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A Modern Approach to Cosmic Ray Transport in the Galaxy

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Abstract. The transport of cosmic rays inside their sources and through the Galaxy, around sources and during their journey through intergalactic space, may be heavily affected by non-linear effects, namely by 1) bulk motions induced by cosmic ray pressure gradients and 2) generation of magnetic perturbations that in turn modify the transport of charged particles. The combination of these effects gives rise to numerous non linear phenomena that are now becoming accessible to observations. This work summarises some recent results in this field of investigation and the implications for current and future observations.

Key words. Astrophysics – High Energy Astrophysical Phenomena – ISM: cosmic rays; magnetic fields – MHD – Physical processes: particle acceleration; Radiation processes: non-therm

1. Introduction

The micro-physical description of the transport of cosmic rays (CRs) plays a central role in the investigation of the origin of these energetic particles. The interaction of charged particles with magnetic perturbations in the plasma shapes the diffusive motion of CRs that in turn is at the basis of particle acceleration at shock fronts and propagation from sources to observers on Galactic scales. Non thermal particles react to the presence of these perturbations and to the motion of the background plasma in which they propagate, but they also create such perturbations and plasma motion in a network of non-linear phenomena that are crucial for a physical description of CR transport (and acceleration).

With the high precision measurements of particle spectra and gamma ray spectra that recently became available, understanding these fundamental aspects of particle transport becomes not only possible, but also a necessary step.

The present article is a short summary of recent work in the direction of investigating the non linear transport of CRs in a variety of situations that range from their role in particle acceleration at the shocks of supernova remnants, to the transport around the sources after escape, to transport on Galactic scales and finally the escape of CRs from the Galaxy.

The article is structured as follows: in section 2 we discuss some implications of the excitation of streaming instability in the proximity of non-relativistic shocks and its implications for the spectra and maximum energy of the accelerated particles. In section 3 we discuss how the particles change the environment around a source after escaping the acceleration region, due to the strong gradient of CR particle density in such regions. In sectioin 4 we briefly summarize the implications of non-linear effects during CR transport through the Galaxy, especially in terms of the spectral shape of primary CR nuclei and secondary/primary ratios, measured by AMS-02 with high precision. In section 6 we discuss the non linear phenomena arising when CRs leave the Galaxy into the intergalactic medium. We conclude in section 7.

2. Acceleration

Non linear effects are very prominent in the proximity of a SNR shock wave, where particle acceleration is expected to occur. These effects are mainly of two types: first, the pressure gradient of CRs in the upstream region exerts a force on the inflowing plasma, thereby slowing it down, a phenomenon known as the shock precursor. Second, the same CR gradient, corresponding to an electric current, causes the excitation of a streaming instability that is responsible for magnetic perturbations to grow in amplitude, thereby enhancing the confinement of CRs in the shock region. A recent review of the non-linear aspects of particle acceleration at shocks was put forward by Blasi (2019a).

The former effect has been discussed by many authors Malkov & Drury (2001); Blasi (2002, 2004): the most important implication of the existence of the precursor is the fact that the compression factor experienced by the accelerated particles becomes momentum dependent, smaller for low energy particles and larger for high energy particles. This in turn causes the spectrum to depart from a power law and become concave. The strength of this effect depends on the efficiency of particle acceleration and on the amount of thermal and magnetic dissipation in the precursor. For typical parameters, it turns out that the deviations from a power law are relatively small, but important to explain some pieces of observations, especially in the radio and X-ray band Morlino & Caprioli (2012).

