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Photodisintegration of cosmic ray nuclei in galaxies and galaxy cluster radiation fields

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We present the results of a new calculation for the photodisintegration of ultra-high energy cosmic ray nuclei on soft photon targets. We include all the relevant photodisintegraton processes i.e giant dipole resonance, quasi-deuteron, baryonic resonances and photofragmentation. In particular, for the giant dipole process we use a recent calculation of the giant dipole cross section. We calculate the mean free path for photodisintegration processes for radiation fields that are likely to exist within galaxies and clusters of galaxies.

1. Introduction

Galaxies produce diffuse radiation fields by direct stellar emission, as well as re-processing of starlight where there is sufficient dust. Furthermore, within galaxy clusters, dust associated with gas stripped from galaxies during infall to a cluster core, or dust ejected into the intracluster medium by intracluster stars, can result in diffuse emission. Therefore, in the vicinity of galaxies, and within the intracluster medium, there may be additional radiation fields that could increase the total diffuse radiation field over the best current model for the infra-red (IR) background in the extragalactic medium (EGM) given by Malkan & Stecker (1998) (MS1998).

The photodisintegration rate of UHE cosmic-ray nuclei depends on the mass number of the nucleus, A, and the soft target photon background. Photonuclear disintegration cross-sections scale with A, making heavier nuclei more subject to disintegration processes. Further, changes in the assumed photon background over the EGM background will alter the photodisintegration mean free path (MFP). Specifically, an enhancement of the target background, without altering the spectral shape, would correspondingly lower the MFP. If the spectral shape of any additional target background differs from EGM background, the importance of the various photonuclear processes (giant dipole resonance, quasi-deuteron, baryonic resonances, and photo-fragmentation; see later) may be altered.

To investigate whether these likely additional diffuse photon backgrounds can be of importance in UHE cosmic-ray propagation, we use a new calculation of photodisintegration of UHE cosmic ray nuclei on soft photon targets. Together with models for the radiation fields of galaxies and dust within clusters, we calculate the MFP for photodisintegration in the vicinity of galaxies, and the intracluster medium, and discuss the possibility of enhancements to the photodisintegration rate of UHE nuclei resulting from these.

2. Interactions of Cosmic Ray Nuclei

Nuclei are subject to photo-erosion, i.e., they lose nucleons through photonuclear interactions mainly with the cosmic microwave (CMBR), IR, and optical backgrounds. This involves the following processes: i) giant dipole resonance (GDR), with a loss of one or more nucleons, as well as α-particles (this process occurs with photons above a threshold of ~ 8 MeV in the nucleus rest frame (NFR)), ii) the quasi-deuteron (QD) process, where a virtual pion interacts with a nucleon pair within the nucleus, leading to the ejection of the pair and possibly additional protons or neutrons (this occurs with photons of typically $20 - 30$ MeV in the NFR), iii) baryonic resonances (BR), where a real pion is produced, ejecting a nucleon and possibly interacting further with a nucleon pair, eventually leading to the loss, on average, of six nucleons for an iron nucleus (this occurs for photons above ~ 150 MeV in the NFR), and iv) the photo-fragmentation (Frag), occurring at very high energy (photons with energies ~ 1 GeV in the NFR) and breaking the nucleus into many fragments of much lower mass and energy.

For the treatment of the GDR cross sections we apply the revised scheme of photonuclear interactions described by Kahn et al. (2005), whereas for the higher energy processes we use the phenomenological parameterisation obtained by Rachen (1996) (see also Allard 2004).

3. Diffuse Photon Fields

Galaxy clusters typically contain a mixture of galaxy types : ellipticals, spirals, and irregulars. Additionally, dust stripped from galaxies during infall, or ejected from intergalactic stars in the cluster, may be present in the intracluster medium (Popescu et al. 2000). All of these may emit diffuse radiation, and we describe the model spectra we use to represent these different sources of radiation.

