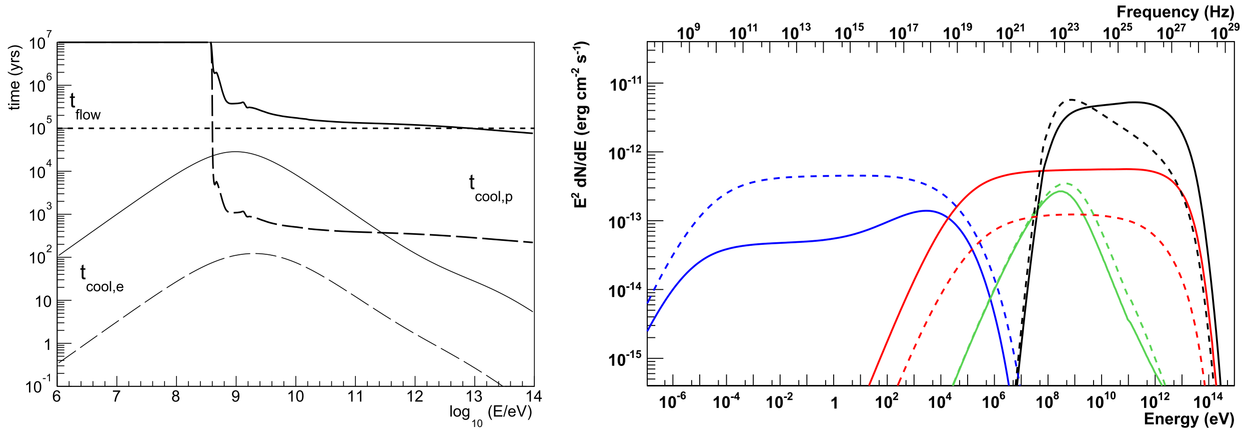

Fig. 2. (a) Relevant cooling timescales for electrons and protons in a starburst galaxy such as M82 or NGC 253 (full lines) and for a ULIRG such as Arp 220 (long dashed lines). The short-dashed line indicates a flow timescale of the central starburst winds of 100 kyr. Electron cooling considers Coulomb, bremsstrahlung, synchrotron and IC processes (taking into account the full Klein–Nishina cross section). Physical parameters used for the timescale calculation are summarised in Table 1. (b) Model spectral energy distributions for two representative starburst galaxies and contributions from IC (red), synchrotron (blue), bremsstrahlung (green) and π^0-decay γ rays (black). Full lines represent the low-magnetic, high-radiation field energy density case. Dashed lines depict the high-magnetic, low-radiation energy density case. The index of injected protons is 2.0 (full), 2.3 (dashed), and 2.0 for electrons in both scenarios (figure taken from [30]).

Table 1
Physical quantities, typical for the starburst environment of NGC 253, and the ULIRG Arp 220.

Object	Distance Mpc	n_H cm^{-3}	B nT	T_{IR} K	u_{IR} $eV\cdot cm^{-3}$	References
NGC 253	3.4	580	15	50	2400	H.E.S.S. Collaboration et al. [23], Heesen et al. [31], Ohm and Hinton [32]
Arp 220	74	$\gtrsim 10^5$	250	100	$\sim 1.5 \times 10^5$	Scoville et al. [33], McBride et al. [34]

3.2. Origin of the γ-ray emission

First model predictions for the non-thermal emission from starburst galaxies were made more than 20 years ago [14,16] and predicted source fluxes at the sensitivity limit of running or planned instruments at that time. Early model predictions and most of the following more detailed calculations are one-zone models and assume the γ-ray emission to be of diffuse origin (e.g., [35–39,23,40]). Depending on the complexity of the study, these models consider numerous non-thermal processes of relativistic electrons and protons as outlined above, such as:

(i) neutral and charged pion production by protons and heavier nuclei, as well as subsequent pion-decay products;
(ii) synchrotron, IC, bremsstrahlung and Coulomb losses of energetic electrons/positrons;
(iii) diffusive escape of CRs and advection in the starburst wind.

