Chapter 2
Cosmic Ray Diffusion in the Galaxy

2.1 Introduction

In this chapter I will describe the physics that stands behind the problem of CR propagation.

- Since the battlefield in which CR propagation takes place is the interstellar medium (ISM) of our Galaxy, I will first present a complete description of the Galactic environment and its components, with particular attention to the interstellar gas, the magnetic field (related to CR diffusion and spallation) and the distribution of pulsars and Supernova Remnants (related to CR origin); I will point out the deep interplay that exist between these components that continuously interact one another: the gas triggers star formation, massive stars quickly generate Supernova explosions that accelerate CRs, the gas returns back again in the ISM and the released energy triggers the turbulence that is responsible of the CR random walk.
- With this scenario in mind, I will treat in a formal way the problem of CR propagation in the Galactic plasma as a kinetic physics problem and I will show that the interaction with CRs with the magnetised medium that permeates the Galaxy is naturally described by a diffusion-reacceleration equation.

2.2 History of CR Measurements

It took almost 40 years to understand what Cosmic Rays actually *are*.

The first signature of their existence was discovered in 1912 by Victor Hess, who was awarded with the Nobel prize for that. Hess observed that the level of ionisation in the atmosphere decreased with elevation up to about 1,000 m (as expected if the only source of ionizing radiation were natural radioactivity on Earth surface) but, above that altitude, it increased considerably, and at $\simeq$5,000 m he measured a value several times that observed at sea level: his conclusion was that there was some kind of unknown high energy radiation penetrating the atmosphere from outer space. His

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discovery was confirmed by Robert Millikan in 1925, who gave the radiation the name *Cosmic Rays* (CRs).

For many years after this important discovery the cosmic origin of the radiation was in doubt: the increased ionisation rate could be due, for example, to some kind of radioactive emanation from the upper atmosphere. Moreover, the radiation was believed to consist of γ rays, since at that time gamma radiation was believed to be the most penetrating.

Only after the discovery of the geomagnetic effect in 1927 it was clearly shown that CRs were charged particles. A complete picture of the composition of CRs was obtained at the end of the 1940s, when it was clear that they were mainly composed of protons, that all heavier nuclei were present in minor quantities, and that also relativistic electrons contributed to the radiation in a quantity that did not exceed 1%.

During the 1930s and the 1940s particle physicists were very interested in CRs and several new particles were discovered in the cosmic radiation, e.g. the positron (1932, Carl Anderson) and the muon (1936, Carl Anderson); on the other hand, the importance of CRs for astrophysics was not completely understood and little was known on their origin.

Enrico Fermi gave a very important contribution to the Astrophysics of Cosmic Rays when he proposed in 1949 a hypothesis on their origin [1]. The idea is that charged particles may be reflected by the moving interstellar magnetic fields either gaining or losing energy, depending on whether the magnetic "mirror" is approaching or receding. Since in a typical environment the probability of a head-on collision is greater than a head-tail one, the particles would, on average, be accelerated. This random process is now called *second-order Fermi acceleration* because the mean energy gain per bounce depends on the square of the mirror velocity.

In 1977 theorists showed that Fermi acceleration by Supernova remnant shocks is particularly efficient, because in this case the motions are not random. In this new mechanism, a charged particle ahead of the shock front can pass through the shock and then be scattered by magnetic inhomogeneities behind it; the particle gains energy from this bounce and comes back across the shock, where it can be scattered by magnetic inhomogeneities ahead of the shock. This enables the particle to bounce back and forth again and again, gaining energy each time. Because the mean energy gain depends linearly on the shock velocity, this process is now called *first-order Fermi acceleration* and is believed to be the mechanism that permits CRs to reach the very high energies recorded by the experiments.

Another important step forward was in the early 1950s when the synchrotron nature of a large part of cosmic radio emission was established: as a result, it became possible to obtain information of the leptonic component of CRs through the Galaxy: in this way the connection between CR science, Astrophysics and Astronomy was strengthened by a large amount.

In more recent times, CR Astrophysics has evolved a lot, and CR propagation has been studied extensively through numerical simulations; moreover, the development of gamma astronomy with the pioneering COS-B mission (1975), the very important EGRET satellite mission (1991–2000) and now Fermi-LAT (launched in 2008 and still operating) permitted to obtain more and more detailed maps of the Galaxy in gamma rays, tracing therefore the CR interactions through the Galaxy.

Nowadays, CRs are considered with interest also by particle physicists once again. In fact one of the most fascinating open problems in Physics is the existence of Particle Dark Matter, a hypothesized gas of neutral weakly interacting particles that would account for the unobserved mass of the Galaxy and can only be inferred from dynamical calculations: many authors believe that the signature of the existence of these new particles can be found in CR spectra. This issue is currently under debate; a Dark Matter interpretation of CR measurements is today less appealing than a couple of years ago for many reasons (I will be more precise in the forthcoming chapters); nevertheless, this possibility increased the interest on a problem which is relevant on its own: the accurate and self-consistent prediction of all observed fluxes of CR electrons, positrons, antiprotons and light nuclei of astrophysical origin; indeed, any excess with respect to these predictions can be easily interpreted in terms of annihilation or decay of exotic particles into standard particles, although it is quite difficult to disentangle such an explanation from alternative scenarios of astrophysical origin.

In order to predict CR fluxes and spectra it is crucial to understand the CR propagation in the Galactic magnetic field, the distribution of CR sources, and therefore a detailed knowledge of the structure of the Galaxy is required. In the following paragraph I will present a short review on the main properties of our Galaxy together with a brief history of the most important discoveries in Galactic astronomy and astrophysics. Then, in Sect. 2.4 I will derive the equations describing CR propagation in such an environment.

2.3 The Interstellar Environment of Our Galaxy

2.3.1 Introductory Considerations

The word *Galaxy* derives from the ancient Greek term $\gamma\alpha\lambda\alpha\xi\acute{\iota}\alpha\varsigma$ literally meaning *Milky* (so it is really a synonym of Milky Way): in fact, it appeared to the naked eyes of a terrestrial observer as a faint band of diffuse white light stretching all the way around the sky. For a great number of centuries little was known about its actual nature, which nevertheless was guessed by many philosophers and astronomers: e.g. the Greek philosopher Democritus (450–370 B.C.) proposed that it could consist of distant stars, and the Andalusian astronomer Ibn Bājjah (Twelfth century) said that it was made up of many stars that almost touch one another. However, the actual proof of the actual composition of the Milky Way came in 1610 when Galileo Galilei with the help of the telescope finally discovered that it is actually composed of a very large number of faint stars.

