Frascati Physics Series Vol. VVV (2004) pp.1-11
FRONTIER SCIENCE 2004, PHYSICS AND ASTROPHYSICS IN SPACE
Frascati, 14-19 June, 2004

PROPAGATION OF COSMIC RAYS AND DIFFUSE GALACTIC GAMMA RAYS

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Abstract

This paper presents an introduction to the astrophysics of cosmic rays and diffuse γ-rays and discusses some of the puzzles that have emerged recently due to more precise data and improved propagation models: the excesses in Galactic diffuse γ-ray emission, secondary antiprotons and positrons, and the flatter than expected gradient of cosmic rays in the Galaxy. These also involve the dark matter, a challenge to modern physics, through its indirect searches in cosmic rays. Though the final solutions are yet to be found, I discuss some ideas and results obtained mostly with the numerical propagation model GALPROP. A fleet of spacecraft and balloon experiments targeting these specific issues is set to lift off in a few years, imparting a feeling of optimism that a new era of exciting discoveries is just around the corner. A complete and comprehensive discussion of all the recent results is not attempted here due to the space limitations.

1 Introduction

Research in astrophysics of cosmic rays (CR) and γ-rays provides a fertile ground for studies and discoveries in many areas of particle physics and cosmology. Examples are the search for dark matter (DM), antimatter, new particles, and exotic physics; studies of the nucleosynthesis, acceleration of nuclei and their transport through CR spectra and composition analysis; the effects of heliospheric modulation; the origin of Galactic and extragalactic diffuse γ-ray emission; formation of the large scale structure of the universe as traced by γ-rays.

In its turn, the astrophysics of CR and γ-rays depends very much on the quality of the data and their proper interpretation. The accuracy of data from current CR experiments on interplanetary spacecraft such as Ulysses, Advanced Composition Explorer (ACE), and the two Voyagers, specialized balloon-borne experiments such as Super-TIGER, BESS-Polar, CREAM, and the new space-based missions such as Pamela and AMS far exceeds the accuracy of the current propagation models, of which the "leaky-box" model has remained one of the main research tools for the last 50 years. The new major γ-ray observatory GLAST will improve the sensitivity for the diffuse high-energy γ-rays produced in CR interactions in the interstellar medium (ISM) by a factor of 30. These near-future missions are specifically designed to search for the signatures of DM, search for antimatter, study the diffuse Galactic and extragalactic γ-rays, and provide outstanding quality data on γ-ray sources and CR species in a wide energy range. This presents a great opportunity for new discoveries that requires accurate, testable and readily accessible modeling to exploit.

On the other hand, the whole of our knowledge is based on measurements done only at one point on the outskirts of the Galaxy, the solar system, and the assumption that particle spectra and composition are (almost) the same at every point of the Galaxy. The latter may not necessarily be correct. γ-rays and radio-waves (synchrotron) are able to deliver the information directly from distant Galactic regions thus complementing that obtained from CR measurements. Some part of the diffuse γ-rays is produced in energetic nucleon interactions with gas via π^0 production, another is produced by electrons via inverse Compton scattering and bremsstrahlung. These processes are dominant in different parts of the spectra of γ-rays, therefore, if deciphered the γ-ray spectrum can provide information about the large-scale spectra of nucleonic and leptonic components of CR. Combining all the data collected by different experiments into a realistic interpretive model of the Galaxy, we have a better chance to understand the mechanisms of particle acceleration and the role of energetic particles in the dynamics and evolution of the Galaxy and make essential progress in related areas.

2 Cosmic Rays and Diffuse γ-rays

CR are energetic particles which come to us from outer space and are measured through satellites, balloon-, and ground-based instruments. The energy density of CR particles is about 1 eV cm^{-3} and is comparable to the energy density of interstellar radiation field (ISRF), magnetic field, and turbulent motions of the interstellar gas. This makes CR one of the essential factors determining the dynamics and processes in the ISM. The spectrum of CR can be approximately described by a single power law with index -3 from 10 GeV to the highest energies ever observed $\sim 10^{21}$ eV. The only feature confirmed by observations of many groups is a "knee" at $\sim 3 \times 10^{15}$ eV. Meanwhile, the origin of the CR spectrum is not yet understood.

The sources of CR are believed to be supernovae (SNe) and supernova remnants (SNRs), pulsars, compact objects in close binary systems, and stellar winds. Observations of X-ray and γ-ray emission from these objects reveal the presence of energetic particles thus testifying to efficient acceleration processes in their neighborhood [1]. Particles accelerated near the sources propagate tens of millions years in the ISM before escaping into the intergalactic space. In the course of CR propagation, secondary particles and γ-rays are produced, and the initial spectra of CR species and composition change. The destruction of primary nuclei via spallation gives rise to secondary nuclei and isotopes which are rare in nature, antiprotons, and pions ($\pi^{\pm}$, π^0) that decay producing secondary $e^{\pm}$'s and γ-rays.

