Model analysis of the VHE detections of the starburst galaxies M82 and NGC 253

P1-65

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Starburst galaxies M82 and NGC 253 have been recently detected at very high energies (VHE). We present a multi-wavelength model successfully accounting for their gamma-ray diffuse emission.

Introduction

Starburst galaxies were anticipated as γ-ray sources [6, 7], provided sufficient instrumental sensitivity, due to their enhance star formation and supernova (SN) explosion rate, in dense (gas and dust enriched) environments. SN remnants and shock winds from massive stars are supposed to accelerate cosmic rays (CR). Due to their collisions with ambient nuclei and subsequent π^0 decay, very energetic γ-rays are produced, and those can in turn be detected both with space-born and ground-based imaging atmospheric Cherenkov telescopes.

Recently, the detection of M82 was presented by the VERITAS collaboration at the ICRC 2009, while the integral flux of the fainter NGC 253 has just been published by the H.E.S.S. collaboration.

Slight and reasonable variations in the parameter space of already published models [2, 3] can fully account for the VHE emission coming from both galaxies, while agreeing with previous data detected from radio to infrared (IR). We explore these changes and some implications they have for the CR distribution in these galaxies.

Description of the model

The aim of this and previous studies is to perform a multi-wavelength model for the emission coming from the central part of the starburst galaxies M82 and NGC 253. To model the high energy emission we use the *Q-DIFFUSE* code, already presented in [1] and improved in [2] and [3]. The computation consists on solving the diffusion-loss equation for a steady state population of both electrons and protons, taking into account losses in each particle population, and also secondary production.

One of the major achievements of this study is presenting an accurate fit to multi-wavelength data. In Fig. 1, a multi-frequency spectrum is overplotted to previous radio and IR data.

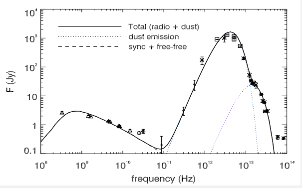

Fig. 1.- Multifrequency spectrum of NGC 253 from radio to infrared. The observational data points correspond to: Carilli (triangles, 1996), Elias et al. (circles, 1978), Rieke et al. (asterisks, 1973), Ott et al. (diamonds, 2005) and Telesco et al. (squares, 1980) (and references therein). The results from modelling correspond to: synchrotron plus free-free emission (dashed), dust emission (dotted) splitted in a cool (blue, T_c = 45 K) and a warm (purple, T_w ~ 200 K) component, and the total emission from radio and IR emission (solid).

M 82

The near, almost edge-on starburst galaxy M82 has a low-mass gas content, mostly concentrated in the inner 2 kpc, and presents a high luminosity both in the far IR and X-ray domain. As part of the M81 group, M82 shows hints of an encounter with some of its members 1Gyr ago. As a result of tidal forces, it harbors a central (300 pc) starburst.

VHE γ-ray emission coming from M82 was just claimed by VERITAS [5]. In Fig. 2, this data is shown together with the spectral energy distribution (SED) of the already published model [3] for a range of parameters and some specific outputs to better predict observed results (see Table 1). A separate contribution is plotted coming from each γ-ray generator: neutral pion (π^0) decay, brems-strahlung and inverse Compton. The latter was computed having the cosmic background (CMB), far and near IR photon densities as targets altogether (see Fig. 1). π^0 decay contribution dominates at VHE energies.

Table 1. Physical parameters used in the multi-wavelength model of M82, both in [3] and the present study, in which values are specified in order to match with the VERITAS detection. The (small) variations explored here are, in any case, inside the former predictions of the original model. Numbering divide the list of parameters in: 1) observational values, 2) derived from 1), 3) obtained from modelling, and 4) assumed. SB stands for starburst.

	Physical parameters	de Cea del Pozo et al (2009)	VERITAS-driven model
	Distance	$3.9 \pm 0.3_{random} \pm 0.3_{systematic}$ Mpc	...
	Inclination	$77 \pm 3\,°$	...
	Radius SB	300 pc	...
	Radius Disk	7 kpc	...
	Height SB	200 pc	...
	Gas Mass SB	$2 \times 10^8 M_\odot$ (H_2)	...
	Gas Mass Disk	$7 \times 10^8 M_\odot$ (HI),	...
(1)		$1.8 \times 10^9 M_\odot$ (H_2)	
	IR Luminosity	$4 \times 10^{10} L_\odot$	...
	SN explosion rate	$0.3\ yr^{-1}$ ($0.1\ yr^{-1}$)	$0.2\ yr^{-1}$ — $0.3\ yr^{-1}$
	SN explosion energy	10^{51} erg	...
	SN energy transferred to CR	10%	10% — 5%
	Convective velocity	600 km s^{-1}	...
	Dust temperature	45 K	...
	Ionized temperature	10000 K	...
(2)	Uniform density SB	$\sim 180 cm^{-3}$	...
	Dust emissivity index	1.5	...
	Emission measure	5×10^5 pc cm^{-6}	...
(3)	Magnetic field	120 μG (270 μG)	170 μG — 210 μG
	Proton to electron primary ratio	50 (30)	...
	Slope of primary injection spectrum	2.1	...
	Maximum energy for primaries	10^6 GeV	...
(4)	Diffusion coeficient slope	0.5	...
	Diffusive timescale	1 – 10 Myr	...