A more refined comprehension of the structure of our Galaxy came much later, when Harlow Shapley (1885–1972) began to study globular clusters and noticed that, unlike ordinary stars, they do not spread uniformly along the Milky Way, but concentrate instead towards the direction of the Sagittarius; he also found that they have a roughly spherical distribution, the center of which, he argued, should approximately coincide with the center of the Galaxy itself: these observations led him to the important conclusion that the Sun is located very far from the Galactic center. Further kinematic studies by Bertil Lindblad (1895–1965) and Jan Oort (1900–1992) supported this result.

Nowadays, it is commonly accepted that we live within a very large system of stars called the Galaxy, similar to billions of other similar systems existing in the observed Universe. The Galaxy consists of a thin disk with radius $\simeq$25–30 kpc and thickness $\simeq$400–600 pc, and the faint band that originated the term Milky Way is simply the disk seen transversally; there is also a spherical system which is itself composed of a bulge with radius $\simeq$2–3 kpc and a dark matter halo extending out to more than 30 kpc away from the center. The position of our Solar System is in the disk, $\simeq$15 pc above the midplane and $\simeq$8.5 kpc away from the center (see [2] and references therein). The stars belonging to the disk rotate around the center in nearly circular orbits; at the Sun's orbit, the rotation velocity is $\simeq$220 km/s: such a speed corresponds to a rotation period of about 240 million years. Disk stars also have a velocity dispersion that causes them to oscillate about a perfectly circular orbit, both in the Galactic plane and in the vertical direction. Instead, the stars that are in the bulge and in the halo rotate more slowly and often have eccentric trajectories. Radio-astronomical observations of interstellar hydrogen indicate that the Milky Way possesses a spiral structure: this is known since the pioneering works of J. Oort [3]; moreover, recent infrared images of the Galactic center region clearly display the signature of a bar: in Fig. 2.1 I put an illustrative image of a recently hypothesized barred spiral pattern based on very recent infrared observations (see e.g. [4, 5]) (Fig. 2.2).

2.3.2 *The Interstellar Gas*

It is important for our purposes to point out that the Galaxy is not only made of stars: indeed the environment in which CR propagation—which is the main topic of our work—takes place is the interstellar medium. It was evident from the first long-exposure photograph of the Galaxy taken by Edward Barnard (1857–1923) that several *dark zones* are present along the Milky Way and it was soon realized that these apparent holes in the star distribution are due to the presence, along the line of sight, of *clouds* of interstellar matter that obscure the starlight coming from behind. To be precise, the dust contained in these clouds is actually responsible for the absorption and scattering of photons coming from background stars, and therefore for their removal from the line of sight. Further studies demonstrated how the space between these very dense clouds was itself filled with a less opaque interstellar gas.

Today we know that interstellar matter contains about 10–15 % of the total mass of the disk. This gaseous, dust-bearing material concentrates near the plane and along

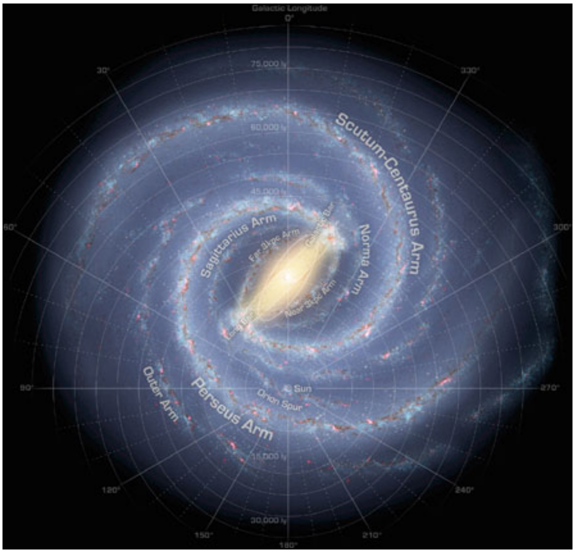


Fig. 2.1 Artist's view of a possible configuration of the Milky Way barred spiral pattern. Taken from the Astrophysical Picture of the Day (APOD) of June 6th, 2008 `http://apod.nasa.gov/apod/ap080606.html`. Illustration Credit: R. Hurt (SSC), JPL-Caltech, NASA. Notice that the Sun is located in an interarm region called *Orion spur* where some important star formation regions—e.g. Orion Nebula—are located (See Sect. 5.7.1 for a discussion on the role of this region on CR propagation). The two main arms are the Sagittarius and Perseus arms. This proposed pattern is slightly different from previous studies in which a four-arms structure was considered: the other two arms (Sagittarius–Carina and Norma) appear in this study as minor arms

the spiral arms and plays an important role in CR physics and in the whole field of high energy astrophysics since

- The magnetic field which is trapped inside the ionized part of this gas is responsible for CR diffusion, as we will see in the forthcoming paragraphs.
- The interaction of CRs with this material, through the process of *spallation*, originates secondary CRs of lower mass; the comprehension of this phenomenon is very important because secondary cosmic ray observations are used to test CR propagation models, as we will see in Chap. 4.
- Finally, the interactions of CR protons, helium, and heavier nuclei with IS gas creates pions; neutral pions decay forming gamma-rays, so a relevant portion of the gamma ray emission of the Galaxy actually traces the spatial distribution of the interstellar medium, as we will see in Chap. 6.

The interstellar gas appears to be very inhomogeneous: half of its mass is concentrated in discrete clouds which occupy a very small portion of the total volume (about 1%).

The interstellar gas can be subdivided in three *phases*:

(a) **(b)**

Fig. 2.2 **a** One of the largest star forming regions ot our Galaxy, the Carina molecular complex. The super-massive star Eta Carinae (more than 100 solar masses) is one of the most energetic ones in the Galaxy; the Keyhole Nebula—discovered by Herschel in the nineteenth century—also houses several of the most massive stars known; the entire Carina Nebula is over 300 light-years wide and is located about 7500 light-years away in the constellation of Carina. This is the most detailed image of this region ever taken: it is actually a composition of 48 high-resolution frames taken by the Hubble Space Telescope two years ago. Image taken from `http://apod.nasa.gov/apod/ap090524.html`. Credit: NASA, ESA, N. Smith (U. California, Berkeley) et al. and The Hubble Heritage Team (STScI/AURA). **b** We show here a 2 light-years wide *pillar* of gas and dust within the giant Carina complex. The outlines are shaped by the winds and radiation of the young and hot massive stars already present in the Carina region; the interior of the structure, instead, hosts several stars in the process of formation, that are revealed in the more penetrating image in the lower panel, taken in the Infrared band, where also two narrow jets blasting outward from an infant star can be seen. Both visible light (*upper*) and near-infrared (*lower*) images were made using the Hubble Space Telescope's newly installed Wide Field Camera 3. Image taken from `http://apod.nasa. gov/apod/ap091001.html`. Credit: NASA, ESA, and the Hubble SM4 ERO Team