Measurements of CR isotopic abundances are able to provide detailed information about the acceleration mechanisms, source composition, and processes in the ISM. However, the energy range below 20 GeV/nucleon is strongly affected by the heliospheric modulation, which is a combination of effects of convection by the solar wind, diffusion, adiabatic cooling, different kinds of drifts, and diffusive acceleration. The Pioneer, the two Voyagers, and Ulysses missions contributed significantly to understanding the global aspects of modulation and limiting the number of modulation models' free parameters, yet the relative importance of various terms in the Parker equation is not established and appears to vary significantly over 22 year period [2]. The most widely used are the spherically symmetric force-field and Fisk approximations [3].

The diffuse γ-ray continuum emission is the dominant feature of the γ-ray sky. It is an evidence of energetic CR proton and electron interactions with gas and the ISRF, and is created via π^0-decay, inverse Compton, and bremsstrahlung. This emission in the range 50 keV – 50 GeV has been systematically studied in the experiments OSSE, COMPTEL, and EGRET on the Compton Gamma-Ray Observatory as well as in earlier experiments, SAS 2 and COS B [4]. The observation of diffuse γ-rays provides the most direct test of the proton and electron spectra on the large Galactic scale.

3 Models of Cosmic-Ray Propagation

The analytical methods include the so-called leaky-box model and diffusion models (e.g., disk-halo diffusion model, the dynamical halo wind model, the turbulent diffusion model, reacceleration model). The leaky-box model treats a galaxy as a box with reflecting boundaries and small leakage, so that a particle travels across it many times before escaping. In this model the principal parameter is an effective escape length or grammage and particles, gas, and sources are distributed homogeneously. The leaky-box model has no predictive power or can even be wrong in cases when the distribution of gas or/and radiation field is important, such as radioactive isotopes (including K-capture isotopes), diffuse Galactic γ-rays, electrons, positrons (because of their large energy losses) etc. It also can not account for spatial variations of CR intensity. Diffusion models [5] are more realistic, distinguishing between the thin Galactic disk and extensive halo, often with different diffusion coefficient. The technique used, e.g., the weighted slab technique, which splits the problem into astrophysical and nuclear parts, may, however, give significant errors in some cases. The alternative way is the direct numerical solution of the diffusion transport equations for the entire Galaxy and for all CR species.

The modeling of CR diffusion in the Galaxy includes the solution of the transport equation with a given source distribution and boundary conditions for all CR species. The transport equation describes diffusion and energy losses and may also include [6] the convection by a hypothetical Galactic wind, distributed acceleration in the ISM due to the Fermi second-order mechanism, and non-linear wave-particle interactions. The boundary conditions assume free particle escape into the intergalactic space.

The study of stable secondary nuclei (Li, Be, B, Sc, Ti, V) allows one to determine the ratio (halo size)/(diffusion coefficient) and the incorporation of radioactive secondaries ($^{10}_{4}$Be, $^{26}_{13}$Al, $^{36}_{17}$Cl, $^{54}_{25}$Mn) is used to find the diffusion coefficient and the halo size [7, 8]. The derived source abundances of CR may provide some clues to mechanisms and sites of CR acceleration. However, the interpretation of CR data, e.g., the sharp peak in the secondary/primary nuclei ratio (e.g., B/C), depends on the adapted physical model. The leaky-box model fits the secondary/primary ratio by allowing the path-length distribution vs. rigidity to vary. The diffusion models are more physical and explain the shape of the secondary/primary ratio in terms of diffusive reacceleration in the ISM, convection by the Galactic wind, or by the damping of the interstellar turbulence by CR on a small scale.

K-capture isotopes in CR (e.g., $^{49}_{23}$V, $^{51}_{24}$Cr) can serve as important energy markers and can be used to study the energy-dependent effects. Such nuclei usually decay via electron-capture and have a short lifetime in the medium. In CR they are stable or live essentially longer as they are created bare by fragmentation of heavier nuclei while their β^+-decay mode is suppressed. At low energies, their lifetime depends on the balance between the processes of the electron attachment from the interstellar gas and stripping thus making their abundances in CR energy-dependent. This opens a possibility to probe the diffusive reacceleration in the ISM and heliospheric modulation [9].

