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A multifrequency view of starburst galaxies

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Abstract. During the past few years, first observations of starburst galaxies at > GeV energies could be made with the Fermi Gamma-ray Space Telescope (GeV range) and Imaging Air Cherenkov Telescopes (TeV range). The two nearest starbursts, M82 and NGC253 were detected, and most recently, the detection of two starburst-Seyfert composites (NGC1068 and NGC4945) were reported. The emission for the two starbursts is best explained by hadronic interactions, and thus providing a first, unique opportunity to study the role of cosmic rays in galaxies. In this paper, the role of cosmic rays for the non-thermal component of galaxies is reviewed by discussing the entire non-thermal frequency range from radio emission to TeV energies. In particular, the interpretation of radio emission arising from electron synchrotron radiation is predicted to be correlated to TeV emission coming from interactions of accelerated hadrons. This is observed for the few objects known at TeV energies, but the correlation needs to be established with significantly higher statistics. An outlook of the possibility of tracing cosmic rays with molecular ions is given.

Key words. starburst galaxies – high-energy photons –cosmic rays – molecular ions

1. Introduction

Galaxies with a high star formation rate provide the opportunity to study the influence of massive stars on the large-scale behavior of galaxies in detail. In particular, the role of gas heating by star formation can be studied by the observation of far-infrared emission and the role of supernova remnants can be investigated by looking at non-thermal radio emission from electron synchrotron radiation. Most recently, first gamma-ray detections using the Fermi Gamma-ray Space Telescope (FGST) and Imaging Air Cherenkov Telescopes like H.E.S.S. and VERITAS were made. The nearest starburst galaxies M82 and NGC253 were detected above GeV energies, tracing the interaction of hadronic cosmic rays with the gas in the galaxy.

In this paper, the multifrequency spectrum of starburst galaxies will be reviewed. In Section 2, the correlation between the far infrared and radio emission is discussed. In Section 3, hadronic interactions at energies $E >$ GeV are discussed in the context of neutral secondary production. In Section 4, cosmic ray-induced ionization is mentioned as a future method of tracing hadronic cosmic rays in galactic environments. In particular, a supernova remnant interacting with a molecular cloud provides an optimal environment for the production of H_2^+, at a level which should be detectable in the future with instruments like Herschel and ALMA.

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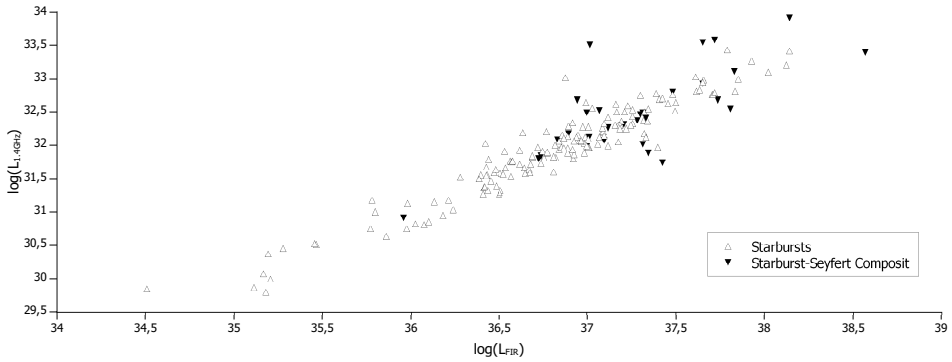

Fig. 1. FIR-radio correlation for a sample of local starburst galaxies at $z \leq 0.03$, showing a linear correlation between the two wavelengths. Luminosities are given in units of erg/s. The sample contains a significant fraction of sources which, apart from the starburst behavior of the galaxy, reveal Seyfert-like properties of the galaxy core. While those galaxies with no Seyfert core identification are shown as open triangles, the supposed Seyfert-starburst composites are shown as filled triangles.

2. The radio-FIR correlation

The correlation between the total radio and far-infrared emission in starburst galaxies is experimentally well established. As an example, a sample of local starburst galaxies with redshifts below $z = 0.03$ is shown in Figure 1. Far-infrared emission arises when newly born, massive stars heat the surrounding gas. Radio emission, on the other hand, is directly correlated to the death of massive stars: electrons are accelerated at supernova remnant shock fronts and lose their energy via synchrotron radiation at radio wavelengths. Thus, from this very general statement, a correlation between radio and far-infrared emission is expected.

