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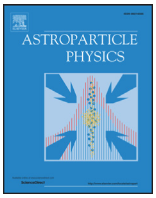

On the non-thermal electron-to-proton ratio at cosmic ray acceleration sites

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ABSTRACT

The luminosity ratio of electrons to protons as it is produced in stochastic acceleration processes in cosmic ray sources is an important quantity relevant for several aspects of the modeling of the sources themselves. It is usually assumed to be around 1: 100 in the case of Galactic sources, while a value of 1: 10 is typically assumed when describing extragalactic sources. It is supported by observations that the *average* ratios should be close to these values. At this point, however, there is no possibility to investigate how each individual source behaves. When looking at the physics aspects, a 1: 100 ratio is well supported in theory when making the following assumptions: (1) the total number of electrons and protons that is accelerated are the same; (2) the spectral index of both populations after acceleration is $\alpha_e = \alpha_p \approx 2.2$. In this paper, we reinvestigate these assumptions. In particular, assumption (2) is not supported by observational data of the sources and PIC simulation yield different spectral indices as well. We present the detailed calculation of the electron-to-proton ratio, dropping the assumption of equal spectral indices. We distinguish between the ratio of luminosities and the ratio of the differential spectral behavior, which becomes necessary for cases where the spectral indices of the two particle populations are not the same. We discuss the possible range of values when allowing for different spectral indices concerning the spectral behavior of electrons and protons. Additionally, it is shown that the minimum energy of the accelerated population can have a large influence on the results. We find, in the case of the classical minimum energy of $T_{0,\mathrm{e}} = T_{0,\mathrm{p}} = 10$ keV, that when allowing for a difference in the spectral indices of up to 0.1 with absolute spectral indices varying between $2.0 < \alpha < 2.3$, the luminosity ratio varies between $0.008 < K_{\mathrm{ep}} < 0.12$. The differential particle number ratio is in the range $0.008 < \widetilde{K}_{\mathrm{ep}} < 0.25$ and depends on the energy.

1. Introduction

For the last couple of years, the search for the origin of cosmic rays, from GeV-energies up to super-EeV events has started to make rapid progress. First Supernova remnants have been identified as hadronic sources [1–3] and first evidence for an astrophysical high-energy neutrino signal has been announced recently [4]. The results from gamma-rays and neutrinos are extremely important first steps in order to have a full identification of the sources for the entire diffuse cosmic ray flux. The theoretical interpretation of the signatures crucially rely on the precise modeling of the sources. This concerns both the prediction of the signal of gamma-ray and neutrino sources, as well as the interpretation of the spectral energy distribution of sources with dominant non-thermal signatures.

One central ingredient for these calculations is the ratio between cosmic ray electrons and protons. The ratio is typically assumed to be fixed to a one hundred times higher proton than electron luminosity for galactic sources (see e.g. [5]). When discussing the sources of ultra high energy cosmic rays, which can accelerate particles up to 10^{21} eV, see e.g. [6,7], it is assumed that the electron luminosity is somewhat higher than for galactic sources, i.e. electron to proton luminosity is 1:10. These values, that are on average supported by astrophysical observations, can also be derived following a theoretical argument also described in e.g. [8]:

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Stochastic acceleration predicts a power-law behavior in momentum,

$$\frac{dN_i}{dp_i} \propto p_i^{-\alpha_i} \tag{1}$$

with $i = e,\ p$ (electrons or protons). It is now assumed that the same total number of electrons and protons are accelerated, $N_p = N_e$ with $N_i = \int dN_i/dT_i\, dT_i$. Here, $T_i = \sqrt{m_i^2 \times c^4 + p_i^2 \times c^2} - m_i \times c^2$ is the kinetic energy of the particles with a minimum kinetic energy of $T_0 = 10$ keV. Assuming further that the two populations have the same spectral index $\alpha_e = \alpha_p =: \alpha$, the expected ratio scales with the masses of the two species:

$$\frac{dN_e/dp_e}{dN_p/dp_p} = \left(\frac{m_e + \frac{T_0}{2\times c^2}}{m_p + \frac{T_0}{2\times c^2}}\right)^{(\alpha-1)/2} \approx \left(\frac{m_e}{m_p}\right)^{(\alpha-1)/2} \tag{2}$$

The last step requires $T_0 \ll m_e \times c^2, m_p \times c^2$. This makes the approximation in Eq. (2) independent of the minimum energy. In contrast to that the exact solution depends strongly on the minimum energy and a possible difference in the minimum energies for protons and electrons as we will show later. With a spectral index of $\alpha \approx 2.2$, which is an approximate value to be expected from diffusive shock acceleration (see e.g. [8] for a summary), one finds a ratio of the order of

$$\widetilde{K}_{\mathrm{ep}} := \frac{dN_e/dp_e}{dN_p/dp_p} \approx \frac{1}{100}\,. \tag{3}$$

Note that for equal spectral indices, $\alpha_e = \alpha_p = \alpha$, the value remains the same for each value of $p_e = p_p$ and it is independent of momentum and thus of energy. Once the indices differ from each other even slightly, this is not the case. As a physical measure, two approaches can be pursued: either, in order to be independent of the energy scale, the total luminosities of electrons and protons can be compared:

$$K_{\mathrm{ep}} := L_e/L_p \tag{4}$$

with

$$L_i = \int_{T_{0,i}}^{T_{\max,i}} dT_i\, \frac{dN_i}{dT_i} \times T_i\,. \tag{5}$$

Alternatively, the differential number ratio as defined in Eq. (3) can be used. Here, it needs to be reviewed carefully for each case at what energies the two particle populations are observed.