The latter effect, namely the self-generation of magnetic perturbations by CRs upstream of the shock is crucial to enhance the confinement time and eventually accelerate particles to high energies. This fact was recognized by Bell (1978); Lagage & Cesarsky (1983) in the context of the so-called resonant streaming instability. However its importance has been fully appreciated only more recently when Bell (2004) discovered a non-resonant branch of the instability that grows much faster. The levels of magnetization predicted on the basis of this branch seems in accord with those estimated from X-ray observations of the non thermal X-ray filaments in virtually all young SNRs Vink (2012). cd The implications of the amplified magnetic field for particle acceleration have been investigated carefully Bell et al. (2013); Cardillo et al. (2015) under some assumptions. In Cristofari et al. (2020) we have used the known growth rates of the non resonant streaming instability to infer the magnetic field and the maximum energy at the shock as a function of time during a SNR evolution, for different types of SN explosions. The flux of CRs produced by an individual SNR was calculated as the sum of two contributions: that of CRs escaping at any given time at the maximum energy at that time, and that of CRs advected downstream and subject to adiabatic losses, that will eventually escape the remnant when the shock dissipates into the interstellar medium (ISM). The Integration in time of these two contributions returns the total spectrum released by a SNR. Such spectrum depends rather strongly upon the environment in which the SN explosion takes place, which in turn depends on the type of SN explosion. This investigation led us to conclude that the only SNRs that can accelerate particles up to PeV energies are rare, very powerful type II SN events in which the shock velocity is very high. Moreover, the level of magnetization behind the shock, which shapes the spectrum of electrons accelerated in SNRs, is also provided by CR streaming instability. Cristofari et al. (2021) calculated these effects in the attempt to explain the observation that the spectrum of electrons and protons in individual SNRs need to be very different Evoli et al. (2020a, 2021)(the latter appreciably harder than the former). We concluded that even in the presence of effective magnetic field amplification, the spectrum of electrons, for energies $\lesssim$ 1 TeV, has the same slope as the spectrum of protons. This conclusion can only be changed if, contrary to expectations, the magnetic field is efficiently amplified also at very late stages of the SNR evolution. The issue of the different source spectra of electrons and protons in CRs remains open (but see also Morlino & Celli (2021)).

3. Escape from sources

The standard picture of the origin of cosmic rays assumes an implicit separation between the phase of acceleration inside the sources and that of transport in the Galaxy. In Nature there is no such separation: particles' escape from the sources is an integral part of the process of particle acceleration, and in fact the production of upstream magnetic perturbations responsible for particle acceleration to the highest energies is due to the current carried by escaping particles Bell (2004); Bell et al. (2013); Cristofari et al. (2020). At the same time, the escape occurs in an environment that is profoundly changed by the same particles trying to leave the source region. Because of this phenomenon, the diffusion properties around the source are quite different from those necessary to describe CR transport in the Galaxy Ptuskin et al. (2008); Nava et al. (2016); Malkov et al. (2013); D'Angelo et al. (2016); Nava et al. (2019).

The implications of the excitation of CR driven instabilities in the region around the sources were recently reviewed by Blasi (2019b): CRs escaping a generic source, even in the absence of additional phenomena, form a halo of enhanced CR density that is present on a spatial extent and for a time duration that both depend upon the rate of injection of particles by the source itself. In a situation in which the coherence scale L_c of the pre-existing magnetic field is larger than the size of the source, one can treat the escape of particles as quasi-one-dimensional, in the sense that the Larmor radius is $\ll L_c$ and the particles stream away from the source mainly along the local magnetic field direction. However, it can be easily shown that this streaming is likely super-Alfvénic, so that a streaming instability is excited and the particles start scattering off their self-produced Alfvén waves (Ptuskin et al., 2008; Nava et al., 2016; Malkov et al., 2013; D'Angelo et al., 2016; Nava et al., 2019), to an extent that is mainly regulated by the amount of damping of these waves, which in turn depends on whether the medium is partially (ion-neutral damping) or fully ionized (non linear Landau damping). A general prediction of these models is that, for several thousands of years after the SN goes off, the diffusion of CRs around the source is dominated by scattering off self-generated turbulence, which leads to a suppression of the diffusion coefficient compared with the one experienced by CRs on Galactic scales. This phenomenon has always been considered as restricted to the magnetic flux tube with length $\sim L_c$ and cross section comparable with the source size.

