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Review

Entering the cosmic ray precision era

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Abstract. Here we outline some recent activities in the theory and phenomenology of Galactic cosmic rays, in the light of the great precision of *direct* cosmic ray measurements reached in the last decade. In the energy domain of interest, ranging from a few GeV/nucleon to tens of TeV/nucleon, data have revealed some novel features requiring an explanation. We shall emphasize the importance of a more refined modeling, of achieving a better assessment of theoretical uncertainties associated to the models, and of testing key predictions specific of different models against the rich datasets available nowadays. Despite the still shaky theoretical situation, several hints have accumulated suggesting the need to go beyond the approximation of a homogeneous and non-dynamical diffusion coefficient in the Galaxy.

Keywords. Cosmic rays—astroparticle physics—interstellar medium.

1. Introduction

The evolution of cosmic ray (CR) astrophysics has been relatively slow, when compared with other branches of astronomy and astrophysics. This is not surprising, given the lack of positional information and the complicated propagation that make the source identification and the interstellar transport characterization such difficult inversion problems. About a decade ago, a few main questions in CR physics and the consensual answers to them had crystallized into a 'standard framework':

- How is CR acceleration taking place? Primarily via 'diffusive shock acceleration'.
- In what type of objects? Predominantly (Galactic) supernova remnants.
- Where are they located? When did the events happen? Randomly in the Galaxy, well approximated by a continuum injection term, with a size much smaller than typical source–Earth distance.
- How do CRs get to us, after leaving their acceleration sites? Diffusing into an externally assigned, roughly scale-invariant turbulent magnetized interstellar medium (ISM).

Obviously, this does not mean that alternative scenarios had not been occasionally considered. And, certainly, some of the above-listed topics have been developed into a remarkable detail. For instance, the study of non-linear effects and their impact on some expectations of diffusive shock acceleration models is now a mature sub-field of theoretical research of its own. But it is fair to say that no stringent test of either the standard or more exotic models had been possible via charged CR measurements till recently, when a wealth of 21st century experiments has significantly improved the precision of the observations, while extending their dynamical range. Take the following list of statements:

- We only have access to cosmic ray fluxes 'modulated' by heliosphere.
- The positron flux is dominated by secondaries, with propagation parameters (as opposed to assumptions on the source and model framework) constituting the dominant source of theoretical uncertainty.
- Primary cosmic ray fluxes have power-law spectra.
- Primary spectra have universal (species independent) spectral indices.

The first item has been disproven by the *unique exploit* of the Voyager Interstellar mission[1] (see, Stone *et al.* 2013, Cummings *et al.* 2016). The second item, usually taken for granted in most phenomenological studies

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[1] https://voyager.jpl.nasa.gov/mission/interstellar-mission/.

over the past 30 years, has not only been shaken by new data, notably—but not exclusively—the celebrated 'PAMELA positron fraction rise' (Adriani *et al.* 2009) but appears nowadays very doubtful (see, for instance, the mini-review of Serpico 2012).

The last two items have become unsteady nearly 7–8 years ago by the more precise measurements available (Ahn *et al.* 2010, Yoon *et al.* 2011, Adriani *et al.* 2011), with a trend still continuing today, notably thanks to AMS-02 (Aguilar *et al.* 2015a, b). Also in the light of the importance of some of these issues for other astroparticle physics applications—notably, indirect dark matter searches—a new scrutiny of the simplest theoretical scenarios is ongoing. Ideally, theorists would like to match theoretical uncertainties with experimental ones, refining the level of predictions and improving our understanding of these high-energy phenomena. At the same time, they face the challenge to come up with a sufficiently predictive framework, not plagued by a proliferation of parameters, which in this field are often too hard or impossible to fix otherwise than by a fit to the data.

