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Cosmic rays, gamma rays, neutrinos and gravitational waves

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Summary. — This paper discusses the relation between the study of the fluxes of cosmic rays, gamma rays and neutrinos, and the connection of these observations with the newly born field of gravitational wave astronomy.

1. – Multi–messenger astrophysics

The discovery of cosmic rays at the beginning of the 20th century was the first glimpse of what is now known as the "High Energy Universe", the ensemble of the astrophysical objects, environments and mechanisms that generate or store very high energy particles. In recent years our understanding of these phenomena has made great progress thanks to studies performed using three "messengers": cosmic rays, gamma rays and neutrinos. Cosmic rays (CRs) are relativistic, electrically charged particles of different types: protons, nuclei, electrons, with smaller but very important contributions of antiprotons and positrons. The studies of these three messengers are intimately connected, and should be considered as the three faces of a single scientific field.

The relation between CRs , γ's and ν's is simple: the dominant source of high energy γ's and ν's is emission from CR particles. Gamma rays can be generated by relativistic hadrons (protons and nuclei) or charged leptons (electrons and positrons). In the first case the emission mechanisms are bremsstrahlung and Compton scattering (where the targets are the soft photons that form the radiation fields in the medium where the $e^\mp$ are propagating). In the second case the photons are generated in the decay of neutral pions ($\pi^0 \to \gamma\gamma$) and other unstable mesons created in the inelastic interactions of relativistic protons and nuclei, with a target that can be a gas of ordinary matter, or a radiation field. The hadronic mechanism is also a neutrino source, because the final state of hadronic interactions also contains particles that decay into ν's. The dominant channel is the chain decay of charged pions ($\pi^+ \to \mu^+\nu_\mu \to (e^+\nu_e\overline{\nu}_\mu)\nu_\mu$ and charge conjugate modes). The rates of production of the three pion states are approximately equal, and therefore the ν and γ emissions are of approximately the same size.

The only significant source of CRs that exists with certainty is the acceleration of electrically charged particles in astrophysical objects (or better "events", since in many cases the sources are transient). The interactions of these accelerated primary CR particles (p, e^- and most nuclei) can then generate gamma rays and neutrinos, and also other secondary CR particles (such as e^+, $\overline{p}$ and rare nuclei such as beryllium or boron). Understanding the properties of the high energy astrophysical sources is a fundamental goal of multi–messenger astrophysics.

The formation of electromagnetic fields sufficiently strong and extended to be able to accelerate particles to relativistic energies is often associated to violent astrophysical events (such as gravitational collapses or mergings of compact objects) where large masses undergo large accelerations. These events are therefore also very powerful sources of gravitational waves (GW), and are very important targets for the GW telescopes. The conclusion is that the high energy universe can be studied using not only the three messengers already listed (CRs, γ's and ν's), but also with a fourth messenger: gravitational waves, that can give unique information about the formation of the sources.

It is possible that acceleration is not the only source of very high energy particles and that a non negligible fraction has a different origin. If the dark matter (DM) is in the form of Weakly interacting massive particles (WIMPs), the self annihilation or decay of these particles generate fluxes of secondaries with an energy spectrum that extends to a maximum energy $E_{\max} \simeq M$ ($M/2$ in the case of decay). Theories based on Supersymmetry do predict the existence of a stable particle with a mass, that (assuming the validity of the concept of "naturalness") should not be much larger that the Weak mass scale (implying a mass for the DM particle of order $M \sim 10^2$–10^4 GeV). Supersymmetric scenarios are currently the object of a large and varied program of experimental studies. Another, more speculative possibility is that the universe contains super massive particles, with a mass of order of the Grand Unification scale ($M \gtrsim 10^{24}$ eV), that could perhaps also form a part or all of the dark matter. If these super–massive particles exist with a sufficiently large density and are unstable, they could generate observable fluxes of ultra high energy particles.

2. – Cosmic rays

It is important to discuss the present and future CR studies in the general context of multi–messenger astrophysics, and in particular together with the information obtained from the observations of γ and ν telescopes. Gamma rays and neutrinos propagate along straight lines, and therefore the angular distribution of their flux maps the space distribution of the emission. This allows to perform detailed studies of individual point-like or quasi point-like sources, and to follow their time evolution (when it is sufficiently fast). In the last decades, gamma ray observations in the GeV and TeV energy ranges have been living through a real "golden age", yielding important results that have deeply transformed our understanding of the high energy universe. Telescopes in space and at groud level have identified a large number of sources (over 3000 in the GeV range and approximately 200 in the TeV range) that belong to several distinct classes of astrophysical objects (supernova remnants, gamma ray bursts, pulsar wind nebulae, microquasars, active galactic nuclei, ...). The study of the structure and properties of these objects is currently a very rich field, with many open problems.