All of these models assume that SNe are the source of non-thermal particles, that a constant fraction of kinetic energy per SN explosion is transferred into CRs, and that these CRs then propagate, interact in the starburst region and finally leave the system in the starburst wind. The predicted emission from electrons and hadrons is then compared to measurements at radio wavelengths and γ-ray energies. The predicted radiation spectra are sensitive to the physical conditions in the starburst region such as the magnetic field, gas density (and structure), and radiation fields. An important ingredient in the modelling is the electron-to-proton (e/p) ratio, which is inferred from Galactic radio measurements and under the assumption of equipartition between magnetic fields and CRs, and is typically found to be 1/100 in the Milky Way.

To illustrate the influence of different quantities on the radiation spectra, Fig. 2b shows two simple one-zone, time-dependent models for the continuous injection of electrons and protons over 200 kyr in two representative starburst environments at 3.5 Mpc (see [30] for a detailed model description). The first model shows the SED for a starburst galaxy where IC losses in the strong radiation fields dominate over synchrotron emission (full lines). The second model illustrates what happens if the magnetic field is enhanced by a factor of two and the radiation field energy density lowered by an order of magnitude. In this case, the synchrotron component at X-rays is much brighter than the IC component seen in γ rays. For protons, two different injection spectra are assumed to illustrate the effect on the predicted γ-ray emission. Changing the radiation field energy densities and magnetic fields in the two cases does not affect the π^0-decay γ-ray spectrum. From Fig. 2b it is also clear that even for the assumed large e/p ratio of 1/10, hadrons dominate the γ-ray emission at almost all energies. Only at energies close to the π^0 production threshold and at multi-TeV energies, electrons can significantly contribute to the emission in this simplified scenario, and for the rather extreme choice of the e/p ratio. This model (and all studies mentioned before) suggest that the diffuse emission in starburst galaxies is of *hadronic origin*. As inelastic proton–proton collisions produce not only neutral, but also charged pions, which further decay into electrons and positrons, these secondary leptons also cool in the starburst ISM. Lacki and Beck [41] have shown that secondaries can significantly contribute, if not dominate, the radio emission in starburst environments. Together with the γ-ray measurement, this gives us an independent measure of the equipartition magnetic field in starburst galaxies and galaxies, where hadrons dominate the γ-ray emission.

3.3. Proton calorimetry and individual source populations

As briefly discussed in Section 3.1, CR diffusion and escape in the starburst wind are the two processes that compete with the γ-ray production in a hadronic scenario, and determine the level of emission seen at γ-ray energies. Following the H.E.S.S. collaboration ([23] and references therein) the energy in interacting CRs L_{coll} that leads to the measured γ-ray emission level

$$L_{\mathrm{coll}} = 4\pi d^2 F_{\gamma}^{\mathrm{meas}} \tag{1}$$

can be compared to the total energy in CRs L_{CR} that is in principle available for γ-ray production

$$L_{\mathrm{CR}}(\pi) = f_{\pi}\, \nu_{\mathrm{SN}} \epsilon E_{\mathrm{SN}}. \tag{2}$$

The main uncertainties in these quantities come from the estimates of the distance d, and the product of SN kinetic energy E_{SN} and conversion efficiency into CRs ϵ. f_{π} is a correction factor, accounting for the γ-ray spectral index and underlying available power per CR energy interval ($f_{\pi} = 1$ for a γ-ray spectral index of 2.0) and ν_{SN} is the SN rate. The ratio $L_{\mathrm{coll}}/L_{\mathrm{CR}}(\pi)$ is often referred to as the *calorimetric fraction* and its value tells us how efficient a starburst galaxy (or a star-forming galaxy in general) is in converting CRs into hadronic γ-ray emission. The values found for M82 and NGC 253 are of the order of 20%–40% [38,23] and agree well with the rough comparison of proton–proton cooling time and escape time in Fig. 2. The CR energy density of pion-producing particles in NGC 253's starburst region is a few hundred times larger than in the Milky Way. The inferred magnetic field strength, assuming equipartition, is $\sim$10 nT [23] and is consistent with estimates by Heesen et al. [31].