The study of transport of the CR nuclear component requires the consideration of nuclear spallation, radioactive decay, and ionization energy losses. Calculation of isotopic abundances involves hundreds of stable and radioactive isotopes produced in the course of CR interactions with interstellar gas. A thorough data base of isotopic production and fragmentation cross sections and particle data is thus a critical element of models of particle propagation that are constrained by the abundance measurements of isotopes, antiprotons, and positrons in CR. Meanwhile, the accuracy of many of the nuclear cross sections used in astrophysics is far behind the accuracy of the current CR experiments, such as Ulysses, ACE, and Voyager, and clearly becomes a factor restricting further progress. The widely used semi-phenomenological systematics have typical uncertainties more than $\sim$30%, and can sometimes be wrong by an order of magnitude [10]; this is reflected in the value of propagation parameters.

Increasingly accurate balloon-borne and spacecraft experiments justify the development of sophisticated and detailed propagation models with improved predictive capability. Ideally, such a model has to incorporate all recent developments in astrophysics, such as detailed 3-dimensional maps of the Galactic gas derived from radio and IR surveys, the Local Bubble structure and local SNRs, the spectrum and intensity of the ISRF, Galactic magnetic fields, details of composition of interstellar dust, grains, as well as theoretical work on particle acceleration and transport in Galactic environments. A detailed gas distribution is important for accurate calculations of the spectra of $e^{\pm}$'s, radioactive species, and for calculation of γ-ray flux and skymaps from electron bremsstrahlung and from the decay of π^0's produced by CR interactions. The ISRF is essential for electron and positron propagation (energy losses) and γ-ray production by inverse Compton scattering. The magnetic field provides useful constraints on the electron spectrum via synchrotron emission, and may establish preferential directions of propagation of CR particles. Inclusion of the Local Bubble and SNRs enables us to study CR intensity and spectral variations in the local ISM.

A well-developed and sophisticated propagation model, in return, provides a basis for many studies in astrophysics, particle physics, and cosmology. The indirect DM search is a good example. A clear feature found in the spectra of CR antiprotons, positrons, or diffuse γ-rays would be a "smoking gun" for DM [11]; but nature is unlikely to be so cooperative. A more reasonable expectation is that the DM signature, if any at all, will be a weak broad signal on top of a background requiring a reliable propagation model to be able to discriminate the signal.

Modern computer codes incorporating recent developments in astrophysics and nuclear physics do exist. One example is GALPROP [8, 12, 13], a numerical model and a computer code (written in C++) of CR propagation in the Galaxy; this is the most advanced 3-dimensional model to date. The model is designed to perform CR propagation calculations for nuclei ($^1_1$H to $^{64}_{28}$Ni), antiprotons, electrons, positrons, and computes γ-rays and synchrotron emission in the same framework; it includes all relevant processes and reactions. The GALPROP model has been proven to be a useful and powerful tool to study the CR propagation and related phenomena. Its results (and the code) are widely used as a basis for many studies, such as search for DM signatures, origin of the elements, the spectrum and origin of Galactic and extragalactic diffuse γ-ray emission, heliospheric modulation etc. The GALPROP code, or components of it, are being used by the members of experimental teams, such as GLAST, AMS, Pamela, HEAT, ACE, TIGER, and requested by many other researchers world-wide.

4 Science Frontiers in Astrophysics of Cosmic Rays

4.1 Diffuse γ-rays and Cosmic-Ray Gradient

The puzzling excess in the EGRET data above 1 GeV relative to that expected [4] has shown up in all models that are tuned to be consistent with local nucleon and electron spectra [12, 14]. Is it a key to the problems of CR physics, an evidence of the Local Bubble, a signature of exotic physics (e.g., WIMP annihilation, primordial black hole evaporation), or just a flaw in the current models? This also has an immediate impact on the extragalactic background radiation studies since its spectrum and interpretation are model dependent. An apparent discrepancy between the radial gradient in the diffuse Galactic γ-ray emissivity and the distribution of CR sources (SNRs) has worsened the problem [12].

The puzzle of the "GeV excess" has lead to an attempt to re-evaluate the reaction of π^0-production in *pp*-interactions. A calculation made using Monte Carlo event generators to simulate high-energy *pp*-collisions confirmed previous results [15]. A parametrization [16] gives larger number of π^0's produced at high energies compared to a standard formalism [17] while consistent with pion data; its effect on diffuse γ-rays is not studied yet.

Another leading reason for the discrepancy discussed is that the local CR particle spectra (nucleons and/or electrons) may be not representative of the Galactic average. The local source(s) and propagation effects (e.g., energy losses) can change the spectrum of accelerated particles. A flatter Galactic nucleon spectrum has been suggested as a possible solution to the

"GeV excess" problem [15, 18]. This requires the power-law index of proton spectrum of about −2.4–2.5, however, it is inconsistent with measurements of CR $\bar{p}$ and e^+ fluxes [19]. Besides, the GeV excess appears in all directions [14] implying that this is not a feature restricted to the gas-related emission. A flatter (hard) electron spectrum, justified by the random nature of CR sources and large energy losses, may explain the GeV excess in terms of inverse Compton emission [20]. However, the required fluctuations are too large and the calculated spectrum of diffuse γ-rays is inconsistent with EGRET data above 10 GeV [14].