A detailed modeling of the correlation, however, remains difficult when trying to explain all observations. While a calorimetric model, in which all electrons lose their entire energy to synchrotron radiation seems feasible in the theoretical framework as presented by Völk (1989), observations of the radio spectral index in starburst galaxies show relatively flat spectra: On average, radio spectra in the GHz range behave as $\sim \nu^{-0.7}$. The synchrotron spectral index $\alpha_{\rm radio}$ and primary particle spectral index α_p are directly connected as (Rybicki & Lightman 1979)

$$\alpha_p = 2 \cdot \alpha_{\rm radio} + 1\,. \qquad (1)$$

Thus, a synchrotron spectral index of $\alpha_{\rm radio} \sim 0.7$ reveals a primary electron population with a spectral index of $\alpha_p \sim 2.6$. In the calorimetric model, however, higher energy electrons should lose all their energy, resulting in spectra as steep as E^{-3}.

An alternative model, based on a cosmic ray driven wind model for starburst galaxies, is discussed by Becker et al. (2009). Here, the non-thermal radio flux, induced by electron synchrotron losses, turns out to be only weakly dependent on the magnetic field of the starburst ($F_\nu \propto B^{0.12}$), even without the assumption of a calorimeter.

The question remains whether or not electrons can partly escape the starburst galaxies and more detailed calculations have to be performed in order to match all observational features.

An additional complication in the interpretation of electromagnetic radiation from starburst galaxies is the apparent co-existence between starburst galaxies and active Seyfert cores. Figure 1 shows those galaxies that reveal an active core in a starburst galaxy as filled triangles. Thus, when the emission cannot be resolved spatially, ambiguities can arise concerning the electromagnetic contribution from the central activity and the starburst part of the galaxy.

3. Hadronic interactions at $E >$ GeV

A significant part of the total energy budget of a galaxy goes into the acceleration of cosmic rays. It is known from the observation of the charged cosmic ray flux at Earth, that the total energy carried by Galactic cosmic rays with energies above 100 GeV corresponds to a total luminosity of $\sim 10^{42}$ erg/s. The shock fronts of supernova remnants are one of the primary candidates for the acceleration of cosmic rays up to 10^{15} eV or higher (Stanev et al. 1993; Biermann et al. 2009, 2010a,b). When interacting with the local gas of the considered galaxy, a significant amount of the primary cosmic rays' energy is put into the production of high-energy photons and neutrinos. While neutrino telescopes have not yet reached the sensitivity to detect diffuse emission from the Milky Way, gamma-ray emission is detected at a level of 10^{39} erg/s. Thus, the transport of cosmic rays in a galaxy is expected to play a significant role considering the dynamics of the galaxy itself. The difficulty in pinpointing the sources of cosmic rays themselves lies in the complexity of the transport of the charged particles through the galactic magnetic field. For the Milky Way, the observed flux of cosmic rays contains information about the total energy budget and the spectral behavior after transport. However, no direct information on the direction of the sources of cosmic rays or about the primary spectra at injection can be deduced from observations. Concerning starburst galaxies, compared to the high cosmic ray flux from the Milky Way, any possible signal in charged cosmic rays would be negligible. So, in general, in order to understand the role of cosmic rays in a galaxy, the search for neutral secondaries like photons and neutrinos from hadronic interactions is one of the most interesting approaches.

High-energy photons and neutrinos are produced in hadronic interactions, in environments with a high flux of high-energy cosmic rays $j_p(E_p)$ and a large target density n_H (Becker et al. 2009):

$$p\,p \rightarrow N(\pi^+/\pi^-/\pi^0) + X\,. \quad (2)$$

Here, $N(\pi^+/\pi^-/\pi^0)$ denotes that multiple pions N are created in the process. Charged pions contribute to the production of high-energy neutrinos,

$$\pi^+ \rightarrow \mu^+\,\nu_\mu \rightarrow e^+\,\nu_e\,\overline{\nu}_\mu\,\nu_\mu \quad (3)$$

$$\pi^- \rightarrow \mu^-\,\overline{\nu}_\mu \rightarrow e^-\,\overline{\nu}_e\,\nu_\mu\,\overline{\nu}_\mu\,. \quad (4)$$

Neutral pions produce high-energy photons, $\pi^0 \rightarrow \gamma\,\gamma$.