Very recently, extended regions of roughly spherical shape where a strong reduction of the diffusion coefficient was inferred were detected around several pulsar wind nebulae (the so-called TeV halos (Sudoh et al., 2019)) and, perhaps, star clusters (Aharonian et al., 2019). It is not clear whether these halos are actually related to the non-linear effects discussed above, but it is certainly one of the most credible possibilities (López-Coto et al., Nature Astronomy, in press).

Some recent developments might play an important role in building a complete theory of the formation of extended regions of suppressed diffusivity around the sources: Schroer et al. (2021) reconsidered the motion of particles with energies $\gtrsim$ 1 TeV around a Galactic source and concluded that simply based on the expected correlation length of the Galactic magnetic field, their motion should be quasi-ballistic, in which case the current they carry is in excess of the minimum current required for the onset of non-resonant modes, already discussed with reference to particle acceleration (Bell, 2004; Amato & Blasi, 2009). This instability grows very fast, on scales of years, and leads to the formation of self-produced turbulence that suppresses the diffusion coefficient more effectively than the resonant streaming instability mentioned above. The region around the source is then filled with CRs that create an overpressurized bubble that in turn expands tending to reach pressure equilibrium with the outside ISM. This phenomenon was studied using particle-in-cell (PIC) hybrid simulations, that showed the formation of a large, roughly spherical, bubble with low diffusion, high level of turbulence, and low gas density. The investigation of the implications of these CR driven non linear phenomena around sources is only at its dawn, and we can expect many new developments in the times to come.

4. Transport in the Galaxy

Once CRs move away from their sources more than a few hundred parsec, their number density and the current they carry becomes too small to excite streaming instabilities, but new gradients arise, on much larger spatial scales, due to the fact that CRs diffuse (and are advected) away from the disc of the Galaxy. At this point we see collective effects of many sources rather than the contribution of an individual source.

For standard diffusion models in the Galaxy, the gradient on Galactic scales is of the order of $\sim n_{CR,disc}/H$, where H is the size of the magnetized galactic halo. When CRs reach the boundary of such halo they are expected to escape so as to maintain a situation of global equilibrium (stationarity) in the Galaxy. In other words, the flux of particles injected at the sources must equal that of escaping CRs. This is true as long as the particles do not lose appreciable energy during propagation, hence it does not apply to electrons and positrons and to heavy nuclei, which are fragmented in spallation reactions.

In the late 60's and early 70's it was realized Kulsrud & Pearce (1969); Holmes (1975) that the CR gradient would be sufficient to excite a resonant streaming instability, so as to guarantee CR confinement in the Galaxy, but only for particles with energies below a few hundred GeV.

Because of this limitation, most of the following investigations of CR transport in the Galaxy were based on a phenomenological approach, that ignored the origin of the scattering, and rather parametrized the propagation by assuming a diffusion coefficient and an advection velocity. These two quantities (and in fact many others) were fitted to the observations. While this approach has been precious to infer general trends, it cannot not provide, by itself, the needed physical understanding.

The recent AMS-02 measurement of the spectra of individual CR elements Aguilar et al. (2015a,b, 2017, 2018) revealed that 1) virtually all of such spectra have a break at rigidity of $\sim$ 300 GV, and 2) that the break is also present and about twice as large in the spectra of secondary nuclei. The second point is best understood if the break is caused by a change in the diffusion coefficient experienced by particles during transport Genolini et al. (2017); Evoli et al. (2019, 2020b). The phenomenological approaches to CR transport parametrized this phenomenon by postulating breaks in the diffusion coefficient, while leaving a physical interpretation of these breaks aside.

Soon after the discovery of the spectral breaks, some of us put forward the possibility that we were just observing the transition from a diffusion coefficient due to scattering off self-generated waves to scattering off pre-existing turbulence Blasi et al. (2012); Aloisio & Blasi (2013); Aloisio et al. (2015). The agreement of this theoretical framework with data is remarkable. In fact, the model was even generalized to produce a magnetized halo around the disc of our Galaxy Evoli et al. (2018), an effort that is still ongoing.

