



Ionisation as indicator for cosmic ray acceleration

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Abstract. Astrospheres and wind bubbles of massive stars are believed to be sources of cosmic rays with energies $E \lesssim 1$ TeV. These particles are not directly detectable, but their impact on surrounding matter, in particular ionisation of atomic and molecular hydrogen, can lead to observable signatures. A correlation study of both gamma ray emission, induced by proton-proton interactions of cosmic ray protons with kinetic energies $E_p \geq 280$ MeV with ambient hydrogen, and ionisation induced by cosmic ray protons of kinetic energies $E_p < 280$ MeV can be performed in order to study potential sources of (sub)TeV cosmic rays.

1 Introduction

While supernova remnants are the main candidate for the acceleration of Galactic cosmic rays (see, e.g., Baade and Zwicky, 1934; Ackermann et al., 2013), i.e., cosmic rays with energies $E \lesssim 10^{18}$ eV, there are other acceleration sources contributing to the total diffuse flux of cosmic rays. Among these are astrospheres and wind bubbles of massive stars, which are capable of accelerating cosmic rays up to kinetic energies of $E \lesssim 1$ TeV and may, in fact, be dominant in this energy domain (see, e.g., Casse and Paul, 1980; Voelk and Forman, 1982; Binns et al., 2005; Scherer et al., 2008). The cosmic ray flux from a single supernova remnant vastly exceeds that from a single astrosphere or wind bubble. However, despite the lower amount of cosmic rays from astrospheres and wind bubbles, they can be measured indirectly via proton-proton interactions of GeV cosmic ray protons with ambient hydrogen, leading to the formation of neutral pions which, in turn, decay into two gamma ray photons. Formed in sufficiently large numbers, these gamma rays can be detected with instruments such as FermiLAT, H.E.S.S., and CTA. When cosmic rays are accelerated to kinetic energies of several GeV, there are also particles of lower energy to be expected. Such cosmic rays, with kinetic energies below the energy threshold for pion formation, $\lesssim 280$ MeV, are

very efficient in ionising both atomic and molecular hydrogen. Subsequently, ionised hydrogen triggers an ion-driven chemistry network, resulting in the formation of molecular ions whose abundances are directly linked with the ionisation rate. As a consequence, large abundances of these molecules, detected via their characteristic rotation-vibration lines, serve as an indicator of an enhanced ionisation rate compared to the ionisation rate induced by the diffuse photon and cosmic ray fluxes in the Galactic plane. In order for astrospheres and wind bubbles to be identified as (sub)TeV cosmic ray acceleration sources, cosmic ray-induced ionisation needs to dominate over photoionisation at these objects and ionisation signatures in spatial correlation with the gamma rays must be found. A correlation study of this kind was performed in Schuppan et al. (2014) for supernova remnants associated with molecular clouds. The model developed therein can be adapted to astrospheres and wind bubbles of massive stars.

2 Cosmic ray-induced ionisation

For a proper description of the propagation of low-energy ($E_p < 280$ MeV) cosmic ray protons in the vicinity of a cosmic ray accelerator with general momentum loss, the

transport equation

$$\frac{\partial n_p(\mathbf{r}, p, t)}{\partial t} - D(p)\Delta n_p(\mathbf{r}, p, t) - \frac{\partial}{\partial p} \left(b(p) \cdot n_p(\mathbf{r}, p, t) \right) = Q(\mathbf{r}, p, t) \quad (1)$$

has to be solved, where $n_p(\mathbf{r}, p, t)$ is the differential number density of cosmic ray protons, $D(p)$ is the scalar diffusion coefficient, Δ denotes the Laplace operator, $b(p)$ is the momentum loss rate, and $Q(\mathbf{r}, p, t)$ is a source function which is adapted to the astrophysical object under consideration. The low energy of the cosmic ray protons allows for a scalar diffusion coefficient because then there is no preferred propagation direction, whereas in a scenario with highly relativistic motion, an anisotropic diffusion coefficient is required. In Schuppan et al. (2014), this transport equation is solved analytically for an arbitrary source function. The Green's function $G(\mathbf{r}, \mathbf{r}_0, p, p_0, t)$ of Eq. (1), i.e., the fundamental solution for a source term consisting of Dirac distributions

