SF2A 2008
C. Charbonnel, F. Combes and R. Samadi (eds)

DYNAMICAL EFFECTS OF COSMIC RAYS IN THE INTERSTELLAR MEDIUM

Marcowith, A.[1]

Abstract. We give a short review of the connection between cosmic-rays (CRs) and the macroscopic structures in the interstellar medium (ISM). Two complementary energy regimes provide information on the interaction of CRs with the interstellar matter. The low energy CR (LECRs) with $E \leq GeV$ usually dominate the energy density of the CR spectrum. The LECRs are of prime importance in the chemistry of diffuse and dark clouds. They can be investigated in the X and gamma-ray wavebands through the spallation reactions and iron fluorescence radiation. The highest energies (HECRs) with $E \gg GeV$ probe the ISM medium over larger scales. The recent detection of gamma radiation from the galactic ridge by the telescope Tcherenkov H.E.S.S. shows a non uniform CR distribution with respect to the local measurements. Some sites where the CRs should have a dynamical effect are finally briefly discussed.

1 Introduction

The Cosmic Ray spectrum has three main dimensions: a mass spectrum, an energy spectrum and an angular spectrum. The CR spectrum is composed of 99% of nuclei and 1% of electrons and positrons. About 89% of nuclei are protons, 9% are helium nuclei and about 1% of metals. CRs have a composition close to solar except for some particular elements produced by spallation reaction; the Lithium-Beryllium and Boron group and the sub-iron elements (Longair 1994). The energy spectrum at energies beyond the GeV can be described by a scale invariant spectrum up to the so-called CR knee at 3×10^{15}eV with an index $s \simeq 2.7$. Beyond, the spectrum softens with an index $s \simeq 3$. The highest energies show several substructures around 3×10^{17} eV and is likely associated with an extragalactic component (Nagano & Watson 2000). The spectrum seems to cut off at energies of a few 10^{20} eV (Abbasi et al 2008). Finally, the CR angular spectrum is isotropic to a level of 0.1% up to the CR knee (Iyono et al 2005). Beyond the Auger experiment has recently found some anisotropy (Abraham et al 2007). The galactic and extragalactic sources of the GeV-EeV component is still a matter of debate (Drury et al 2001, Berezinsky et al 2006). Several arguments (energy budget, diffusive shock acceleration, composition) favor the supernova remnants as a probable sources of the galactic CR component (GCR). At energies $E \leq$ GeV, the CR spectrum is modulated by the solar wind and the effective spectrum is unknown. We will see that several evidences exist for the presence of MeV CR particles in the ISM (see section 2). Higher energies (TeV-PeV) can be searched through the interplay of high energy instruments (see section 3).

The local energy density of CRs at energies close to 1 GeV is $e_{\rm CR} \simeq 1{\rm eV/cm}^3$. This energy density is of the same order of the energy density of the magnetic field and of the gas (Ferrière 2001). This fact has some important physical consequences on different domains of modern astrophysics. First as mentionned above, the assumption of an homogenous CR distribution applied all over the Galaxy implies that the supernova are the probable sources of CRs up to the knee or even a few hundred of PeV (even if no definite theoretical proof does exist). The high energy density of CRs is also important in the mechanism of the Parker instability (see Parker 1992). The CR pressure produces magnetic field loops necessary for the realisation of an $\alpha\omega$ dynamo, the principal mechanism of magnetic field generation in the Galaxy (see a review by Kulsrud 1999). The variations of CR pressure in the molecular clouds can also have an effect in the process of the cloud collapse in the star formation regions (see section 2). Finally, in some star forming regions, recent X-ray observations have concluded to an energy crisis; Cooper et al (2004) for instance reported that the mechanical energy injected by the stellar winds

[1] Laboratoire de Physique Théorique et d'Astroparticule
CNRS, Université Montpellier-II, place Eugène Bataillon, 34095 Montpellier Cédex, France

and the supernovae are not recovered in the kinetic energy of the observed expanding structures. Butt & Bykov (2008) argued that the missing energy can be injected into CRs and in turbulent motions.
The two next sections discuss observationnal evidences of the interaction of CRs with the ISM matter. The section 4 presents some aspects of the dynamical effects of CRs and discusses some interesting perspectives.