For the radiation field in spiral galaxies, we use the results of Porter & Strong (2005). Their code allows the radiation field to be calculated at all points within a specified volume in and surrounding a galaxy. By specifying a distribution of stars and dust, the radiation field can be efficiently calculated from the optical to IR. Absorption and scattering by the assumed dust model is taken into account, and a heating code calculates the IR emission by grains undergoing transient and equilibrium heating in the interstellar medium. We use the stellar and dust models they assume for the Milky Way, and a cylindrical geometry (with symmetry about the galactic plane and in azimuth). We calculate the radiation field for two representative positions : the galactic centre (GC), and for a distance 50 kpc from the GC. The spectrum we obtain for the Milky Way is similar to the spectra Popescu & Tuffs (2002) obtain for late-type spirals in the Virgo cluster.

We use the results of Mazzei et al. (1994) for our model of the radiation field in elliptical galaxies. Their model includes a stellar distribution obtained from an evolution code, and dust emission by two dust components : warm dust heated in regions of high radiation intensity (e.g. OB clusters), and cold dust heated by the general interstellar radiation field. We adopt their results for the most evolved model they consider ($T = 15$ GYr, their Fig. 4; see also their Table 1). We take the spectrum from their model to represent the radiation field at a distance ~ 10 kpc from the elliptical GC. We obtain spectra for the GC and a distance 50 kpc from the GC by multiplying by factors 100 (GC), and $1/25$ (50 kpc) respectively. Naturally, the size range for ellipticals is quite large, and we would not expect this model to be a completely realistic representation across the full size range, but it should be sufficient for our current purposes.

For the intracluster dust spectra, we use the results of Popescu et al. (2000). In Fig. 1a we show the spectral density of our assumed radiation fields for spirals, ellipticals, and dust in the intracluster medium. Also shown is the MS1998 EGM background. We can see immediately that the emission by intracluster dust is far too low to be significant. However, the intensity of the radiation fields for spiral and elliptical galaxies is considerable at the GC, and still comparable with the EGM background at ~ 50 kpc from the GC regions.

4. Photodisintegration Mean Free Paths

Figure 1b shows our calculated MFP in the GC IR background for the spiral galaxy model, for the different photodisintegration processes. We can see that the GDR and BR processes give the main contribution to the

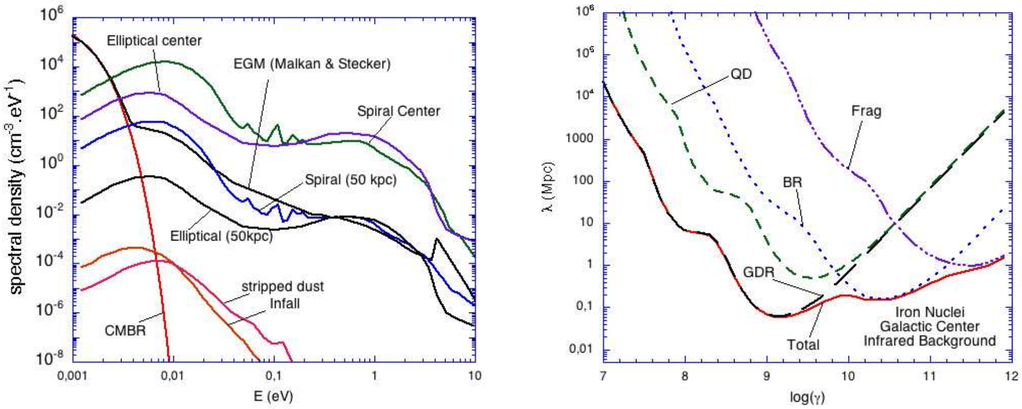

Figure 1. Left (a): Spectral density as a function of the energy for the backgrounds we consider (see text). Right (b): Contribution of the different photonuclear processes to the total MFP as a function of the Lorentz factor of an iron nucleus for the infrared background at the centre of our spiral galaxy model.

total MFP for Lorentz factors up to $\sim 4 \times 10^{11}$. Above this, fragmentation becomes the leading contributor to the MFP. From the figure, the effect of the different energy thresholds for the various photodisintegration processes can clearly be seen. The total MFPs therefore exhibit a complex shape, with several features due to the contributions of the different processes. This is true whatever background spectrum is considered.