All models discussed so far consider SNRs as the sole source of high-energy particles in starburst galaxies. The population of Galactic GeV and TeV γ-ray sources, however, is diverse and dominated by PWNe, rather than SNRs. Mannheim et al. [42] proposed PWNe as the source class, responsible for the bulk of the TeV emission from NGC 253 and M82. In their work, they scaled the population of Milky Way PWNe to both starbursts. As discussed in Section 3.1, the physical conditions in starburst galaxies, however, are significantly different from the typical ISM in the Galaxy and cooling times for TeV-emitting electrons are very short. Ohm and Hinton [32] performed a more detailed modelling of the PWN populations in NGC 253 and M82, using a time-dependent two-zone model. They consider a stage where particles are accelerated and cool in the PWN environment early on, and a later stage where particles escape the PWN and cool in the starburst region. Although assumptions are very different, [42] and [32] reach similar conclusions, namely that PWNe are potential contributors to the TeV emission from starburst galaxies. Note that for the latter model, a steeper spectral index in the TeV range requires pulsars to have very short birth periods of $\sim$15 ms and fast particle escape in order not to violate radio measurements. Both models predict a feature, where (energy-dependent) diffusion results in a steepening of the γ-ray spectrum, and where the harder γ-ray spectrum produced by PWNe starts to dominate the emission. The sensitivity of current instruments is not yet good enough to probe such a feature, but it should be noted that no indication of a break or cutoff in the NGC 253 spectrum is apparent, which would support the PWN interpretation.

4. Starburst galaxies in the CTA era

As is clear from the previous sections, starburst galaxies are weak γ-ray emitters and only a limited number of nearby objects can be studied. Any improvement in statistics, which results in better measured γ-ray spectra requires either longer observations and/or better γ-ray detectors. Fermi-LAT continues to collect data of starburst galaxies thanks to its all-sky capabilities, and will improve the used analysis techniques. This will provide a better determination of the γ-ray spectrum at GeV energies. The angular resolution might not be sufficient to resolve the starburst nucleus, or to even detect an intrinsic extension of the γ-ray source. For Cherenkov telescopes, on the other hand, increasing the exposure does not improve things too much, since these instruments are already operating at the sensitivity limit. This is especially true for NGC 253, were already more than 150 h of data have been collected and for which advanced analysis techniques are used.[1]

The sensitivity of Fermi-LAT and current ground-based Cherenkov telescopes is not sufficient to search for spectral signatures associated with different source populations, different energy-loss processes or γ–γ absorption features. A significant improvement in sensitivity for energies between several tens of GeV and hundreds of TeV energies is expected from the upcoming Cherenkov Telescope Array (CTA) [43]. CTA is currently in the prototyping phase, will consist of about 100 telescopes and be located in two sites, one in the northern and the other in the southern hemisphere (see [44] in this issue

[1] A better description of the M82 TeV spectrum may be possible by employing advanced analysis techniques and by increasing the observation time with VERITAS. MAGIC observations could improve the spectral coverage below $\sim$500 GeV.