For additional information about the non linear aspects of CR transport in the Galaxy we refer the reader to (Blasi, 2019b) and to the recent review article by Amato & Blasi (2018). In these articles one can also find a general description of another non linear phenomenon associated to CRs, and not discussed here, namely the launching of CR driven winds in those locations in the Galaxy where the force on the background plasma due to the CR pressure gradient overcomes the gravitational force, due to both baryons and dark matter.

5. Simulating the γ-ray emission from the Galaxy

One should realize that the problem of CR transport in the Galaxy is rather complex and the number of observables to describe is very large, especially if diffuse gamma ray and radio emissions are included. Neutral messengers are of prominent relevance in this framework since they allow one to probe the CR population, hence the CR transport properties, especially around sources (e.g. in dense star forming regions), where non linear effects are expected to be most important, or in regions of the Galaxy where the ISM and the magnetic fields could be different from those around the Solar System. The combination of increasingly more accurate data (as those of Fermi-LAT, HAWC, LHAASO and in the future of CTA for the gamma rays and SKA for the radio) and increasingly more realistic models will be crucial to reach a better understanding of CR origin and propagation.

In this perspective, an important effort was the development of the HERMES (High-Energy Radiative MESsengers) code (Dundovic et al., 2021a,b). This code is designed to use any CR distribution as predicted based upon either analytical or numerical models of CR propagation, and even possible components arising from dark matter annihilation or decay, and calculate the corresponding sky maps of non thermal radiation (in all the relevant frequency bands) and neutrinos.

The physical processes implemented in the code are Free-Free emission and Synchrotron emission (including self-absorption), gamma ray emission from pion production and decays, Inverse Compton scattering and Bremsstrahlung.

The full capabilities of HERMES have been discussed in detail by (Dundovic et al., 2021a,b), where we provided example sky maps and spectra computed using up-to-date input models from the literature, including the simulated spectra of the prompt and secondary diffuse gamma-ray emission due to the annihilation of a realistic DM particle physics candidate. A run configuration, including the ingredients to compute the map and the resolution parameters, is fully specified through a Python or C++ script file to be compiled linking HERMES as an external library.

The program source code is licensed under the GNU General Public License v3 and is publicly available together with installation instructions and examples at `https://github.com/cosmicrays/hermes`.

An illustration of the potential applications of HERMES is shown in Fig. 1, in the form of two simulated diffuse gamma ray emission sky-maps computed using up-to-date models of the relevant Galactic components at energy 10 GeV, as it corresponds to the energy with the best sensitivity for FERMI-Lat. The left panel shows the sky-map of the diffuse gamma ray emission due the π^0-decay, using the target gas distribution as a set of column density full-sky maps associated to different Galactocentric rings (for more details see Dundovic et al., 2021b). The distributions of CR nuclei was calculated as in Fornieri et al. (2020), so as to fit local observations. The gamma-ray production cross-section for pp collisions is based on the model developed in Kamae et al. (2006). The right panel of Fig. 1 shows the sky-map of the gamma ray emission due to ICS. For the ISRF we adopted the model of Vernetto & Lipari (2016), which includes three main components: the uniform cosmic microwave background (CMB), and the spatially dependent infrared (radiated by interstellar dust heated by stars) and stellar emissions. Fig. 1 illustrates the well known fact that the gamma ray emission is dominated by pion production in the inner Galaxy, and along the Galactic Plane, and by ICS at intermediate latitudes.