$$Q_G(\mathbf{r}, p, t) = \delta^3(\mathbf{r} - \mathbf{r}_0) \delta(p - p_0) \delta(t),$$

is given by

$$G(\mathbf{r}, \mathbf{r}_0, p, p_0, t) = \frac{\Theta(p_0 - p) \delta\left(t + \int_{p_0}^p b(p')^{-1} dp'\right)}{b(p) \cdot \left(4\pi \int_{p_0}^p D(p')/b(p') dp'\right)^{3/2}} \cdot \exp\left(\frac{-(\mathbf{r} - \mathbf{r}_0)^2}{4 \int_{p_0}^p D(p')/b(p') dp'}\right), \quad (2)$$

where $\Theta(\cdot)$ is the Heaviside step function. This solution is convoluted with the source function $Q(\mathbf{r}_0, p_0, t_0)$ of an astrosphere or a wind bubble, yielding the differential number density of cosmic ray protons at any position \mathbf{r} at time $t \geq 0$ with momenta lower than the injection momentum $p \leq p_0$

$$n_p(\mathbf{r}, p, t) = \iiint G(\mathbf{r}, \mathbf{r}_0, p, p_0, t) Q(\mathbf{r}_0, p_0, t_0) dt_0 d^3r_0 dp_0. \quad (3)$$

The momentum-dependent component of the source function $Q(\mathbf{r}_0, p_0, t_0)$ can be obtained from observational gamma ray data for a hadronic formation scenario of the gamma rays (Schuppan et al., 2012), while the spatial dependence is constructed reflecting the geometry of the source region, e.g., a spherical (shell) volume with a constant emission over a specific period of time.

The ionisation rate of molecular hydrogen induced by low-energy cosmic ray protons can be calculated following Padovani et al. (2009)

$$\zeta^{\text{H}_2}(\mathbf{r}, t) = (1 + \phi) \int_{E_{\min}}^{E_{\max}} \frac{d^3 N_p(\mathbf{r}, E_p, t)}{dE_p dA dt} \sigma_{\text{ion}}^{\text{H}_2}(E_p) dE_p, \quad (4)$$

where $d^3 N_p / (dE_p dA dt)$ is the differential flux of cosmic ray protons, $\sigma_{\text{ion}}^{\text{H}_2}(E_p)$ is the direct ionisation cross-section of molecular hydrogen, and $\phi \approx 0.6$ denotes the number of secondary ionisation events per primary ionisation (Cravens Dalgarno, 1978). The differential flux can be derived from the differential cosmic ray proton number density (Eq. 3) by differentiating with respect to the cosmic ray particle kinetic energy E_p and subsequent multiplication with the effective cosmic ray particle speed, which is given by a superposition of diffusion and the relativistic, kinematic motion. This total speed is also used to link the space and time components, leading to a description which assumes all particle speeds to be equal to the statistic expectation value. Then, the time since the injection, which is usually unknown, is not required.

In this model, the effects of magnetic fields, particularly magnetic focussing and magnetic mirroring, are not accounted for. Taking them into consideration, Padovani and Galli (2011) found that in dense molecular clouds magnetic fields lead to a net decrease of the ionisation rate induced by cosmic rays by a factor of, on average, 3–4. In less dense regions, like swept up stellar ejecta at the shocks of astrospheres or stellar wind bubbles, the decrease of the cosmic ray-induced ionisation rate is lower.

3 Cosmic ray composition

In Padovani et al. (2009), a method taking not just ionisation induced by cosmic ray protons, but also by heavier nuclei into account was introduced using the Bethe–Bloch approximation for the direct ionisation cross-section (Bethe, 1933) and a correction factor for the differential cosmic ray flux in Eq. (4),

$$\eta = \sum_{k \geq 2} Z_k^2 \cdot \frac{f_k}{f_p},$$

where k is the atomic number of the cosmic ray particles heavier than hydrogen with the corresponding charge number Z_k and f_k/f_p is the relative abundance of cosmic ray particles of atomic number k with respect to cosmic ray protons. For relative abundances detected in the solar system (Anders and Grevesse, 1989; Meyer et al., 1998), the correction was calculated in Padovani et al. (2009) and Indriolo et al. (2009) as $\eta_{\odot} \approx 0.5$. At the acceleration regions, the composition may well differ. In order to obtain data with as little influence from the Sun as possible, observational data of the cosmic ray composition taken during solar minima, when the impact of the Sun on the cosmic ray flux is minimal, should be used. Therefore, the calculation of the correction is done for observational data from the solar minima in 1977 (Simpson, 1983) or in 1988 (Meyer et al., 1998). The resulting corrections are $\eta_{77} \approx 1.8$ and $\eta_{88} \approx 1.4$ (in agreement with the results in Indriolo et al., 2009), respectively, indicating that, on the one hand, the impact of the Sun on the composition of

