Chapter 7

Conclusions and outlook

The propagation of cosmic rays and their interaction with the surrounding medium is the subject of this thesis. Two different topics are addressed here: how do extragalactic ultra-high energy cosmic rays interact collisionlessly with the intergalactic medium and how do Galactic cosmic rays interact with the interstellar medium via collisions?

Regarding the interaction of cosmic rays with the intergalactic medium binary collisions are negligible, since the intergalactic medium is a very dilute plasma. Therefore, electromagnetic interactions dominantly contribute to the relaxation of cosmic rays and influence their propagation. Especially electrostatic and electromagnetic instabilities, which can be generated by an anisotropic distribution function and which describe the amplification of electrostatic and electromagnetic fields, can lead to a significant energy loss and a redistribution of the cosmic rays.

For the theoretical modeling of a plasma a crucial question is, whether it is magnetized or not. The magnetization of the intergalactic medium has recently been intensely discussed in the astrophysical community, since Nerenov and Vovk predicted a large-scale intergalactic magnetic field on the basis of the nondetection of GeV-photons in the blazar spectrum in 2010. In contrast to this prediction Broderick et al. and Schlickeiser et al. showed in 2012 that reactive electrostatic instabilities, which are driven by a monoenergetic distribution function without a perpendicular spread with respect to the wavevector, are of the order of 10^{-6} Hz. This leads to an energy loss of the pair beams even in the nonlinear regime and thus to a reduction of the estimated GeV flux. Miniati and Elyiv claimed in 2013 that a small, but finite, perpendicular spread significantly damp all instabilities and, therefore, cannot explain the nondetection of GeV-photons. Contrary to the claims of Miniati and Elyiv we completely analytically showed that even if the electron-positron pairs have a perpendicular spread with respect to the wavevector direction and are not monoenergetically distributed, electrostatic instabilities are nevertheless of great significance and even lead to an order of magnitude greater maximum growth rate and therefore to an energy loss of the pair beams (Chapter 4). We concluded that no large-scale magnetic fields are necessary to explain the nondetection and that the predicted strength of the IGM magnetic field by Neronov and Vovk (2010) has at least to be modified.

With the result that the IGM can be unmagnetized we focused on the collisionless interaction of ultrahigh-energy cosmic rays with the IGM (Chapter 5). In order to prevent a large-scale magnetic field, which would be induced by the charged current of the cosmic rays, we assumed a drift velocity for the protons of the intergalactic medium (in the rest-frame of IGM electrons), which is antiparallel to the propagation direction of the cosmic rays.

In the first paper in 2014 we calculated the reactive instabilities, both electrostatic and electromagnetic, which are induced by monoenergetic cosmic rays traversing the cold intergalactic medium. We showed that the maximum electrostatic growth rate, which is driven by the protons of the intergalactic medium, is very high and of the order of $\gamma_{IGM} \approx 1\,\mathrm{Hz}$. The cosmic ray induced electrostatic growth rate is orders of magnitude lower ($\gamma_{CR} \approx 6 \cdot 10^{-7}\,\mathrm{Hz}$). Since the linear relaxation time $\tau_{r,l} = 100\gamma^{-1}$ is much shorter than the propagation time ($t_F \approx 1.6 \cdot 10^7\,\mathrm{yr}$), both would significantly influence the distribution function of the IGM protons and cosmic rays, respectively. Strong nonlinear effects, namely the modulation instability, hamper the linear relaxation, lead to an increasing relaxation time, and therefore, stabilize the distribution functions.

The electromagnetic instabilities are orders of magnitude weaker than electrostatic ones. Since they are both aperiodic, it is not possible to determine the relaxation time and thus, to estimate whether they influence the propagation or not.

In the second paper on this topic in 2016 we used a different distribution function for the intergalactic medium and for the cosmic rays. The intergalactic medium is modeled with a Maxwell distribution and the cosmic rays are assumed to be Lorentzian distribution (Schlickeiser 2015b). We investigated the parallel electrostatic instabilities, for which the wavevector and the propagation direction are parallel. In this case the distribution functions are much more stable and the growth rates decrease several orders of magnitude. The relaxation time becomes much longer than the propagation time and, thus, the electrostatic interactions do not influence the propagation.

Our focus for upcoming investigations on this topic lies on the analysis of kinetic instabilities of electrostatic and electromagnetic waves with an arbitrary orientation of the cosmic ray beam with respect to the wavevector. This could lead to an amplification of the instabilities. Especially for perpendicular orientation we expect an electromagnetic instability, namely the so called Weibel instability, which could potentially isotropize the ultrahigh-energy cosmic rays and explain their very low anisotropy. Another aspect, which needs to be further investigated, is the density of the ultrahigh-energy cosmic rays. Since the instabilities are dependent on the density ratio of the cosmic rays and the background, an increase of the cosmic ray density would result in stronger instabilities. Such an increase can easily occur in the closer vicinity of a cosmic ray source. Another topic, which will be investigated in detail, is the relaxation of an aperiodic electromagnetic instability. This is important to decide, whether the electromagnetic instabilities can influence the propagation of the ultrahigh energy cosmic rays and could potentially isotropize their distribution function.

In the second part of this thesis we investigated the interaction of Galactic cosmic rays with the interstellar medium (Chapter 6). We focused on the continuous energy loss of cosmic rays and calculated an energy loss rate due to pion production in proton-proton interactions. The calculation is based on the parameterized energy spectrum of pions of Kelner et al. (2006), which is based upon the cosmic ray particle shower simulation softwares SIBYLL and QGSJET. The newly calculated energy loss rate of cosmic rays due to pion production is valid in a very broad energy range of $1\,\mathrm{GeV} \ll E_{CR} \leq 10^8\,\mathrm{GeV}$, where the energy loss due to pion production is the dominant energy loss in the interstellar medium for cosmic ray protons, and has a break around 200 GeV, which also leads to a break in the cosmic ray energy spectrum. This break was measured by different experiments. The calculation of the cosmic ray proton spectrum taking this energy loss rate into account is the topic of the second part of that Chapter. To model the cosmic ray energy spectrum we used a spatially one-dimensional, steady-state diffusion transport equation and we could show that the measured break can be reproduced almost perfectly without any additional assumptions.

Since the break is also detected in the spectrum of cosmic ray metals like helium, a generalization of the energy loss rate to arbitrary mass and charge numbers is important. This derivation and the calculation of the energy spectrum of cosmic ray metals will be one of our future topics.