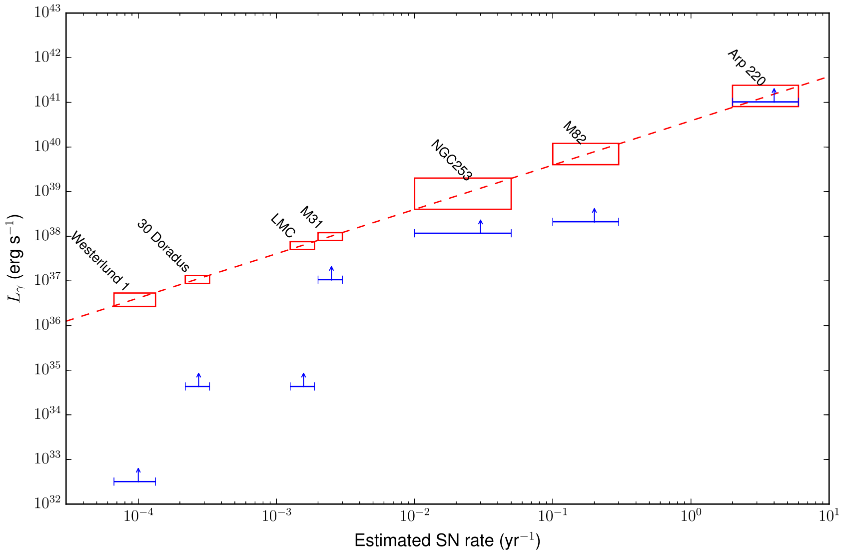

Fig. 3. Expected calorimetric γ-ray flux of nearby star-forming galaxies with varying star-formation and SN rates. Red boxes indicate uncertainties in SN rates and distance of the source. See text for a detailed description. The expected CTA sensitivity is shown as blue arrows and the red dashed line indicates the expected γ-ray flux in the calorimetric limit (see text).

for more details on the future of γ-ray astronomy). In the following, I will outline the CTA potential for the study of starburst galaxies, the measurement of the calorimetric fraction and how to extend the sample to nearby star-forming galaxies and Galactic star-forming regions – similar to what has been done by the Fermi-LAT collaboration [22] at GeV energies. Here we follow the approach described in [23] and calculate the γ-ray flux above 300 GeV in the calorimetric limit where $L_{\mathrm{coll}} = L_{\mathrm{CR}}(\pi)$ using Eq. (2). This estimate mainly depends on the SN rate of the galaxy, the energy in CRs per SN explosion, and the assumed γ-ray spectral index. This flux is then compared to the sensitivity of CTA. Rather than making a detailed model for each individual source using the expected CTA sensitivities as presented in [45], we simply assume a ten times better sensitivity than H.E.S.S. [46] and a 100-h observation. This results in an energy flux sensitivity above 300 GeV for an assumed spectral index of $\Gamma = 2.2$ of $\sim 1.5 \times 10^{-16}$ W·m^{-2} (or 0.1% Crab). For several reasons, this is only a rough guidance: more advanced analysis techniques will be employed; northern and southern arrays will have different sensitivities; and observation times and conditions will most likely vary from one source to another. Fig. 3 shows the expected calorimetric flux from stellar clusters in the Milky Way and the LMC, the nearby star-forming galaxies M31 and the LMC, the starburst galaxies NGC 253, and M82, and the ULIRG Arp 220. Also shown is the assumed CTA sensitivity. First of all, this simple model already shows that CTA is very well suited to study the connection between γ rays and the star-formation process over a wide range of SFR and SN rates. It is also clear that, even for a long exposure, the predicted flux from the ULIRG Arp 220 is at the limit of the CTA sensitivity. Another limitation of this model is that it assumes an equilibrium situation. While this assumption is certainly valid for entire galaxies, for which the SN rate is shorter than the typical acceleration time in SNRs, this is not true for objects like Westerlund 1, or 30 Doradus. Here the measured γ-ray emission level may depend on the recent SN explosion history.

