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Starburst galaxies as seen by gamma-ray telescopes

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

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ABSTRACT

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.

RÉSUMÉ

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

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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 $(m_p/m_e)^4$. 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

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