- **Molecular gas**. This phase presents the highest level of clumpiness, since it is mostly confined in very cold and dense complexes called *molecular clouds*. These clouds are very cold ($\sim$10 K) and the densest regions within them can reach a number density $\sim 10^6\,\mathrm{cm}^{-3}$, which is extremely tenuous for terrestrial standards (14 orders of magnitude smaller than the average density of the lower atmosphere) but quite large if compared to the typical value of the insterstellar matter ($\sim$0.1–1 cm^{-3}). As we will see below, these objects play a crucial role in the Galactic "ecosystem" since they are the typical environment where star formation occurs. As far as chemical composition is concerned, the molecular gas mainly consists of Hydrogen; unfortunately the H_2 molecule is not directly observable both at optical and radio wavelengths: since it does not possess a permanent electric dipole moment and has a very small moment of inertia, all its permitted transitions lie outside the observable domain. The CO molecule, instead, has a rotational transition at a radio wavelength of 2.6 mm: for this reason, the corresponding emission line has become the primary tracer of molecular interstellar gas. CO radio surveys permitted to reconstruct three-dimensional maps of the molecular Hydrogen distribution through the Galaxy: this is not an easy task since, for each line of sight, it requires to analyse the CO emission spectrum, convert doppler shifts into relative velocity, and—knowing the Galactic rotational curve—mapping each part of the spectrum to a position in the Galaxy. I will go through all the details and explain the tricky aspects of these procedures in Chap. 6.

An important milestone in the history of this kind of observations was the complete CO survey of the whole Galaxy (described in [6]) based on a combination of data from the Millimeter-wave Telescope at Cerro Tololo (Chile) and the Columbia Telescope in New York City; using this important dataset Bronfman et al. [7] were able to derive the radial and vertical distribution of molecular gas in the Galaxy; in Fig. 2.5 the radial gas distribution is shown together with models for pulsar and OB star distribution; concerning the vertical one, it is generally modelled as a Gaussian: $\mathrm{n_{gas}} \propto \exp\left[-(z - z_0(R))^2 \cdot \ln(2)/z_{1/2}(R)\right]$, with the height scale $z_{1/2}(R)$ ranging from 58 to 83 pc in the inner Galaxy (being 80 pc at Solar position). More recently H. Nakanishi and Y. Sofue [8] computed a 3D map of the molecular and atomic gas in our Galaxy, revealing hints of the spiral arms structure; an even more detailed work was performed by M. Pohl et al. [9] who derived a 3D distribution of the molecular gas that points out, as supported by many radio observations, the presence of a bar besides the spiral pattern: this is one of the most accurate mapping of the interstellar gas in our Galaxy computed so far. These models are shown in Fig. 2.3.

- **Atomic gas**. The neutral phase of Hydrogen is not observable in the optical wavelength: particle collisions are so infrequent in the interstellar environment that nearly all H atoms have their electron in the ground energy state, and so all electromagnetic transitions between the ground level and an excited state lie in the UV (Lyman series). Neutral Hydrogen (HI) is therefore observed with radio telescopes: in fact, the interaction between the magnetic moment of the electron and that of the proton leads to a splitting of the electronic ground level into two extremely close energy levels, in which the electron spin is either parallel (upper level) or antiparallel (lower level) to the proton spin: the transition between these levels results in a 21 cm line that lies in the domain of Radio Astronomy. Nowadays, 21-cm emission line measurements covering the whole sky have been able to yield the Hydrogen space-averaged density as a function of position in the Galaxy. These maps show how HI too is organized in a spiral pattern, like H_2, and also its structure is quite complex, with overdensities and holes: for example, our Solar System itself is now believed to lie in a sort of cavity with a noticeable underdensity of neutral Hydrogen (the so called *local bubble*), whose origin is likely to be connected with the Supernova explosion that originated the nearby Geminga pulsar.

  Concerning large-scale distribution (see [2] and references therein) HI extends up to 30 kpc away from the Galactic center, and the vertical distribution is broader

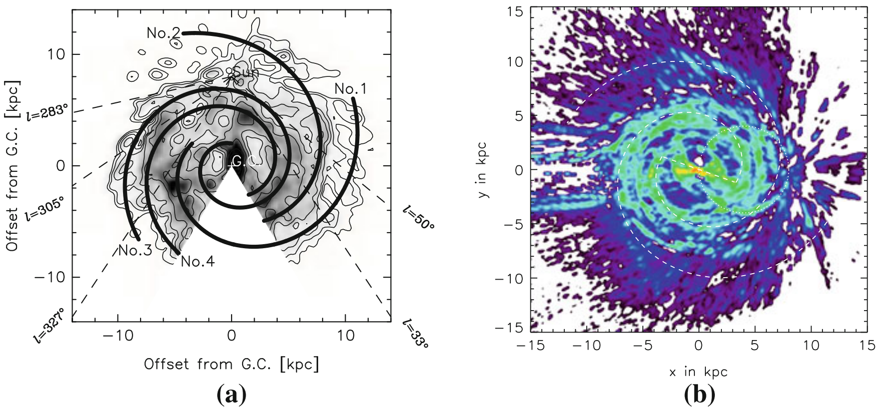


Fig. 2.3 3D gas distributions from Nakanishi and Sofue [8] and Pohl et al. [9]. **a** Gas distribution from Nakanishi and Sofue 2006, **b** Gas distribution from Pohl et al. 2008

compared to the H_2: the thickness of the HI layer is $\sim$100 pc for $R < 3$ kpc, $\simeq$230 pc for $3 < R < 8.5$ kpc (twice the H_2) and then grows more than linearly with R in the outer Galaxy, reaching $\sim$3 kpc at the outer Galactic boundary.

- **Ionized gas**. Ionized gas can be observed in the Optical band because of radiative recombination of Hydrogen and Helium ions with free electrons to excited states, and consequent radiative de-excitation; of special importance are the Hydrogen Balmer lines produced by electronic transitions from an excited state ($n > 2$) to the first excited state ($n = 2$): in fact, each recombination of a free proton with a free electron into an excited Hydrogen atom leads, sooner or later, to the emission of Balmer photon. In this way it is possible to map the HII distribution: ionized Hydrogen is detected in compact regions (HII regions) around massive stars, because of their emission of UV ionizing photons; moreover, diffuse ionized gas exterior to these regions exists in all directions around us. More recent, high-resolution maps display a complex structure made of patches, filaments and loops of enhanced Balmer H emission,[1] superimposed on a fainter background. Unfortunately, due to the obscuration effect of the interstellar dust, the region that can be probed with H is limited to a cylindrical volume of radius $\sim$2–3 kpc around the Sun.