2. Spectral breaks

In order to illustrate this theoretical trend, we describe a specific example: the impact of the fact that primary cosmic ray fluxes in the GeV to TeV energy range, in particular protons and He nuclei, *do not* manifest a simple power-law spectrum. As already mentioned, the evidence in favour of spectral shapes closer to *broken* power-laws has accumulated over the past decade, from the indications in balloon-borne experiments, such as ATIC (Panov *et al.* 2009) and especially CREAM (Yoon *et al.* 2011), through the first measurements in a single space-based experiment, PAMELA (Adriani *et al.* 2011), till the recent high-precision determinations by AMS-02 on board the International Space Station (Aguilar *et al.* 2015a, b). In Fig. 1, the latest proton (*top panel*) and helium (*bottom panel*) fluxes from the AMS-02 experiment are reported. They have been extracted with the on-line cosmic ray database tool http://lpsc.in2p3.fr/crdb/ (see, Maurin *et al.* 2014), which can also be easily used to compare with the older datasets (not reported here to avoid clutter).

What is 'wrong' with these observations? To assess, take the simplest expectation which, nonetheless, matched data fairly well till recently. For stationary, homogeneous and isotropic diffusive propagation problems, and observations taken at a single location (i.e. the Earth) the diffusion operator ruling the flux Φ can be effectively replaced by a 'diffusive confinement' time

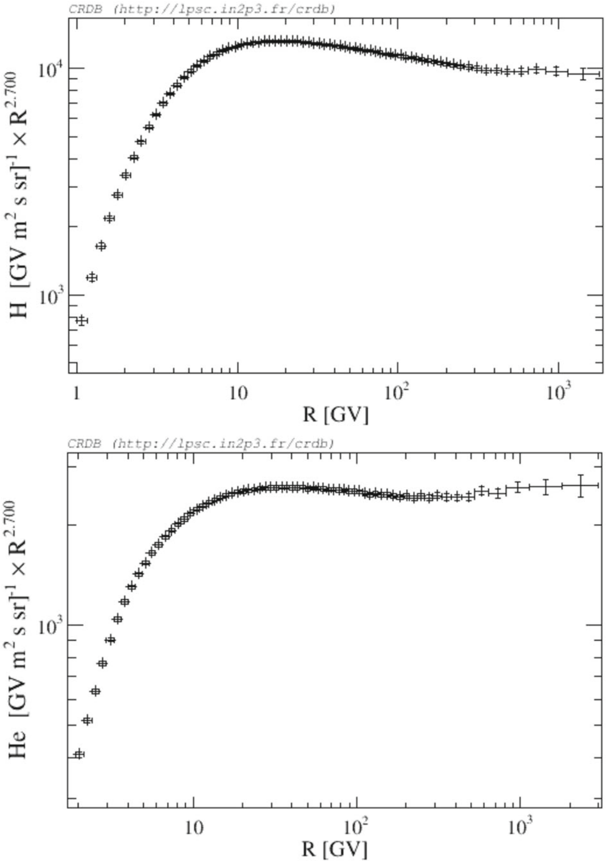

Figure 1. The proton (*top*) and He (*bottom*) fluxes measured by AMS-02 (Aguilar *et al.* 2015a, b) vs. rigidity R (ratio of momentum to charge, hence measured in GigaVolts, GV), rescaled by $R^{2.7}$, extracted via the on-line cosmic ray database tool http://lpsc.in2p3.fr/crdb/. It is visible to the naked eye that the slope in tens of GV to ~200 GV are different from the slopes above the latter rigidity value. Also note the remarkably small error bars.

$$\tau_{\rm diff}(E):\frac{\partial \Phi}{\partial t} - K\nabla^2\Phi = Q \Rightarrow \frac{\Phi}{\tau_{\rm diff}} = Q \text{ (at steady state)}. \qquad (1)$$

If both the source term Q and the diffusion coefficient K (with $\tau_{\rm diff} \propto K^{-1}$) are power-laws in rigidity R, as customarily believed and theorized, then a puzzle arises. This schematic exercise naturally suggests (classes of) solutions, where one drops one or several of the following assumptions (examples of actual physical motivations for that below, in italics):

- *Homogeneity (and possibly isotropy) of K.* Example: multi-phase character of the Galactic interstellar medium (and nature of magneto-hydro-dynamical (MHD) turbulence).

- *Power-law behaviour in K*. Example: multiple sources/mechanisms for the MHD turbulence in the ISM.
- *Power-law behaviour in Q*. Example: multiple classes of sources or spectral feature of a single source class.
- *Homogeneity in Q*. Example: prominent local, discrete sources.