In the new analysis of the Galactic diffuse γ-ray emission [14], CR $\bar{p}$ data were used to fix the Galactic average proton spectrum, while the electron spectrum is adjusted using the spectrum of diffuse γ-rays themselves. The derived electron and proton spectra are found to be *compatible* with those measured locally considering fluctuations due to energy losses, propagation, or possibly details of Galactic structure. The effect of anisotropic inverse Compton scattering in the halo can increase the high-latitude Galactic γ-ray flux up to 40% [21]. The model shows a good agreement with EGRET spectra of diffuse γ-ray emission from different sky regions (<100 GeV). Some part of the excess can be associated with SNRs where freshly accelerated particles strike gas particles nearby producing harder γ-ray spectra [22]. The increased Galactic contribution to the diffuse emission reduces an estimate of the extragalactic γ-ray background [14]. The new extragalactic background shows a positive curvature, which is expected if the sources are unresolved blazars or annihilations of the neutralino DM [23].

The discrepancy between the radial gradient in the diffuse Galactic γ-ray emissivity and the distribution of SNRs [24], believed to be the CR sources, can be plausibly solved [25] if the $X_{\rm CO}$-factor ($\equiv N_{\rm H_2}/W_{\rm CO}$) increases by a factor of 5–10 from the inner to the outer Galaxy. The latter is expected from the Galactic metallicity gradient.

4.2 Secondary Antiprotons in CR

Secondary antiprotons are produced in the same interactions of CR particles with interstellar gas as positrons and diffuse γ-rays. Their unique spectral shape is seen as a key link between physics of CR and diffuse γ-rays and could provide important clues to such problems as Galactic CR propagation, possible imprints of our local environment, heliospheric modulation, DM etc.

New $\bar{p}$ data with larger statistics [26] triggered a series of calculations of the secondary $\bar{p}$ flux in CR. The diffusive reacceleration models have certain advantages compared to other propagation models: they naturally reproduce secondary/primary nuclei ratios in CR, have only three free parameters (normalization and index of the diffusion coefficient, and the Alfvèn speed), and agree better with K-capture parent/daughter nuclei ratio. The detailed analysis shows, however, that the reacceleration models produce too few $\bar{p}$'s [13] because matching the B/C ratio at all energies requires the diffusion coefficient to be too large. The discrepancy in $\bar{p}$ flux is ~40% at 2 GeV.

The difficulty associated with antiprotons may indicate new effects. It may indicate [13] that propagation of low-energy particles is aligned to the magnetic field lines instead of isotropic diffusion. If our local environment (the Local Bubble) influences the spectrum of CR, then the problem can be solved by invoking a fresh "unprocessed" nuclei component at low energy [27]; the evidence for SN activity in the solar vicinity in the last few Myr supports this idea. More intensive CR flux in distant regions will also produce more antiprotons and diffuse γ-rays [14].

The computed interstellar flux of secondary antiprotons can be used to test the models of solar modulation. Using a steady-state drift model of propagation in the heliosphere, the predictions are made for p's and $\bar{p}$'s fluxes near the Earth for the whole 22 year solar cycle [13, 28]; this includes different modulation levels and magnetic field polarities.

4.3 Indirect Searches for Dark Matter

The nature of the non-baryonic DM is a mystery. One of the preferred candidates for non-baryonic DM is a weakly interacting massive particle (WIMP). In most models the WIMP is the lightest neutralino χ^0 [29], which arises naturally in supersymmetric extensions of the Standard Model of particle physics. Another candidate is a Kaluza-Klein particle [30], a hypercharge B^1 gauge boson, whose thermal relic density is consistent with the WMAP measurements. Annihilations of DM particles produce leptons, quarks, gluons, and bosons, which eventually decay to ordinary particles. The DM particles in the Galactic halo or at the Galactic center [31] may thus be detectable via their annihilation products (e^+, $\bar{p}$, $\bar{d}$, γ-rays) in CR [32]. The approach is to scan the SUSY parameter space to find a suitable candidate particle to fill the excesses in diffuse γ-rays, $\bar{p}$'s, and e^+'s over the predictions of a conventional model. A preliminary results of the "global fit" to the e^+'s, $\bar{p}$'s, and diffuse γ-ray data simultaneously look promising [33].

5 Conclusion

The choice of topics discussed in this paper is personal and by no means complete. More complete list would include the origin of 511 keV line from the inner Galaxy, γ-ray bursts, ultra-high energy CR, as well as a more comprehensive discussion of the DM, SUSY, and dark energy. Other contributions to the Conference will fill these gaps.

This work was supported in part by a NASA Astrophysics Theory Program grant.

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