  For more distant regions, astronomers rely on a totally different phenomenon: the *dispersion of pulsar signals*. It is well known that electromagnetic waves travelling through an ionized medium interact with the free electrons in such a way that their group velocity decreases with increasing wavelengths. This occurs to pulsar emission too: the lower frequency part of the emission propagates more slowly through interstellar space and, therefore, arrives later at the observer; the resulting spread in the arrival times is a measurable quantity (called *Distance Measure*, DM) and can be shown to be directly proportional to the column density of free

[1] The H line corresponds to a transition between $n = 3$ and $n = 2$.

electrons between the pulsar and the observer. In this way it is possible to map the ionized gas density in a much wider region.

The DM database allowed to investigate both the radial and vertical distribution of ionized gas; it has been known for a long time that the scale height of this component is much broader than both H_2 and HI; for example in Reynolds 1991 [10] it is modelled as the sum of two Gaussians: $n_{\mathrm{HII}} = 0.015\,\exp(|z|/70\,\mathrm{pc}) + 0.025\,\exp(|z|/900\,\mathrm{pc})\,\mathrm{cm}^{-3}$.

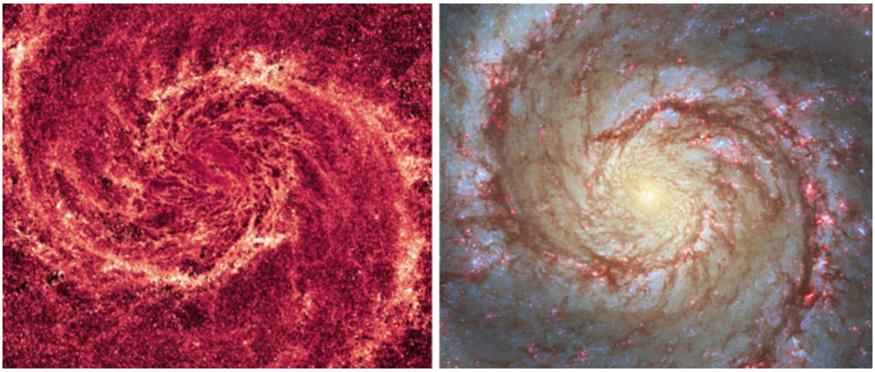
More recently, an important contribution to the distribution of ionized gas came from the work of J. M. Cordes and T. J. Lazio [11] who developed `NE2001`, a 3D model for the spatial distribution of free electrons based on a large collection of DMs of pulsars and extragalactic objects. The derived electron density consists of several components: a thin disk, a thick disk, a contribution from spiral arms and in addition a large number of source complexes, which is, however, not complete; the ionized gas at high latitudes is primarily due to the thick disk component with a scale-height of about 1 kpc and a mid-plane density of about $0.034\,\mathrm{cm}^{-3}$. The face-on map of the Galaxy obtained in this work clearly shows the spiral arm pattern.

The interstellar gas must not be considered as a static, stand-alone entity completely independent from the other components of the Galaxy. Conversely, it is animated by turbulent motion, is strongly coupled to the chaotic magnetic fields that deflect the CR path, and experiences a continuous interchange with the stellar population: in the densest regions of giant molecular complexes star formation takes place, then the material is processed inside the stars themselves, enriched with heavy elements and finally returns to the interstellar space either in a continuous way (through stellar winds) or by Supernova explosions.

A detailed understanding of all these processes is required to fully understand the origin and propagation of CRs, so I will go through a review of them (see e.g. [12])

The Giant Molecular Clouds (GMCs) are the most important environments from this point of view. GMCs contain most of the molecular Hydrogen present in the Galaxy. One may ask how these immense structures (with masses ranging from $\sim 10^4$ to $\sim 10^7$ solar masses) can survive in the severe environment of interstellar space, filled with energetic radiation (e.g. UV photons) that are able to dissociate the weak molecular bounds. Actually the neutral Hydrogen and the dust present in the outer layers contribute to absorb and scatter the ionizing radiation: the deep interior of the cloud is therefore protected and is composed by H_2 and other molecules (CO, OH). The temperature of the internal regions is $\sim 10\,\mathrm{K}$, fixed by the balance between the heating due to CR ionization and the cooling due to CO radio emission. The structure of a GMC is highly clumped: a high-resolution imaging can reveal dense *clumps* within a cloud, each clump being similar in its shape to the whole complex: this *self-similarity* has led to a fractal description of cloud structure, at least down to some lower characteristic length scale [13, 14] (Fig. 2.4).

The process of star formation starts when a cloud or a part of it is dense enough that the gas pressure is insufficient to support it: the cloud or the clump then undergoes



(a) (b)

Fig. 2.4 **a** This image of the nearby M51 galaxy (the Whirlpool Galaxy) in *infrared* light highlights the dust that traces the dense star-forming molecular gas. The light coming from stars was digitally removed to better isolate the gaseous structures, which appear to be concentrated along spiral arms. **b** The optical image of the same galaxy reveal how HII regions originated by young, massive O and B stars—that appear as *red* diffuse spots in the picture—also concentrate in spiral arms, in correspondence with the molecular dust-rich complexes visible in the infrared, where most star formation takes place. Images taken from `http://apod.nasa.gov/apod/ap110126.html`. Credit. Infrared: NASA, ESA, M. Regan and B. Whitmore (STScI), R. Chandar (U. Toledo); Optical: NASA, ESA, S. Beckwith (STScI), and the Hubble Heritage Team (STScI/AURA)

gravitational collapse; this process can be triggered by some violent events: e.g. a collision with another cloud, or a Supernova explosion. [2]

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[2] A quantitative description of these phenomena is based on magneto-hydro-dynamics (MHD). From the MHD equation of motion:

$$\rho\left[\frac{\partial\vec{v}}{\partial t}+(\vec{v}\cdot\vec{\nabla})\vec{v}\right]=-\vec{\nabla}p+\rho\vec{g}+\frac{1}{4\pi}(\vec{\nabla}\times\vec{B})\times\vec{B} \tag{2.1}$$

it is possible to derive the *Virial theorem*:

$$\frac{1}{2}\ddot{I}=2(T-T_s)+M+W \tag{2.2}$$

where

- I it the momentum of inertia
- T, is defined by the following equation: $T\equiv\int_V\left(\frac{3}{2}P_{th}+\frac{1}{2}\rho v^2\right)\mathrm{d}V$ and represents the internal kinetic energy, with a random microscopic component (thermal energy) and a macroscopic contribution (due to turbulent motions) that is often dominant.
- T_s, defined by: $T_s\equiv\frac{1}{2}\oint_S P_{ext}\vec{r}\cdot\mathrm{d}\vec{S}$ takes into account the pressure of the external medium that surrounds the cloud.
- W is the gravitational energy.
- M is the magnetic term: $M=\frac{1}{8\pi}\int(B^2-B_0^2)\mathrm{d}V$, where B_0 is the intensity of the field present in the surrounding medium.