2 Low energy (MeV-GeV) CRs

2.1 Induced chemistry in the ISM

Several ion species produced in CR-ISM matter interaction are of prime interest in the chemistry of the ISM; H_3^+,HCO^+, CO, H_3O^+ .... For instance, H_3^+ is at the init of an important chain in interstellar chemical reactions:

$$H_2 \ + \ CR \rightarrow H_2^+ \ + \ e^- \ ,$$

$$H_2 \ + \ H_2^+ \rightarrow H_3^+ \ + \ H \ .$$

The H_3^+ abundances included in a network of chemical reactions allow the calculation of the local CR ionisation rate ξ (expressed in s^{-1}). Solar values are $\xi_\odot = 3 \times 10^{-17}$ s^{-1}. High ionisation rates typically $10 \times \xi_\odot$ are found in diffuse clouds (Mc Call et al 2003, van der Tak 2006), whereas low rates typically $\sim \xi_\odot/10$ have been found in some dark (opaque and dense) clouds (Caselli et al 2002). High irradiation rates have also been found in star forming or active regions ξPer and SgrB2 (Oka et al 2005). The factor 40 of enhancement of low energy CR irradiation in the central part of the galaxy corroborates the conclusions deduced from the diffuse TeV emission of the GC (Aharonian et al 2006) where a CR flux enhancement above 1 TeV by a factor 3-9 is found with respect to the local values (see section 3). There are however some possible biases to explain these high rates, noticably if the clouds are dynamically evolving (Lintott & Rawlings 2006). A possible explanation of the diffuse/dark clouds effect has been advanced recently by Padoan & Scalo (2005). The authors invoked the effect of the CR self-confinement associated with the generation of resonantly interactiong waves produced by the streaming instability. The LECR with a streaming velocity larger than the Alfvèn speed do generate Alfvèn waves, the scattering off the waves by the particles exclude the latter from the densest parts; the inner parts of a molecular cloud (Cesarsky & Völk 1978). Padoan & Scalo did found a CR density scaling $n_{\rm i}^{1/2}$ ($n_{\rm i}$ is the local ion density).

2.2 Spallation reactions

A possible signature of the acceleration of low energy particles in the ISM can be obtained from the interaction of CRs with the ambient medium. Several processes are associated with these interactions (see Tatischeff 2003). Energetic particles can produce continuum X-rays through Inverse Bremsstrahlung radiation (the interaction between an energetic ion and an electron) or by direct Bremsstrahlung radiation from electron/positron secondary pairs. The interaction produces also several X and gamma-ray lines: fluoresence of the Iron line (see the case of SgrB2 clouds treated in Park et al 2004), the nuclear lines excited by the CRs like ^{12}C producing a line at 4.4MeV or a line at 6.13 MeV for the oxygen 16, at 1.63 MeV for the Neon 20, at 0.845 MeV for the Iron 56 (Ramaty & Lingenfelter 1979). The gamma-ray continuum is produced by a combinaison of Inverse Compton, Bremsstrahlung radiation and neutral pion decay. Up to now any of these signatures have been found in the Galaxy (to the exception of X- and gamma-ray radiation from the Sun). However, some hints of CRs interaction have been observed again in molecular complexes in the Perseus OB2 region. In particular, Knauth et al (2000) did observed a ratio $[^7Li/^6Li] \sim 2$ in clouds close to the star ø Persei itself close a cluster of massive stars IC348 in the superbubble Perseus OB2. This ratio has to be compared to local meteoritical values close to 12. Such a ratio can be explained by the interplay of spallation reactions producing the ^7Li and ^6Li in important quantities. These radiation are now tracked by the INTEGRAL satellite and will be among the major scientific goals of the next generation of Compton telescopes.

