The cosmic ray ionization rate in the central parsec of the Galaxy

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Abstract. Cosmic rays represent a unique crossing point of high-energy astrophysics and astrochemistry. The cosmic ray ionization rate of molecular hydrogen (ζ_2) measured by H_3^+ spectroscopy in the central parsec of the Galaxy is 2 orders of magnitude higher than that in the dense clouds outside the Galactic center. However, it is still too short, by the factor of 10,000, to agree with an extremely high ζ_2 that accommodates the new γ-ray observations of Sgr A* and its environment.

Keywords. Galaxy: center — cosmic rays — astrochemistry — ISM: clouds — ISM: lines and bands — ISM: molecules — stars: individual (GCIRS 1W, GCIRS 3)

1. Cosmic rays

Cosmic rays are the high energy particles ($E > \mathrm{MeV}$), mostly consisting of protons, that precipitate on the Earth's atmosphere every second. The cosmic rays are a subject of interest not only in high-energy astrophysics, but also in low-energy astrochemistry, because they are the source of ionization in dark clouds. In the cold interstellar medium, neutral-neutral reactions are prohibitively slow, because of their reaction barriers. Ion-neutral reactions that proceed with high Langevin rates are the main propellant of the chemistry in the ISM. Deep inside a molecular cloud, where ionizing UV photons from the interstellar radiation field are attenuated, the cosmic rays are the sole source of ionization that trigger the ion-neutral reactions. The production of interstellar molecules is sometimes strongly dependent on the ionization of the seed molecules by cosmic rays. The abundance of such molecules serves as an excellent measure of the cosmic ray flux in the medium in question.

H_3^+ is the best chemical probe of the cosmic rays, because the number of the reactions involved is virtually one (Oka 2006). The formation of H_3^+ starts with the ionization of molecular hydrogen by a cosmic ray. H_2^+ is unstable, and quickly reacts with another molecular hydrogen to form H_3^+. This reaction is faster than other competing processes; every H_2^+ formed eventually turns to H_3^+ under normal dense cloud conditions. Therefore the abundance of H_3^+ is a direct measure of the efficiency of the first path, the ionization rate of H_2 by a cosmic ray.

High angular resolution γ-ray telescopes recently online provide direct estimates of the high-energy cosmic ray flux in the interstellar medium. The underlying assumption is that TeV γ-rays are produced by neutral pion decays following the collisions of accelerated protons with the ambient cold nuclei. In this contribution we will compare the cosmic ray ionization rate of molecular hydrogen ζ_2 in the central parsecs of our Galaxy measured in two ways: one by the means of astrochemistry using H_3^+ spectroscopy, and the other by proton injection model to reproduce the observed γ-ray spectrum discovered near Sgr A*.
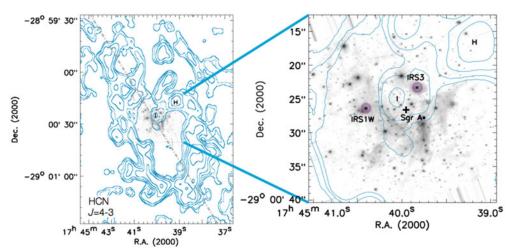
Figure 1. HCN $J = (4-3)$ map of the circumnuclear ring (**left**, blue contours; Montero-Castaño *et al.* 2009), and a blow-up view of the central part (**right**) overlaid with the near-infrared (K-band) image of the Central cluster. The height of the field of the right panel is 5 pc. The clumps identified by Montero-Castaño *et al.* (2009) are labeled with I and H. [A COLOR VERSION IS AVAILABLE ONLINE.]

2. Laboratory

The Galactic center is very energetic and contains vast reservoirs of molecular gas at the same time. One tenth of the molecular mass of whole Milky Way is supposedly concentrated in the central molecular zone (CMZ) in 200 pc of the Galactic center (Morris & Serabyn 1996). On the other hand, supernova outbursts happen 2000 times more frequently than outside the Galactic center (Crocker *et al.* 2011). The Galactic center harbors plenty of bright infrared sources that enable high-precision infrared absorption spectroscopy. The Galactic center is a unique laboratory to study how a high energy x-ray and γ-ray sources have a direct impact on the chemistry.

Figure 1 shows a near-infrared image of the Central cluster of our Galaxy overlaid with the circumnuclear ring (CNR) mapped by HCN $J = (4-3)$ (Montero-Castaño *et al.* 2009). Note that the line of sight to the bright infrared source GCIRS 3 overlaps with a clump in the CNR, while the line of sight to another member of the Central cluster GCIRS 1W is clear. The absorption toward the Galactic center is the sum total of the absorption along the line of sight over 8 kpc, including diffuse molecular clouds in the CMZ, and the dense clouds in the foreground spiral arms. In order to pick up exclusively H_3^+ absorption in the dense clump in the CNR, the H_3^+ spectrum of GCIRS 1W was subtracted from that of GCIRS 3. The projected distance of the two sources is 0.3 pc. The foreground absorption that takes place in the common path should be canceled out.