The background radiation in our galaxy models is the sum of the contributions by the CMBR, IR, and optical backgrounds. In Fig. 2a we display the contribution of these backgrounds (considering all the processes mentioned above) to the total MFP in the spiral galaxy model GC. We clearly see that the different radiation fields have a successively dominant contribution according to their spectral density peak energy range. In the case of the GC spectrum, the MFPs are extremely small in the whole Lorentz factor range.

The magnitude of the radiation field for either of our galaxy models will diminish with distance from their respective GCs. At some point, the intensity will become similar to that of the EGM background. From Fig. 1a, this is ~ 50 kpc for both models. Correspondingly, we would expect the MFPs calculated for either galaxy model to rise with increasing distance from the centre region. In Fig. 2b we show the MFPs calculated for our galaxy models for the GC region and 50 kpc from the GC, along with the EGM background MFP. The MFPs are significantly increased at 50 kpc when compared to those calculated for the GCs.

5. Discussion

We have shown that the radiation fields within, and in the vicinity of, galaxies can cause a decrease in the MFPs for photodisintegration processes. The intracluster dust, on the other hand, provides virtually no modification to the photodisintegration MFPs.

At the centres of galaxies, the radiation field is significantly larger than the EGM background and, therefore, the photodisintegration MFP is very small. However, even if the magnetic fields are greatly enhanced in the centre of galaxies, UHE particles cannot remain confined for a sufficiently long time to be significantly affected by photodisintegration processes. This remains true even if a whole galaxy comparable to our spiral model is considered where the IR background is quite high in the disc, especially in the spiral arms.

However, when we consider the region in which the MFP is lower than that for just the pure EGM background,

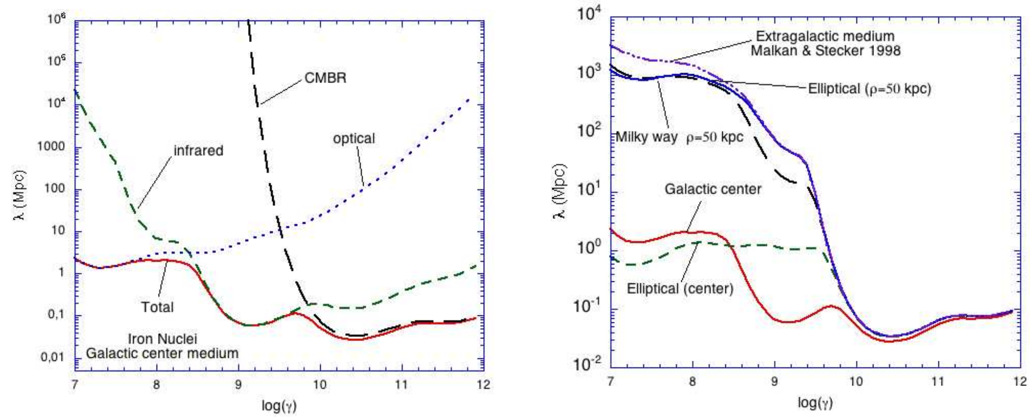

Figure 2. Left: Contribution of the different backgrounds at the Galactic center to the total MFP as a function of the Lorentz factor of an iron nucleus. Right: Comparison of the MFPs in different media (the contribution of the CMBR and the extragalactic radiation field is added for the MFPs of spirals and ellipticals).

the situation is more interesting. Figure 2a shows a region ~ 50 kpc in radius has a MFP that is lower than the pure EGM background. Generally, the size of this region will depend on the luminosity of the galaxy, its dust content, and its size. This seems to indicate that the interaction rate should be higher in the intracluster medium than in the EGM.

Having shown that the extended radiation fields of galaxies can alter the photodisintegration rate above the usual EGM rate, we intend to study this further. We will perform a study, carefully incorporating cluster structure, intracluster galaxy distances, and galaxy properties. This forthcoming study will be of particular interest for UHE cosmic-ray propagation, since the presence of high radiation fields, combined with the high magnetic fields expected in the intracluster medium, could prevent the UHE nuclei from escaping without significant interactions and energy losses, and could also lead to a significant neutrino emission sub-product of the neutron emission from photodisintegration.

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