It is also important to perform detailed spectral and morphological studies of individual objects with CTA. It will for instance be possible to probe the γ–γ absorption feature, predicted to lead to a cutoff in the spectrum at several TeVs [47]. Although challenging, the CTA angular resolution might be sufficient to detect an extension of the γ-ray source and to confirm the origin in the starburst nucleus. The γ-ray emission from the disk of NGC 253 is expected to be an order of magnitude dimmer than the starburst nucleus [23]. However, the CTA sensitivity will be an order of magnitude better than H.E.S.S., which should allow us to constrain the emission from the disk component. While the next major observational progress is expected soon, the modelling of the γ-ray emission from starburst galaxies will likely extend existing one-zone models. Some authors for instance have already started to consider the multiple gas components in the starburst nucleus, while others have extended single-zone models to multiple zones, or considered different non-thermal source populations in the extreme environments of starbursts.

Starburst galaxies are in many respects interesting objects:

(i) their study is important for the understanding of galaxy formation and evolution;
(ii) their measured γ-ray emission and the γ-ray emission from star-forming galaxies in general can comprise up to a quarter of the extragalactic background light [22];
(iii) some significant fraction of the astrophysical neutrino flux, first detected with IceCube [48], can possibly be explained by star-forming galaxies for rather hard source spectra as observed at γ-ray energies [49–51].

Another possibility is that CRs, pre-accelerated in the starburst nucleus can potentially be accelerated beyond the knee of the CR spectrum in the galactic wind [52]. To summarise, observations of star-forming galaxies in general and starbursts in particular have made major progress in the past five years, with new and exciting discoveries. There is ongoing development in the theoretical modelling of CRs and their impact on the star-formation process. With the advent of CTA and other major facilities at lower wavelengths, exciting times are ahead of us for the study of the connection of CRs and the star-formation process.

Acknowledgements

I would like to warmly thank Gérard Fontaine and Bernard Degrange for their invitation to write this review, Heinz Völk for his constant interest and support, as well as Matthias Füssling for carefully reading the manuscript.