In contrast, the trajectories of (electrically charged) CRs are bent by magnetic fields, and this results in fluxes that are approximately isotropic and carry very little information about the space and time distributions of the sources. This is clearly a very significant limitation, however, the energy spectra of the CR particles encode very valuable information about the CR sources that is important for the understanding of the high energy universe and that is difficult to infer from γ and ν observations, as they are determined by the space and time averaged spectra released by the sources. The CR

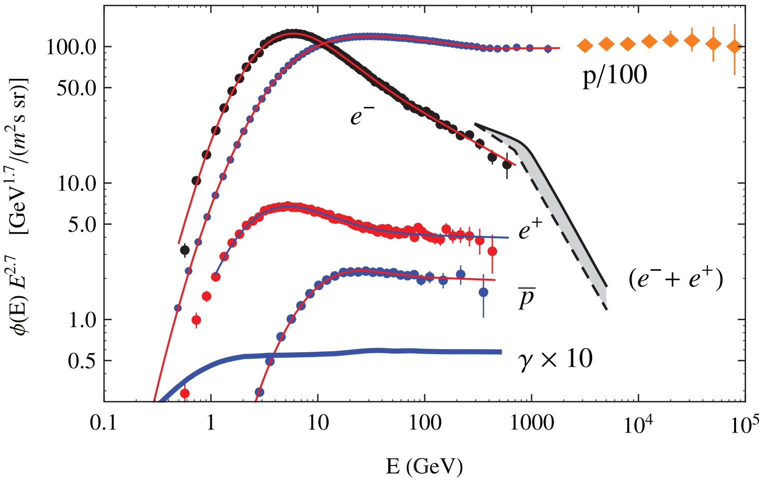

Fig. 1. – Energy spectra of different types of CR particles (p, $e^\mp$ and $\bar{p}$) (by AMS02 and CREAM). The measurements of the $(e^+ + e^-)$ flux have been obtained by the ground–based Cherenkov telescopes (HESS, MAGIC and VERITAS). The average diffuse Galactic gamma ray flux measured by the *Fermi* telescope is also shown. The p and γ spectra have been rescaled. For references see [1].

fluxes are also shaped by the properties of propagation of relativistic, electrically charged particles in Galactic and extragalactic space, and therefore also give unique information about the astrophysical magnetic fields.

A very compact summary of the main properties of the CR energy spectra is contained in figs. 1 (for lower energy) and 2 (for higher energy). A first, obvious, but very important point is that the CR spectra extend up to $E \simeq 10^{20}$ eV, an energy six order of magnitude larger that the highest observations of existing Cherenkov telescopes. The fact that the CR sources are capable of generating particles of such high energy is an essential constraint for the modeling of the sources.

2·1. *Galactic cosmic rays*. – The flux of Galactic CR of type j observable at a point $\vec{x}$ in the Galaxy can be written as the product

$$\phi_j(E,\vec{x}) \simeq \langle Q_j(E)\rangle \;\; P_j(E,\vec{x}), \tag{1}$$

where $\langle Q_j(E)\rangle$ is the space integrated and time averaged rate of release of CR particles of type j and energy E in the entire Galaxy, and $P_j(E,\vec{x})$ is a “propagation function” (with dimension time divided by volume) that encodes the residence time and confinement volume of CR of type j and energy E, and depends on the properties of CR propagation in the Galaxy(1). This equation illustrates the fundamental difficulty in the interpretation of the CR flux measurement: the disentangling of the effects of the sources and of propagation in the formation of the observed spectra.

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(1) In principle, it is possible that the observable CR flux receives significant contributions from one (or a few) near, young sources. In this case the (time averaged) stationary solution for eq. (1) is not a viable model.