According to which term prevails, the cloud or a part of it is considered self-gravitating (if the internal pressure due to thermal and turbulent motions is balanced by the gravitational field of the

It is important to point out that stars always form in groups. The most massive and energetic ones, although less numerous than the low-mass ones, play a very important role in the evolution of the environment that gave birth to them: these stars, belonging to O and B spectral type, are very bright, and emit copious amounts of ultraviolet radiation that rapidly ionizes the surrounding interstellar gas of the giant molecular cloud, forming the so-called *HII regions*; moreover, they are very short-living and don't move very far from the sites they were formed; their life ends with a dramatic Supernova explosion and originates a compact object (a pulsar or a black hole) and an Supernova Remnant that finally merges with the surrounding Interstellar Medium.

2.3.3 SNRs and Pulsars

The picture described so far contains some elements that are very important for our purposes, in fact it shows how the sites where a lot of gas is present and Star Formation takes place (the Giant Molecular Clouds) are often associated with other astrophysical environments such as pulsars and Supernova Remnants (SNRs) that are crucial in CR physics.

SNRs, as we pointed out, have long been considered as the primary candidates for the origin of Galactic Cosmic Rays, and the diffusive shock acceleration described in the previous paragraph is widely accepted as the main acceleration mechanism.

Many observational data support this theory: SNRs are bright radio, X and gamma-ray emitters, whose spectra have been extensively studied. In particular, is is very interesting to examine the gamma-ray emission spectra, both in the GeV region (and very accurate data are being collected in current years by Fermi-LAT) and in the TeV region (with ground experiments, such as H.E.S.S., MAGIC, etc.) because these datasets can help to distinguish between two scenarios, that we will describe in a quantitative way in Chap. 6 when we discuss gamma-ray diffuse emission from the Galaxy:

- A *leptonic* scenario in which gamma-rays are emitted by accelerated *electrons* via Synchrotron (in the radio domain) and Inverse Compton emission (in the Gamma domain).
- A *hadronic* scenario in which gamma-rays are emitted by accelerated *protons* and *nuclei* that interact with the surrounding gas, produce pions, and eventually gamma rays via π^0 decay.

In some remnants the *hadronic* picture seem to give a better fit of the data: this is the case, for example, of Cas A (Fermi-LAT recently reported [16] that the spectrum

(Footnote 2 continued)
cloud itself) or pressure-confined (if the external medium with its pressure does the same job). Star-forming clouds or clumps are generally self-gravitating. When the density gets too high, due to an external perturbation, the gravitational term becomes dominant and the cloud undergoes a collapse, which is the first step of star formation.

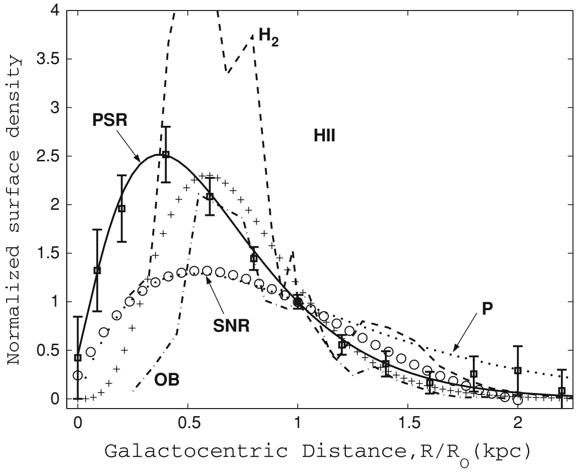

Fig. 2.5 Radial distribution of molecular gas, pulsars, SNRs, OB association in our Galaxy. Taken from [15]

is better fit by a hadronic model); an extensively studied remnant is also RX J1713.7-3946, a shell-type SNR interacting with a molecular cloud, whose very high energy emission measured by HESS is well correlated with CO emission: the gamma photons should be therefore produced by π^0 decay [17].

So, SNRs should be the sites where the acceleration of the bulk of CR protons takes place; of course the definitive proof of such an interpretation would be the observation of neutrino emission by existing or forthcoming experiments such as IceCube or NEMO (in fact in a hadronic scenario also charged pion decay is present, and this process produces neutrinos).

For these reasons a detailed knowledge of the SNR distribution in our Galaxy is very important to model the CR source term. An updated catalogue [18] is available online [19]: it contains observational data for 274 Supernova Remnant in our Galaxy. Unfortunately, the difficulties related to SNR observations make the list very incomplete and the accuracy of distance estimates very low, so it is not easy to derive a map of SNRs in our Galaxy. Since the spatial distribution of SNRs is not known with precision, and therefore the source term of CR propagation, it is then useful to consider the above outlined deep link existing between CR sources and well known astrophysical environments and objects such as pulsars or OB associations whose distribution is known with better precision.

For example, as far as *pulsars* are concerned, the ATNF catalogue available at [20] is a very useful resource; it includes all published rotation-powered pulsars, including those detected only at high energies; a complete description can be found at [21].

This large number of accurate measurements permitted to derive a spatial distribution of pulsars (see for example [15, 22]). Considering what we have showed up to this point, these curves are often used as source terms for CR propagation models; in Fig. 2.5, taken from [15], a comparison between the derived radial distribution of

Pulsars, SNRs, OB stars and molecular Hydrogen is plotted: the reader can see very clearly the strong correlation that I pointed out in this paragraph.

Now we can briefly discuss another element that plays an important role in CR physics and permeates the whole Galaxy: the magnetic field.

