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EFFECTS OF THE COSMIC RAY COMPOSITION ON GALACTIC GAMMA-RAY AND NEUTRINO EMISSION

M. Breuhaus[1, 2], J. A. Hinton[2], V. Joshi[3], B. Reville[2] and H. Schoorlemmer[2,4, 5]

Abstract. Within the last years, the Tibet ASγ, LHAASO and HAWC telescopes provided the first observations of the diffuse Galactic emission above energies of 100 TeV. The cosmic rays responsible for these γ rays stem from the so-called knee region and its composition can not be inferred from direct satellite measurements anymore, but only indirectly with detectors on Earth. In this study, we investigate the effects of different cosmic-ray compositions on the resulting γ-ray and neutrino spectra in the very-high-energy (VHE) to ultra-high-energy (UHE) regime. For this, we make use of the wounded-nucleon model of nucleus interactions and develop a parametrisation of the resulting emission. We demonstrate, that the shielding of nucleons produces measurable effects especially close to breaks and cutoffs in the cosmic ray spectra. In the case of diffuse Galactic emission, compositional changes around the 'knee' have a noticeable effect on the γ-ray spectra in the crucial energy range between 10 TeV and 1 PeV. Current and future detectors will be able to probe these differences and be able to test the universality of the cosmic ray spectrum and composition within the Galaxy.

Keywords: radiation mechanisms: non-thermal, cosmic rays, Neutrinos, Gamma-rays: ISM

1 Introduction

Inelastic collisions of energetic cosmic rays (CRs) with target nuclei lead to the production of neutral (π^0) and charged pions ($\pi^\pm$). The pions decay quickly into the stable end-products γ rays, electrons, positrons, and neutrinos, which carry information about the CRs and the target species populations. The charge and mass of beam and target do have an impact on the resulting secondary products (see Kafexhiu et al. 2014, and references therein). However, these effects are often overlooked in high-energy astrophysics, typically simplifying interactions as proton-hydrogen collisions.

Although at energies well above the pion production threshold, the composition of nuclei may often be neglected or approximated with moderate scaling factors (see for example Mori 2009), significant errors arise near spectral breaks or cutoffs (e.g. Kachelriess et al. 2014). Because in most cases hadronic γ-ray or neutrino sources will have rigidity-dependent maximum particle energies, the composition should be taken into account. The same applies to the modeling of diffuse γ-ray and neutrino emissions from Galactic CR interactions with the interstellar medium (ISM) around the "knee" feature in the CR spectrum, at a few PeV.

The CR knee plays an important role in the theory of Galactic CRs (e.g. Hillas 2005), since it might mark the transition from Galactic to extragalactic CRs and be shaped by the rigidity-dependent cutoff of a Galactic source population. While supernova remnants (SNRs) were long proposed to be this source population, no PeV SNR was detected so far, and the conditions for acceleration of PeV particles do likely only occur shortly at the beginning of the SNR evolution (Bell et al. 2013; Marcowith et al. 2018). However, it was shown recently that the situation for SNRs in massive stellar clusters is very different and much higher energies can be reached (Vieu & Reville 2023).

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[1] Centre de Physique des Particules de Marseille, 163, avenue de Luminy, 13009 Marseille, France
[2] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[3] Friedrich-Alexander-Universität Erlangen-Nürnberg, ECAP, Erwin-Rommel-Str. 1, 91058 Erlangen, Germany
[4] IMAPP, Radboud University Nijmegen, Nijmegen, The Netherlands
[5] Nationaal Instituut voor Kernfysica en Hoge Energie Fysica (NIKHEF), Science Park, Amsterdam, The Netherlands

There is an increasing number of detections of γ-ray sources above 100 TeV (Abeysekara et al. 2020; Cao et al. 2024), which might contribute to the Galactic CR production. Future advancements in identifying and characterizing these sources are expected with current as well as the next generation of instruments, such as the Cherenkov Telescope Array (CTA Consortium et al. 2019). The Tibet ASγ Collaboration was the first to measure the diffuse Galactic emission above energies of 100 TeV (Amenomori et al. 2021), followed by measurements from LHAASO (Cao et al. 2023), and very recently, HAWC (Alfaro et al. 2024). These observations are anticipated to improve significantly in the future. As such, it is crucial to investigate the effects of varying CR compositions on both individual sources and the diffuse flux in this energy range. Here, we present a detailed study of the impact of target and beam composition on hadronic emissions utilizing the open-source GAMERA code (Hahn 2015). The majority of the results presented here rely on Breuhaus et al. (2022).

2 Compositional effects in sources with rigidity dependent cut-off

The maximum energy of CRs in astrophysical sources is expected to be rigidity-dependent, and the composition is influenced by the environmental conditions surrounding the accelerator. For instance, young SNR shocks interact with the wind from their progenitors, which may have reduced hydrogen content compared to the typical ISM (e.g. Langer 2012).

