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Towards models of Galactic cosmic-ray $e^{\pm}$

J. Lavalle⋆

Instituto de Física Teórica (UAM/CSIC) & Departamento de Física Teórica (UAM)
Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid — Spain
e-mail: `lavalle@in2p3.fr` ⋆ Multidark fellow

Abstract. We discuss potential ways of getting more accurate predictions of the local GeV-TeV cosmic-ray electron and positron fluxes at the Earth. We focus on the contribution from the known local sources, supernova remnants and pulsar wind nebulæ. This delineates a roadmap towards predictions at the Galactic scale.

Key words. Galaxy: cosmic-ray sources — Galaxy: cosmic-ray propagation

1. Introduction

In the last decade, an impressive amount of cosmic-ray (CR) data has been collected in the MeV-TeV energy range, providing us with fresh material to challenge our understanding of the CR sources and CR transport in the Galaxy. Notably, CR electrons and positrons ($e^{\pm}$) are now being measured with interesting statistics up to TeV energies, for instance by the experiments PAMELA (Adriani et al., 2009, 2011), ATIC (Chang et al., 2008), Fermi (Abdo et al., 2009), and HESS (Aharonian et al., 2009) — a clean datum of the positron-only flux is still missing, the most precise but indirect measurement at hand being that of the positron fraction for the moment. Although these data seem to be qualitatively well understood (*e.g.* Delahaye et al., 2010), there are still big theoretical and phenomenological efforts to make before reaching an accurate and consensual description of the full underlying physics. Indeed, while the theoretical building blocks of CR acceleration at sources and of CR transport have been settled down for quite a long time (*e.g.* Ginzburg & Syrovatskii, 1964; Drury, 1983; Berezinskii et al., 1990), it is now the link between them, *i.e.* how CRs escape from sources, which is now to represent the main missing piece of the puzzle (*e.g.* Drury, 2011; Blasi & Amato, 2010). As regards $e^{\pm}$, the old idea that pulsar wind nebulae (PWNe) may inject primary high energy positrons—more precisely $e^{\pm}$ pairs—in the interstellar medium (ISM) (*e.g.* Harding & Ramaty, 1987; Boulares, 1989; Aharonian et al., 1995; Chi et al., 1996) has been confirmed by the PAMELA observations. They add up to the primary electrons accelerated at supernova remnant (SNR) shocks. Moreover, the not less old idea that local sources likely induce features in the observed spectra due to the energy-loss-induced short propagation range of GeV-TeV $e^{\pm}$ (*e.g.* Shen, 1970) starts to be accounted for self-consistently in predictions (*e.g.* Kobayashi et al., 2004; Delahaye et al., 2010). What mostly remains to undertake to refine this global picture is to design a satisfying modeling of the escape of high en-

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ergy $e^{\pm}$ from known local sources, which have been shown to dominate the local budget despite the large theoretical uncertainties coming from the too loose description of these local sources (Delahaye et al., 2010). We shortly review the main ingredients involved in the predictions of the local GeV-TeV $e^{\pm}$ fluxes, and we then delineate a potentially efficient roadmap to achieve significant improvements in the modeling of local sources.