2.3.4 The Magnetic Field

Magnetic fields are embedded in the ionized gas that permeates our Galaxy and are a fundamental component of the interstellar medium (ISM): they are essential in the formation of stars, they provide the pressure balance that prevents gravitational collapse of our Galaxy; they also undoubtedly play a role in the creation of galaxies as well as the formation of galaxy clusters. It is interesting to point out that, in our Galaxy, the energy density of interstellar magnetic fields is comparable to the energy density of diffuse starlight, of Cosmic Rays, and of the kinetic energy density of interstellar gas: this is an important hint of the interplay between all these components.

There are several techniques that permit to investigate the structure of the magnetic field in the interstellar medium (see [24] for a quick review). The most useful effect that permits to probe the large scale structure is the *Faraday Rotation of Linearly Polarised Radiation*: pulsars and extragalactic sources, usually external galaxies, emit linearly polarised radiation which rotates as it passes through regions that are filled with free electrons with and an embedded magnetic field; the amount of this rotation ψ defines the *Rotation Measure*, RM via the following equation:

$$\psi = \lambda^2 \int n_e \vec{B} \cdot \mathrm{d}\vec{l} = \lambda^2 \cdot \mathrm{RM} \tag{2.3}$$

The observation of the RM permits to calculate the magnetic field component along the line of sight, relying on a model for the electron density distribution (such as `NE2001` by Cordes and Lazio).

The Galactic magnetic field consists of two components: a regular part and a turbulent part.

The regular field is itself subdivided into a disk field and a halo field.

It is generally accepted that our Galaxy has an organized large-scale disk field similar to other nearby Galaxies (see [23] and references therein); the field more or less follows the spiral pattern; the models for the field orientation in the Galactic plane are generally classified into an axi-symmetric spiral (ASS) with no dependence on the azimuthal angle or a bi-symmetric spiral (BSS); two different ASS models together with a BSS models are pictured in Fig. 2.6.

Little is known, unfortunately, on the halo field. In [23] the following parametrization is adopted, in cylindrical galactocentric coordinates:

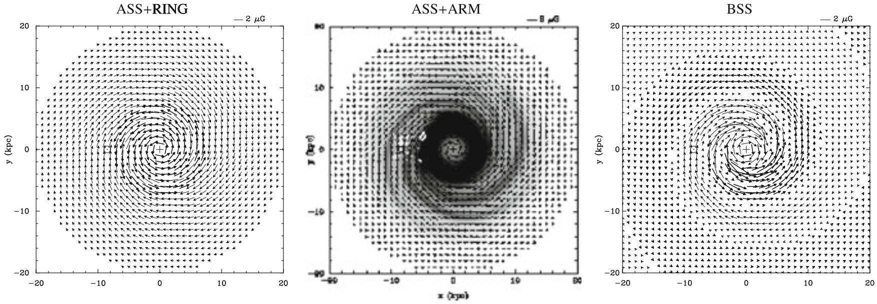

Fig. 2.6 Three different disk magnetic field models. Taken from [23]

$$B_\phi^H(R, z) = B_0 \frac{1}{1 + \left(\frac{z - z_0}{z_1}\right)^2} \frac{R}{R_0} \exp\left(\frac{R - R_0}{R_0}\right) \tag{2.4}$$

with the follwing choice for the parameters: $z_0 = 1.5$ kpc, $z_1 = 0.2$–0.4 kpc for z–z_0, $B_0 = 10\,\mu$G, $z_0 = 4$ kpc.

In [25] these parameters are revised. In fact, the above values would lead to a strong toroidal field with large values at high Galactic latitudes: such a field would produce—via interaction with CR electrons—a strong synchrotron emission which is not observed in the radio maps of the Galaxy. So, the new values of $z_0 = 1.5$ kpc, $z_1 = 0.2$–4 kpc for z–z_0, $B_0 = 2\,\mu$G, $z_0 = 4$ kpc are considered. These numbers give a spatial distribution of B compatible with Synchrotron observation.

This is only one of the possible parametrizations, and actually there is a very large uncertainty on the shape and scale height of the halo field, which—as we will see—is a very important ingredient of a model for CR diffusion.

Besides the regular magnetic field, the existence of a random component is very important: in fact, as we will prove in the next paragraph, the interaction with this component forces the CRs to undergo a random walk instead of simply propagating in spirals along the regular field lines.

The equations of Magneto-hydro-dynamics (MHD) imply that, for very low resistivity, the field lines are *frozen* in the plasma and follow its motion (this is called the Alfvén theorem of *flux Freezing*): so the random component of the magnetic field is related to the turbulent motion in the interstellar gas, which is observed over a wide range of scales, from $\sim$100 pc down to $\sim 10^{-6}$ pc or less [26].

A simple and very powerful model for turbulence in fluids was developed by Kolmogorov [27]. This model applies to a generic turbulent fluid: some driving energy is injected at large scales and then cascades to smaller scales by interactions between *eddies* of different size; the cascade is local in Fourier space (i.e. each eddy provides energy only to a slightly smaller one) and proceeds at a rate independent of scale; finally energy is dissipated by viscosity at the smallest scales. This model implies a power spectrum

$$E(k) = C\epsilon^{2/3} k^{-5/3} \tag{2.5}$$

where ϵ is the energy transfer rate and k is the inverse of the length scale. This equation describes, under very general hypotheses, how turbulent kinetic energy is distributed as a function of the scale considered.

Another model for the energy spectrum of turbulence was built by Kraichnan [28] and takes into account the presence of magnetic field. The energy spectrum for Kraichnan MHD turbulence is:

$$E(k) \propto k^{-3/2} \tag{2.6}$$

Nowadays it is commonly accepted that the driving energy is injected in the ISM at large scale by Supernova explosions; the spectrum, instead, is not known with precision, and it is uncertain if a Kolmogorov-like or a Kraichnan-like dependence on the scale is a good description of turbulent energy distribution over all the length scales. Armstrong et al. [29] collected a large number of independent observations on local Interstellar Medium on a very wide range of scales: from $\sim 10^6$ m to $\sim 10^{18}$ m and found that low-scale fluctuations can be connected to large scale ones via a Kolmogorov-like power spectrum, but the Kraichnan hypotesis is not excluded.

2.4 CR Propagation: The Diffusion Equation

2.4.1 Introductory Considerations

There are two important observations that must be taken into account in order to build a model describing CR propagation.

