SF2A 2009
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SUMMARY OF THE 2008-2009 PCHE WORKSHOPS ON THE GALACTIC DIFFUSE GAMMA-RAY EMISSION

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Abstract. We report on the two PCHE workshops on the *Galactic diffuse gamma-ray emission* held at LPTA-Montpellier in November 2008 and at LAPTH-Annecy in May 2009.

1 Introduction

The Galactic diffuse gamma-ray emission (DGRE) is a powerful tool to study cosmic ray (CR) physics in the MeV-TeV energy range on the one hand, and the interstellar medium (ISM) on the other hand, since it results from the interaction between both. It could also contain information on exotic physics, *e.g.* traces of dark matter (DM) annihilation, which could, however, only be interpreted so if the standard astrophysical processes are under control. Although the global understanding of the overall standard astrophysical processes at stake was considerably improved those last two decades, large theoretical and observational uncertainties still remain in the characterization of the different ingredients. Because the related expertnesses belong to rather separated scientific communities, it is worth trying to elevate the current understanding by means of an interdisciplinary framework. It is fortunate that French laboratories host experts in all of the relevant domains, and it is likely useful to federate an interdisciplinary network on this topic. This was precisely the aim of the two workshops that we recently organized at LPTA-Montpellier in November 2008, and at LAPTH-Annecy in May 2009, thanks to GDR PCHE fundings. These workshops gathered experts in the ISM, Galaxy dynamics and formation, CR sources and propagation, magneto-hydrodynamics (MHD), experimentalists as well as theorists. This offered a nice pedagogical platform to discuss the state-of-the-art in those different fields, during which students were fully involved, and allowed to settle down some specific issues and potential perspectives in the refinement of the techniques currently used in both theoretical and experimental analyses. Here, we summarize the most discussed points[1].

2 The ISM

A review on the ISM can be found in Ferrière (2001). The ISM constitutes the target "material" for interactions with CRs, which are at the origin of the DGRE. It is featured by a gas component, and a radiation component, the latter including (but not conventionally) the magnetic field. The interstellar gas (ISG) is involved (i) in nuclear interactions with CR nuclei that generate pions whose neutral component decays in gamma-rays of energies above $m_{\pi^0}/2$, and (ii) in electromagnetic interactions, mostly with the CR electrons through Bremsstrahlung processes that can also produce gamma-ray emission in the MeV-GeV energy range. The interstellar radiation field (ISRF) is due to the UV and optical starlight and to the IR dust emission concentrated in the Galactic disk, and seeds the inverse Compton (IC) interactions with CR electrons that also generate gamma rays; there is an additional contribution from the cosmic microwave background (CMB), which acts as an homogeneous target field for IC interactions. As observed from the Earth, the DGRE is the integral over the line of sight

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of all of these processes, and can be considered as a *partial* tracer of the ISM — since degenerate with the distribution of CRs. Therefore, in order to model, predict or understand the DGRE properly, it is important to characterize the ISM as precisely as possible, by describing its components in detail, in particular their density and their spatial distribution. The ISG exhibits different phases, and is mainly composed of hydrogen ($\sim 90\%$) in the form of neutral (HI), ionized (HII) and molecular gas (H_2), of helium ($\sim 10\%$) and of metals (gas or dust). Dust releases IR radiation that can feed the DGRE and affect the transport of CR electrons through IC scattering. The study of the different phases of the ISG unveils natural connections between them and the important role of turbulence to drive its structure evolution or to trigger phase transitions (Falgarone et al. 2007; Hennebelle et al. 2007). Very roughly, the gas distribution tracks the light distribution in the Galaxy, being concentrated in the bulge and the disk, and having its density decreasing rather quickly away from the disk or going towards the radial outskirts beyond the solar circle. A closer look involves spiral arms, which are more difficult to characterize observationally and to model (Pohl et al. 2008). Anyway, an accurate modeling of the ISG is necessary to derive consistent predictions of the DGRE, and is still to be investigated more deeply in the future. Viewed slightly differently, a good knowledge of CR physics could allow to infer interesting information on the interstellar gas from observations of the DGRE (*e.g.* Grenier et al. 2005). As radiative counterparts, the ISRF components mainly include the standard radiation generated by stars and dust, the CMB and the magnetic field. The former ones are responsible for IC processes with CR electrons. Aside from CMB, the ISRF components are spatially connected to the distribution of the ISM. As for the ISM, a good knowledge of the spatial features of the ISRF is important to control the IC processes and thereby the transport of CR electrons. The spatial distribution of the magnetic field is also an essential information regarding CR diffusion and synchrotron processes. It can be constrained from polarization measurements, but also from radio observations, which signs the synchrotron emission of CR electrons. As implicit above, emerges the need of a global picture of the Galaxy, wherein all components evolve in an intricate manner. There are already some promising studies on the way, relying on powerful numerical simulations, addressing *e.g.* the ISM phases (Fromang et al. 2006) or even the gaseous disk formation in the cosmological context (Agertz et al. 2009). CRs, which are described below, would be an additional component to consider within such frameworks. Observations of the DGRE provide a suited mean to test this global picture, complementary to other wavelengths.

