Mem. S.A.It. Vol. 82, 919

Memorie della

Cosmic-ray ionization and chemistry: observations

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Abstract. The interaction between cosmic-rays and the dense regions of the ISM has important consequences on the physical and chemical state of the ISM. A major consequence is the ionisation of the ISM. I review here how the cosmic rays ionisation rate ζ is measured in the ISM and the values so far measured in "average" galactic clouds. I then discuss new observations in the direction of clouds spatially associated with bright γ-rays TeV sources. The TeV emission is believed to be caused by the decay of π^0 pions created by the irradiation of molecular clouds by large fluxes of cosmic rays just produced in SNRs. The measured ζ, enhanced by a factor 100 in at least one case, confirms this hypothesis. In addition, the high ζ causes a peculiar chemistry with the cloud possessing regions in Low and High Ionisation Phases (called LIP and HIP, in the literature), also briefly reviewed in this contribution.

Key words. Cosmic rays – ISM: abundances – ISM: molecules

1. Introduction

Cosmic rays (CR) are ubiquitous in the Galaxy and a major actor in its overall energetic balance as much as evolution. In star formation, they play a crucial role in ionising molecular clouds, where stars form, and in ionising protoplanetary disks, where planets form. Indeed, the dynamics in both cases is largely governed by the ions, as ions are coupled to the magnetic fields which counteract the gravitational force, so that CR largely influence both the star and planet formation processes.

In fact, when ≤GeV CR hit the hydrogen atoms of the dense ISM, namely the molecular clouds, they ionise H and H_2 which very fast react with H_2 to form H_3^+. This is *the* key molecule that starts the whole chemistry in molecular clouds (as the reactions involving ions are much faster than those involving neutral species at low temperatures). The whole process of ionisation is summarised in the astro-chemistry studies in the *CR ionization rate* ζ, regardless of the details of the physical processes entering in defining its value. In fact, these processes matter, of course, and this is seen when comparing the values derived in dense molecular clouds (with visual extinction $A_v \geq 5$ mag) and diffuse molecular clouds ($A_v \leq 5$ mag), also called "diffuse" or "translucent" clouds. This will be briefly discussed in section 2.

Another effect due to the interaction of CR with the ISM is the production of γ rays via π^0 decay (Hayakawa 1952; Stecker 1971). Since the predicted γ-ray luminosity L_γ is proportional to local CR density and to the irradi-

Send offprint requests to: C.Ceccarelli ated molecular cloud mass (e.g. Aharonian & Atoyan 1996), molecular clouds close to bright γ-ray sources and SNRs (where CR are believed to be accelerated) can be bright γ-ray sources. The last section, §3, will review recently published observations in direction of such clouds, where ζ is hugely enhanced. I will briefly discuss the effects of large ζ to the chemical composition of the cloud. A last section will draw some conclusions.

2. Observations of the cosmic-rays ISM interaction in galactic clouds

The way to measure the CR ionization rate ζ depends on whether the cloud is dense or diffuse. Similarly, a posteriori, it is now clear that not only the measuring methods are different but also the measured value of ζ is different. We describe separately in some detail the methods and observations results in the following two subsection.

2.1. Diffuse clouds

In diffuse clouds, the value of ζ is obtained directly by measuring the abundance of the H_3^+ in the cloud (Geballe et al. 1999). In fact, equating the H_2 ionisation rate (which leads to H_3^+ formation) to the H_3^+ recombination rate (which dominates the H_3^+ destruction in diffuse clouds) it holds:

$$\zeta = \mathrm{N}(\mathrm{H}_3^+)\frac{k_e}{L}\frac{n(e)}{n(\mathrm{H}_2)} \tag{1}$$

where the electron density $n(e)$ is equal to the gaseous carbon abundance, L and $n(H_2)$ are the depth and density of the cloud, and k_e is the H_3^+ recombination rate. Thus, the measure of $N(H_3^+)$ is a straightforward measure of ζ.

