THE ASTROPHYSICS OF GALACTIC COSMIC RAYS

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The aim of the workshop series at the International Space Science Institute (Bern, Switzerland) in October 18-22, 1999, and May 15-19, 2000, was to examine the cosmic ray phenomenon in the context of our evolving understanding of the Galaxy as an astrophysical system. Observations of cosmic rays and theoretical models of their origin and propagation have been surveyed critically. The extend to which these reinforce, or conflict with other astronomical information about the Galaxy was a major theme of the workshop. Other themes were the extent to which Galactic-scale processes can be illuminated by studies of analogous heliospheric processes, and the identification of key questions for future investigations. The convenors, L. Drury, D. Ellison, J.R. Jokipii, J.-P. Meyer, D. Müller, and H.J. Völk have brought together physicists working in the fields of cosmic-ray origin and propagation, structure evolution and composition of the Galaxy and the interstellar medium, and relevant areas of radio, optical, X-ray and gamma-ray astronomy. The workshop sessions were divided into the themes of key observations on Galactic Cosmic Rays, lessons from the heliosphere, radiation from the Galaxy, structure of the interstellar medium, and theory. This book is organized correspondingly.

1. Key Observations from the Galaxy

To large extent, our understanding of the Milky Way Galaxy is determined from energetic particle observations, indicating its spatial, temporal (Mewaldt, 2001), and chemical (Connell, 2001; Wiedenbeck, 2001) evolution. However, many pecularities of Galactic Cosmic Rays need to be considered before drawing general conclusions. In particular, the light elements such as Be (Ramaty, 2001) have brought new information to cosmic-ray studies, specifically to the issue of the origin of the seed material of the cosmic rays. The primary nature of the Be evolution strongly suggests that supernova ejecta are the sources of this material. Relying on the observational evidence about the Li, Be and B Galactic evolution as well as about the distribution of massive stars, Parizot (2001) shows that most of the energetic bubbles responsible for the production of light elements must be accelerated

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inside superbubbles, as is probably the case for the standard Galactic cosmic rays as well. Simple energetics provide the most convincing argument that supernovae power the bulk of cosmic rays (Swordy, 2001). There is now strong observational evidence that the composition of the Galactic Cosmic Rays (GCRs) exhibits some significant deviations with respect to the abundances measured in the local (solar neighbourhood) interstellar medium (ISM) due to massive stars, particularly of the Wolf-Rayet (WR) type (Meynet *et al.*, 2001).

Cosmic Ray observations may solve the fundamental question whether the symmetry between matter and antimatter, which is evident on a microscopic scale, applies to the universe as a whole (Tarlé and Schubnell, 2001, and references therein). The detection of a single heavy nucleus would require the existence of an antistar. Current measurements constrain the $\overline{\mathrm{He}}/\mathrm{He}$ abundance ratio to values below 10^{-6}. Positrons and antiprotons are secondary products from collisions of high-energy cosmic rays with the interstellar medium (ISM). With improved balloon-borne spectral measurements, however, additional processes such as the annihilation of supersymmetric dark matter in the Galactic halo may be observable. Unfortunately, extragalactic cosmic rays, and thus extragalactic antimatter, cannot penetrate the barrier of intergalactic magnetic fields over cosmological distances.

It is speculated, however, that particles observed with very high energies of up to 10^{21} eV, far beyond the so-called "knee" at $\sim 10^{15}$ eV, are of extragalactic origin (see Müller, 2001, and references therein). The smooth spectrum below the "knee" is believed to represent Galactic particles accelerated by super-nova driven shocks. No process inside or outside the Galaxy is known that could accelerate cosmic rays to energies much beyond the "knee." Surprisingly, the spectral slope beyond the "knee" not only steepens, but flattens again at the so-called "ankle" at $\sim 10^{18}$ eV. Asymmetries observed at these energies (Uchihori *et al.*, 2000), where the particle gyroradii are of the order of the Galaxy's size, identify the particles still to be of Galactic origin. At even higher energies, an isotropic flux of particles is seen, which may indicate their extragalactic origin. An argument against this hypothesis is the fact that the "GZK-cutoff" (Greisen, 1966; Zatsepin and Kuzmin, 1966) has not been observed within the statistical uncertainty. This cut-off is due to energy losses of protons by photo-pion-production with the cosmic microwave background. This inhibits an extragalactic origin of cosmic rays with energies $> \sim 5 \times 10^{19}$ eV at larger distances than ~ 100 Mpc. Possibly, the observed particles are decay products of cosmological ultraheavy and ultrastable particles generated from topological defects in the early universe or from a primordial quantum field.