For the numerical computations, we implemented the γ-ray and neutrino production for arbitrary nuclei into the open-source GAMERA code (Hahn 2015). For the γ-ray and neutrino production we followed the method from Kelner et al. (2006), with an improved inelastic cross section from Kafexhiu et al. (2014). The presence of heavier CR and target nuclei is taken into account by using the wounded nucleon model (Białłas et al. 1976; Rybczyński & Broniowski 2011). In this model, interactions between individual nucleons are neglected and the total interaction is approximated as several interactions between individual nucleons. This is a quite accurate description for energies well above the pion-production threshold. For the final implementation, we followed the scheme from Kafexhiu et al. (2014). We also developed a parametrisation for arbitrary CR species following exponential cutoff power laws. The details can be found in Breuhaus et al. (2022).

To test the compositional influence for sources with rigidity-dependent cutoffs, we considered a hypothetical source with a fixed amount of energy injected into the accelerated CRs and used a typical local ISM composition as in Meyer (1985). The effect of a heavier ISM composition is nearly energy-independent. If the ISM has the same number density as in the assumption of pure hydrogen, the same amount of atoms has now an increased size, and therefore the produced γ-ray and neutrino content increases by $\sim$20 %. However, if instead the mass density as in the pure hydrogen ISM is preserved, shielding effects inside the nuclei reduce the emission by $\sim$5 %. Taking different ISM compositions into account therefore only changes the normalisation. The CR composition on the other hand affects not only the normalisation but also the position of spectral features. Using a heavier CR composition leads to a reduction of the emission. This effect becomes more significant for heavier species and it increases drastically for softer power-law indices. Additionally, spectral breaks such as the cutoff in the γ-ray and neutrino spectra occur at lower energies compared to pure hydrogen CRs, even though the rigidity-dependent cutoff energy is higher. The reason is, that at these energies the emission is produced by collisions between individual nucleons rather than the whole nucleus, and one nucleon carries less energy than the nucleus. Because the fraction of charge to mass number is $\sim$0.5 for most particle species, the cutoff in the γ-rays occurs at approximately half the energy of the pure CR proton case. Since in most sources hydrogen CRs are still expected to be the most abundant CRs, the overall effects for CR power-laws $\propto E^{-2}$ is small. However, the effects become stronger for softer CR distributions. For neutrinos, the effects on the resulting particle spectra are the same as for the γ rays.

3 Effects on the Galactic diffuse emission

At energies between 0.1 and 10^3 GeV, where the diffuse Galactic emission was measured by Fermi-LAT (Ackermann et al. 2012), the composition can be accounted for using nuclear enhancement factors, as provided by Mori (2009) or Kachelriess et al. (2014). However, this approach is no longer valid at higher energies between 100 TeV and 1 PeV. In this range, the Tibet ASγ collaboration made the first measurement of the Galactic diffuse flux (Amenomori et al. 2021).

To assess the impact of different compositions on the resulting γ-ray spectra and compare it to the Tibet ASγ measurements, we developed a simple CR model containing the most abundant species H, He, C, O, Mg,

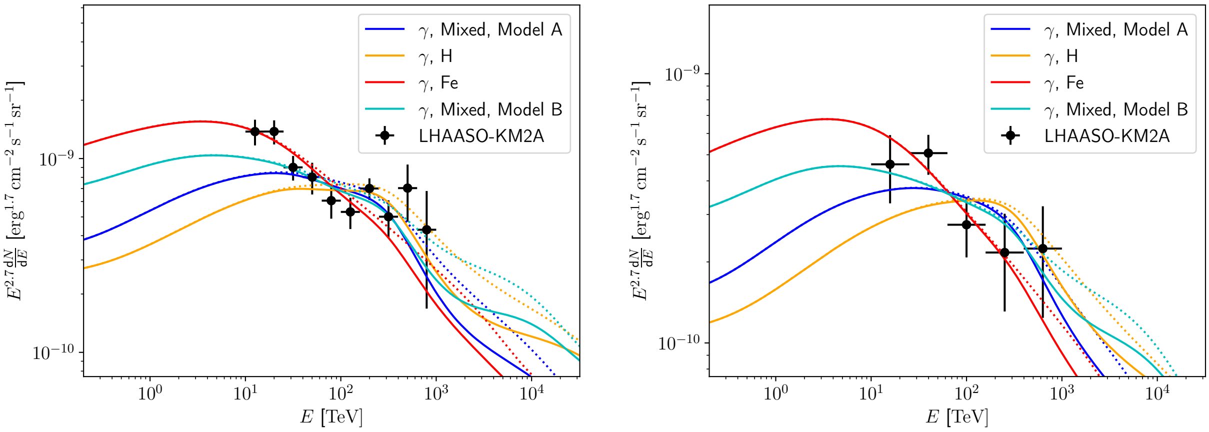

Fig. 1. LHAASO data (Cao et al. 2023) of the inner ($|b| < 5°$,$15° < l < 125°$, left panel), and the outer Galactic region ($|b| < 5°$, $125° < l < 235°$, right panel). The solid lines are the mixed composition Model A (blue), the pure hydrogen case (orange), the pure iron case (red), and the mixed composition Model B (cyan).