Assuming that the dominant part of charged cosmic rays below 10^{15} eV is accelerated in supernova remnants, the target density directly at the acceleration site is important as a local effect. At high hydrogen densities, cosmic rays interact directly at the source and the neutral interaction products reveal the spectral shape at injection. For sources that have proton-proton optically thin environments, most protons will escape the acceleration region and change their energy spectrum due to transport effects. Then, interactions with the diffuse gas in the galaxy serve as a tracer of the cosmic ray spectrum after transport. Measurements concerning the transport of cosmic rays through the Milky Way's magnetic field indicate that diffusion steepens the injection spectrum by a factor of $\sim E^{-0.3} - E^{-0.6}$ (Gupta & Webber 1989). With the observed spectrum being close to $E^{-2.7}$, the expected cosmic ray energy spectrum at injection is expected to be close to $E^{-2.1} - E^{-2.4}$. At gamma-ray energies above $\sim$ 300 MeV, the photon spectrum roughly follows the charged cosmic ray spectrum in the case of hadronic interactions. Thus, the observation of the spectral behavior of gamma-rays from a galaxy can help to identify if the interactions on average take place close to the remnant, at injection, or rather in the interstellar medium, after transport. While observations of our own Galaxy indicate that propagation steepens the cosmic ray spectrum before interactions take place, the two starburst galaxies with observed gamma-ray spectra, M82 and NGC253, reveal a quite flat spectral behavior of around $E^{-2.3}$. Thus, it is expected that a large fraction of the cosmic ray interactions happen in the vicinity of the sources.

3.1. Gamma-ray observations of starburst galaxies

As of today, there are six objects observed at gamma-ray energies, where the emission appears to arise from hadronic interactions:

- **M82 (Starburst galaxy)**
- **NGC253 (Starburst galaxy)**
- **The Milky Way**
- **Star-forming region 30 Doradus (Large Magellanic Cloud)**
- **NGC1068 (Starburst-Seyfert composite)**
- **NGC4945 (Starburst-Seyfert composite)**

Although the statistics with only six objects revealing hadronic interactions is still low, it is worth to have a first look at what kind of correlations to expect and to investigate if those show up in this still very small sample. It is clear that there are many caveats when looking for correlations in this small sample: the only true starburst galaxies are M82 and NGC253. The star-forming region 30 Doradus is only a part of the dwarf galaxy. The Milky Way is a regular galaxy with contributions to the FIR emission from stars that do not explode as supernovae. Thus, the Milky Way is not expected to lie on the FIR-radio correlation curve. The two starburst-Seyfert composites could have contributions from the active core in all wavelength ranges. Thus, future observations of a larger sample of pure starburst galaxies will have to confirm or reject the results presented below.

3.2. Interpretation of measured gamma-ray spectra as the product of hadronic interactions

From Fermi- and IACT-observations, the gamma-ray flux from M82, NGC253, the Milky Way and the star-forming region 30 Doradus in the LMC are known (Abdo et al. 2010a). The measurements give a unique opportunity to draw conclusions about the primary cosmic ray flux.

First of all, the gamma-ray spectra for M82 and NGC253 appear to be very flat, i.e. $E^{-2.3}$ and flatter. In the observed energy region (> GeV), the hadronic gamma-ray flux follows the spectral behavior of the primary cosmic rays.

Since the gamma-ray spectrum reproduces the same spectral shape as the interacting primary particles, most of the interactions must happen close to the acceleration region: while the injection spectrum is expected to be close to $E^{-2.0} - E^{-2.3}$ (Stanev et al. 1993; Biermann et al. 2009, 2010a,b), transport through the galactic magnetic field steepens the charged primaries' spectrum to $E^{-2.7}$. Interaction after transport into the ISM would therefore lead to a steep gamma-ray spectrum of close to $E^{-2.7}$,

$$j_\gamma = \frac{dN_\gamma}{dE_\gamma \, dt \, dA_{Earth}} \,, \tag{5}$$

in units of $\mathrm{GeV}^{-1}\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}$.

The number of pion-decay induced gamma-rays of a single SNR in a starburst per unit time, volume and energy is given (Kelner et al. 2006),

$$\Phi_\gamma\ (E_\gamma) = n_H \cdot \cdot \int_{E_\gamma}^{\infty} \sigma_{\mathrm{inel}}(E_p) \cdot j_p(E_p) \cdot F_\gamma\left(\frac{E_\gamma}{E_p},\ E_p\right) \frac{dE_p}{E_p} \,. \tag{6}$$

