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Probing Cosmic-Ray Acceleration and Propagation with H_3^+ Observations

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Abstract. As cosmic rays traverse the interstellar medium (ISM) they interact with the ambient gas in various ways. These include ionization of atoms and molecules, spallation of nuclei, excitation of nuclear states, and production of pions among others. All of these interactions produce potential observables which may be used to trace the flux of cosmic rays. One such observable is the molecular ion H_3^+—produced via the ionization of an H_2 molecule and its subsequent collision with another H_2—which can be identified by absorption lines in the 3.5–4 μm spectral region.

We have detected H_3^+ in several Galactic diffuse cloud sight lines and used the derived column densities to infer ζ_2, the cosmic-ray ionization rate of H_2. Ionization rates determined in this way vary from about 7×10^{-17} s^{-1} to about 8×10^{-16} s^{-1}, and suggest the possibility of discrete sources producing high local fluxes of low-energy cosmic rays. Theoretical calculations of the ionization rate from postulated cosmic-ray spectra also support this possibility. Our recent observations of H_3^+ near the supernova remnant IC 443 (a likely site of cosmic-ray acceleration) point to even higher ionization rates, on the order of 10^{-15} s^{-1}. Together, all of these results can further our understanding of the cosmic-ray spectrum both near the acceleration source and in the general Galactic ISM.

Keywords: Interstellar Medium; Supernova Remnants; Cosmic Rays
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INTRODUCTION

Cosmic rays are ubiquitous throughout our Galaxy, and it is assumed that the particle spectrum is relatively uniform everywhere. This is because the charged particles diffuse along magnetic field lines, essentially performing a random walk around the Galaxy. Another result of this diffusion is that particles observed at Earth cannot be traced back to their sources. Due to the large amount of energy necessary to produce the observed spectrum of Galactic cosmic rays though, it has long been theorized that supernova remnants are the primary accelerators of such particles. Recent observations of molecular clouds near supernova remnants with *Fermi*-LAT [1, 2], *VERITAS* [3], HESS [4] *MAGIC* [5], and *AGILE* [6] support this theory as they show gamma-ray emission spectra consistent with those expected from π^0 decay. Neutral pions are produced via inelastic collisions between hadronic cosmic rays with $E_{kin} > 280$ MeV and the ambient interstellar material, so these results suggest a large flux of particles entering the observed clouds from nearby supernova remnants.

However, lower energy particles cannot be traced by such observations. To do so, we perform spectroscopic observations searching for absorption lines of the molecular ion H_3^+. H_3^+ is formed when an H_2^+ (presumably ionized by a cosmic ray) collides with an H_2, and is primarily destroyed via dissociative recombination with electrons (in diffuse molecular cloud environments). Because the cross section for ionization of H_2 by protons increases with decreasing particle energy, these H_3^+ observations should track the flux of lower-energy ($\sim$MeV) cosmic rays. Setting up a steady-state equation for the formation and destruction of H_3^+ results in [7]

$$\zeta_2 n(\mathrm{H_2}) = 3Dk_e n_e n(\mathrm{H_3^+}), \tag{1}$$

where ζ_2 is the ionization rate of H_2 and k_e is the dissociative recombination rate coefficient of H_3^+ with electrons. Solving for the ionization rate and substituting in column densities for number densities gives

$$\zeta_2 = 3Dk_e x_e n_{\mathrm{H}} \frac{N(\mathrm{H_3^+})}{N(\mathrm{H_2})}, \tag{2}$$

where $x_e \equiv n_e/n_{\mathrm{H}}$ is the fractional abundance of electrons and $n_{\mathrm{H}} \equiv n(\mathrm{H}) + 2n(\mathrm{H_2})$ is the density of hydrogen nuclei. Equation (2) can then be used to infer the cosmic-ray ionization rate of H_2 in sight lines where H_3^+ has been observed.

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OBSERVATIONS & RESULTS

Due to various properties of the H_3^+ molecule, the only observable absorption lines arise from ro-vibrational transitions in the infrared and are rather weak—typically only about 1–2% deep. As a result, spectroscopic observations of H_3^+ require the combination of a large telescope and high-resolution infrared spectrograph. To date, we have searched for H_3^+ in about 50 diffuse molecular cloud sight lines and detected it in 20 of those [8, 9]. Example spectra from some of these observations are shown in Figure 1. Ionization rates inferred along these sight lines [see 9, for a discussion of how variables on the right-hand side of equation (2) are determined] range from about 2×10^{-16} s^{-1} to 8×10^{-16} s^{-1}, while 3σ upper limits for some sight lines with non-detections are as low as 7×10^{-17} s^{-1}.