2. The local $e^{\pm}$ fluxes

A complete description of the CR $e^{\pm}$ transport will be found in Delahaye et al. (2010), and references therein, to which we refer the reader for more details. In the GeV-TeV energy range, the propagation of $e^{\pm}$ is mostly set by spatial diffusion (scattering off magnetic turbulences) and energy losses, the latter being characterized by synchrotron and inverse Compton processes involving all components of the interstellar radiation field. In the Thomson approximation (not valid for an accurate treatment, for which Klein-Nishina effects must be considered), the typical energy loss rate can be expressed as $b(E) \simeq b_0\,[E/1\,\mathrm{GeV}]^2$, with $b_0 \approx 10^{-16}\,\mathrm{GeV/s}$. This translates into a timescale of $\tau_l(E) = E/b(E) \approx 317\,\mathrm{Myr}\,[E/1\,\mathrm{GeV}]^{-1}$. Assuming an homogeneous diffusion coefficient $K(E) = \beta K_0\,[\mathcal{R}/1\,\mathrm{GV}]^{\delta}$, with $K_0 \approx 10^{-2}\,\mathrm{kpc}^2/\mathrm{Myr}$ and $\delta \approx 0.5$, typically (Putze et al., 2010), we may then define a typical propagation scale for the CR $e^{\pm}$, $\delta l(E) \approx \sqrt{K(E)\,\tau_l(E)} \approx 300\,\mathrm{pc}\,[E/1\,\mathrm{TeV}]^{(\delta-1)/2}$. This scale is quite small, implying that ~ TeV $e^{\pm}$ detected at the Earth cannot come from very far away; they must originate from the kpc scale around the Earth. Nevertheless, such a small scale inherently leads to large statistical fluctuations in the TeV $e^{\pm}$ density, due to the small number of contributing sources. Indeed, if we consider a constant SN explosion rate of $\Gamma_{\star} \approx 3\times10^4/\mathrm{Myr}$ in the Galaxy, homogeneously distributed inside an infinitely thin Galactic disk of radius $R = 20$ kpc, then the average number of sources contributing to the TeV $e^{\pm}$ budget is $N \approx \tau_l(E)\,\Gamma_{\star}\,(\delta l(E)/R)^2 \approx 24@1\,\mathrm{TeV}$. This suggests that an efficient way to design a model of CR $e^{\pm}$ is to treat differently the local sources and the more distant sources. For the latter, relevant to local $e^{\pm}$ energies $\lesssim 50$ GeV, averaged properties can be safely considered, since a large number of them will contribute to the local flux. For the former, in contrast, the specific properties of each of them must be plugged to the model since they are much fewer. Therefore, a consistent model may consider a smooth spatial distribution of distant sources, with averaged properties, with a ~ kpc scale cut-off radius around the Earth, inside which all (known) sources are treated individually. This method was implemented in a consistent manner in *e.g.* Kobayashi et al. (2004) and Delahaye et al. (2010). At this stage, one might argue that it is not possible to self-consistently include all nearby sources, since some of them are likely not observed yet, due to instrumental sensitivity limits; and one might suggest that a Monte-Carlo (MC) approach becomes necessary to correct for this lack. Nevertheless, Delahaye et al. (2010) have demonstrated that the currently observed nearby sources are also those which dominate the local $e^{\pm}$ yield, despite the large theoretical uncertainties in their intrinsic properties. This is actually quite simple to understand. Observed sources (at any wavelength relevant to non-thermal processes) are obviously the most intense among existing sources, a mere consequence of the instrumental sensitivity selection effects. Since the non-thermal source luminosity is proportional to the CR density n_{CR} accelerated at the source, for either hadronic and leptonic emission processes, the more luminous the more CRs released in the ISM and subsequently propagating to us. In fact, the observed luminosity is proportional to n_{CR}/d^2, where d is the source distance, which means that even adopting a larger distance (*e.g.* to account for some uncertainties) is somewhat compensated by the larger CR density required from the observed luminosity. An MC simulation taking the instrumental sensitivity limits into account, such that any random object must lie below the experimental sensitivities unless corresponding to a known object, would find that the overwhelming majority of high energy $e^{\pm}$ contributors are actually those which are already observed. An MC is therefore poorly relevant to local studies, while it is likely an interesting approach for more distant regions, *e.g.* the Galactic center, where some powerful sources might still hide behind the large foreground. There are of course many different parameters featuring a source, but given a power-law spectrum for the accelerated CR $e^{\pm}$, the most important ones are (i) the amount and energy of CRs escaping the source, (ii) the distance and (iii) the age. All of them can be estimated and constrained from observations, though with some uncertainties, and their impacts on the local predictions have been thoroughly studied in Delahaye et al. (2010). We will discuss this in the next section. We still note that ages and distances are no longer issues for the distant component, for which averaged properties can be safely considered. Finally, a complete model of CR $e^{\pm}$ should include at least two main types of sources: SNRs and PWNe. The former mostly accelerate electrons and nuclei at non-relativistic shocks, and the latter mostly accelerate at relativistic shocks those $e^{\pm}$ pairs created in the highly magnetized pulsar magnetospheres. Note that each PWN should be associated with an SNR companion for consistency reasons (not necessarily observed—use sensitivity constraints in that case), while the reverse is not required. Although the knowledge of the precise fraction of the leptons accelerated among CRs suffers big uncertainties, it might be inferred from multiwavelength (hereafter λ^{++}) data. For CR positrons only, one must also include accurate predictions of the so-called secondary component arising from the nuclear interactions of Galactic CR with the ISM gas. Indeed, they are expected to dominate the observational data at low energy; this calculation is now rather well controlled, in contrast to the predictions of the primary components (Moskalenko & Strong, 1998; Delahaye et al., 2009, 2010; Lavalle, 2011).