Before coming back to the first options in the final part of this article, we will briefly concentrate on the latter option to illustrate some recent theoretical efforts within the above-mentioned strategy, while addressing the reader to Serpico (2016) for a broader overview of the alternatives, in particular, concerning multiple source or source spectral effects.

3. Local sources

A number of publications have studied the possibility that the CR spectral breaks emerge from a 'local' source contribution becoming predominant over a diffuse contribution representative of a Galactic average. Usually, but not always, the local contribution is considered to dominate at high-energy. The emphasis has often been on finding a viable fit, sometimes supplemented by a qualitative assessment on the goodness of the model. For instance, one typically needs fast diffusion and low supernova explosion rates for these scenarios to work, which has often been argued to be in tension with other observations.

One may however ask the more general question: How likely is such a hypothesis in itself, given 'Galactic variance', i.e., the spatial discreteness (and impulsive time-dependence) of the sources? Conventional models, in fact, replace the actual sources with a continuum 'source jelly', with a smoothly varying injection rate per unit volume and time. This corresponds to a 'coarse-grained' ensemble average of the actual physical model, and by construction the average theoretical expectation matches the prediction obtained in such a simplification. But, assuming that a discrepancy between observations and data is found, how safely can we attribute it to a failure of the model? Couldn't it be due to a relatively large statistical fluctuation with respect to the average prediction, which is in fact compatible with the model in a more realistic calculation?

In Genolini *et al.* (2017a), we have outlined the first elements of such a theory. The task is made non-trivial by the fact that the theoretical probability distribution for the flux is of 'fat-tail' type, with infinite variance: The Central Limit theorem does not apply and the familiar Gaussian statistics toolbox cannot be used. We have argued that a generalized Central Limit theorem holds, and that the flux probability distribution functions are remarkably well approximated by 'stable laws', characterized by analytically computable parameters. We tested these conclusions with extensive numerical simulations (see Fig. 2 for an example).

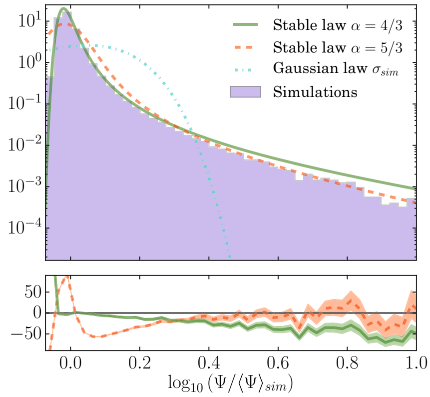

Figure 2. The blue histogram is the pdf of the Galactic CR flux at 1 TeV (vs. the flux normalized to its mean) obtained numerically via 10^6 Monte Carlo realizations of pure diffusive transport. The dot-dashed blue line represents the (highly unsatisfactory) Gaussian approximation fitted to the numerical results. The solid green line reports the theoretical prediction based on fat-type stable law distribution for the limiting case of an infinitely thin two-dimensional model of the Galactic magnetic halo, whereas the dashed red curve corresponds to the 3D isotropic limit, expected to be valid respectively at low and high flux (dominated respectively by far and near sources). The per cent residuals between theory and simulations are displayed in the panel below, with bands showing their 1-σ Poisson error. Adapted from Genolini *et al.* (2017a), which we address to for further details.

As a result, we arrived at two interesting conclusions:

- For currently viable *homogeneous and isotropic* diffusion models, the observed breaks only emerge rarely, with a realistic *upper limit* around 0.1%. Hence, such explanations appear to require a high-degree of fine-tuning.
- Even if this effect is probably insufficient to account for the breaks, these 'irreducible theoretical errors' are not negligible anymore, given the precision of the data: by taking the experimental error $\sigma_{\exp}$ reported by AMS-02 on the proton flux measurement (Aguilar *et al.* 2015a), we estimate, for instance, that a 3 $\sigma_{\exp}$ deviation from the average flux expectation at $E \sim 50$ GeV is obtained in about 5% of the theoretical realizations. Put otherwise, if the viability of a

model is naively assessed only based on experimental error, a significant bias in the statistical level of the conclusion is likely. Till recently (including, for instance, PAMELA data), the precision was sufficiently low to make these 'theory error' effects negligible, justifying *a posteriori* that such fine effects were neglected in phenomenological analyses.