The difficulty of the method is that, being a symmetric molecule, H_3^+ does not have a permanent dipole moment, and, consequently, pure rotational transitions. Therefore, the observations are carried out in the NIR (rovibrational lines), and the lines, by definition, are not in emission (which would imply a too warm and dense gas), but in absorption. While, on the one hand, the method to obtain the ζ is straightforward, on the other hand, it cannot applied everywhere, but only in the directions where there exists a strong background IR source. So far, NIR H_3^+ observations have been obtained in the direction of $\sim$ 20 diffuse clouds and, on average, a value of $\zeta \sim 10^{-16}$ s^{-1} has been measured (e.g. Indriolo, Geballe, Oka & McCall 2007). Recently, other methods have been used to measure ζ in diffuse clouds. The advent of the Herschel satellite, has provided the possibility to observe (again in absorption) lines from OH^+ and H_2O^+ (Gerin et al. 2010; Neufeld et al. 2010). Also these observations confirm a value of $\zeta \sim 10^{-16}$ s^{-1} in diffuse clouds.

2.2. Dense clouds

In dense clouds, it is not possible to directly measure the H_3^+ abundance (as the background sources are totally obscured by the cloud itself). Other methods are used. The most popular one is measuring the abundance ratio of HCO^+ and DCO^+ (Guelin et al. 1997). Briefly, HCO^+ and DCO^+ are formed by the reaction of CO with H_3^+ and H_2D^+ respectively: $CO + H_3^+ \rightarrow HCO^+ + H_2$ and $CO + H_2D^+ \rightarrow DCO^+ + H_2$. Consequently, the DCO^+/HCO^+ ratio directly depends on the H_2D^+/H_3^+ only, as follows:

$$\frac{\mathrm{DCO}^+}{\mathrm{HCO}^+} = \frac{\mathrm{H_2D^+/H_3^+}}{3\cdot(1+\frac{2}{3}\cdot\mathrm{H_2D^+/H_3^+})} \tag{2}$$

It is possible to demonstrate that, in standard molecular clouds, the H_2D^+/H_3^+ ratio depends in first instance on known parameters, like the CO and elemental deuterium abundance and the electron abundance, as follows (e.g. Ceccarelli & Dominik 2005):

$$\frac{\mathrm{H_2D^+}}{\mathrm{H_3^+}} = \frac{2\cdot[\mathrm{D}]k_1}{k_\mathrm{e}x_\mathrm{e} + k_\mathrm{CO}x_\mathrm{CO} + 2k_{HD}[\mathrm{D}]} \tag{3}$$

where k_{HD}, k_e and k_{CO} are the rate coefficients of the reactions of H_2D^+ with HD, electrons and CO respectively, x_e and x_{CO} are the electronic and CO abundances, and [D] is the elemental abundance of deuterium relative to H nuclei, equal to 1.5×10^{-5}; k_1 is the rate coefficient of the reaction of H_3^+ with HD which forms H_2D^+. In normal conditions, therefore, the only unknown in Eq. (3) is the electron abundance, which can been constrained by measuring the DCO^+/HCO^+ abundance ratio. Both DCO^+ and HCO^+ have a permanent dipole moment, and have low Js rotational transitions accessible from ground and excited at the cold molecular clouds conditions. Several observational studies have applied this method (e.g. Butner et al. 19995) and the results is an average value of $\zeta \sim 10^{-17}$ s^{-1} (Caselli et al. 1998), namely about ten times smaller than in diffuse clouds.

2.3. Conclusive remarks

An exhaustive compilation of the published measures of ζ can be found in Padovani, Galli & Glassgold (2009). After a vivid debate lasted a few years, it is now clear that the CR ionization rate ζ is ten times larger in diffuse clouds than in dense clouds. The origin of this difference is not fully understood but it seems likely due to a low energy component of CR, which is absorbed at the "skin" of the clouds and cannot, therefore, penetrate in dense clouds (Indriolo et al. 2007).