2. Lessons from the Heliosphere

Composition data of GCRs must be interpreted carefully according to experiences with energetic particle observations in the heliosphere (Mason *et al.*, 2001). Data from SWICS/ULYSSES (Gloeckler and Geiss, 1998) have fully confirmed the theory of Fisk *et al.* (1974) that pick-up ions derived from the interstellar gas, pre-accelerated inside the heliosphere and re-accelerated at the solar-wind termination shock (Pesses *et al.*, 1981), are the main source of the Anomalous Cosmic Rays (ACR). This fractionation occurs at interplanetary shocks such as those of co-rotating interaction regions (Balogh *et al.*, 1999) and coronal mass ejections (Bamert *et al.*, 2001). Not the bulk particles with about the typical solar wind speed, but the $1.8 - 2.5$ times faster suprathermal ion population, strongly dominated by interstellar pick-up ions, is the seed population that gets accelerated. This puts constraints on any interpretation of GCR abundances as indicators for chemical processing in the Galaxy, if other stars and their winds behave similarly. Anomalies may be reduced, though, when averaging the composition of many stars.

Meyer *et al.* (1997) proposed a completely new way of interpreting data on GCRs. It turned out that the abundance enhancements of elements compared to their solar system abundances are ordered by their mass-to-charge ratio, A/Q. Volatile elements show a stronger abundance variation with A/Q because they are evaporated first in explosive events and therefore accelerated in shocks as individual particles. Refractory elements remain condensed inside dust grains which are accelerated as single particles with large A/Q. This may explain why the abundances of the refractory elements from the Galaxy are observed to be relatively enriched by about one order of magnitude over their solar system abundances, but this enrichment varies only little among individual refractory elements.

The dynamics of dust particles in the heliosphere (Grün and Landgraf, 2001) may enable injection of complete grains into diffusive acceleration. Micron-sized or bigger dust particles reach speeds of $\sim$30 to 40 km/s at 1 AU due to solar gravity. Smaller particles that are generated close to the Sun can be driven out of the solar system by the radiation pressure. Solar UV radiation typically charges dust grains in the heliosphere to $+5$ Volts by the photo effect. Nanometer-sized dust stream particles have been found which were accelerated by Jupiter's magnetic field to speeds of $\sim$300 km/s. Furthermore, effects of the solar wind magnetic field on interstellar grains passing through the solar system have been observed.

3. Structure of the Interstellar Medium

The vertical equilibrium of the ISM is given by the balance of the vertical gravity with the gradients of the thermal and turbulent pressures of the gas components as well as magnetic and cosmic ray pressures (Parker, 1966, 1967; Hanasz and Lesch, 2001). Parker (1992) found that such a configuration is unstable with respect to buoyancy. The most recent model by Ferrière (1998) predicts stability only up to heights of 200 pc, corresponding to the height of our Sun. Hanasz and Lesch (2001) discuss in more detail how a helical structure of the magnetic field develops within $\sim$100 Myr and how the propagation of GCRs is influenced while they are in a state of dynamical coupling to the gas and the magnetic field in the Galaxy.

As Beck (2001) points out, the global structure of the regular Galactic magnetic field is not yet fully known. Unlike in external galaxies, several large-scale field reversals were detected, possibly due to a mixture of dynamo modes, or preserved chaotic seed fields, or large-scale anisotropic field loops. The mean *total* Galactic magnetic field strength is $6 \pm 2\mu$G locally and $\sim 10 \pm 3\mu$G at 3 kpc Galactic radius. The Galaxy consists of a thin disk surrounded by a thick disk of radio continuum emission of similar extent as in edge-on spiral galaxies. The thin disk has a magnetic field of quadrupole symmetry and a local *regular* field strength constrained to the range of $\sim 1 - 4\ \mu$G, while the thick disk may be of dipole type. The Galactic center region hosts highly regular fields of up to milligauss strength which are oriented perpendicular to the plane. The local regular field may be part of a "magnetic arm" between the optical arms.

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