- The first one is the high level of isotropy of CRs compared to the strong anisotropy of the sources that—as we saw in the previous paragraph—are mainly distributed on the Galactic plane and should in principle lead to an increased flux towards the central regions of the Galaxy.
- The second one is the large abundance of some light elements (namely Li, Be, B) compared, e.g., to the solar abundances; this discrepancy can find an explanation in the process of *spallation* that we presented in the previous paragraph, i.e. the interaction of heavy CRs with interstellar gas that originates lighter nuclei. Simple calculations show that, in order to explain the observed abundances of these elements, a CR should go through a column density of $\sim 5\,\mathrm{g/cm^2}$ before reaching us: this number, compared to the average column density along a line of sight in the Galaxy $\sim 10^{-3}\,\mathrm{g/cm^2}$, leads to the conclusion that CR propagation can't occur along straight lines: there must be some mechanism to confine the particles within the Galaxy.

A very simple model to describe CR confinement is the so called *leaky box model*: in this simplified phenomenological picture CRs are assumed to propagate freely within a cylindrical box and reflected at the boundaries; the loss of particles is parametrized assuming the existence of a non-zero probability of escape for each encounter with the boundary.

The equation is very simple:

$$\frac{\partial N}{\partial t} = \frac{N}{\tau_{\rm esc}(E)} + Q(E) \tag{2.7}$$

where $\tau_{\rm esc}(E)$ is the escape time, which is shorter at higher energy, and Q is the source term.

Leaky box models are very useful to provide an effective description of some general properties of CR physics—and we will adopt them to prove simple features of propagated primary and secondary spectra—but a more realistic description of the mechanism CR confinement is needed. We discussed in the previous paragraph the existence of a magnetic field in the Galaxy, with a regular and a random component: now we will show that the interaction of CRs with such field provides the confining mechanism and this process can be described by a diffusion equation.

2.4.2 Diffusion Equation

The problem we have to solve is the interaction of a collection of relativistic charged particles with an astrophysical magnetized plasma (the problem is described in detail in [26], and we refer to that book for a complete derivation of the results summarized here).

Since in the astrophysical context the collision term is negligible, we have to solve the well known *Vlasov equation*:

$$\frac{\partial f(\vec{x},\vec{p},t)}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{x}} + \vec{F}\frac{\partial f}{\partial \vec{p}} = 0 \tag{2.8}$$

Since the force acting on those particles is the Lorentz force the equation can be written as:

$$\frac{\partial f(\vec{x},\vec{p},t)}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{x}} + Ze\left(\vec{E} + \frac{\vec{v}}{c}\times\vec{H}\right)\frac{\partial f}{\partial \vec{p}} = 0 \tag{2.9}$$

The common approach is the *quasi-linear approximation*, based on the separation of electric and magnetic fields into their average values and the random fluctuations, corresponding to an ensemble of waves with random phases:

- $\vec{H} = \vec{H}_0 + \vec{H}_1$, where $\langle\vec{H}\rangle = \vec{H}_0$ and $\langle\vec{H}_1\rangle = 0$.
- $\vec{E} = \vec{E}_0 + \vec{E}_1$, where $\langle\vec{E}\rangle = 0$ and $\langle\vec{E}_1\rangle = 0$ (the electric field average is of course zero: there is no net charge).

Also the distribution function is distinguished between the average f_0 and the fluctuating part f_1.

Averaging Eq. 2.9 over the ensemble of waves and assuming their amplitude to be small, we obtain:

$$\frac{\partial f_1}{\partial t} + (\vec{v} \cdot \vec{\nabla}) f_1 + \frac{Ze}{c}(\vec{v} \times \vec{H}_0)\frac{\partial f_1}{\partial \vec{p}} = -Ze\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{H}_1\right)\frac{\partial f_0}{\partial \vec{p}} \tag{2.10}$$

At this point, it is useful to write the random fields as a Fourier integral:

$$\begin{aligned}\vec{E}(t,\vec{r}) &= \sum_\alpha \int \vec{E}^\alpha(\vec{k}) e^{-i\omega^\alpha(\vec{k})t + i\vec{k}\cdot\vec{r}} \mathrm{d}^3x \\ \vec{H}_1(t,\vec{r}) &= \sum_\alpha \int \vec{H}_1^\alpha(\vec{k}) e^{-i\omega^\alpha(\vec{k})t + i\vec{k}\cdot\vec{r}} \mathrm{d}^3x\end{aligned} \tag{2.11}$$

where the summation is over the various types of waves propagating in the plasma.

Introducing cylindrical coordinates $p_\parallel$, $p_\perp$ and ϕ in momentum space (see [26] for further details) after some manipulations it is possible to obtain the following condition for an effective particle-wave scattering:

$$\omega^\alpha(\vec{k}) - k_\parallel v_\parallel - s\omega_H = 0 \tag{2.12}$$

where s is a integer. This is a *resonance condition*: it tells that the frequency of the wave (with Doppler effect taken into account) must be a multiple of the cyclotron frequency of the particle in the regular magnetic field H_0; in other words, particle-wave scattering occurs only with waves whose wavelength is comparable with the Larmor radius of the Cosmic Ray.

The waves we are interested in are Alfvén and magnetosonic waves.

Alfvén waves are travelling oscillation of the plamsa velocity and the magnetic field. The mechanism generating such waves can be pictured in the following way: a perturbation in the plasma velocity perpendicular to the external field $\vec{H}_0$ "bends" the magnetic field lines like a guitar string; the magnetic tension provides the restoring force; the oscillation created this way propagates with wave vector $\vec{k}$ parallel to the external magnetic field line, with a dispersion relation

$$\omega(\vec{k}) = \pm|k_\parallel| v_A \tag{2.13}$$

where

$$v_A \equiv \frac{H_0}{4\pi\rho} \tag{2.14}$$

is the Alfvén velocity.

Although the Alfvén wave propagates in the direction of the magnetic field, waves exist at oblique incidence too and smoothly change into the *magnetosonic wave*: this kind of perturbation is longitudinal and very similar to actual sound waves, in fact the propagation is perpendicular to the magnetic field and the restoring force is the magnetic pressure which is itself directed perpendicularly to the field.

Implementing the interaction of CR particles with Alfvén waves under a number of simplifying assumptions (in particular: a time scale larger than the scattering rate, the isotropy of the distribution function, an equal scattering rate for the regular field direction and the opposite one) one can obtain an equation of this kind [26]:

$$\frac{\partial f_0}{\partial t} = \frac{\partial}{\partial z} D_{xx} \frac{\partial f_0}{\partial z} + \frac{1}{p^2} \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} f_0 + Q \tag{2.15}$$

where Q is a source term.

