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Cosmic-ray phenomenology from sub-GeV to ZeV

Principal Authors:
Name: Allard Denis Institution: APC
Email: allard@apc.in2p3.fr
Phone: +33 1 57 27 61 43
Name: Marcowith Alexandre Institution: LUPM
Email: Alexandre.Marcowith@umontpellier.fr
Phone:+33 467144257

Co-authors: (names and institutions)
Baret Bruny (APC), Cohen-Tanugi Johan (LUPM), Derome Laurent (LPSC), Casse Fabien (APC), Gabici Stefano (APC), Lavalle Julien (LUPM), Maurin David (LPSC), Neronov Andrii (APC), Parizot Etienne (APC), Semikoz Dmitry (APC)

Abstract :
This contribution is proposed by a part of the French community of cosmic-ray phenomenologist/theorist, it aims at showing (i) the global coherence of our activities across the whole cosmic-ray spectrum, including multi-messenger counterparts, (ii) the adequacy of these activities with the present and future international experimental program in the field, (iii) the important role of the French community in the international effort to understand the origin of cosmic-rays, (iv) the need for a strong support from the institute, in particular by providing permanent positions for cosmic-ray phenomenologists independently from those attributed to experimental programs.
The document is divided in four parts of equal importance covering (i) sub-GeV to multi-TeV cosmic-rays, (ii) γ and ν counterparts of Galactic cosmic-rays, (iii) very-high and ultra-high-energies, (iv) theory of cosmic-ray transport and acceleration.

Foreword and disclaimer : This common contribution is the consequence of the long term links which exist between the different members of the community across the institute (and also between institutes) which probably owe a lot to the structuring role of the PNHE (formerly GDR PCHE). Several events over the years, such as the PARC school of Goutelats2003 or more recently the CFRCos workshops, funded and organized with the support of the GDR or the PNHE, had a strong positive impact in connecting the different members of our community. We thus stress that ensuring a strong support to the PNHE is important for our community.
Nota bene: this contribution is not an exhaustive list of all the potentialities and assets of the French community. In particular, it is biased toward IN2P3 activities, with a lower emphasis on the contributions of our colleagues from INSU or CEA (or on our international collaborations). Likewise, the link between cosmic rays and the physics and astrochemistry of the interstellar medium, which is a important part of the domain, of its coherence and of its links to other astrophysical domains, is mostly left to another contribution (Gabici et al. GT12).

1) sub-GeV to multi-Tev Galactic cosmic-rays

A lot of progress has been made in recent years in the direct measurement of Galactic cosmic rays (GCR), from tens of MeV/n up to a few hundreds of PeV. These measurements have triggered a strong progress in astrophysics and astroparticle studies. In particular, close collaborations between IN2P3, INP and

INSU teams have resulted in a steady and strong scientific production, with an expertise and results recognized by the international community. This issued in particular with the development of the USINE code https://dmaurin.gitlab.io/USINE/ .

Precision measurements with AMS-02: The AMS-02 experiment is installed on the International Space Station (ISS) since 2011. The collected data (nuclei, electrons, positrons and antiprotons) are for the first time dominated by statistical errors, ~few percent from GeV to TeV, bringing GCR physics into a precision era. Among the major results, fluxes of secondary species Li, Be and B (Aguilar 2018) show a spectral break beyond 200 GV that differs from the one primary H, He, C and O data. This hints at a change of diffusion regime in the Galaxy (Génolini 2017, 2019), which can be linked to the microphysics of the turbulence (Evoli et al., 2018). Regarding indirect detection of dark matter, antiprotons remain one of the most constraining channel with GeV-TeV γ-rays (eg, Conrad & Reimer, 2017), and AMS-02 has already detected tens of thousands of them (Aguilar et al., 2017). These data were shown to be compatible with a purely astrophysical production (Boudaud et al, 2019c), and the constraints on dark matter candidates can therefore be improved. Future AMS-02 analyses on anti-deuteron and anti-He can also go further. The unprecedented data quality also stimulates synergies with related fields of research: (i) AMS-02 data interpretation is limited by the precision of production cross sections (Genolini et al., 2018) so that synergies with nuclear physics (via the IN2P3 GDR RESANET) and particle physics are required. For instance, in 2018, CERN experiments (LHCb and NA61) started to get involved in these measurements[1]; (ii) the AMS-02 collaboration published, in 2018, six years of monthly H and He fluxes, and these data of unprecedented temporal resolution, show a sensitivity to the inversion of polarity of the solar magnetic field (which took place between November 2012 and March 2014). This makes it possible to refine the models of Solar modulation and to improve the predictions of space weather.