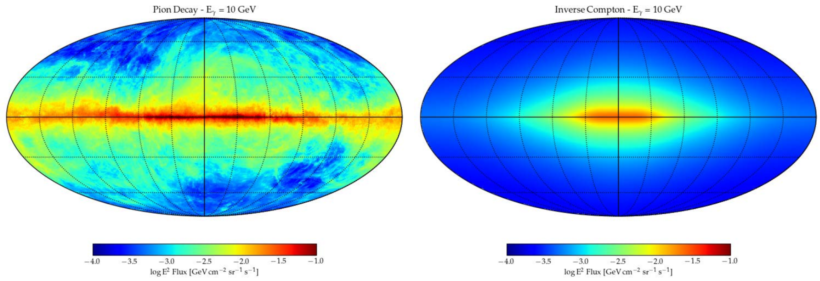

Fig. 1. Gamma-ray sky maps at $E_\gamma = 10$ GeV computed with `HERMES`. Left panel: the pion-decay γ-ray emission. Right panel: the Inverse Compton γ-ray emission.

In (De la Torre Luque et al., 2022), `HERMES` was exploited to simulate the γ-ray diffuse emission with energy up to the PeV from the Galactic plane and compared with the recent detection of a VHE large-scale emission by Tibet AS-γ and LHAASO collaborations.

6. Escape from the Galaxy

One of the fundamental processes that shape the spectrum of CRs observed at the Earth is the escape from the Galaxy. While the escape is mathematically modelled through a free escape boundary condition at the edge of the Galactic halo, the physical processes that determine such edge are all but clear. Evoli et al. (2018) described CR transport with only a boundary condition at infinity, while using self-generated turbulence and cascading of turbulence injected in the disc and advected away from the disc. They showed that a halo, namely a region where diffusion is qualitatively as observed, appears naturally on scales of order $\sim v_A \tau_{cas}$, where v_A is the Alfvén speed and τ_{cas} is the typical time scale for the non linear cascading of turbulence from large to small scales. A halo of several kpc is typically obtained in this way. Even this attempt is affected by several assumptions, for instance about the strength of the regular magnetic field in which turbulence develops.

If the magnetic field on large scales is due to the same process of gravitational collapse that gave rise to the Galaxy, one would expect that the field drops to virtually zero (or the intergalactic field strength) at some distance from the disc. What do we expect to happen when CRs reach that region?

The question was recently addressed by Blasi & Amato (2019): if the correlation length L_c of the intergalactic magnetic field is large enough compared with the size of the Galaxy, and if the Larmor radius of CRs is smaller than L_c, the particles are expected to stream quasi-ballistically along the magnetic field lines. In these conditions, the current carried by the CRs escaping the Galaxy is well known from flux conservation arguments. Blasi & Amato (2019) found that if the magnetic field in the intergalactic medium is lower than $\sim 10^{-8}$ Gauss, a non resonant streaming instability is excited (Bell, 2004) and the growth time scale is very fast. As a result, the streaming particles are slowed down and accumulate until their pressure impresses to the background plasma a bulk motion with speed of the order of the Alfvén speed in the amplified magnetic field, $v_A \sim 100$ km/s. The picture that arises is that if CRs are allowed to stream freely at some point outside the Galaxy, the magnetic perturbations are such that they bring the diffusion coefficient to very small values and the transport turns to being advection dominated, with speed $\sim v_A$. In the region where this phenomenon occurs, typically on scales of tens of kpc outside the Galaxy, the CR density becomes large and it makes sense to ask whether CR interactions may have any observable consequences. Blasi & Amato (2019) found that if the gas density is of order $\sim 200\Omega_b\rho_{cr}$ (where Ω_b and ρ_{cr} are the baryon fraction and the critical density of the universe respectively), as expected on average inside the virial radius of any virialized structure, the flux of high energy neutrinos produced in this region is at the same level and with similar spectrum as the one observed by IceCube.

Another implication of the picture discussed above is that there should be a region around the Galaxy, a few tens of kpc large, where the magnetic field should be of order $\sim 2 \times 10^{-8}$ Gauss. In fact, the implication is somewhat more profound: as also mentioned in some previous work (Blasi et al., 2015), similar magnetized halos should exist around any extragalactic CR source, to an extent that depends upon the CR luminosity of the source. In such extended regions, CRs can be confined for very long times, even cosmologically long times, thereby affecting the CR spectrum contributed by such sources to the flux at the Earth.