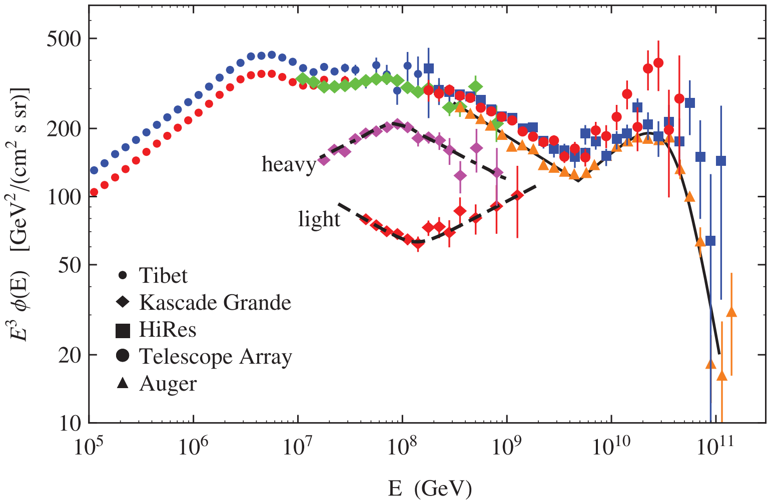

Fig. 2. – Measurements of the all-particle CR flux (shown in the form $E^3\phi(E)$ *vs.* E). For the Kascade–Grande data also measurements of the fluxes of events selected as "light" (p rich) and "heavy" (iron rich) are shown. For references see [2].

The determination of the (time averaged) source spectra for CR of different types: $\langle Q_p(E)\rangle$, $\langle Q_{e^-}(E)\rangle$, … released in interstellar space by the Galactic sources is obviously a problem of great importance. The most commonly accepted theory is that most of the Galactic CRs are accelerated in young SNRs, but there are also alternative hypothesis. It has been for example proposed that the dominant source of CR are GRBs, and an alternative possibility is that the main CR source is a single object, the supermassive black hole at the Galactic Center, during periods of enhanced activity.

Considering the "standard model" of CR acceleration in SNRs, at the present time the Milky Way contains a finite number of sources, each emitting spectra of γ's and ν's that are determined by the populations of relativistic particles contained in each source and by the properties and structure of the object (such as gas density or magnetic fields). The γ and ν emissions are directly observable at the Earth, but is far from easy, and strongly model dependent, to estimate from the ensemble of these observations, (that capture a single "snapshot" of the evolution for each source) the time integrated spectra of cosmic rays $[N_p^{s,\mathrm{out}}(E), N_{e^-}^{s,\mathrm{out}}(E), \ldots]$ that each source s will release in interstellar space during its activity. In fact, the observations show the existence very large differences in the γ emission of different SNRs that very likely reflect not only the differences in the properties of the sources and their environments, but also a strong time dependence of the emission. The measurements of the CR fluxes, that are determined by the space and time averaged spectra released by the sources are therefore of great importance to constrain the modeling of the sources. This study however requires a sufficiently good understanding of the properties of CR propagation in the Galaxy to estimate the Galactic source spectra from the CR observations.

Some crucial problems emerge naturally. The first one is the determination of the exponent of the source spectra for protons, nuclei and electrons. In the energy range $E \sim 10$–10^3 GeV the proton flux is reasonably well described by a power law with exponent $\alpha_p \simeq 2.7$–2.8, while the electron spectrum is significantly softer with an exponent $\alpha_e \simeq 3.1$–3.2 (see fig. 1). If the shape of the observable flux is modeled as the softening of a (power law) source spectrum because of propagation effects, the spectral indices of protons and electrons can be written as the sum $\alpha_p \simeq \alpha_p^0 + \delta_p$, and $\alpha_e \simeq \alpha_e^0 + \delta_3$, where $\alpha_{p,e}^0$ is the index of the source spectrum, and $\delta_{p,e}$ describes the energy (or rigidity) dependence of the propagation effects. A crucial task is the determination of the values of the exponents δ_p and δ_e, to establish if the difference in spectral shape between protons and electrons is determined by the sources, or by propagation effects.

A second problem that has an answer with broad and profound implications is the origin of the so called "knee" in the all-particle flux at energy $E_{\rm knee} \simeq 3 \times 10^{15}$ eV (see fig. 2). It is common to interpret this spectral structure as the manifestation of a maximum acceleration energy in the CR sources that has values confined to a very narrow range. The alternative hypothesis is that this knee is imprinted by propagation effects on a smooth source spectrum. The implications for the modeling of the sources are obviously very important. In the first case the Galactic CR sources must be "PeVatrons", reaching a maximum energy proton enegy of order 3 PeV, approximately equal in all objects. In the second case, the CR sources must be capable of reaching sigificantly higher energies, challenging theorists.

2˙2. *Positron and antiproton spectra.* – The study of the e^+ and $\overline{p}$ spectra is probably the topic in CR studies that has received most attention in recent years. This strong interest is a consequence of the fact that the antiparticle spectra are important probes to study the existence of DM in the form of WIMPs. Also the intriguing possibility that e^+'s are created and accelerated in astrophysical sources has been considered by several authors.