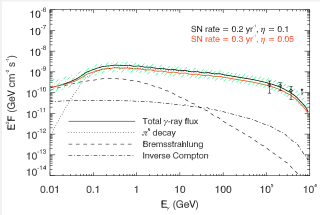

Fig. 2.- Energy distribution of the differential gamma-ray fluxes of M82, exploring a range of uncertainties in supernova explosion rate and efficiency to inject energy from SN to CR. The shaded green area corresponds to the original model of de Cea del Pozo (2009). Data points and upper limit correspond to the VERITAS detection.

NGC 253

The also near, barred-spiral starburst galaxy NGC 253 has been deeply studied through the years. Its continuum spectrum peaks in the far IR with a high luminosity. Its inner (100 pc) region is characterized, as well as M82, by starburst activity.

The integral flux published by H.E.S.S. constraints previously predictions for NGC 253. A set of curves for the SED are specifically plotted in Fig. 3 to achieve this low flux, exploring uncertainties in the distance to this galaxy and subsequent ranges in the magnetic field and diffusive timescale. Apart from diffusing away during 10^{6-7} yrs (see Table 2), particles can escape the inner starburst convectively, carried away by winds (~ 300 km s^{-1}), and through pion collisions with ambient gas, in even shorter timescales of around a few 10^5 yrs. Since the diffusion timescale of the particle depends on the energy, the shorter it is, the steeper the γ-ray spectrum gets (the higher the losses are). The diffusion coefficient associated is ~ 10^{26-27} cm^{-2} s^{-1} at 1 - 10 GeV, compared to the ~ 10^{28} cm^{-2} s^{-1} value in our Galaxy.

Table 2. Physical parameters used in the multi-wavelength model of NGC 253, as presented both in the previous [2] paper and in the present study, which explores some variations allowed within the model in order to explain the H.E.S.S. detection. Numbering like in Table 1. SB stands for starburst.

	Physical parameters	Domingo & Torres 2005	H.E.S.S.-driven model
	Distance	2.5 Mpc	2.6 Mpc — 3.9 Mpc
	Inclination	78°	...
	Radius SB	100 pc	...
	Radius Disk	1 kpc	...
	Height SB	70 pc	...
	Gas Mass SB	$3 \times 10^7 M_\odot$	...
(1)	Gas Mass Disk	$2.5 \times 10^8 M_\odot$	
	IR Luminosity	$(2-4) \times 10^{10} L_\odot$	...
	SN explosion rate	$0.08\ yr^{-1}$	...
	SN explosion energy	10^{51} erg	...
	Convective velocity	300 km s^{-1}	...
	Dust temperature	50K	45 K
	Ionized temperature	10000 K	...
(2)	Uniform density SB	$\sim 600 cm^{-3}$	...
	Dust emissivity index	1.5	...
	Emission measure	5×10^5 pc cm^{-6}	...
(3)	Magnetic field	300 μG	200 μG — 270 μG
	Proton to electron primary ratio	50	30
	Slope of primary injection spectrum	2.3	2.1
	Maximum energy for primaries	10^6 GeV	...
(4)	Diffusion coeficient slope	0.5	...
	Diffusive timescale	10 Myr	1 Myr — 10 Myr

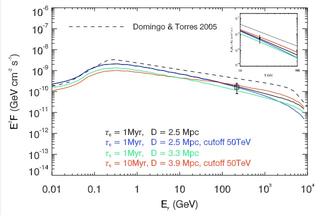

Fig. 3.- Energy distribution of the differential gamma-ray fluxes of NGC 253, exploring the uncertainty in distance, a range of timescale diffusion (τ_0) and possible cutoffs in the proton injection spectrum. The original model from Domingo & Torres (2005) is also shown for comparison, as well as the integral flux from the H.E.S.S. detection in the upper right corner.

Concluding remarks

Our multi-wavelength model explains reasonable well the VHE emission coming from the two closest starburst galaxies M82 and NGC 253, within a range of explored parameters. Every component of the emission can be tracked to one and the same original CR population, and result as a consequence of all electromagnetic and hadronic channels from the primary and subsequently-produced secondary particles.

CR enhancement present in these starburst galaxies is reflected in the high energy density values that can be obtained from the steady proton population. Above a proton energy of ~1500 GeV (corresponding to E_γ ~ 250 GeV), the energy density is around 10 eV cm^{-3} for M82 and similar value for NGC 253.

Now that the VHE regime has been finally achieved by ground-based telescopes, detections of these and similar starburst galaxies can be expected at a bit lower energies (~ 100 MeV), i.e. with the Fermi spatial telescope, to obtain a full picture of γ-ray emission.

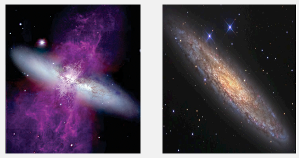

Fig. 4. Left: Optical (+ Hα galactic wind) image of M82, ® M. Westmoquette et al (WIYN/NOAO/NSF, NASA/ESA). Right: Optical image of NGC 253, ® R. Jay GaBany (Cosmotography.com)

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Acknowledgments

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