3. Observations of clouds next to sources of cosmic-rays

3.1. Where to search for

There is little doubt that CR are accelerated in the expanding shocks of supernova remnants (SNRs, e.g. Hillas 2005; Caprioli et al. 2011). As mentioned in the Introduction, when CR hit the hydrogen atoms they create π^0 pions which decay emitting γ-rays. This was already predicted 60 years ago (Hayakawa 1952), but only recently, with the advent of a new generation of γ-ray telescopes (HESS, MAGIC, FERMI-LAT...), it has been possible to associate bright γ-ray sources with molecular clouds next to SNRs (e.g. Montemerle 2010). Until very recently, the association has been based on the *spatial* coincidence of the γ-ray source with a molecular cloud, so that no quantitative measure of ζ existed which actually demonstrates a *physical* association.

3.2. Clouds with enhanced CR ionisation rate

The situation has changed in the last year. A first study was published by Indriolo et al. (2010) towards the diffuse clouds next to the SNR IC443, where a bright γ-ray source is also detected. The measured ζ is, however, enhanced with respect to the average value in diffuse clouds (§) in only two lines of sight out of the surveyed six. Mostly important, the enhancement is modest, just a factor five.

A second study just appeared in the literature (Ceccarelli et al. 2011). In this case, the target is a dense cloud in the SRN W51C, coincident with the HESS source J1923+141, and, again five lines of sights have been studied (Figure 1). In one of them, the measured ζ is, this time, about a factor 100 higher than the average value in molecular clouds , and probably even higher in the others!

These new measurements have several implications, whose the two most important are, as listed by the authors themselves:

1. The fact that the cloud where such a large enhancement of ζ coincides with a TeV γ-rays source close to a SNR conforts the idea that this cloud is irradiated by an enhanced flux of freshly formed low-energy CR. It has been, therefore, identified a location close to a CR accelerator with both enhanced low-energy CR ionization and high CR γ-ray emission, suggesting novel ways to study the acceleration and the diffusion of CR close to SN shocks.
2. The high low-energy CR flux induces a very peculiar chemistry, which had been predicted for years (e.g. Pineau des Forêts et al. 1992), but never observed before. In the next subsection we discuss what this chemistry is about.

3.3. The chemistry of clouds with high ζ

In 1992, Pineau des Forêts and coworkers predicted that the increase of ζ in a dense cloud causes a gradual increase of the ionisation until a point where a small further increase of ζ induces a jump in the ionisation. The two states were called "Low Ionisation Phase" (LIP) and