This study represents more of a beginning than an end to the story. Extending the theory to account for energy bin-to-bin correlations or to include anisotropy observables is certainly something to wish for, to bypass the need for extensive Monte Carlo simulation in order to compare theoretical predictions with data.

4. Testing break models

Of course, besides refining theory models and the uncertainty assessments, one is also interested in discriminating among competing models for the new features that have been uncovered by the data. As already stressed in Serpico (2016) regarding break models, the most promising channels to probe the different classes of explanations for the spectral breaks are the so-called 'secondary' nuclei. These are relatively fragile nuclei such as Li, Be, B, easily destroyed in stellar processes and thus present but in traces in stellar astrophysical environments. It turns out that they are comparatively abundant in CRs. This fact is interpreted as the result of spallation of 'primary' nuclei accelerated at sources (e.g. supernova remnants) onto interstellar material during the CR diffusive propagation to the Earth. While CR are sensitive to both acceleration and propagation effects, the ratio of secondary to primary species is used to constrain propagation parameters, being largely insensitive to injection spectra. Since the Lorentz factor of a nucleus is approximately conserved in a spallation event, with a bit of oversimplification for ratios plotted in terms of energy/nucleon (or, to some extent, rigidity) one expects the following:

- For a 'source' origin for the break, the feature maps correspondingly in the secondaries (see the sketch in Fig. 3) and thus no feature is expected in the secondaries/primaries ratios.
- For a 'propagation' origin for the break, the same break should be seen in secondaries/primaries, since secondary spectra should show a more pronounced break than primary ones, inheriting 'twice' the break present in the diffusion coefficient (see Fig. 4).

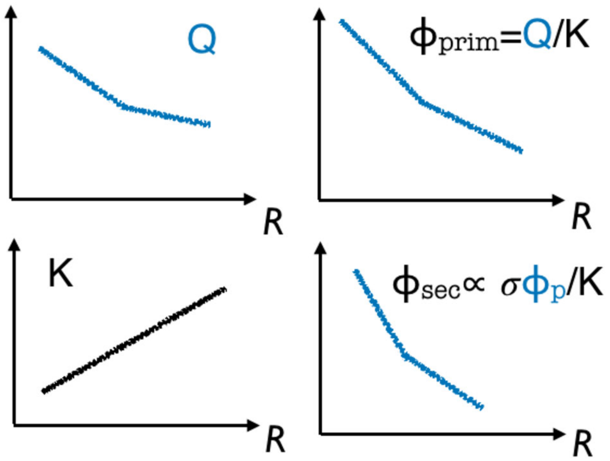

Figure 3. Sketch of the source term (*top left*), diffusion coefficient (*bottom left*), primary (*top right*), and secondary flux (*bottom right*) behaviour vs. R, for a *source* model of the primary break.

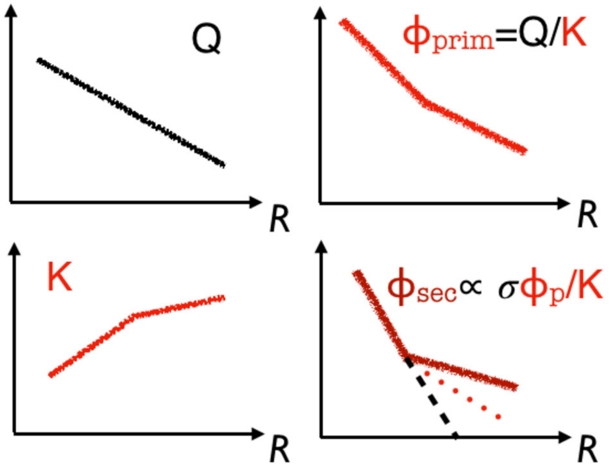

Figure 4. As in Fig. 3, for a *propagation* model of the primary break.