Here, n_H is the density of the ambient medium and $\sigma_{\mathrm{inel}}(E_p)$ is the cross section of inelastic proton-proton interactions[1]. The function $F_\gamma(x,\ E_p)$ implies the number of photons in the energy interval $(x, x\ +\ dx)$ per collision and is a dimensionless probability density distribution function. The flux of relativistic protons at the source is given as

$$j_p(E_p) = a_p \cdot \Phi(E_p) \,. \tag{7}$$

Here, j_p is given per energy, time and area interval. The spectral shape of the interacting proton flux is contained in the function $\Phi(E_P)$ and can be expected to follow a power-law, $\Phi \sim E^{-p}$, while a_p is defined as the normalization factor, i.e. how many protons there are

[1] Kelner et al. (2006) use the cosmic ray density, while here the cosmic ray flux is used.

per energy, time and area interval. This normalization can be done at an arbitrary energy, we chose $E_p = 1$ GeV to normalize the spectra. Using other values yields the same result when applying the same units consistently throughout the calculation.

To account for the total gamma-ray flux as observed at Earth, in units of per time, area and energy interval, Equation (6) needs to be multiplied by the volume of the interaction region V of a single SNR and the number of SNRs $N_{\rm SNR}$, which scales directly with the SN rate $R_{\rm SN}$ of the galaxy. Further, assuming isotropic emission, the detected flux scales with $1/(4\,\pi\,d^2)$. The observed flux is then directly connected to the produced density as

$$\Phi|_\oplus = \Phi_\gamma(E_\gamma) \cdot V \cdot N_{\rm SNR} \cdot \left(4\pi\,d^2\right)^{-1} \quad (8)$$

$$= \frac{n_H \cdot V}{4\pi\,d^2} \cdot \quad (9)$$

$$\cdot \int_{E_\gamma}^{\infty} \sigma_{\rm inel}(E_p) \cdot j_p(E_p) \cdot F_\gamma\left(\frac{E_\gamma}{E_p},\, E_p\right) \frac{dE_p}{E_p}\,.$$

Assuming a proton flux at the source following a power-law with normalization a_p and a spectral shape $\Phi(E_p)$ yields

$$\Phi|_\oplus = a_\gamma \cdot \quad (10)$$

$$\cdot \int_{E_\gamma}^{\infty} \sigma_{\rm inel}(E_p) \cdot \Phi_p(E_p) \cdot F_\gamma\left(\frac{E_\gamma}{E_p},\, E_p\right) \frac{dE_p}{E_p}\,,$$

with

$$a_\gamma = \frac{a_p \cdot n_H \cdot V \cdot N_{\rm SNR}}{4\pi\,d^2}\,. \quad (11)$$

This factor needs to be fixed to a certain value to match the observations, and conclusions about the parameters on the right-hand side can be drawn.

The proton spectral normalization, a_p can be calculated using the conservation of energy:

$$\int_{E_{min}}^{\infty} j_p\,E_p\,dE_p = a_p \cdot \int_{E_{min}}^{\infty} \Phi(E_p)\,E_p\,dE_p$$

$$= \frac{W_p \cdot c}{V}\,. \quad (12)$$

where W_p is the total proton energy budget of protons with a minimum energy of $E_{\rm min}$, assuming the protons travel approximately at the speed of light. Solving the equation for a_p gives:

$$a_p = \frac{W_p \cdot c}{V \cdot \int_{E_{min}}^{\infty} \Phi(E_p)\,E_p\,.dE_p}\,, \quad (13)$$

Thus, the normalization of the photon spectrum can be written as

$$a_\gamma = \frac{W_p \cdot c \cdot n_H \cdot N_{\rm SNR}}{4\pi d^2 \cdot \int_{E_{min}}^{\infty} \Phi(E_p)\,E_p\,dE_p}\,. \quad (14)$$

Given the distance to the source and determining the average shape of the primary particle spectrum from the shape of the gamma-ray spectrum, the product of the total cosmic ray energy budget, the target density and the number of SNRs, $W_p \cdot n_H \cdot N_{\rm SNR}$ determines the gamma-ray flux normalization. Alternatively, the cosmic ray energy density $\rho_{\rm CR} = W_p/V$ can be used, and in this case, it is the product with the total interacting mass,

$$\rho_{\rm CR} \cdot M \cdot N_{\rm SNR} = \rho_{\rm CR} \cdot n_H \cdot V \cdot N_{\rm SNR} \quad (15)$$

is the determining factor. Thus, assuming a constant cosmic ray energy density and a direct scaling of the number of SNRs with the supernova rate $R_{\rm SN}$ would result in a direct proportionality between the observed gamma-ray emission and the total interacting gas mass.