7. Conclusions

CRs affect the environment in which they propagate both because of their dynamical action (they exert a force on the background plasma, due to their pressure gradients) and because of the excitation of instabilities that lead to the growth of waves. In turn these waves change the scattering properties of non thermal particles. This simple scheme applies to a variety of situations of astrophysical interest that range from the acceleration of CRs at newtonian shocks to the escape of CRs from sources, from the transport in the Galaxy to the escape from a host galaxy, including our own.

Taking into account these effects requires the development of non linear theories of transport, which is technically, and sometimes conceptually, difficult. Because of these difficulties, the transport of CRs is often described using effective phenomenological models, which have the advantage of providing quick insights into the problem, but often inhibit a complete physical understanding of the underlying physics.

The results of our recent and ongoing research show that these non-linear effects, and more specifically the excitation of CR driven instabilities, are crucial if SNR shocks are the acceleration sites of CRs to very high energies. Even accounting for such phenomenon it seems that only rare and rather exceptional SN explosions may allow for particle energization to $\sim$ *PeV* energies Cristofari et al. (2020). Because of these difficulties we have also searched for alternative scenarios of particle acceleration, such as particle acceleration in regions of intense star formation (Bykov et al., 2020) and at the termination shock of stellar clusters collective winds (Morlino et al., 2021). The theory developed to describe this phenomenon is being also generalized to the similar problem of particle acceleration at the termination shock of the wind of starburst galaxies (Peretti et al., 2019, 2020).

The escape of CRs from the acceleration region plays a crucial role in the process of magnetic field amplification both at the shock and in the region around the sources. This latter aspect may be of great importance for the understanding of the so-called TeV halos that have recently been detected in TeV gamma rays from around selected sources, mainly PWNe but also some SNRs (see for instance Nava & Gabici (2013)). The main recent development in the investigation of non linear phenomena associated to CR escape from sources is the understanding that the current they carry may be sufficient to excite a non resonant instability that drastically slows down the diffusive motion of CRs, thereby creating an overpressurized CR dominated bubble, expanding out to several tens of pc Schroer et al. (2021). The implications of the formation of such bubble for gamma ray observations and for the grammage accumulated by CRs is currently ongoing.

The transport of CRs on Galactic scales is also affected by the action of CRs both in terms of production of waves on which CRs can scatter and in terms of force exerted on the background plasma due to the CR pressure gradient. As discussed in our previous work (see (Amato & Blasi, 2018) for a review), the transition from scattering off self-generated waves to scattering off pre-existing turbulence can explain the spectral breaks recently measured with high accuracy by AMS-02.

After escape from the Galaxy, a phenomenon that is usually modeled from a mathematical point of view by assuming free escape from the edge of the halo, particles are expected to propagate ballistically into the intergalactic medium.

This scenario was studied by Blasi & Amato (2019) who found very interesting implications: the current of the escaped particles was found to be sufficient to excite a non resonant streaming instability in the circumgalactic and lead to efficient self-generated scattering. As a result, CR transport becomes dominated by advection with waves, occurring at about the Alfvén speed in the self-produced field, $\sim$ 100 km/s. This makes the return of the particles backwards toward the Galaxy very unlikely, so that no major change is expected in terms of Galactic CR transport. Moreover, if the gas density in the circumgalactic medium is as expected, a few hundred times the baryonic critical density, the flux of neutrinos expected because of *pp* scattering in this extended region around the Galaxy is of the same order of magnitude as the flux observed by IceCube. PIC hybrid simulations of this phenomenon are now being carried out to confirm the findings of Blasi & Amato (2019).

Similar phenomena are expected in all CR sources in the universe: they should all be surrounded by regions with enhanced CR density and rather turbulent, self-generated magnetic fields. The strength of these effects depends on the CR luminosity of the sources, being more pronounced near bright sources.

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