3 High energy (TeV-PeV) CRs

There have been a recent revival interest of the expected signature of gamma-ray radiation produced by neutral pion decay from molecular clouds. This interest results from the last observations of the Tcherenkov telescopes and with the launch of the GLAST-Fermi satellite. The H.E.S.S. telescope has detected several supernova

remants (SNR) as well as diffuse radiation from the galactic ridge (see the review by Hinton et al 2006 and the references therein). Even if the origin of the gamma-ray radiation is still matter of debate (Inverse Compton radiation or neutral pion decay), several hints in favor of the interaction of the SNR with molecular clouds have been advanced (Aharonian et al 2008 and 2009 in the W28 and CTB37A cases respectively). The MAGIC telescope has recently detected some gamma-ray radiation from the SNR IC443 (Albert et al 2007). One way to ascertain the neutral pion decay origin is to produce comparitive maps in gamma-rays and in CO or to search for maser radiation. In particular several OH masers at 1720 MHz have been observed to be associated with TeV gamma-rays.
The penetration properties of CRs into molecular clouds have been investigated in a long series of work; Skilling & Strong (1976), Cesarsky & Völk (1978), Dogel' & Sharov (1990), Aharonian (2001). The effect is controlled by several processes: radiative/adiabatic losses, advection by the turbulent flow, diffusion into the magnetised medium, reacceleration by stochastic Fermi acceleration, the distance to the accelerator. Gabici et al (2007) have developped a phenomenological model of gamma-ray emission in a passive cloud embedded in a flux of CRs. The energy limit of the self-exclusion of CRs appears to depend on the cloud and turbulence parameters: the cloud density profile, the spectral index and level of the turbulence. If the gamma-ray as well as the secondary emission are not strongly sensitive to these parameters, the core emission appears extremely variable once a parameter study is undertaken. A typical core size of a pc can be resolved by Tcherenkov telescopes like H.E.S.S. and this investigation shows that TeV observations can serve as a tool to constrain the above parameters.

4 Dynamical effect of Cosmic-Rays: perspectives

The cosmic rays have an important dynamical action in the Galaxy since their energy density is approximately equal to the energy density of the galactic magnetic field and to the energy density of the interstellar gas. The CR pressure $P_{\rm cr}$ is essential in maintaining the equilibrium distribution of the gas and the magnetic field in the gravitational field above the galactic plane. The dynamical effects of CRs have also to be searched in the CR pressure gradient; i.e. in the force exerted on the magnetised fluid and not only in the local energy density of the particles. The dynamical role of CRs on the ISM structures is a subject still widely underdevelopped. It seems important to look after different situations depending on the distance of the source to the interacting site. One particular aspect connected with the work of Padoan & Scalo (2005) is the induced effect of a strong CR gradient on the dynamics of the MC core. In effect, the transition from the diffuse to the dark part of the cloud marks the position of the maximum reflexion of the CR by the self-generated waves. The position coincides also with the strongest CR gradient. The pressure gradient on the core collapse process is still to be clarified. But this effect is likely strongly dependent on the CR diffusivity in the clouds still badly known. The distance of the cloud to the CR source also dictates the main instability at the origin of the interaction; the cloud is then active or passive.

Snodin et al (2007) did investigated in a general way the effect of the CR diffusivity on macroscopic structures of the ISM. This diffusivity depends strongly on the CR spatial diffusion coefficient parallel and perpendicular to the mean magnetic field. The coefficients rely on the local properties of the turbulence. Because of this diffusive properties, the CR gas is generally found to be more uniformly distributed than the thermal gas and the magnetic field. A connexe aspect is the loosely known properties of the CR diffusion in the Galaxy. The secondary to primary ratios indicate the CR diffusion coefficient at energies of $\sim GeV$ is around $D_0 \simeq 10^{28}$ cm^2/s. However recent developments in theory of magnetohydrodynamical (MHD) turbulence find anisotropic solutions where most of the energy cascade proceeds perpendicularly to the mean magnetic field (Goldreich & Sridhar 1995 and S.Galtier in these proceedings). This type of turbulence has been shown to be highly inefficient to confine the CRs (Yan & Lazarian 2004) precisely because of this anisotropy; both linear and non-linear calculations of wave-particle interaction give estimations of the diffusion coefficients $D \gg D_0$. A correct calculation of the dynamical role of the CRs strongly depends on a better understanding of their interaction process with the electromagnetic instabilities pervading the interstellar space.