- For 'local source' models: qualitatively, since the interstellar target material on which secondaries are produced is more homogenous than the source distribution, the secondary source term should be closer to the naively computed 'unbroken' average Galactic source spectrum than the primary one (see Fig. 5). In most realizations, one thus expects that the ratio shows *softening* rather than hardening. However, this is just an average expectation, with the actual result depending upon the assumed properties of the local sources and of the local environment. In general, no deterministic prediction can be made.

A pictorial summary of the secondary/primary behaviour vs. R for the three classes of models is reported in Fig. 6. In Genolini *et al.* (2017b), we have

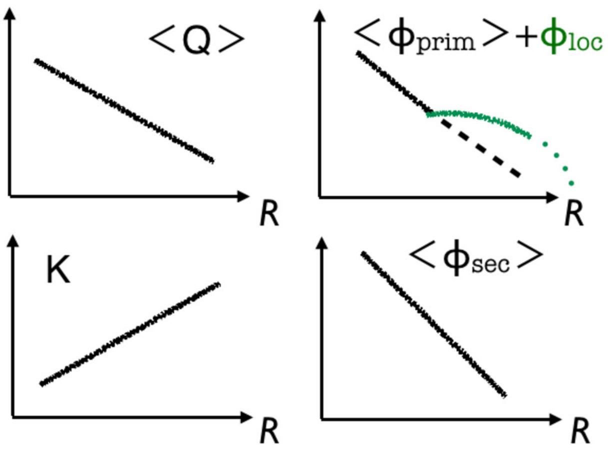

Figure 5. As in Fig. 3, for a *local source* model of the primary break.

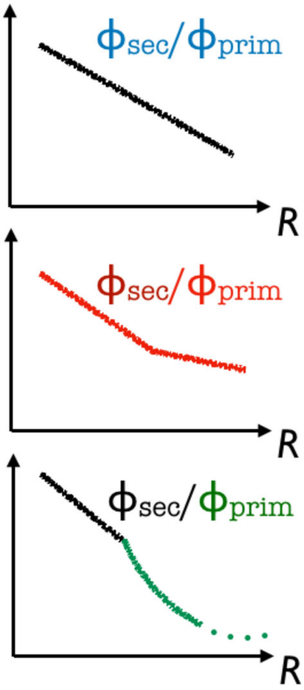

Figure 6. Summary of the secondary/primary behaviour vs. R expected for the source, propagation, and local source models (from top to bottom, respectively).

recently performed a first test *a priori* on the AMS-02 B/C data published only a few months before (Aguilar *et al.* 2016), comparing a baseline model with a power-law function $K(R)$ vs. a case with a break in $K(R)$, whose parameters are fixed by the proton and helium data, so that the fit to B/C data (above 15 GV) has the same number of free parameters in the two cases.[2]

In all cases tested, a significant preference for the scenario with a break in $K(R)$ is obtained ($\Delta\chi^2 > 10$). This result is robust with respect to: (i) sub-leading transport phenomena (at high rigidity) such as convection or reacceleration, treated as nuisance parameters; (ii) different treatments of AMS-02 systematic errors; (iii) assumed spallation cross-sections (from existing libraries) as well as a physically motivated logarithmic growth with energy ‘inherited’ from nucleon–nucleon cross-sections; (iv) the expected amount of ‘grammage at the source’, the so-called secondaries at the source.

A more recent analysis (Reinert & Winkler 2018), with different techniques for the solution of CR propagation equation, a different approach to the treatment of spallation cross-section, and a slightly different dataset has further corroborated our results.

5. Towards a new paradigm?

Only a few months after our preliminary analysis (Genolini *et al.* 2017b), AMS-02 has published two important articles on ‘mostly primary’ and ‘mostly secondary’ CR species, respectively. In Aguilar *et al.* (2017), it reads as follows: “Above 60 GV, these three spectra [He, C, O] have identical rigidity dependence. They all deviate from a single power law above 200 GV and harden in an identical way.”

In the second article of Aguilar *et al.* (2018), it reads as follows: “All three fluxes [Li, Be, B] have an identical rigidity dependence above 30 GV […]. The three fluxes deviate from a single power law above 200 GV in an identical way. […] Above 200 GV, the secondary cosmic rays harden more than the primary cosmic rays.”