In situ measurement of interstellar fluxes: Voyager 1 crossed the Solar cavity boundary in 2012, measuring for the first time interstellar fluxes at MeV/n energies (Stone et al., 2013); Voyager 2 did the same in 2018 and will also provide complementary data. The low-energy electron data have been used in an original way to put strong constraints on dark matter models (Boudaud et al., 2017, 2019a,b). On the astrophysics side, these low-energy nuclear and electron fluxes were also found to be insufficient to explain the degree of ionization of the interstellar medium and the abundances of the observed molecules, and the mystery remains as to their origin (see Gabici et al, GT12).

Data above hundreds of GeV and complementarity of γ−ray data: At higher energy, the CALET experiment on the ISS and the DAMPE satellite (Ambrosi et al., 2017) measured lepton fluxes up to 10 TeV, shedding new light on possible local sources of electrons and positrons (supernova remnants and pulsar wind nebulae); nuclear fluxes are also under way (Adriani et al., 2019). In addition to these direct measurements, the discovery of an extended γ-ray emission around Geminga by HAWC (Abeysekara et al., 2017) – also observed by Fermi-LAT (Di Mauro et al., 2019) at a lower level energy – highlights specific properties of turbulence and diffusion coefficient in large regions around these new sources, stimulating theoretical and numerical simulation studies around these accelerators.

Anisotropies: Diffusion processes lead to a quasi-isotropic flux of GCRs. Experimental progress in the last decades (ARGO-YBJ, IceCube, HAWC, KASCADE-Grande, Tibet ASγ, etc.) have made it possible to better characterize these anisotropies (≤0.1%), with two major issues (see Ahlers and Mertsch 2017 for a review): (i) the observed values from TeV at PeV are much greater than predicted in simple scattering models; (ii) unexpected small-scale structures (up to 10°) have been observed, which could be explained in terms of heliospheric effects, anisotropic scattering, source stochasticity effects (eg, Savchenko et al., 2015), etc. Note that the AMS-02 and Fermi-LAT experiments also put upper limits on the anisotropy, but on leptons: with more data, the latter may allow to distinguish between dark matter and astrophysics sources to explain the TeV electron flux

Future GCR activities: Several experiments are still running (AMS-02, DAMPE, CALET) and will produce results for the next 5 years. The GAPS balloon (Aramaki et al., 2016), dedicated to anti-deuteron

[1] For an illustration of these synergies, see the XSCRC19 conference (https://indico.cern.ch/event/820869).

detection, is expected to take data around 2021-2022. In the longer term, the Aladino and AMS-100 projects (Schael et al., 2019) have been proposed as part of the "Voyage 2050" ESA program. However, despite a strong activity and expertise on GCR phenomenology in France, only one IN2P3 laboratory (two people) in France remains today involved in the AMS-02 analyses. Consideration must be given to the relevance of the participation in future direct GCR detection projects. If the evolution observed in recent years continues on the same trajectory, there will be *no more experimental activity in France within 5 years*. Finally, phenomenological studies require various expertise and are best carried out within INSU/IN2P3/INP collaborations. If these activities are now strong, the synergies remain fragile and would benefit from dedicated human resource support on the long term to be viable.

2) γ-ray and ν counterpart (in particular of Galactic cosmic-rays)

Cosmic rays produce secondary gamma rays and neutrinos via pion production in interactions with background photons and gas.

Neutrinos: Neutrinos carry precious information about their production sites because they can travel across cosmic distances without being affected by interactions with matter or radiation. A flux of astrophysical neutrinos produced by 0.1-100 PeV protons and nuclei has been discovered by the IceCube experiment (Aartsen et al., 2014). The analysis of the anisotropy of the neutrino flux and the evidence of a neutrino signal from the blazar TXS 0506+056 (Aartsen et al., 2018) indicate that a sizeable part of the signal might be of extragalactic origin. On the other hand, an isotropic flux of neutrinos could also be produced within the Galaxy, as the result of cosmic ray interactions in a large gaseous halo (Taylor et al., 2014). Independently on the origin of the isotropic flux of neutrinos, the Galactic plane must account for a fraction of the signal, due to cosmic-ray interactions in the interstellar gas. MILAGRO observations of the Galactic disk in very-high-energy gamma-rays suggested that such contribution could be larger than previously expected, and detectable by km^3 detectors (Gabici et al., 2008). Indeed, the consistency of the spectral properties of the neutrino signal with the spectrum of the gamma-ray emission from the sky in the TeV range (Neronov and Semikoz 2016) and the $2.5 - 3\sigma$ evidence for an anisotropy in the neutrino signal towards the Galactic Plane (Neronov and Semikoz 2016; Aartsen et al., 2019) indicate the presence of a Galactic component in the neutrino flux. Such a component is most likely subdominant, but possibly not negligible, as indicated by a detailed analysis of ANTARES and IceCube data (Albert et al., 2018). Remarkably, massive clouds of interstellar gas located in the vicinity of Galactic sources of cosmic rays might be detected in the future as a discrete sources of neutrinos (Gabici and Aharonian, 2007). Finally, it is not excluded that part of neutrino signal originates from exotic processes, like the decays of super-heavy dark matter particles (Neronov et al., 2018). IN2P3 theoreticians developed Galactic models for neutrino production from cosmic rays and Dark Matter (Taylor et al., 2014; Neronov et al., 2018) and extragalactic neutrino production in astrophysical sources (Neronov and Semikoz, 2002). These activities complement experimental developments of KM3Net neutrino experiment, in which many IN2P3 researchers are involved and will be key for the interpretation of the data to come in the next decade.