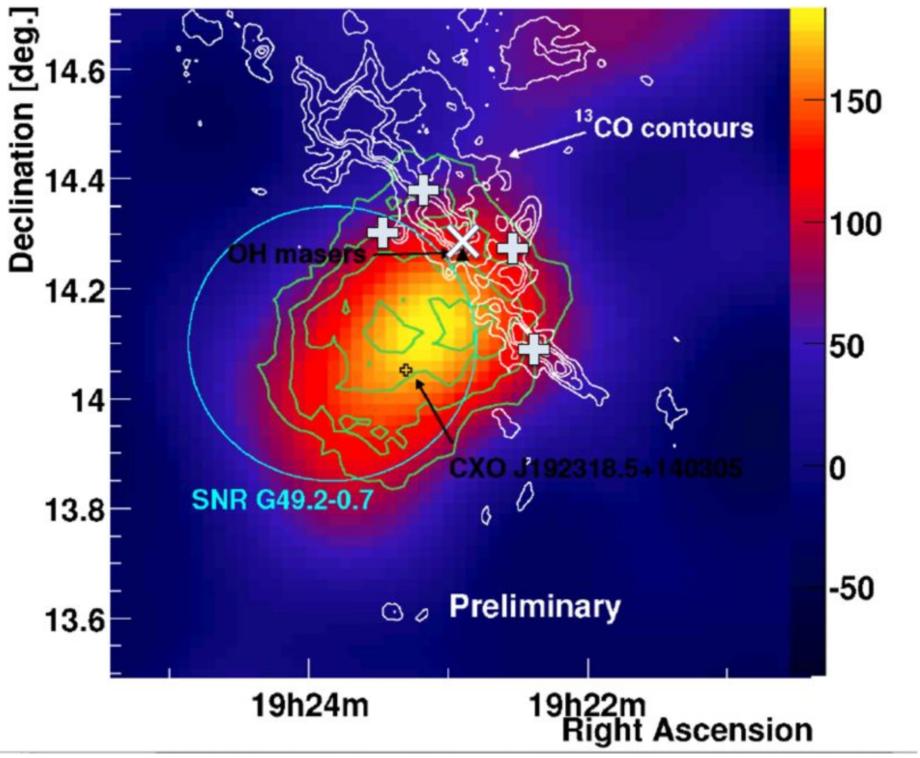

Fig. 1. Map of the W51C region, observed by Ceccarelli et al. (2011). The colours refer to the TeV emission observed by HESS (Feinstein et al. 2009). The circle shows the approximate SNR border and the white contours show the ^{13}CO line emission associated with the molecular cloud. The OH maser in the region is marked by a black triangle (Hewitt et al. 2008). The white crosses indicate the lines of sight targeted by Ceccarelli et al. (2011): the largest cross shows the point where an enhanced ζ value has been reported.

"High Ionisation Phase" (HIP). The LIP/HIP jump is due to the high non-linearity of the chemical network in dense clouds. Soon after, it was recognised that the LIP/HIP transition passes through a bistable phase, where the LIP and HIP overlap (in the ζ parameter space, for a given density). In other words, at a given ζ, two solutions are possible, a LIP and a HIP solution. Where the gas "falls in" depends on its history (Le Bourlot et al. 1997). The reality of this bistable phase has been vividly debated and several studies have discussed what is the possible cause for it and the key parameters for the bistability to occur (Wakelam et al. 2006; Boger & Sternberg 2006).

The observations by Ceccarelli et al. (2011) have shown that there exists at least one cloud in our Galaxy where both the LIP and HIP coexist. The (theoretically derived) chemical structure of the W51C cloud with enhanced ζ is shown in Fig. 2. The cloud has three distinct zones: a first zone, the cloud skin with $A_v \leq 1$ mag, where the chemistry is dominated by the IS FUV photons; a second zone, $1 \leq A_v \leq 9$ mag, where the high ζ create a HIP region and an important fraction of carbon remains ionised; a third, innermost zone at $A_v \geq 9$, in the LIP status where ionisation is brought by molecular ions, like HCO^+.

In the future, it will be important to find other sources where ζ is highly enhanced to better understand the chemistry in these extreme conditions. It is worth mentioning that these conditions are in fact expected to be com-