First Fermi results seem to suggest that a correlation between the gamma-ray luminosity and the product of the supernova rate and the total gas mass is present (Abdo et al. 2010a). However, the calculation has several caveats: For once, it is not likely that the cosmic ray energy density is constant for all starburst galaxies. In addition, it is assumed here that all SNRs have the same cosmic ray energy spectrum, although it is known that the spectrum actually strongly depends on their age and the local environment of the sources, see e.g. Blasi et al. (2005) and references therein. One might consider to rather search for a correlation between the product of the SN rate and the gas density with the total gamma-ray flux. However, even in this case, the above calculations rely on the fact that the energy budget for each SNR is the same. However, it is expected that it depends on the total mass of the stars and the energy put into cosmic rays might not even be a constant for the same progenitor star mass, but depend on the local environment. Further, the spectral behavior of the cosmic rays might vary depending on the local environment. And, finally, the average observed

density of the galaxy might not represent the average density in which the secondary photons are produced.

3.3. A correlation between radio and gamma-ray emission

The non-thermal radio emission at GHz frequencies is expected to come from synchrotron radiation of electrons accelerated at supernova shock fronts. The gamma-ray emission, on the other hand, is believed to have the same origin, following the interpretation of the signal as the interaction of cosmic rays with the ambient medium. Thus, a correlation between the radio and gamma-ray luminosities is expected to be present. Figure 2 shows the gamma-ray luminosity for the six objects versus their radio luminosity. A clear trend of increased gamma-ray emission at enhanced radio emission is observed. While the performed power-law fit is compatible with a linear correlation of the two emission features, the lack of statistics does not allow for the formulation of a quantitative statement on this correlation. This might still be a first hint that there is a connection between the two wavelengths, which could further be used to study acceleration processes.

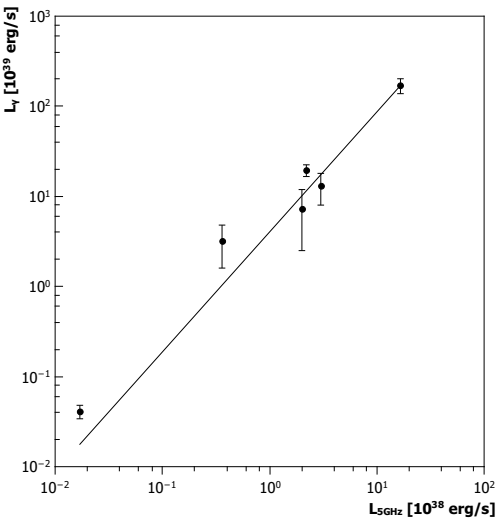

Fig. 2. Luminosities at gamma-ray energies as measured by Fermi versus radio luminosities at 5 GHz. Shown are the LMC, the Milky Way, M82, NGC253, NGC1068 and NGC4945, using the data as summarized by Lenain et al. (2011). The line represents a power-law fit to the data. Due to the small number of sources, the error of the correlation is still too large to make a quantitative statement. Qualitatively, the result is compatible with a linear correlation.

3.4. High-energy neutrinos

Due to the co-production of high-energy photons and neutrinos, hadronically produced gamma-rays are always accompanied by a neutrino flux. Due to their low interaction probability, the detection of neutrinos requires the use of kilometer-scale natural water or ice reservoirs, see e.g. Becker (2008). As of December 18, 2010, the first cubic-kilometer scale neutrino detector IceCube was completed at the geographic South Pole. The detection technique allows for the observation of the entire northern hemisphere at a duty cycle of more than 99%. The main background are neutrinos produced in the Earth's atmosphere. Point source searches can be performed for single sources as well as by the stacking of a source list. If a contribution from unresolvable sources is expected, which is the case for instance for several classes of active galactic nuclei, a search for a diffuse flux can be performed. Since astrophysical sources are expected to produce relatively flat neutrino energy spectra for interactions at the source ($\sim E^{-2} - E^{-2.3}$), the explicit search for enhanced emission at the highest energies reduces the background of the very steep atmospheric neutrino flux ($\sim E^{-3.7}$).