References

[1] R.C. Kennicutt, N.J. Evans, Star formation in the Milky Way and nearby galaxies, Annu. Rev. Astron. Astrophys. 50 (2012) 531–608.
[2] Mark R. Krumholz, The big problems in star formation: the star formation rate, stellar clustering, and the initial mass function, Phys. Rep. 539 (2) (2014) 49–134.
[3] P. Caselli, et al., The ionization fraction in dense cloud cores, Astrophys. J. 499 (1998) 234–249.
[4] A. Dalgarno, Interstellar chemistry special feature: the galactic cosmic ray ionization rate, Proc. Natl. Acad. Sci. USA 103 (2006) 12269–12273.
[5] N. Indriolo, B.J. McCall, Investigating the cosmic-ray ionization rate in the galactic diffuse interstellar medium through observations of H_3^+, Astrophys. J. 745 (2012) 91.
[6] Nick Indriolo, Benjamin J. McCall, Cosmic-ray astrochemistry, Chem. Soc. Rev. 42 (2013) 7763–7773.
[7] A. Socrates, S.W. Davis, E. Ramirez-Ruiz, The Eddington limit in cosmic rays: an explanation for the observed faintness of starbursting galaxies, Astrophys. J. 687 (November 2008) 202–215.
[8] P.P. Papadopoulos, et al., Extreme cosmic ray dominated regions: a new paradigm for high star formation density events in the Universe, Mon. Not. R. Astron. Soc. 414 (June 2011) 1705–1714.
[9] P.P. Papadopoulos, W.-F. Thi, The initial conditions of star formation: cosmic rays as the fundamental regulators, in: D.F. Torres, O. Reimer (Eds.), Cosmic Rays in Star-Forming Environments, in: Adv. Solid State Phys., vol. 34, 2013, p. 41.
[10] C.M. Booth, et al., Simulations of disk galaxies with cosmic ray driven galactic winds, Astrophys. J. Lett. 777 (November 2013) L16.
[11] M. Salem, G.L. Bryan, Cosmic ray driven outflows in global galaxy disc models, Mon. Not. R. Astron. Soc. 437 (February 2014) 3312–3330.
[12] A.M. Bykov, Nonthermal particles and photons in starburst regions and superbubbles, Astron. Astrophys. Rev. 22 (November 2014) 77.
[13] R. Beck, Cosmic magnetic fields: observations and prospects, in: F.A. Aharonian, W. Hofmann, F.M. Rieger (Eds.), American Institute of Physics Conference Series, in: American Institute of Physics Conference Series, vol. 1381, September 2011, pp. 117–136.
[14] H.J. Völk, U. Klein, R. Wielebinski, M82, the Galaxy, and the dependence of cosmic ray energy production on the supernova rate, Astron. Astrophys. 213 (April 1989) L12–L14.
[15] A. Akyuz, N. Brouillet, M.E. Ozel, M82 in gamma-rays, Astron. Astrophys. 248 (August 1991) 419.
[16] T.A.D. Paglione, et al., Diffuse gamma-ray emission from the starburst galaxy NGC 253, Astrophys. J. 460 (March 1996) 295.
[17] J.J. Blom, T.A.D. Paglione, A. Carramiñana, Diffuse gamma-ray emission from starburst galaxies and M31, Astrophys. J. 516 (May 1999) 744–749.
[18] N. Götting, Nachweis von TeV-Gamma-Strahlung aus der Richtung der Blazare H1426+428 und 1ES1959+650 sowie der Radiogalaxie M87 mit den HEGRA-Cherenkov-Teleskopen, PhD thesis, Universität Hamburg, Germany, 2007.
[19] H.E.S.S. Collaboration, F. Acero, et al., Detection of gamma rays from a starburst galaxy, Science 326 (2009) 1080–1082.
[20] VERITAS Collaboration, V.A. Acciari, et al., A connection between star formation activity and cosmic rays in the starburst galaxy M82, Nature 462 (2009) 770–772.
[21] Fermi-LAT Collaboration, A.A. Abdo, et al., Detection of gamma-ray emission from the starburst galaxies M82 and NGC 253 with the large area telescope on Fermi, Astrophys. J. Lett. 709 (2010) L152–L157.
[22] Fermi-LAT Collaboration, M. Ackermann, et al., GeV observations of star-forming galaxies with the Fermi large area telescope, Astrophys. J. 755 (2012) 164.
[23] H.E.S.S. Collaboration, A. Abramowski, et al., Spectral analysis and interpretation of the γ-ray emission from the starburst galaxy NGC 253, Astrophys. J. 757 (2012) 158.
[24] MAGIC Collaboration, J. Albert, et al., First bounds on the very high energy γ-ray emission from Arp 220, Astrophys. J. 658 (2007) 245–248.
[25] Q.-W. Tang, X.-Y. Wang, P.-H.T. Tam, Discovery of GeV emission from the direction of the luminous infrared Galaxy NGC 2146, Astrophys. J. 794 (2014) 26.
[26] J.-P. Lenain, et al., Seyfert 2 galaxies in the GeV band: jets and starburst, Astron. Astrophys. 524 (2010) A72.
[27] H.E.S.S. Collaboration, A. Abramowski, et al., Diffuse galactic gamma-ray emission with H.E.S.S, Phys. Rev. D 90 (12) (2014) 122007.
[28] H.E.S.S. Collaboration, A. Abramowski, et al., The exceptionally powerful TeV γ-ray emitters in the Large Magellanic Cloud, Science 347 (2015) 406.
[29] R. Bird, Very-high-energy gamma-ray observations of M 31 with VERITAS, in: The X-ray Universe 2014, 2014, p. 230.
[30] S. Ohm, J.A. Hinton, High-energy emission from galaxies: the star-formation/gamma-ray connection, ArXiv e-prints: arXiv:1202.0260, 2012.
[31] V. Heesen, et al., Cosmic rays and the magnetic field in the nearby starburst galaxy NGC 253 III. Helical magnetic fields in the nuclear outflow, Astron. Astrophys. 535 (2011) A79.
[32] S. Ohm, J.A. Hinton, Non-thermal emission from pulsar-wind nebulae in starburst galaxies, Mon. Not. R. Astron. Soc. 429 (2013) L70–L74.
[33] N. Scoville, et al., ALMA imaging of HCN, CS and dust in Arp 220 and NGC 6240, Astrophys. J. 800 (2015) 70.
[34] J. McBride, et al., Parsec-scale magnetic fields in Arp 220, Mon. Not. R. Astron. Soc. 447 (2015) 1103–1111.
[35] E. Domingo-Santamaría, D.F. Torres, High energy γ-ray emission from the starburst nucleus of NGC 253, Astron. Astrophys. 444 (2005) 403–415.
[36] Y. Rephaeli, Y. Arieli, M. Persic, High-energy emission from the starburst galaxy NGC 253, Mon. Not. R. Astron. Soc. 401 (2010) 473–478.
[37] B.C. Lacki, T.A. Thompson, E. Quataert, The physics of the far-infrared-radio correlation. I. Calorimetry, conspiracy, and implications, Astrophys. J. 717 (July 2010) 1–28.
[38] B.C. Lacki, et al., On the GeV and TeV detections of the starburst galaxies M82 and NGC 253, Astrophys. J. 734 (2011) 107.
[39] T.A.D. Paglione, R.D. Abrahams, Properties of nearby starburst galaxies based on their diffuse gamma-ray emission, Astrophys. J. 755 (2012) 106.
[40] T.M. Yoast-Hull, et al., Winds, clumps, and interacting cosmic rays in M82, Astrophys. J. 768 (2013) 53.
[41] B.C. Lacki, R. Beck, The equipartition magnetic field formula in starburst galaxies: accounting for pionic secondaries and strong energy losses, Mon. Not. R. Astron. Soc. 430 (2013) 3171–3186.

