Variability of the Cosmic-Ray Ionization Rate in Diffuse Molecular Clouds

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ABSTRACT
The energy spectrum of cosmic-rays --- a product of particle acceleration and subsequent diffusion --- is generally assumed to be uniform throughout the Galaxy (Webber 1998). As a result, the cosmic-ray ionization rate inferred in similar environments (e.g. in several diffuse clouds) should also be relatively constant. However, current estimates of the ionization rate in diffuse molecular clouds vary over the range $(1-8) \times 10^{-16} \text{ s}^{-1}$. In addition, there are a few sight lines resulting in the cosmic-ray ionization rate inferred in similar environments (e.g. in several diffuse molecular cloud sight lines). These ionization rates were then compared to various other parameters (Galactic latitude, Galactic longitude, hydrogen column density) in a search for correlations. Also, sight lines in close proximity are compared to each other to determine the variability of the ionization rate on small spatial scales.

BACKGROUND
The ionization rate of molecular hydrogen due to cosmic-rays can be derived from observations of $H_3^+$ and various other parameters. To demonstrate why this is so, we examine the chemistry associated with $H_2$ formation and destruction. First, an $H_2$ molecule is ionized (predominantly by cosmic rays in diffuse and dense molecular clouds). The $H_2^+$ ion then collides with another $H_2$ molecule, resulting in an $H_3^+$ ion and $H$ atom. Cosmic-ray ionization occurs much more infrequently than collisions with $H_2$, so the first step can be taken as the rate limiting process. Once created, $H_3^+$ is predominantly destroyed by electron recombination in diffuse molecular clouds. The reaction scheme surrounding $H_2^+$ in diffuse molecular clouds can thus be represented by three simple processes:

$$H_2 + p \rightarrow H_2^+ + e^- + p$$
$$H_2^+ + H \rightarrow H_3^+ + H$$
$$H_3^+ + e^- \rightarrow H_2 + H or H + H + H$$

Assuming steady state chemistry where the formation and destruction rates of $H_3^+$ are set to be equal, the reactions above can be represented by the equation (Geballe et al. 1999):

$$\zeta_2 n(H_2) = k_e n(e) n(H_3^+)$$

where $\zeta_2$ is the ionization rate, $k_e$ is the $H_3^+$-electron recombination rate coefficient, and the various $n(X)$'s are number densities of species X. Rearranging the equation to solve for $\zeta_2$ and substituting in observable quantities results in

$$\zeta_2 = 2 N(H_3^+) k_e n_H \frac{n(e)}{f N_H}$$

where $f$ is the fraction of hydrogen nuclei in molecular form and the subscript H denotes the total hydrogen number or column density (i.e. $N_H = 2N(H_2)+N(H_3^+)$). Because the chemistry associated with $H_3^+$ is so simple, this molecule is a rather robust probe of the ionization rate.

RESULTS
Cosmic-Ray Ionization Rate vs. Hydrogen Column Density Per Cloud

Ionization rate vs. hydrogen column per cloud. Black squares and blue diamonds are derived from $H_3^+$ detections and shown with 3σ error bars. Blue diamonds, however, are sight lines with multiple velocity components in $H_2^+$, and so $N_H$ has been scaled accordingly. Red triangles are derived from 3σ upper limits on the $H_2^+$ column. Data are from McCall et al. (1998), McCall et al. (2002), Indriolo et al. (2007), and currently unpublished results. As expected, the ionization rate tends to decrease with increasing hydrogen column. This is because the low energy cosmic-rays primarily responsible for ionizing $H_2$ cannot travel through a column much greater than a few times $10^{21} \text{ cm}^{-2}$ before losing all of their energy (Cravens & Dalgarano 1978).

SUMMARY
By using observations of $H_3^+$, we have inferred the cosmic-ray ionization rate along several diffuse molecular cloud sight lines. These ionization rates were then compared to various other parameters, including Galactic coordinates and hydrogen column density. As expected due to cosmic-ray propagation, the ionization rate tends to decline as $N_H$ increases. While the ionization rate does not seem to vary significantly with Galactic longitude, sight lines probing the Galactic plane are more likely to have $H_3^+$ detections than those at higher latitudes. Because it is believed that cosmic rays are accelerated by energetic shocks (e.g. supernova remnants, OB associations), it is not surprising that the ionization rate would be higher in the Galactic plane where these sources are more highly concentrated.

REFERENCES

SPATIAL VARIABILITY
Variation in the Ionization Rate with Respect to Galactic Coordinates

The positions of our target sight lines in Galactic coordinates. Larger symbols correspond to a higher ionization rate. Black squares are based on detections of $H_3^+$ and red triangles on upper limits. The ratio of ionization rate to hydrogen column density may be relatively constant. The red triangles are based on upper limits of $H_3^+$ detections and shown with 3σ uncertainties.