Gamma-rays: Gamma-rays are produced in cosmic-ray interactions together with neutrinos also carry information on the mechanisms of production and propagation of cosmic rays. It was proposed a long time ago that gamma-ray observations of supernova remnants would test the idea that Galactic cosmic rays are accelerated at such astrophysical objects (Drury et al., 1994). Such test has been successfully performed both for individual objects (e.g. Lemoine-Goumard and Renaud, 2012) and for the entire Galactic supernova remnant population (Cristofari et al., 2013). Unfortunately, the detection of gamma rays from supernova remnants is a necessary but not sufficient condition to prove that cosmic rays are indeed accelerated in such objects (this is mainly because the gamma-ray emission could well be leptonic). For this reason, the search for the sources of Galactic cosmic rays is still open. In particular, it is not clear whether supernova remnants are able to accelerate particles up to the energy of the knee in the cosmic ray spectrum (a few PeV). The recent detection in multi-TeV gamma rays of a PeVatron in the Galactic center (most likely not a supernova remnant) (HESS collaboration, 2016) and of the gamma ray emission from some super-bubbles (Fermi Collaboration, 2011; HESS collaboration, 2015; Maurin et al,

2016) revived the interest in alternative scenarios to explain the origin of Galactic cosmic rays. The advent of gamma-ray facilities such as the Cherenkov Telescope Array will possibly provide us with an answer to the long standing issue of cosmic ray origin (Acero et al., 2013; Christofari et al., 2017; Christofari et al., 2018). The interactions of cosmic rays in the interstellar gas produce a diffuse gamma-ray emission from the galactic disk. Interestingly, the spectrum of diffuse Galactic emission measured by Fermi/LAT up to 3 TeV is consistent (in the slope and normalization) with the IceCube astrophysical neutrino signal above 30 TeV (Neronov et al., 2018; Neronov and Semikoz, 2019). Future detection of the Galactic diffuse emission flux in the 3-30 TeV gap between the gamma-ray and neutrino data by CTA would lead to the first multi-messenger signal study of gamma rays and neutrinos from the same source(s) in the same energy range.

3) The ultra-high energy domain

In this Section, we underline the assets of the French community in the domain of the phenomenology and theory of very-high-energy (VHE) and ultra-high energy (UHE) cosmic rays, which includes considerations of various aspects: spectrum, composition, arrival directions, and multi-messenger counterparts. In all these domain, French experts have taken a leading role in presenting new ideas, which were then adopted by the larger community, or remain at the heart of the questions to be answered in the coming decade.