Considering the observation of electrons and hadrons that presumably originate in our own Galaxy, i.e. cosmic rays from below the knee and directly observed electrons, the ratio for the total luminosities of the two particle populations comes very close to 1: 100. For extragalactic sources, however, the comparison between the central source candidates (Active Galactic Nuclei (AGN) and Gamma-ray bursts (GRBs)) rather suggest a ratio of 1: 10 [6]. These back-of-the envelope calculations have their pitfalls as well, of course, as they rely on the comparison of the spectra after transport, including all loss processes. When an integral over source regions in which losses are differentially important the effective spectral index for the electrons can be steeper by a factor of 1 compared to protons from the same region [9]. In particular when concerning the electron spectra, that means that a fraction of the total number of particles is actually lost as they enter a non-relativistic regime and the numbers are not easily comparable with the calculation presented above. Even without these difficulties, the electron-to-proton fraction that is observed strongly depends on the choice of the lower integration limit. As the propagated electron and proton spectra naturally have very different spectral behavior, the luminosities are compared rather than the differential values. This adds a further uncertainty in the calculation. These considerations emphasize that also from the observational point of view, the number ratios of 1: 100 or 1: 10 for extragalactic sources needs to be treated with care. One prominent example is the choice of lower integration limit for the luminosity of ultra high energy cosmic rays. In order to obtain the ratio 1: 10, it is assumed that the lower threshold is at the ankle, i.e. at $E_{\min} = 10^{18.5}$ eV. It can, however, be possible that there is a significant part of the UHECR source flux even below the ankle, as also discussed by Ahlers et al. [10], which would enhance the typically assumed ratio. If we assume $E_{\min} = 10^{17.3}$ eV as the beginning of the extragalactic part of the spectrum as the KASCADE Grande data [11,12] suggests the ratio would decrease to 1: 25. This is discussed in more detail in Section 4.3.

From the theoretical point of view, first results from PIC simulations show that the acceleration of protons and electrons in shock fronts yields differences in the spectral behavior [13]. If the acceleration itself does not only depend on the charge but also on the Larmor radius of the particles such differences are expected. Radio observations of SNRs can also be used to show that the electron and proton spectra at the source differ significantly from each other [14]. However, this concerns the loss-dominated electrons and it is not trivial to compare these values to the spectra immediately after acceleration, which is needed as an input for our calculations (see also [15]).

Given the arguments from above, we revisit the theoretical calculation of the electron-to-proton ratio in more general terms as was done before in order to examine the possible range for individual source classes. The assumptions we use are the following:

1. We assume a power-law behavior in momentum for both species,

   $$\frac{dN_i}{dp_i} = A_i \times p^{-\alpha_i}\,. \tag{6}$$

   This type of spectral behavior is expected from diffusive shock acceleration processes and is in agreement with the observed spectrum of leptonic and hadronic cosmic rays, see e.g. [16] for a review.
2. We drop the assumption of equal spectral indices ($\alpha_e \neq \alpha_p$), as the acceleration process itself may depend on the particle masses as suggested in PIC simulations (see e.g. [17]). This implies that the ratio of electrons to protons becomes energy dependent when considering it in dN_i/dp_i: $\widetilde{K}_{\mathrm{ep}} = \widetilde{K}_{\mathrm{ep}}(E_{\mathrm{p}},\ E_{\mathrm{e}})$. We therefore also calculate the ratio of total luminosities K_{ep} as a true observational measure for the electron-to-proton ratio given in Eq. (4).
3. We assume that the total number of particles accelerated in a source is the same for electrons and protons:

   $$N_p = N_e\,. \tag{7}$$

   This assumption is supported by the following argument: The overall particle number, accelerated and non-accelerated, is the same for protons and electrons due to charge balance $N_{\mathrm{tot},p} = N_{\mathrm{tot},e}$. If we assume the particles to be in a thermal equilibrium in the absence acceleration, the number of particles N_i above a certain energy threshold T_0 is the same for protons and electrons. A plasma in a thermal equilibrium is described by a Maxwellian distribution with equal temperature for protons and electrons, which leads to:

   $$N_i = N_{tot,i} \times \int_{T_0}^{\infty} 2\sqrt{E/\pi}\,(k_bT)^{3/2} \exp\left(-\frac{E}{k_bT}\right) \mathrm{d}E\,. \tag{8}$$

   Therefore, the number of particles above threshold energy T_0 is independent of the particle mass.
4. We use a general lower kinematic energy threshold which is not necessarily the same for protons and electrons, $T_{0,\,e} \neq T_{0,\,p}$. The value of this lower kinematic threshold depends on the