In the absence of such "exotic" mechanisms, the main source of CR antiparticles is their creation in the inelastic interactions of primary particles. The crucial question is then to determine if the observed e^+ and $\overline{p}$ fluxes are (or are not) consistent with the hypothesis that the standard mechanism of production is their only source. It is intriguing [1](2) that the observed fluxes of e^+ and $\overline{p}$ have the spectral shapes and the relative normalization that are consistent with the hypothesis that: i) they are created by the standard mechanism, and ii) the effects of propagation are equal for the two antiparticles ($P_{e^+}(E) \approx P_{\overline{p}}(E)$). These result can be most easily seen in fig. 1 noting that the e^+ and $\overline{p}$ fluxes for $E \gtrsim 20$ GeV, are power laws with the same spectral index and a ratio $e^+/\overline{p} \approx 2$ that is equal to the ratio of the source spectra. The simple, natural interpretation of this result is that e^+ and $\overline{p}$ are both of secondary origin, and that the propagation effects are small in size and approximately equal for both antiparticle types. Since the energy loss rate of relativistic $e^\pm$ is much larger than the loss rate of p and $\overline{p}$ (because of the contributions of synchrotron and Compton losses), this implies that the residence time of $e^\pm$ is sufficiently short so that the total energy loss remains negligibly small. It then also follows that the different spectral shape of p and e^- is generated by the sources and not determined by propagation effects. The alternative possibility requires the introduction of a new hard source of positrons. The clarification of this problem has broad and profound consequences.

2˙3. *Galactic/extragalactic cosmic rays.* – It is obviously of great importance to separate the populations of CRs generated by sources in our Galaxy and by extragalactic sources. It is firmly established that most of the lower energy particles are of Galactic

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(2) A more complete list of references can be found in refs. [1] and [2].

origin, and it is also very likely that the highest energy CRs are extragalactic. What the "transition energy" E^* is where the Galactic and extragalactic components are approximately equal remains controversial.

The determination of E^* is a task of crucial importance, because it provides an essential constraint on the properties of the Galactic and extragalactic CR sources. It is natural to expect that at the transition energy the CR energy spectrum should correspond to an hardening of the CR spectrum. Inspecting the all-particle spectrum in fig. 2 one can see that there is only one significant hardening feature in the all-particle CR flux, the so called "ankle" at $E_{\rm ankle} \simeq 4 \times 10^{18}\,$eV. The identification of $E_{\rm ankle}$ with E^* implies that some Galactic sources must be capable to accelerate CRs up to very high energy. Several theories predict however that E^* is at lower energy, and corresponds to a softening spectral feature. This requires some "fine tuning" of the shapes of the two components or the existence of some, yet not understood, physical mechanism, to have a sufficiently smooth transition. In the popular "dip model" introduced by Berezinsky and collaborators, the ankle is interpreted as an absorption feature (due to the effects of pair production interactions $p\gamma \to pe^+e^-$ acting on a proton-dominated extragalactic flux), and the extragalactic component becomes dominant at $E \simeq 10^{17}\,$eV, the energy of the so called "second knee".

2˙4. *CR Anisotropies.* – The study of the structure and rigidity dependence of the large scale CR anisotropies is a very important tool to understand the properties of CR confinement in the Galaxy. However the deviations from isotropy of the CR angular distributions are small and difficult to measure. The anisotropies remain below (or close) to the level of 10^{-3} at lower energy, and reach the level of $\sim 1\%$ for $E \simeq 10^{18}\,$eV and $\sim 4\%$ at the highest energies ($E \gtrsim 8 \times 10^{18}\,$eV). These effects remain unfortunately poorly understood.

An attractive possibility is that at very high rigidity ($E/Z \gtrsim 10^{19}$–$10^{20}\,$eV) the CR magnetic deviations, even for propagation across extragalactic distances, are sufficiently small to allow the identification of the sources, opening the window of "proton astronomy". Some intriguing hints of correlations between the directions of very high energy events and the positions of near Active Galactic Nuclei (AGN) have been obtained by the Auger observatory, but the results remain inconclusive. Another interesting effect is the possible signal (with 1.4% of probability) of an excess of events in a cone of 15° around the direction of Centaurus A, that at a distance of 4 Mpc is the AGN closest to the Earth. One can conclude that very large exposures at very high energy are necessary for the unambiguous imaging of CR sources.

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