These results confirm the basic predictions (Serpico 2016) as well as the first indications (Genolini *et al.* 2017b) in favour of a (diffusive) propagation origin of the observed spectral features, possibly marking another milestone in our description of CR propagation.

Yet, even accepting that as dominant origin for the observed flux shapes, the theoretical interpretations may differ in the details. For instance, in Blasi *et al.* (2012), it was proposed that CR above the break essentially reflect the standard lore of diffusion onto external turbulence generated, e.g. by supernova explosions, while CR below the break are sufficiently numerous to alter the turbulence spectrum via waves generated by the CR streaming itself (a phenomenon already subject to general studies in the past (see Ptuskin *et al.* 2008). In this proposal, we would be thus observing an inherently non-linear aspect of the CR diffusion phenomenon, which is not captured by conven-

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[2] Note that the two cases are not ‘epistemologically’ identical: the first leaves the p-He data unexplained (source effect?) and the second attributes the breaks to propagation.

tional propagation schemes (as those implemented in GALPROP (Moskalenko *et al.* 2006), USINE (Maurin *et al.* 2018), DRAGON (Evoli *et al.* 2015). This idea suffers perhaps from the technical difficulty of generalizing the solution to realistic geometries, but within the constrained situations to which it can be applied it leads to good fits (Aloisio *et al.* 2015). It has also the intellectually appealing property of offering a microscopic understanding of the observed features. On the other hand, it is also possible to fit the data by *assuming* that the CR transport properties are spatial-dependent in different regions of the Galaxy, in such a way that the diffusion coefficient is not separable into energy and space variables (Tomassetti 2012). In fact, this property would arise generically as a consequence of the idea in Blasi *et al.* (2012), but can have a different origin (without necessarily invoking non-linear effects), such as different sources for turbulence in different regions of the Galaxy. If adopted on a mere phenomenological level, the free parameters entering the generalized diffusion coefficient can, in fact, be fit to reproduce the data to great accuracy (Tomassetti 2012, Guo & Yuan 2018).

Needless to say, the best way to confirm this generic expectation is to access 'non-local' information in CR, i.e. elsewhere in the Galaxy. This can be done to some extent via CR anisotropy studies (which depend among others on CR flux gradients) and the latitude profile of diffuse Galactic gamma-rays in the GeV range. These gamma-rays are dominantly emitted by π^0 decays, in turn produced via CR inelastic interactions onto the ISM, and probe the integral of the CR flux along the line-of-sight. Interestingly, both observables are difficult to explain within a homogeneous diffusion approach to CR. In Evoli *et al.* (2012), it was shown that both these long-standing problems could be solved if the diffusion coefficient also depends on the Galactocentric distance (qualitatively expected in scenarios such as the ones mentioned above). Recent analyses confirm the viability of these models in the light of AMS-02 data (Guo & Yuan 2018, Recchia *et al.* 2016, Liu *et al.* 2018).

Another way to test the (lack of) viability of homogeneous diffusion is to perform a multi-channel CR analysis, separating 'light' (e.g. p, $\bar{p}$, He) vs. 'heavy' species (e.g. Be, B, C, N, O), each group containing at least one dominantly primary and one dominantly secondary species. Due to their different inelastic cross-sections, in a statistical sense the light (heavy) elements are collected from a larger (smaller) ISM region, so that e.g. the inferred diffusion coefficients are truly averages over different volumes. We are talking here about differences in radius of several kpc (see, for instance, Taillet and Maurin (2003)). The results in Johannesson *et al.* (2016) suggest that such differences are in fact present in the data.