Concerning the case of starburst galaxies, the gamma-ray detection from M82 gives a first concrete test case of the expected neutrino flux from a point source. It turns out that the flux of M82 as a single source is relatively low and it is not expected to be detected within the first years of operation with IceCube. It may still be possible to observe M82 after a longer period of measurement, as the lifetime of IceCube is expected to be longer than 10 years. On the other hand, the stacking of a source catalog of nearby starburst

galaxies strongly improves the detection significance. As the significance roughly scales with the signal over the square root of the background, adding more signal to the search helps to reveal the signal over background. A first stacking search for starburst galaxies has been performed with partially completed configurations of the IceCube detector, see Dreyer et al. (2010); Abbasi et al. (2010). It is expected that within the next few years, the limits can be improved using a detector of more than twice the size. The detection of a diffuse flux from starburst galaxies is rather challenging, since the maximum neutrino energy may be as low as 10^{14} eV.

4. Molecular ions as cosmic ray tracers

While protons with GeV energies and above contribute to the neutrino- and photon flux of a galaxy, low-energy cosmic rays in the keV-GeV range ionize the interstellar medium. In the Milky Way, the average ionization level is observed to be of the order of $\zeta \approx 2 \cdot 10^{-16}$ s^{-1} (Gerin et al. 2010; Neufeld et al. 2010). Hydrogen ionization immediately leads to the formation of H_2^+, which in turn initiates the formation of larger molecules like H_3^+, OH^+, H_2O^+ etc., see e.g. (Black 1998) and references therein. Those molecules can be observed by detectors like Herschel and ALMA and can be used as direct tracers of cosmic ray ionization. The search for molecular ions at potential cosmic ray acceleration sites with suitable targets might help to trace the sources of cosmic rays and by that improve the understanding of the role of cosmic rays in the dynamical processes of galaxies.

In the Milky Way, several systems of supernova remnants and molecular clouds (SNR-MC systems) have been detected at gamma-ray energies in the past years. In particular, the detections of the sources W51C (Abdo et al. 2009), W44 (Abdo et al. 2010c), W28 (Abdo et al. 2010b), IC443 (Abdo et al. 2010d) and W49B (Abdo et al. 2010e) with the Fermi Gamma-ray Space Telescope are best-fit with a hadronic interaction model. The observed gamma-ray spectra can be used to estimate the primary cosmic ray spectra at the source above GeV energies. Extrapolating the spectrum down to below GeV energies then gives the opportunity to perform calculations concerning interaction of the low-energy part of the cosmic ray spectrum leading to the ionization of the local medium. Details of the calculation are presented in Becker et al. (2011). Due to the enhanced flux of cosmic rays, the ionization level is expected to be enhanced by a few orders of magnitude at the discussed SNR-MC systems. In such an environment, the detection of line emission spectra from H_2^+ and H_3^+ would be the most direct tracer for cosmic ray ionization.

Line emission from H_3^+ has been discussed previously in the context of cosmic ray ionization, and it represents one of the molecules observed in astrophysical contexts, see e.g. (Black 1998) and references therein. With the launch of the Herschel telescope, detailed observations of the abundance of H_3^+ is now possible in astrophysical environments. In Indriolo et al. (2010), for instance, an H_3^+ abundance corresponding to an ionization rate of $\sim 2 \cdot 10^{-15}$/s was observed.

Although H_2^+ is the first product of cosmic ray ionization, it is usually destroyed too quickly to produce significant line emission. However, in an environment of extreme ionization level as it seems to be the case for SNR-MC systems, the detection of H_2^+ seems to be possible and would provide a unique method to trace the sources of cosmic rays.

Due to their high star formation rate, starburst galaxies are bound to host a larger number of SNR-MC systems. In the future, it would therefore be interesting to try to combine gamma-ray measurements with the search for molecular line emission in order to be able to pin-point the cosmic ray component of the galaxies.

5. Discussion

ARNON DAR: Theoretical arguments rather point to a correlation between the gamma-ray flux and the density of the galaxy, and not to a scaling with the total gas mass.

JULIA BECKER: Assuming a constant total energy budget for all SNRs, this is correct, the scaling should be with the target density of the interaction. However, assuming a constant cosmic ray energy density gives a scaling with the total gas mass. The difficulty with both arguments is that there still are a lot of assumptions in both statements: For instance, in both calculations, all SNRs are assumed to have the same cosmic ray injection spectrum. This is not the case in reality. In addition, the average density of the galaxy does not necessarily represent the actual density relevant for the interactions.

WOLFGANG KUNDT: How do you avoid the production of hard electrons from ionization?

JULIA BECKER: The ionization cross sections decreases rapidly with energy and can thus be neglected above GeV energies. This is why below GeV energies, ionization processes dominate and above GeV energies, hadronic interactions are prevailing.

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