This wide variation in ionization rates is rather intriguing as it suggests that the flux of low-energy cosmic rays may not be uniform throughout the Galaxy. If this is the case, perhaps sight lines with higher ionization rates probe material which is closer to the site of cosmic-ray acceleration. Given that clouds in close proximity to supernova remnants show evidence for hadronic cosmic-ray acceleration, we have undertaken an observing campaign to search for H_3^+ in sight lines that probe such environments. Using NIRSPEC at Keck and IRCS at Subaru, we have observed 6 sight lines in the vicinity of IC 443, a well-studied case of a supernova remnant interacting with the surrounding molecular clouds. Large column densities of H_3^+ were detected toward ALS 8828 and HD 254577, and the ionization rates inferred along these sight lines are both about 2×10^{-15} s^{-1} [10]. Combined with the previous results, these data point to even larger variations in the cosmic-ray ionization rate in the ISM.

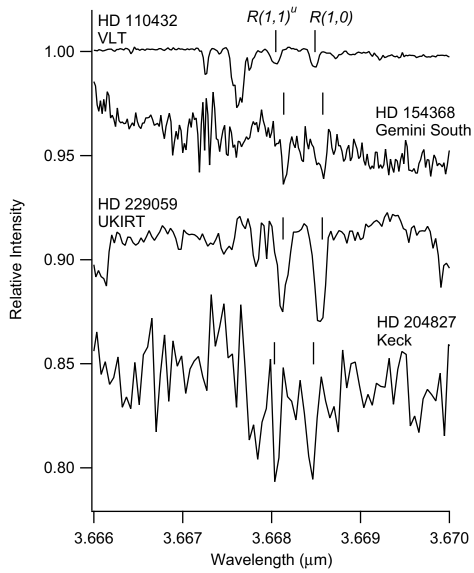

FIGURE 1. Example spectra from our various observations showing absorption lines from the $R(1,1)^u$ and $R(1,0)$ transitions of H_3^+ along 4 diffuse cloud sight lines. Spectra are labeled with the name of the background star and the telescope at which the observations were performed. Vertical lines mark the expected positions of the H_3^+ lines given interstellar gas velocities.

DISCUSSION

Finding variability in the cosmic-ray ionization rate spanning about 2 orders of magnitude has been a rather unexpected result of our observations. Still, there are various physical effects that can readily account for variations in the low-energy cosmic-ray flux. Lower-energy cosmic rays have relatively short ranges (2 MeV particles can travel through about 10^{21} cm^{-2} of gas before losing all of their energy), such that the flux of these particles will decrease drastically with distance away from the acceleration site. Because these particles are the most efficient at ionizing H_2, their loss will decrease the ionization rate. Magnetohydrodynamic effects may also exclude low-energy particles from denser regions or decrease the time cosmic-rays spend in a cloud, both of which lead to a lower ionization rate in denser clouds. Finally, it is unclear whether low-energy particles can escape from the site of diffusive shock acceleration, or if they are advected downstream into supernova remnants. In this scenario, a high flux of low-energy particles exists inside of young and intermediate aged supernova remnants, and only escape when such remnants are much older ($\sim 10^5$ yr). Overall, it is likely that all of these effects play some part in creating variations in the low-energy cosmic-ray flux, although which acceleration and propagation effects are most important remains to be determined.

SUMMARY

At present, our observations of H_3^+ in Galactic diffuse clouds have resulted in detections along 20 of about 50 sight lines surveyed. Cosmic-ray ionization rates inferred from these observations have generally been larger than those assumed previously, and vary by over 1 order of magnitude. Including our recent observations near the supernova remnant IC 443, these variations point to a non-uniform flux of low-energy cosmic rays throughout the Galaxy. Continued observations of H_3^+ in diffuse cloud sight lines and near supernova remnants will allow us to better map variations in the cosmic-ray ionization rate, and give us better insight into the physical effects responsible for such variations.

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