Si, and Fe. Until several hundreds of TeV, direct measurements of the CR composition from satellite or balloon missions exist, such as AMS02 (Aguilar et al. 2020), CREAM (Yoon et al. 2017) or NUCLEON (Grebenyuk et al. 2019). At higher energies, only all-particle data is available such as from IceCube/IceTop (Rawlins & IceCube Collaboration 2015), the Pierre-Auger observatory (The Pierre Auger Collaboration et al. 2015), or KASCADE-Grande (The KASCADE-Grande Collaboration et al. 2013; Schoo et al. 2015). We developed a CR model matching the direct CR measurements at energies below ∼1 PeV, and the all-particle data at higher energies (see Breuhaus et al. 2022, for more details). Because there are larger discrepancies in the individual direct CR measurements at the highest energies, we developed two different models: The so-called Model A follows the data from NUCLEON, and Model B follows the one from CREAM. Above several PeV, both of them converge again and match the all-particle data.

To test different compositions, we assumed the two most extreme but unrealistic cases that all CRs are H or Fe. Since the normalisation of the CRs throughout the entire Galaxy is subject to large uncertainties, we assumed that the overall CR density behaves as in Lipari & Vernetto (2018), Equ. 16, but allowed for an additional overall normalisation. The effect of the composition is such, that for heavier CRs the spectral break from the CR knee occurs at lower energies. Therefore, measuring the turnover in the γ-ray spectra is a way to measure the composition at the knee, assuming that the spectral index does not change throughout the Milky Way. For the data from Tibet ASγ, we found that the mixed Model A and the pure hydrogen CR case describe the data best. However, even taking into account data from ARGO-YBJ (Bartoli et al. 2015) between several hundreds of GeV up to few TeV does not yet allow to draw firm conclusions.

After the publication of the measurements of the diffuse emission by LHAASO (Cao et al. 2023), we also compared our models to this dataset. The LHAASO collaboration, like Tibet ASγ, consider two different regions: An inner Galactic region for Galactic latitudes of $|b| < 5°$ and longitudes $15° < l < 125°$, and an outer region with $|b| < 5°$ and $125° < l < 235°$. Unfortunately a joint fit with Tibet ASγ and ARGO-YBJ is not possible because of the different regions considered. Figure 1 shows the LHAASO data of the inner region (left panel) and the outer region (right panel) together with the mixed composition Model A (blue), the pure hydrogen case (orange), the pure iron case (red), and the mixed composition Model B (cyan). For each model, as in Breuhaus et al. (2022), we allowed the overall normalisation to vary and fitted it to the LHAASO data to compare the different shapes. As can be seen, none of the models can match all data points well. Model A and the pure hydrogen case, which matched the Tibet ASγ data best, are not able to account for the two lowest energy points of LHAASO. This is in line with the results from Zhang et al. (2023), who introduced an additional component of unresolved sources to account for the excess. One also should note, that the diffuse fluxes measured by LHAASO are significantly lower than the results from Tibet ASγ (a factor of ∼0.4 for Model A), although their inner Galactic regions overlap for large parts. This might be explained by unresolved sources, which are expected to have a very significant impact at these energies (Vecchiotti et al. 2022), and the different source masking. It seems that currently, lighter CR models are preferred over a heavier composition at the knee, but the data does not yet allow more accurate comparisons.

4 Conclusions

We have shown, that the CR composition can have an important influence on the resulting γ-ray and neutrino emission. A different ISM composition will change the normalisation. For heavier CRs, the resulting emission will be reduced due to shielding and other normalisation effects depending on the spectral index, and spectral breaks or cutoffs will occur at lower energies compared to pure hydrogen CRs. This is especially important for the diffuse Galactic emission in the knee region because depending on the CR composition, the knee break will occur at different energies in the γ-ray spectra. Therefore, γ-ray measurements are a way to measure the CR composition throughout the Milky Way, although spectral changes in the CR shape can have the same observational effects. With current measurements, it is not yet possible to draw conclusions about the composition, but with more data from the LHAASO and HAWC observatories and the future CTA telescope, this task will be achievable.

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