The H_3^+ spectra from the rotational levels $J = 1, 2, 3$ obtained by CRIRES spectrograph at the Very Large Telescope are shown in Figure 2. GCIRS 3 shows excess absorption at the positive velocity. The line profile of HCN $J = (4-3)$ extracted at the position of GCIRS 3 matches well to H_3^+ $R(2,2)^l$. The agreement lends convincing support to the idea that the excess absorption indeed arises in the clump local to the CNR. The column density of H_3^+ required to reproduce the excess absorption is $N(H_3^+) = 6 \times 10^{14}$ cm^{-2}, which is $\zeta_2 > 1.6 \times 10^{-15}$ s^{-1}, if the pathlength of the cloud is smaller than the projected distance between GCIRS 3 and GCIRS 1W (Goto *et al.* 2013a; Goto *et al.* 2013b). This cosmic ray ionization rate measured is the closest measured rate in position to Sgr A* by
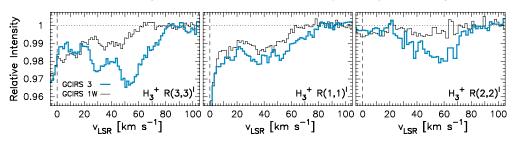
Figure 2. Infrared H_3^+ absorption spectra of GCIRS 3 and GCIRS 1W.
[A COLOR VERSION IS AVAILABLE ONLINE.]

the astrochemistry, and is two orders of magnitude higher than that of the dense clouds outside the Galactic center (Figure 3).

3. γ-ray observations

A TeV γ-ray source HESS 1745−290 was discovered by the HESS collaboration in the Galactic center (Aharonian *et al.* 2004), and subsequently localized to a few arcminutes of Sgr A*. The proton flux required to reproduce the γ-ray spectra observed by the HESS and the *Fermi*/LAT is 7×10^4 proton cm^{-2} sr^{-1} s^{-1} (GeV/nucleon)$^{-1}$ at the energy 1 GeV in 10 pc of Sgr A* (Chernyakova *et al.* 2011). This is 100,000 times more than the cosmic ray flux in the solar neighborhood at the same energy. If we take the cosmic ray spectrum proposed by Indriolo *et al.* (2009) at the extrapolation of the flux to MeV regime, the cosmic ray ionization rate of H_2 comes up to 1.1×10^{-11} s^{-1}, which is 10,000 times larger than that we found by H_3^+ spectroscopy at the same place.

4. Possible explanations

There are at least three issues that might be treated incorrectly in the calculations above. First, we extrapolated the cosmic ray spectrum over 3 orders of magnitudes from GeV to MeV to calculate ζ_2 from γ-ray observation. TeV-γ ray spectroscopy provides a constraint on the cosmic ray flux down to $\sim$1 GeV, while the cosmic rays that affect ζ_2 most are of $\lesssim$ MeV, because the ionization cross section of H_2 peaks at $\sim$100 keV. We used the cosmic ray spectrum of Indriolo *et al.* (2009), which is consistent with the latest H_3^+ spectroscopy in the Galactic diffuse clouds; but other choices of spectra with strong turnovers in low-energy regime (e.g. Webber 1998) reduce ζ_2 significantly. In-situ measurements of the cosmic ray spectrum by Voyagers outside the heliosphere is awaited (Stone *et al.* 2013; Webber *et al.* 2013).

Second, the dissociative recombination of H_3^+ with the electrons may not be negligible even in a dense cloud, if the cosmic ray ionization rate is significantly larger than 10^{-15} s^{-1}. The crucial assumption that leads H_3^+ abundance to be proportional to ζ_2 is that the destruction of H_3^+ happens primarily through the chemical reaction with CO in dense clouds. This is a reasonable assumption in normal dense clouds where the electron density is much smaller than the CO abundance. If, however, the dissociative recombination is not negligible, the abundance of H_3^+ becomes smaller, and ζ_2 calculated with the incorrect premise is subject to a substantial underestimation.

The third possibility that I learned during the symposium is the possibility of a source misidentification with the pulsar wind nebula G359.95−0.04 (Wang *et al.* 2006). If a part of γ-ray emission observed by HESS is attributed to the inverse Compton scattering by
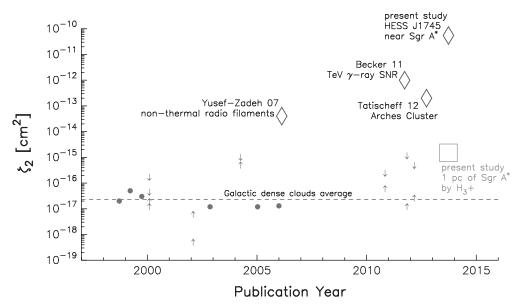
Figure 3. The history of the measurements of the cosmic-ray ionization rate by astrochemical probes in dense clouds (filled circle; Williams *et al.* 1998; McCall *et al.* 1998; Bergin *et al.* 1999; Padoan *et al.* 2004; Lee *et al.* 2004; Wakelam *et al.* 2005), and in the Galactic center from the present study. The open diamonds are the recent predictions of ζ_2 from high-energy observations (Yusef-Zadeh *et al.* 1007; Becker *et al.* 2011; Tatischeff *et al.* 2012).

electrons accelerated in the pulsar wind (Hinton & Aharonian 2007), the proton flux calculated by Chernyakova *et al.* (2011) may be reduced significantly.

An extreme ζ_2 ($> 10^{-14}$ s^{-1}) predicted by high-energy observations either in x-rays or γ-rays is not an exception any more (Figure 3). Such a high ζ_2 has a huge impact on the chemistry. However, there is a gap between the observations and the predictions as is shown in the present study. Further H_3^+ observations with better spatial sampling in the CNR should be in order to find an experimental solution to the problem.

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