At a different spatial scale, another complementary (but concordant) piece of information concerning inhomogeneous diffusion comes from the detection of an extended TeV emission surrounding two nearby pulsars, Geminga and Monogem, by the HAWC collaboration (Abeysekara *et al.* 2017). The inferred diffusion coefficient has been argued to be in tension with a pulsar origin for the cosmic ray positrons, but this naive conclusion is strongly relying on the simplistic model now believed to be inconsistent with other data. It is more and more appreciated theoretically that self-confinement around the sources due to streaming instability (e.g., Yan & Lazarian 2004, Malkov *et al.* 2013, D'Angelo *et al.* 2016) is an important effect, with an effective diffusion coefficient on scales of tens of pc around the source much smaller than the truly ISM value. Not only this is believed to reconcile the apparent contradiction between HAWC data and the currently favored explanation for positron CR (Hooper & Linden 2017, Profumo *et al.* 2018), but it is probably associated to sizable production of the so-called secondary species from regions around the sources (see, for instance, D'Angelo *et al.* 2018). Very recently, Aharonian *et al.* (2018) have also discussed evidence for a one to two orders of magnitude reduced diffusion coefficient inferred from the radial profile of gamma-emission (from Fermi-LAT and HESS data) around a few prominent Galactic clusters. This also brings further support to the possibility that star clusters, rather than isolated massive stars, may be associated to acceleration of the highest energy Galactic CRs.

Anyway, the realistic perspective of slow diffusion around sources, with a highly inhomogeneous diffusion coefficient at 'small' scales, raises particularly delicate questions when analyzing antiprotons, an exquisite channel for DM indirect searches. This novel astrophysical contribution, if unaccounted for, could easily fake a DM signal, a worry already expressed in the past (Blasi & Serpico 2009, Pettorino *et al.* 2014, Giesen *et al.* 2015) but still poorly appreciated, in my opinion.

6. Conclusion

The observational improvements in cosmic ray (CR) astrophysics have shown the first cracks in the simplest models for CR production and propagation. Many ideas have been proposed for their origin, and still more are likely to appear. In general, however, we face a double theoretical challenge: To provide a more refined modeling to account for new facts *and* to keep theoretical errors under control, or at least assess them. Without the former, the models become less and less interesting, but without the latter, the newly attained experimental precision becomes worthless.

Here we focused on the case of spectral breaks, which can be 'naturally' explained within broad classes of models. In fact, finding a model that fits the data is not the hardest task, notably if including a lot of additional free parameters. Much more challenging is to find models that provide statistically probable explanations, or that *predict* (as opposed to *postdict*) features that one can test.

We have recently provided (Genolini *et al.* 2017a) a first estimate of the irreducible ('Galactic variance') theoretical error due to space–time discreteness of the CR sources, whose exact location and times are obviously unknown. Alone, this effect is unlikely to explain the spectral breaks firmly observed at least in p and He, but it introduces an uncertainty comparable or even larger than the AMS-02 statistical ones, and should be taken into account.

We have summarized the results of a first test on the 2016 AMS-02 B/C data, to investigate if they prefer a propagation origin for the breaks, obtaining intriguing hints in that sense (Genolini *et al.* 2017b). Later, an independent analysis confirmed our findings (Reinert & Winkler 2018). Then AMS-02 published a new data that further reinforced these conclusions (Aguilar *et al.* 2017, 2018).

We then argued that multi-channel and multi-messenger probes have reinforced the theoretical urge to go beyond the homogenous diffusion coefficient approximation for Galactic CR probes. Strong indications for variations with respect to the local ISM average value have been found both at the scale of few tens of pc around sources and at a more coarse-grained level, over several kpc distances from us. The likely culprits of this phenomenon are the inhomogeneous source distribution in the Galaxy, the varying ISM properties in the Galactic environment, and non-linear plasma phenomena coupling CRs to the MHD turbulence that determine transport properties, but other origins of course still deserve scrutiny.

More experimental precision, resolving more CR species (including isotopic abundances), and accessing an even broader energy range will help refine such studies, but further theoretical and phenomenological progresses are crucial to bring us closer to a global understanding of the Galactic CR phenomenon. We have, for instance, still a rudimentary understanding of the possible causes of the non-universality of spectral indices (for some ideas, see Serpico 2016), which remains a trickier issue to settle, both experimentally and theoretically. In any case, major progresses in this area would also prove beneficial (if not essential) to sharpen the CR channel potential for astroparticle applications, such as indirect dark matter searches in CR antimatter fluxes. For the time being, we would caution that current analyses may be either underestimating or—more likely—overestimating the sensitivity of these probes to DM signals.

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