This is a diffusion-reacceleration equation in which the following coefficients are used:

$$D_{xx} = \frac{v^2}{2} \int_0^1 \mathrm{d}\mu \frac{1-\mu^2}{2\nu_\mu} \tag{2.16}$$

$$D_{pp} = p^2 (v_A/v)^2 \int_0^1 \mathrm{d}\mu (1-\mu^2) \nu_\mu \tag{2.17}$$

In this equation we introduced the following terms:

- $\mu \equiv \cos\theta$ where θ is the pitch angle, i.e. the angle between $\vec{p}$ and $\vec{H}_0$,
- ν_μ is the scattering rate, defined by the equation:

$$\nu_\mu \simeq 2\pi^2 |\omega_H| \frac{K_{\mathrm{res}} W^\alpha(k_{\mathrm{res}})}{H_0^2} \tag{2.18}$$

  where ω_H is the cyclotron angular frequency, k_{res} is the angular wavenumber at resonance, $W^\alpha(k_{\mathrm{res}})$ is the the wave energy density (calculated at resonance).

This equation shows how the transport of CR particles in a turbulent magnetized plasma is well described by a *diffusion* in space, along the direction of the regular magnetic field, accompanied by a *stochastic reacceleration* of the particle, which is more effective for larger values of v_A.

Now, if we assume that the energy spectrum of the waves has a power-law behaviour:

$$W(k) \propto \left(\frac{k}{k_0}\right)^{-s} \tag{2.19}$$

making use of Eqs. 2.18, 2.16 shows this energy dependence:

$$D_{xx} \propto \frac{H_0^2}{H_{\mathrm{random}}^2} \left(\frac{2\pi r_H}{\lambda_0}\right)^{2-s} \tag{2.20}$$

where r_H is the Larmor radius of the particle in the magnetic field H_0; r_H depends on the particle rigidity in the following way:

$$r_H \sim 10^{-6} \frac{R[\mathrm{GV}]}{B[\mu\mathrm{G}]} pc \tag{2.21}$$

After a simple calculation based on the assumption of a Kolmogorov-like turbulence in a typical environment with $H_0 = 5\,\mu\mathrm{G}$ one can obtain (see [26]):

$$D_{xx} \simeq 3 \cdot 10^{28} \frac{H_0^2}{H_r^2} \frac{v}{c} \left(\frac{R}{7\mathrm{GV}}\right)^{(0.3)} \mathrm{cm}^2/\mathrm{s} \tag{2.22}$$

From this formula one can estimate $D \simeq 10^{28}$–$10^{29}\,\mathrm{cm}^2/\mathrm{s}$ at some GeV, i.e. a reasonable value that—as we will see—permits to reproduce the observed CR spectra.

As we discussed in the previous paragraph, the nature of the actual turbulence spectrum in the interstellar medium is currently matter of debate; it is not known if a unique power law (Kolmogorov-like, Kraichnan-like or different from the two) describes the power spectrum of the inhomogeneities in the interstellar plasma from the $\sim$100 pc scale down to $\sim 10^{-6}$ pc, i.e. the scales corresponding to resonant scattering with particles from $\sim 10^{17}$ eV down to $\sim$1 GeV. For this reason, the turbulent spectrum is considered as a free parameter and therefore the rigidity dependence of the diffusion equation: for a Kolmogorov turbulence Eq. 2.20 leads to $D \propto R^{1/3}$, while for a Kraichnan turbulence we have $D \propto R^{1/2}$.

So far we showed how, the framework of quasi-linear theory, i.e. for small turbulence, the resonant scattering on a weakly turbulent field leads mainly to a diffusion *along* the field; in this theory the perpendicular diffusion coefficient turns out to be very small:

$$\frac{D_\perp}{D_\parallel} = \frac{1}{1 + \left(\lambda_\parallel / r_L\right)^2} \tag{2.23}$$

where $\lambda_\parallel$ is the mean free path in the regular field direction which is much greater than r_L.

However, in the typical conditions of interstellar space, the turbulence level is high: $A \equiv \frac{H_{\mathrm{random}}}{H_0} \sim 1$ and so the quasi-linear theory does not provide a satisfactory description of the diffusion in the perpendicular direction: we expect indeed that in such conditions parallel and perpendicular diffusion have comparable strength because the contribution of the regular field, which defines a favourite direction, becomes less important.

Moreover, we expect that in the perpendicular direction another mechanism called *field line random walk* (see e.g. [30]) is active, a mechanism that has been known for more than 40 years but whose modelization is quite hard: the idea is that, even though particles tend to random walk along the regular magnetic field lines, since the field lines themselves are braided and mixed in the orthogonal direction, the result is a movement of the particles in the direction normal to the average regular field direction.

Considering non-linear effects is quite complicated and may alter some of the result described above. In particular, very recent works (e.g. [31]) show how a steeper dependence of the diffusion coefficient upon rigidity ($D \propto R^{0.6}$) may be obtained in presence of a Kolmogorov spectrum of turbulence, in contrast with the predictions of non linear theory (which would bring $D \propto R^{0.33}$).

Separating the contribution from parallel and perpendicular diffusion, the CR diffusion equation can be written in the general form, with respect to a generic regular magnetic field orientated along (b_r, b_ϕ, b_z):

$$\frac{\partial f_0}{\partial t} = \frac{\partial}{\partial x_i} D_{ij} \frac{\partial f_0}{\partial x_j} + \frac{1}{p^2} \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} f_0 + Q \tag{2.24}$$

where we introduced the *diffusion tensor*:

$$D_{ij} \equiv \left(D_\parallel - D_\perp\right) b_i b_j + D_\perp \delta_{ij} \tag{2.25}$$

In order to clarify the reason of such a decomposition, notice that, *i* the coordinate system is chosen so that the regular magnetic field lies along one of the axes, e.g. the x axes, the diffusion tensor becomes diagonal and its elements are simply $D_{\mathrm{xx}} = D_\parallel$, $D_{\mathrm{yy}} = D_{\mathrm{zz}} = D_\perp$.

In the case of our Galaxy it is convenient to adopt cylindrical coordinates. Under the simplifying hypothesis that the regular field is directed along ϕ, and assuming azimuthal simmetry, the diffusion equation simplifies to the following form (see Appendix A for the details of the calculation):

$$\begin{aligned} \frac{\partial f(r, z, p)}{\partial t} &= \phi \frac{\partial f}{\partial r} + \psi \frac{\partial f}{\partial z} + \alpha \frac{\partial^2 f}{\partial r^2} + \beta \frac{\partial^2 f}{\partial z^2} \\ &\quad + \frac{1}{p^2} \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} f_0 + Q \end{aligned} \tag{2.26}$$

where $\alpha = \beta = D_\perp$, $\phi = \frac{1}{r} D_\perp + \frac{\partial D_\perp}{\partial r}$ and $\psi = \frac{\partial D_\perp}{\partial z}$.

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