the cosmic ray spectrum at low energies cannot be neglected and, on the other hand, that the composition of the cosmic ray spectrum at the acceleration regions shows significantly larger abundances of nuclei with $Z > 2$ than the corresponding abundances in the solar system. Adapting the momentum loss $b(p)$, which for cosmic ray protons is dominated by Coulomb losses and adiabatic deceleration in the relevant kinetic energy range of $10\text{MeV} \leq E_p \leq 280\text{MeV}$ (see, e.g., Lerche and Schlickeiser, 1982) to cosmic ray particles with $k \geq 2$, the solution given in Eq. (2) can also be used to describe the propagation of those heavier cosmic ray particles, resulting in an even more accurate calculation of the cosmic ray-induced ionisation rate.

4 Photoionisation

Besides cosmic ray-induced ionisation, photoionisation is the other process capable of efficient ionisation of ambient matter with soft X-rays and UV radiation being particularly efficient. Consequently, photoionisation needs to be exceeded by ionisation induced by hadronic low-energy cosmic rays in order to attribute enhanced ionisation rates to those cosmic rays via the suggested correlation study for astrospheres or stellar wind bubbles with nearby clouds acting as a target for both photons and cosmic rays. Therefore, spatially resolved spectral measurements of photon fluxes are important for estimates of the photoionisation rate. The attenuation of photon fluxes due to traversed matter can be described by means of the Beer–Lambert law

$$F_\gamma(\mathbf{r}, E_\gamma) = F_{\gamma,0}(E_\gamma) \cdot \exp(-\tau(\mathbf{r}, E_\gamma)), \quad (5)$$

where F_γ is the differential photon flux, $F_{\gamma,0}$ is the differential photon flux at the surface of a cloud located near the source, and $\tau(\mathbf{r}, E_\gamma)$ is the optical depth inside the cloud. For the special case of matter distributed homogeneously with density n_{H} , the optical depth can be expressed in terms of the distance from the source region as

$$\tau(\mathbf{r}, E_\gamma)_{\text{hom}} = |\mathbf{r}| \cdot n_{\text{H}} \cdot \sigma_{\text{pa}}(E_\gamma), \quad (6)$$

where $\sigma_{\text{pa}}(E_\gamma)$ is the total photoabsorption cross-section. This formula leads to an overestimate of the photon flux at large distances from the source region, because it does not account for scattering, which would in effect increase the distance the photons travel. Hence, the energy attenuation of the photon flux within the cloud is underestimated. The photoionisation rate of molecular hydrogen can be calculated following Maloney et al. (1996)

$$\zeta_{\text{H}_2}^{\text{H}_2}(\mathbf{r}) = \frac{f_{\text{i}}}{I_{\text{H}_2}} \int_{E_{\text{min}}}^{E_{\text{max}}} F_\gamma(\mathbf{r}, E_\gamma) \cdot E_\gamma \cdot \sigma_{\text{pa}}(E_\gamma) dE_\gamma, \quad (7)$$

where $f_{\text{i}} \approx 0.4$ is the fraction of the photon energy absorbed by ambient matter leading to ionisation (Voit, 1991;

Dalgarno et al., 1999), and $I_{\text{H}_2} = 15.4\text{eV}$ is the ionisation potential of molecular hydrogen. The integral describes the total energy deposition by the absorbed photons per hydrogen nucleus. A parametrised description of the total photoabsorption cross-section $\sigma_{\text{pa}}(E_\gamma)$ is provided as an empirical, broken power-law fit to experimental data.