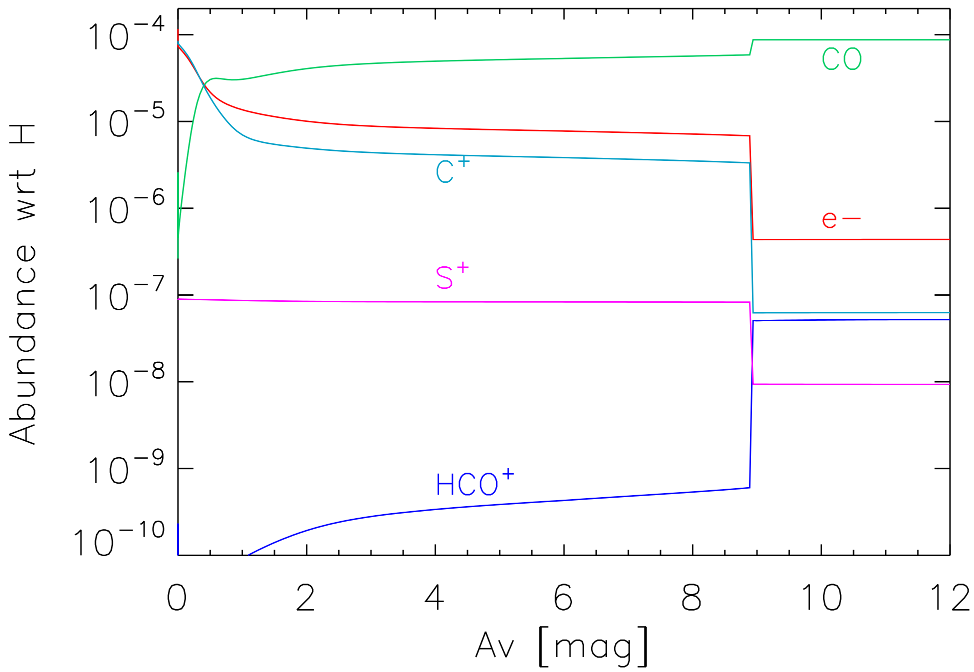

Fig. 2. Predicted chemical structure of the W51C line of sight where ζ has been measured to be $\sim 10^{-15}$ s^{-1}, namely 100 times the average value in galactic dense clouds (Ceccarelli et al. 2011).

mon in AGNs, to mention just one example where this new knowledge may have important applications.

4. Conclusions

Cosmic rays are an important component of our Galaxy and, likely, of the Universe. They are likely created in the violent explosions of SuperNovae, accelerated at the shocks where the ejected material encounters the quiescent surrounding ISM, and then diffused throughout the whole Galaxy by the magnetic fields, bringing their unthinkable energy all around the Galaxy. When CR hit the hydrogen atoms in the ISM, even at several kiloparsecs from where the CR were actually conceived, the CR ionise the H atoms becoming the major source of ionisation of the dense ISM, where FUV photons do not penetrate. This ionisation, even if "small" is of paramount importance in the life of the ISM and of the Galaxy. In fact, since ions get coupled with magnetic fields, the CR ionisation is a major way to counteract the gravitational force. Consequently, CR play a crucial role in the processes of star and planet formation.

Several studies have, therefore, been focused on measuring the rate at which CR ionise the dense ISM. All the physics is concentrated in the value of this rate, called ζ in the literature. Behind this number lies a whole field and plenty of questions: what is the spectrum of the MeV ionising CR? what component exactly ionises the ISM?... The available observations show that there is a low energy CR component that ionises the diffuse clouds but does not penetrate in denser clouds. The ionisation caused by this low energy component is about ten times the ionisation of "standard" CR. Its nature is still source of debate.

Another chapter has been recently added by the discovery of regions where the CR ionisation rate is enhanced by two orders of magnitude. These regions lie close to shocks believed to accelerate the CR. Thus, they posses the information of the shock emerging CR spectrum, before CR are dispersed and diffused in the Galaxy, loosing their original imprint. This is a crucial information that models will certainly use to constrain the physics of the CR acceleration. In addition, the large flux of ionising CR causes a peculiar chemistry, predicted for a long time but never observed before. Briefly, the highly non linear chemical reaction network occurring in dense and cold molecular clouds causes an instability, actually a bistability, in the chemical composition of the cloud. The cloud flips from a Low Ionisation Phase (LIP) to an High Ionisation Phase (HIP), with all the various imaginable consequences. How many of these clouds exist? Theoretical models predict that whether the cloud actually ends up in a LIP or HIP depends on the history of the cloud. Do they exist clouds with similar CR irradiation (density, depth, elemental abundances...) and a different chemical composition? Can this be used to "retrieve" the pas history of the cloud? They are all fascinating questions that need many more observations to be answered.

Acknowledgements. I am grateful to Guillaume Dubus who introduced me in the TeV world, to Thierry Montmerle who helped me to swim in it, and to Pierre Hily-Blant for sharing the enthusiasm of knowing more about it.

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