3. Modeling local sources

One of the most challenging issues when trying to predict the local $e^{\pm}$ flux originating from nearby sources is to constrain the properties and amount of CRs released in the ISM, before they diffuse to the observer. A simplistic way is to use the λ^{++} data available for each source and try to constrain the $e^{\pm}$ component at the source, but there is a timescale problem in doing so. Indeed, what we observe today through λ^{++} measurements is an information carried by photons corresponding to a time $t_{\rm obs}(d) = d/c = 326\,{\rm yr}\,[d/100\,{\rm pc}]$ ago—c is the speed of light and d the source distance. However, the timescale relevant to CR propagation is quite different since CRs experience diffusive motion. It is actually set by the diffusion coefficient: $t_{\rm prop}(E) = d^2/K(E) \approx 30\,{\rm kyr}\,[E/1\,{\rm TeV}]^{-1/2}[d/100\,{\rm pc}]^2$. There is a tremendous difference between $t_{\rm obs}$ and $t_{\rm prop}$, which means that we cannot, unfortunately, use the current λ^{++} datum as it is to cook any source model relevant to the CR $e^{\pm}$ observed here and now. What can be done instead is to constrain a source model with current observations, and then to evolve it backwards in time until an age corresponding to $t_{\rm prop}$. Before going into more details, we summarize and complete the timescale census: (i) because $e^{\pm}$ lose energy efficiently, the nearby sources contributing to the local $e^{\pm}$ flux at energy E have ages[1] $t_\star \lesssim \tau_l(E) \approx 317\,{\rm kyr}\,[E/1\,{\rm TeV}]^{-1}$; (ii) their ages are also such that the escaped $e^{\pm}$ have enough time to diffuse to the observer given their distances, *i.e.* $t_\star \gtrsim t_{\rm prop}(d, E)$. Therefore, the TeV $e^{\pm}$ budget comes from those nearby sources in the age range 10 - 350 kyr (the younger the more intense due to diffusion effects, assuming a fixed amount of escaped CR $e^{\pm}$ per source). The timescales being set, let us come back to the source dynamics, which we have to consider to constrain a model from current observations. The way CRs escape from sources is far from understood for the time being (*e.g.* Drury, 2011), but there were recently some very interesting attempts to tackle this problem. For instance, Ohira et al. (2011) have proposed a dynamical model of CR accelerator SNR in which they decompose the predicted λ^{++} emission into different contributions: one corresponding to those CRs

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[1] Note that the *true* age $t_\star$ is the *observed* age $\tilde{t}_\star$ (observed SN explosion date, dynamical estimate, spin-down age, *etc.*) corrected by the distance: $t_\star = \tilde{t}_\star + d/c$.

which have escaped from the SNR, and another one for the CRs which are still confined within the SNR shock; they have included the contributions of both CR protons and electrons. Although their model likely contains arguable assumptions, such an approach paves an interesting road as to our purpose. What remains to do is, beside refinements, to evolve this kind of models backwards in time to define the source term of the CR $e^{\pm}$ transport equation. And then, test the associated predictions against the data. This, of course, rises many other issues. For instance, other timescales, inherent to CR acceleration, show up. As well exemplified by Ohira et al. (2011), the CR $e^{\pm}$ escape starts at a given but still uncertain time after the SN explosion (typically from the beginning of and all over the Sedov phase), but then the energy-dependent escape timescale must be shorter than the synchrotron loss timescale over the energy range of interest, which is strongly model dependent. This is even worst for PWNe, since another ballistic timescale has to be taken into account: CR $e^{\pm}$ can hardly escape before PWNe themselves have escaped their SNR shell counterparts. Assuming a pulsar kick velocity of $\sim$ 500 km/s, this leads to an additional timescale of $40 - 50$ kyr (Blasi & Amato, 2010). Despite the apparent difficulty of designing robust models for nearby CR $e^{\pm}$ accelerators, there is still a heartening fact to consider: the local $e^{\pm}$ flux is due to a very few of them, for which we have plenty of λ^{++} data (Delahaye et al., 2010). Such a program is therefore fully manageable.

4. Conclusion

The whole methodology presented above is undoubtedly suffering a still large dose of empiricism. However, we may hope that forthcoming theoretical developments will provide more fundamental grounds in the future. In any case, empirical arguments are not necessarily wrong since based on observations, and proceeding that way is for sure expected to improve the local $e^{\pm}$ flux prediction quite significantly, as it will be shown very soon (Delahaye et al., 2011). This game is clearly worth it, since it will allow to test simultaneously our understanding of CR acceleration in sources, and our understanding of CR transport in the local Galactic medium. This program will also be applied to other interesting regions, for instance the Galactic center, as well as in the context of non-thermal diffuse emission studies.

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