3 CR sources and propagation

The understanding of the DGRE also implies that of CRs. CR physics involves the modeling of CR sources as well as CR transport in the ISM. Technically, the purpose is to predict the CR density and spectral features at any point $\vec{x}$ given an injection at any other source point $\vec{x}_s$. The propagation of Galactic CRs is well described phenomenologically since the early 1960's, though further important developments have followed (Ginzburg & Syrovatskii 1964; Berezinkii et al. 1990; Strong et al. 2007). It is mainly characterized by spatial diffusion due to scattering processes on moving magnetic turbulences that make the trajectories erratic, contrary to gamma rays that travel along geodesics. It is formally difficult to connect the spatial diffusion of CRs to the magnetic properties of the ISM because the latter are still not well understood. Instead, spatial diffusion is very often described by an isotropic and rigidity-dependent diffusion coefficient that one can constrain from both theoretical arguments and observational constraints; yet, it is still unclear whether or not diffusion proceeds isotropically (*e.g.* Marcowith et al. 2006). The spatial current of CRs is also characterized by convection that can be connected to galactic winds which drives flows of matter away from the disk in the vertical direction. Other important ingredients arising in the description of CR transport are the energy losses and reacceleration, which characterize diffusion in momentum space. The latter is related to spatial diffusion because also due to interactions with the moving magnetic scatterers. It depends on the diffusion coefficient and on the typical velocity of the scatterers, the Alfèn velocity in the frame of MHD; reacceleration is negligible above a few GV, typically. Energy losses turn out to play a major role for CR electrons, but have impact only on the low energy part of the spectrum for CR nuclei. These losses are due to convection, because of the adiabaticity of this phenomenon, to interactions with the ISG and to interactions with the ISRF (for CR electrons). A good description of the energy losses is therefore intimately related to that of the ISM. Finally, CR nuclei can also experience destructive nuclear interactions with the ISG, called spallation, or decay if instable (*e.g.* radioactive species). The full transport equation can be solved semi-analytically or numerically (for nuclei see *e.g.* Strong & Moskalenko 1998; Maurin et al. 2001; for electrons *e.g.* Moskalenko & Strong 1998; Delahaye et al. 2009) depending on the considered situations and on the assumptions. Except energy losses and spallations which are fixed by the description of the ISM and the interaction cross sections, the other transport parameters are usually constrained from observational data on CR nuclei. The characterization of CR sources remains an important challenge for the future, though significant progress has been achieved in the last two decades. Indeed, whereas it has been well established for a long time that Galactic sources are connected with supernova explosions, many uncertainties makes it difficult to feature these sources in details. Not only are the sources important as injecting CRs in the ISM, but also as contributing directly to the DGRE whenever unresolved. Basic principles of CR acceleration from shock waves in sources are understood (Malkov & O'C Drury 2001; Ellison et al. 2007), but being highly non-linear, this topic is still subject to intense research: the precise features of the CRs injected in the ISM are still lacking, from their relative composition and absolute density (*e.g.* electrons versus protons) to their spectral shape (*e.g.* acceleration efficiency, time evolution). It is obviously a complicated task since the source environment is likely to play an important role. Fortunately, considerable improvements in the observational devices, especially in X-ray and gamma-ray telescopes, have allowed very detailed multiwavelength analyses in the last decade, and to extract better constraints on source modeling. Nevertheless, there is still a crucial need of theoretical efforts in this domain. Again, numerical simulations can play an important role there, and some efforts are already made in that way (Ferrand et al. 2008). As said above, a global picture up to the Galactic scale would be very interesting because CR sources are expected to play an important role in the evolution of the ISM itself. This would permit many consistency tests, such as the spatial distribution of sources, its potential correlation with molecular clouds or other ISM phases, etc. Connected to this latter point, the study of interactions of CRs with molecular clouds at the vicinity of active sources offers an alternative way to survey both transport and acceleration processes (Gabici et al. 2009).