[42] K. Mannheim, D. Elsässer, O. Tibolla, Gamma-rays from pulsar wind nebulae in starburst galaxies, Astropart. Phys. 35 (2012) 797–800.

[43] M. Actis, et al., Design concepts for the Cherenkov Telescope Array CTA: an advanced facility for ground-based high-energy gamma-ray astronomy, Exp. Astron. 32 (2011) 193–316.

[44] J. Knödlseder, The future of gamma-ray astronomy, C. R. Physique 17 (6) (2016) 663–678, in this issue.

[45] CTA Consortium, K. Bernlöhr, et al., Monte Carlo design studies for the Cherenkov Telescope Array, Astropart. Phys. 43 (2013) 171–188.

[46] H.E.S.S. Collaboration, F. Aharonian, et al., Observations of the Crab nebula with HESS, Astron. Astrophys. 457 (2006) 899–915.

[47] F. Acero, et al., CTA Consortium, Gamma-ray signatures of cosmic ray acceleration, propagation, and confinement in the era of CTA, Astropart. Phys. 43 (2013) 276–286.

[48] IceCube Collaboration, M.G. Aartsen, et al., Observation of high-energy astrophysical neutrinos in three years of IceCube data, Phys. Rev. Lett. 113 (10) (2014) 101101.

[49] L.A. Anchordoqui, et al., What IceCube data tell us about neutrino emission from star-forming galaxies (so far), Phys. Rev. D 89 (12) (2014) 127304.

[50] I. Tamborra, S. Ando, K. Murase, Star-forming galaxies as the origin of diffuse high-energy backgrounds: gamma-ray and neutrino connections, and implications for starburst history, J. Cosmol. Astropart. Phys. 9 (2014) 043.

[51] X.-C. Chang, X.-Y. Wang, The diffuse gamma-ray flux associated with Sub-PeV/PeV neutrinos from starburst galaxies, Astrophys. J. 793 (2014) 131.

[52] E.A. Dorfi, D. Breitschwerdt, Time-dependent galactic winds. I. Structure and evolution of galactic outflows accompanied by cosmic ray acceleration, Astron. Astrophys. 540 (2012) A77.