VHE- and UHECR spectrum and composition: The combined results of the KASCADE-Grande experiment and the Pierre Auger observatories have provided the most important constraints for the physics of the transition from Galactic to extragalactic cosmic-rays by showing (i) the existence of the long anticipated heavy knee (Ape1 et al., 2011), (ii) the presence of an ankle in the spectrum of the light cosmic-ray component around 10^{17} eV (Ape1 et al., 2013) and (iii) a CR composition going from light to heavier elements above a few 10^{18} eV (Aab et al., 2014a; Aab et al., 2014b). These data suggest that the light and heavy extragalactic components have significantly different spectra (respectively soft and very hard). This has been presented by some authors as a proof of existence of at least two distinct extragalactic components. On the contrary, we have shown that this spectral difference could also be understood in the context of a single extragalactic component, as a natural consequence of the photo-disintegration of CR nuclei trapped in the astrophysical source, acting as a high-pass filter effect for the high rigidity particles escaping from the sources (Globus et al., 2015a; Globus et al., 2015b). This perspective was furthermore shown to possibly provide a unified explanation for both the extragalactic UHECR and the VHE neutrinos observed by IceCube (Giacinti et al., 2015a; Kachelriess et al. 2017). These important works are some examples of the leading role of the French community in the understanding of the phenomenology of the GCR/EGCR transition and more generally of the origin of UHECRs. The French community also developed numerical codes and phenomenological models for the transport of UHECRs in the Galactic magnetic field (Rouillé d'Orfeuil et al., 2014; Giacinti et al. 2015b; Giacinti et al., 2018), which are important to discuss and constrain the highest energy part of the GCR spectrum. In the next few years, a wealth of new experimental data will show in greater detail the evolution of the CR spectrum and composition above the knee. The most promising experiments in this domain should be LHASSO, IceCube Gen2, TA/TALE and Auger Prime. The French phenomenologist community is well prepared to contribute significantly to the interpretation of these data to come, which should shed more light on this part of the spectrum and help answering the current open questions such as the nature and maximum energy of the GCR accelerators, and the number of different components shaping to the CR spectrum above the knee.

UHECR arrival directions: Important data showing overall moderate anisotropies have been provided by Auger and the Telescope Array (TA). A dipolar modulation exceeding the 5σ-significance threshold above 8.10^{18} eV has been demonstrated (Aab et al., 2017) and hints have been found of the presence of "hotspots" at intermediate angular scales (~30 degrees), although with lower significance (Abbasi et al., 2014; Aab et al., 2015). It is worth noting that the current most significant excess in the Auger sky is located close to the nearby radio galaxy Centaurus A. One of the greatest challenges of the coming years for CR phenomenologists will be to be able to relate predictions of astrophysical models (i.e based on a hypothesis on the nature of the sources, their cosmic-ray output and their spatial and luminosity distributions) with all the new observational constraints (on the spectrum, composition and anisotropy, and their evolution with energy) that will be provided by Auger-prime, TA×4 and hopefully a space mission (e.g. JEM-EUSO). To this purpose the French community has produced a set of numerical tools simulating the propagation of UHECRs from their sources to the Earth, taking into account all the relevant energy loss processes of protons and nuclei and their deflection by extragalactic and Galactic magnetic fields. These tools can be used to determine what types of models can be discriminated by future data from UHECR observatories with larger exposures (following Rouillé d'Orfeuil et al., 2014), which are the most relevant observables to this end. They can also be used to discuss the possible astrophysical origin of the discrepancy between the highest energy spectra measured by Auger and TA, without violating the very moderate anisotropies observed by both experiments (Globus et al., 2017a). They will moreover be very valuable to refine the scientific goals of the JEM-EUSO program, which aims at increasing the statistics (and the anisotropy signal) at the highest energy and provide for the first time a full sky coverage with roughly uniform exposure. Finally, they can be used to evaluate the potentialities of the approach proposed by Auger-Prime, to increase the signal-to-noise ratio of the anisotropy signal at lower energy by improving the resolution on the composition (which may allow to isolate the lightest, least deflected particles).

Multi-messenger counterparts and in particular UHE neutrinos (i.e neutrino above a few 10^{16} eV): **T**hese neutrinos will be key to investigate the existence of sources able to accelerate protons above 10^{20} eV. The composition results from Auger are suggesting that these hypothetical powerful accelerators are rare or even totally absent in the nearby universe (that is within the *GZK sphere*), but UHE neutrinos are not subject to the GZK effect, and can thus reveal such sources beyond the GZK horizon. The search for these UHE neutrinos is thus an important experimental challenge for the coming years, which can only be faced by future extremely large exposure experiments such as GRAND or JEM-EUSO/CHANT/POEMMA. These UHE neutrinos are an important piece of the "ultra-energetic universe" puzzle. The French community is in a very good position to contribute to this fields, since we have shown in the recent years our capability to produce models of particle acceleration in various types of sources such as AGN, Starbust galaxies, GRBs (e.g (Giacinti et al., 2015a; Kachelriess et al., 2017; Globus et al., 2015a), including the associated neutrino and gamma-ray emission. These competences will be important to interpret UHE neutrino signals (or their absence) from point sources. Moreover, it should be stressed that the multi-messenger strategy does not apply to individual sources only. When describing the high-energy universe, one must be able to account for the diffuse emission as well, i.e. also explain the relative fluxes and spectra of UHECRs, neutrinos and gamma-ray backgrounds, which depend on the distribution and cosmological evolution of the sources. In particular, any astrophysical model for one of these messengers must satisfy the constraints provided by the other backgrounds. The joint study of these multi-messenger backgrounds as a function of energy are one the recognized competences of the French community (Semikoz and Sigl, 2004; Decerprit and Allard, 2011; Neronov et al., 2016; Globus et al., 2017b).