4 Experiments

The experimental landscape associated with the DGRE has undergone important improvements in the last decade, and is one of the main pillar for future theoretical developments. We have already emphasized the importance of multiwalength observations to better understand the ISM, the CR sources and propagation. Here we deliberately bias our review towards experiments in which French groups are involved. Since its launch in June 2008, the most efficient telescope to date to measure the gamma-ray sky in the energy range 10 MeV - 200 GeV, the LAT instrument onboard the Fermi satellite (Atwood et al. 2009), has already allowed the data analysis of the DGRE from a mid-latitude region (Abdo et al. 2009b). Aside from the obvious breakthrough that Fermi is about to offer thanks to the huge number of sources it will observe compared to its ancestor EGRET, Fermi is also able to measure the local CR electron flux with unprecedented statistics (Abdo et al. 2009a), and might even provide some information on CR nuclei (Lavalley & Piron 2008). Nevertheless, it will take years before a very detailed sky map is available, and many efforts in terms of gathering complementary information from other wavelengths, or in terms of theoretical model developments may be done in the meantime. At lower energy, the INTEGRAL satellite, which was devised to observe in the range $\sim$ 15 keV - 10 MeV, *i.e.* down to the hard X-rays, has already been used to feature the corresponding Galactic diffuse emission. The separation of the diffuse emission from point-sources was part of the challenges achieved from noteworthy upturns in the data analysis techniques (Bouchet et al. 2008). Among the broad information released from INTEGRAL data, the intense diffuse emission in gamma-ray around 511 keV detected in the Galactic bulge, involving the annihilation of electron-positron pairs at rest, is still unsolved, and is a nice example of the connection of the diffuse emission with CR propagation (Weidenspointner et al. 2008). At MeV energies and low latitudes, the DGRE is likely dominated by IC scattered photons, but predictions still hardly reach the measured intensities, though in better agreement with the latest INTEGRAL data than before, likely due to a better subtraction of point-sources. As regards the CR source studies, it is useful to recall that the INTEGRAL catalog is now rich of more than 400 objects (Krivonos et al. 2007). The data taking is programed until 2012. At ground, improvements in the detection and analysis techniques have made Cerenkov telescopes reach very good sensitivities and angular resolutions, allowing detailed studies of CR sources (Horns 2008). Among these experiments, HESS has been performing a survey of the Galactic plane for few years, leading to the detection of many (some extended, some even new) sources (Aharonian et al. 2005). In particular, this permitted to scrutinize astrophysical sites of CR interactions with molecular clouds (Aharonian et al. 2008b). HESS was also used recently to measure the CR electron flux on Earth (Aharonian et al. 2008a), unveiling a spectral cut-off around a few TeV. This demonstrates the potential of Cerenkov astronomy to deliver crucial information either for the understanding of CR sources, for the study of CR interactions with the ISM, and for that of very high energy CR electrons.

The analysis of the DGRE is still challenging because of the high level of systematic errors to control, but future developments in the analysis techniques as well as of Cerenkov arrays themselves, like the CTA project, will hopefully lead to interesting steps forwards in this domain (de Naurois & Rolland 2009). Coming now to CRs themselves, key measurements that provide powerful constraints on transport, whatever the model, are those of nuclei, more precisely of the ratio of secondaries to primaries. In particular sub-carbon to carbon, or sub-iron to iron ratios, are rather good tracers of the diffusion process, while radioactive species provide complementary information on different spatial scales. Most of experiments taking data on CR nuclei are balloon-borne experiments, like the CREAM experiment. The CREAM project corresponds to a series of flights using an apparatus designed to measure and identify CR nuclei with Z =1-26 and for energies in the range 1-1000 GeV/n. The data release of the Dec. 2008 flight is expected by the end of 2009, which will help reducing the experimental error bars compared to previous flights (Ahn et al. 2008). The measures can also be performed in space. The PAMELA satellite can measure the B/C ratio, but was more designed to observe light CR particles. Interestingly, since PAMELA data on the positron fraction were published (Adriani et al. 2009), it has become clear that the electron and positron component of CRs is still far from being understood accurately. Those CR electrons precisely provide an important contribution to the sub-GeV DGRE, and it could even help better understanding diffusion itself from its synchrotron emission at intermediate latitudes, as observed in radio — for instance, a lot can be learnt from the PLANCK satellite, which observes in the $\sim$ 10-850 GHz frequency band, in particular on the synchrotron Galactic foreground. While Fermi is also relevant in the observation of CR electrons, major improvements are expected with the installation of AMS02 onboard the ISS, foreseen in 2010. AMS02 offers a much better sensitivity compared to PAMELA, and was also designed to collect and identify CR nuclei up to $Z = 26$ in space with much better precision and statistics (Battiston 2007).

5 Conclusion

These workshops made emerge among the participants the will to maintain and even increase the efforts towards not only sharing knowledges between the different communities interested in the information DGRE may deliver, but also starting some new collaborations. We wish that this will be the case in the future, and that this dynamics will be fruitful. We thank all the participants and local organizers in Montpellier and Annecy, for the nice spirit they conveyed to the scientific (and other) discussions. Last but not least, we are indebted to the PCHE scientific committee for having supported our project.

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