The main issue computing the photoionisation rate is obtaining a solid estimate of the photon flux at low energies, i.e., $E_\gamma \lesssim 0.1\text{keV}$. Since the total photoabsorption cross-section increases toward lower photon energies, the corresponding photons can contribute significantly to the photoionisation rate, depending on spectral shape of the photon flux in this energy range. Hence, observing the low-energy photon fluxes is an important task in estimating the photoinduced ionisation. Particularly the UV component of the photon flux is very efficient in ionising ambient hydrogen close to the surface of a cloud and, thus, has a great impact on the photoionisation rate.

In contrast to the examination of, e.g., supernova remnants associated with molecular clouds, a solid estimate of the low-energy photon fluxes in astrospheres can be provided much more reliably via the classification of the star and usage of the typical corresponding black-body radiation spectrum. Since in most situations there is only very little information about the UV domain of the photon flux, which is a major issue for the estimate of photoionisation rates, astrospheres are promising targets for the suggested correlation study in this regard.

5 Ionisation signatures

The total ionisation rate, i.e., the sum of the photoinduced and the cosmic ray-induced ionisation rates, can be used as input for astrochemistry models in order to compute signatures indicating an enhanced ionisation rate, e.g., in the form of rotation-vibration lines of molecular ions formed by ion-driven chemistry, detectable with instruments like ALMA. While the ionisation rate is not directly detectable, its impact on ambient matter, e.g., diffuse molecular clouds in star-forming regions containing wind bubbles of massive stars, or interstellar matter swept up by stellar winds, results in the formation of molecular ions that are otherwise not formed in observable abundances. Among the molecular ions formed in these environments, H_3^+ is especially suitable as a tracer of ionisation, because its formation scheme is rather simple and directly linked to the ionisation rate of hydrogen (see, e.g., Indriolo et al., 2010).

An example for a tool to calculate rotation-vibration lines of molecular ions is the radiative transfer code RADEX (van der Tak et al., 2007). It allows rapid computation of, e.g., rotation-vibration emission line intensities of molecules, including H_3^+ , as was shown in Becker et al. (2011) for molecular clouds near supernova remnants, based on input parameters such as the abundances of several atomic and molecular

species, the electron number density, and a few others. Furthermore, it provides different geometries and the option to include a background radiation field.

Some of the molecules and molecular ions are best seen in absorption, so their rotation-vibration lines need to be detected as absorption features in the spectra of background sources. While for supernova remnants associated with molecular clouds it is difficult to find an adequate (sufficiently bright) background source with known photon spectrum, this does not pose a problem for astrospheres, since the classification of the star provides a reasonable estimate of the local radiation field at the corresponding wavelengths in the IR- and submm-domain.

Another method to determine the ionisation rate via observations is to look for the ratio of the abundances of certain molecular species, e.g., the $\text{DCO}^+/\text{HCO}^+$ ratio, but any other ratio of molecular abundances sensitive to the ionisation rate can be chosen as well. A detection of either these ratios or predicted rotation-vibration lines, whether in emission or absorption, would be a strong hint at an enhanced ionisation rate.

In the supernova remnant complexes IC 443, W28, and W51C, enhanced ionisation rates were observed by Indriolo et al. (2010), Nicholas et al. (2011), and Ceccarelli et al. (2011), respectively, via H_3^+ abundances, ammonia (NH_3) emission lines, and the $\text{DCO}^+/\text{HCO}^+$ ratio, respectively, indicating that the detection of enhanced ionisation rates can be performed with current-generation telescopes. With ALMA, even more detailed studies of the substructure of interesting objects are possible.

6 Conclusions

A correlation study of both gamma rays formed via proton-proton interactions of cosmic ray protons of kinetic energies $E_p \geq 280$ MeV with ambient matter and ionisation signatures induced by cosmic ray protons of lower energies can be used to examine cosmic ray acceleration in many different astrophysical sources, such as supernova remnants, astrospheres, and wind bubbles of massive stars. To this end, the position-dependent ionisation profiles induced by photons and cosmic ray protons can be calculated in order to determine the total ionisation rate, which in turn leads to the formation of molecular ions. These ions can be observed via their rotation-vibration line spectra with current-generation telescopes, among which ALMA is particularly well-suited due to its high spatial resolution, while the detection of the gamma rays can be done with instruments such as FermiLAT, H.E.S.S., and CTA. Observational evidence of enhanced ionisation rates which can only be explained by cosmic rays can help establish astrospheres and wind bubbles of massive stars as sources of (sub)TeV cosmic rays, leading to a better understanding of these objects.

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