4) Theoretical studies of Cosmic Ray acceleration and transport

The origin of Cosmic Rays (CR) is still a mystery more than one hundred years after their discovery. We know that CR in order to reach the highest energies have to be confined in a source of sufficiently high magnetic field strength. The recent years of theoretical studies of CR acceleration and transport have focused on analyzing the electro-magnetic fluctuations which develop in CR sources and their impact over particle acceleration processes (see eg Marcowith et al 2016 for a review). These analyses have been made possible due to the rapid growth of simulation power and the development of performant numerical techniques capable to handle this multi-scale physics problem.

Shock formation and particle acceleration: *Particle-in-cell* (PIC) codes solve the evolution of each charged particles (in fact treated as an ensemble of particles) under the effect electro-magnetic fields calculated from the Maxwell equations. This powerful technique and some important associated analytical studies have revolutionized this field of research. We now know that shocks behave differently depending on three main parameters: the shock velocity, the magnetic obliquity (the angle between the ambient (upstream) magnetic field and the shock normal), the ambient medium magnetization (the ratio of magnetic to matter rest mass energy density), see eg Sironi et al (2015). Low magnetization relativistic shocks are found to be efficient particle accelerators. However the acceleration is slow as the turbulence in these shocks is at scales smaller than the CR gyroradius, then ultra-relativistic shocks do not appear as sources of UHECRs. Mildly- or non-relativistic shocks can accelerate CR through the interplay of several self-generated instabilities. Among these, the non-resonant streaming instability (Bell 2004) seems the most promising and simulations using hybrid and magneto-hydrodynamics (MHD) models have confirmed that CR can trigger this instability while drifting in the ambient interstellar medium. PIC techniques are now combined with MHD to investigate long-term CR acceleration (van Marle et al 2018, 2019). Several studies using the same numerical tools have also uncovered magnetic reconnection as an important mechanism for particle acceleration.

Cosmic Ray transport studies: The transport of CR in the interstellar (or galactic) medium (ISM, IGM) is loosely constrained due to our poor knowledge of the magnetic turbulence which pervades these media. New data from AMS-02 as well as anisotropy studies by IceCube and HAWC require more refined models of particle transport (Lopez-Coto & Giacinti 2018). Here again MHD now combined with PIC techniques have been proved to be an efficient tool to study particle transport especially in the investigation of the turbulence self-generated by the particle drift with respect to the background medium. Recent detections of CR halos around some nearby pulsar also refined models including turbulence produced by CRs. It appears now that the release of CRs by their source is an important milestone in the CR journey in our Galaxy (Nava et al 2019)

5) Concluding remarks and recommandations

- Synergies and collaborations obviously exist between the researchers involved in the different sub themes discussed in this contribution. Some aspects of these synergies could however be strengthened. In particular there are little interactions between the phenomenologists involved in sub-GeV to multi-TeV cosmic-ray physics (mostly connected to direct measurement) and those involved VHE-UHE cosmic-ray physics (mostly connected to air shower detection experiments). These phenomenologist are however all interested in the origin of Galactic cosmic-rays and are using different but complementary approaches to tackle this fascinating question.
  One of the reasons of this relative lack of synergy/interaction is probably the historical absence of involvement of the French community in the cosmic-ray experiments in the energy range across the knee which would represent a very natural convergence point for the two above-mentioned communities. It is thus probably worth considering a future involvement in ambitious experiments such as LHASSO (which was considered a few years ago) if a critical mass of interested French researchers can be found.
- The recent years have seen a clear recognition and an improved support of IN2P3 for the theory. But it should be stressed that the techniques used by theorists in this field of research is similar to the one used in particle physics (scattering theory, renormalization techniques …) but applied to the context of plasma physics. Thus we expect Cosmic Ray studies to be fully considered by the institute as a proper research field in theoretical physics. This aspect remains to be clarified and improved for this prospective exercise.
- Particle acceleration and transport are very complex phenomena which require heavy numerical simulations. It is therefore important to increase the support to code developments and help to their scientific exploitation in order to compete efficiently on an international level and hence to join the effort with the gamma-ray community to interpret data (models of point sources and diffuse emission) from the next gamma-ray facilities, especially by the Cerenkov Telescope Array.
- The numerical tools developed in this field of research are also used by power laser and space plasma communities. It is therefore important to support inter-disciplinary research programs by the mean of specific actions.

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