5 Conclusion

The CRs spectrum is now investigated from the MeV to Eev range. Only (till the exploration of the local ISM by the Voyager I and II missions) indirect measurements through the ionisation of the molecular clouds or the spallation reactions do probe the CR spectrum at low energies. At higher energies, the recent experimental improvements the Tcherenkov telescope technics as well as the launch of the GLAST-Fermi satellite allow (or will allow) a detailed probe of the interaction of CRs with large scale structures in the ISM. The H.E.S.S.experiment has already shown a non uniform distribution at high energies with an enhanced flux from the galactic ridge. The dynamical effects of CRs have been investigated mostly in the context of the so-called Parker instability. It however appears that the CR gradients close or far from the sources may induce important effects in the dynamical evolution of the structures in the ISM especially in connection with the star formation cycle.

The author thanks P. Hennebelle, K. Ferrière and C. Joblin for the organisation of the interdisciplinary meeting on the dynamical processes in the universe held during the SF2A 2008 workshop.

References

Abbasi, R.U. et al, 2008, PRL, 100, 1101

Abraham, J. et al, 2007, Science, 318, 938

Aharonian, F.A. et al 2009, accepted.

Aharonian, F.A. et al 2008, A&A, 481, 401

Aharonian, F.A., 2001, SSR, 99, 187

Albert, J. et al, 2007, 664, L87

Berezinsky, V. et al, 2006, PRD, 74, 043005

Butt, Y. & Bykov, A., 2008, ApJ, 677, L21

Caselli, P. et al, 2002, ApJ, 565, 344

McCall, B.J. et al, 2003, Nature, 422, 500

Cesarsky C.J. & Völk, H.J., 1978, A&A, 70, 367

Cooper, R.L. et al, 2004, ApJ, 605, 751

Dogel' V. & Sharov, G.S., 1990, A&A, 229, 259

Drury, L.O.'C. et al, 2001, SpSR, 99, 329

Ferrière, K., 2001, RMP, 73, 1031

Gabici, S. et al, 2007, ApSS, 309, 465

Goldreich, P. & Sridhar, S., 1995, ApJ, 438, 763

Hinton, J.A. et al, 2006, JPhCS, 54, 140

Iyono A. et al, 2005, proceedings of the 29^{th} ICRC conference, 101

Knauth, D.C. et al, 2000, Nature, 405, 656

Kulsrud, R., 1999, ARA&A, 37, 37

Lintott, C.J. & Rawlings, J.M.C., 2006, A&A, 448, 425

Longair, M.S., 1994, High energy Astrophysics, Cambridge university press.

Oka, T. et al, 2005, ApJ, 632, 882

Nagano M. & Watson, A.A., RMP, 72, 689

Padoan, P. & Scalo, J., 2005, ApJ, 624, L97

Park, S. et al, 2004, ApJ, 603, 548

Parker, E.N., 1992, ApJ, 401, 137

Ramaty, R. & Lingenfelter, R.E., 1979, Nature, 278, 127

Skilling, J. & Strong, A.W., 1976, A&A, 53, 253

Snodin, A.P. et al, 2006, MNRAS, 373, 643

van der Tak, F.F.S. et al, 2006, A&A, 454, L99

Tatischeff, V., 2003, EAS Publications Series, Volume 7, 2003, Final Stages of Stellar Evolution. Edited by C. Motch and J.-M. Hameury,

Yan H. & Lazarian, A. 2004, ApJ, 614, 757