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

N. Indriolo[1], T. R. Geballe[2], T. Oka[3], & B. J. McCall[1]
[1]University of Illinois at Urbana-Champaign, [2]Gemini Observatory, [3]University of Chicago

## 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)×$10^{-16}$ $s^{-1}$. In addition, there are a few sight lines with 3σ upper limits of $\zeta_2 \leq 10^{-16}$ $s^{-1}$, suggesting even lower ionization rates in some clouds. This roughly order of magnitude difference in the cosmic-ray ionization rate between sight lines contradicts the concept of a spatially uniform cosmic-ray flux.

We present cosmic-ray ionization rates derived from several published and unpublished spectroscopic observations of $H_3^+$ in diffuse cloud sight lines. These ionization rates are then compared with 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 $H_3^+$ 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 $H_3^+$ in diffuse molecular clouds can thus be represented by three simple processes.

$$\mathrm{H_2} + p \rightarrow \mathrm{H_2^+} + e^- + p$$

$$\mathrm{H_2^+} + \mathrm{H_2} \rightarrow \mathrm{H_3^+} + \mathrm{H}$$

$$\mathrm{H_3^+} + e^- \rightarrow \mathrm{H_2} + \mathrm{H} \text{ or } \mathrm{H} + \mathrm{H} + \mathrm{H}$$

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):

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

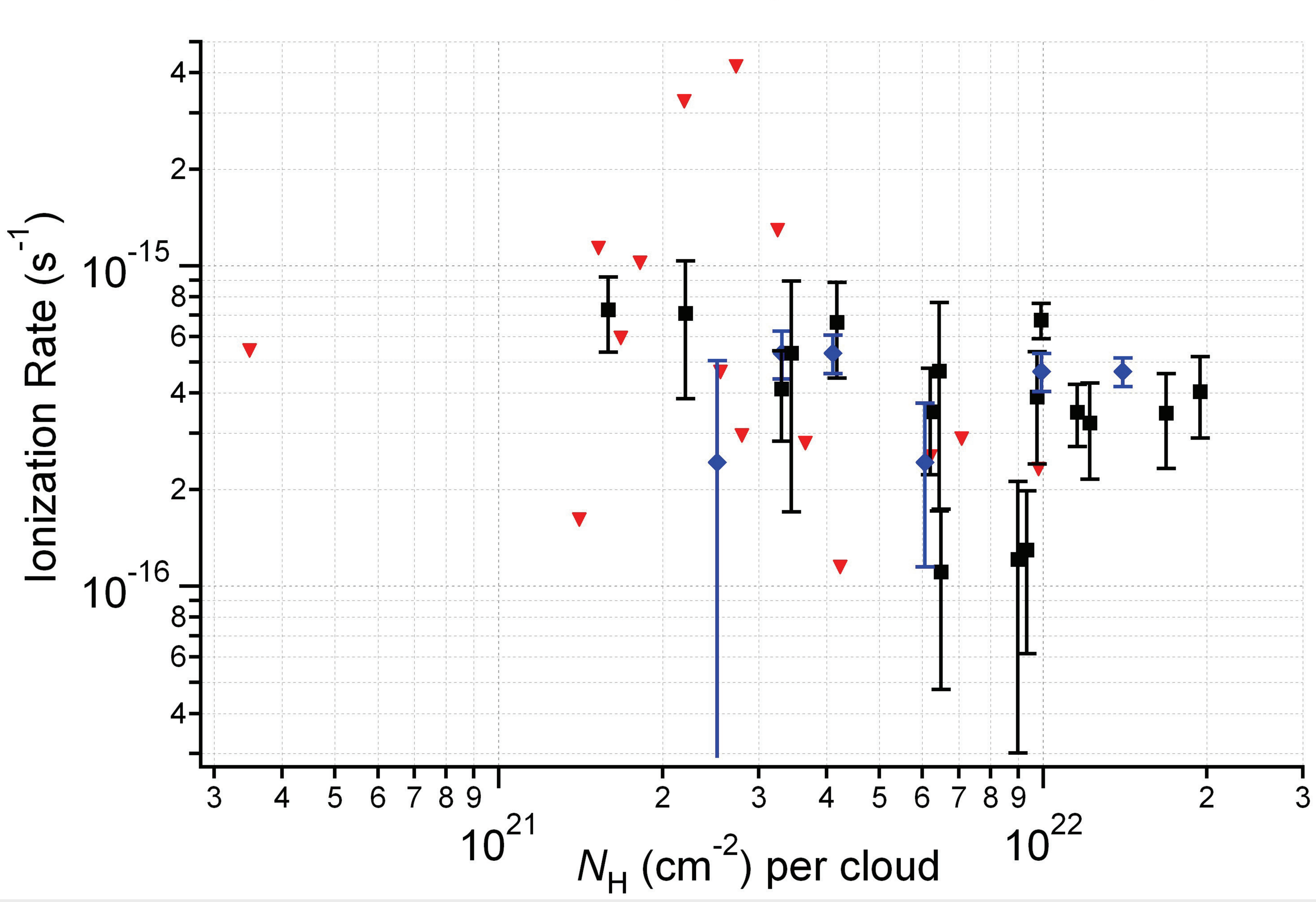
where $\zeta_2$ is the ionization rate, $k_e$ is the $H_3^+$-electron recombination rate coefficient, and the various $n$(X)'s are number densities of species X. Rearranging the equation to solve for $\zeta_2$ and substituting in observable quantities results in

$$\zeta_2 = 2N(\mathrm{H_3^+}) \frac{k_e}{f} \frac{n_\mathrm{H}}{N_\mathrm{H}} \left[ \frac{n(e)}{n_\mathrm{H}} \right]$$

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. $N_H$=$N$(H)+2$N$($H_2$)). Because the chemistry associated with $H_3^+$ is so simple, this molecule is a rather robust probe of the ionization rate.

## RESULTS

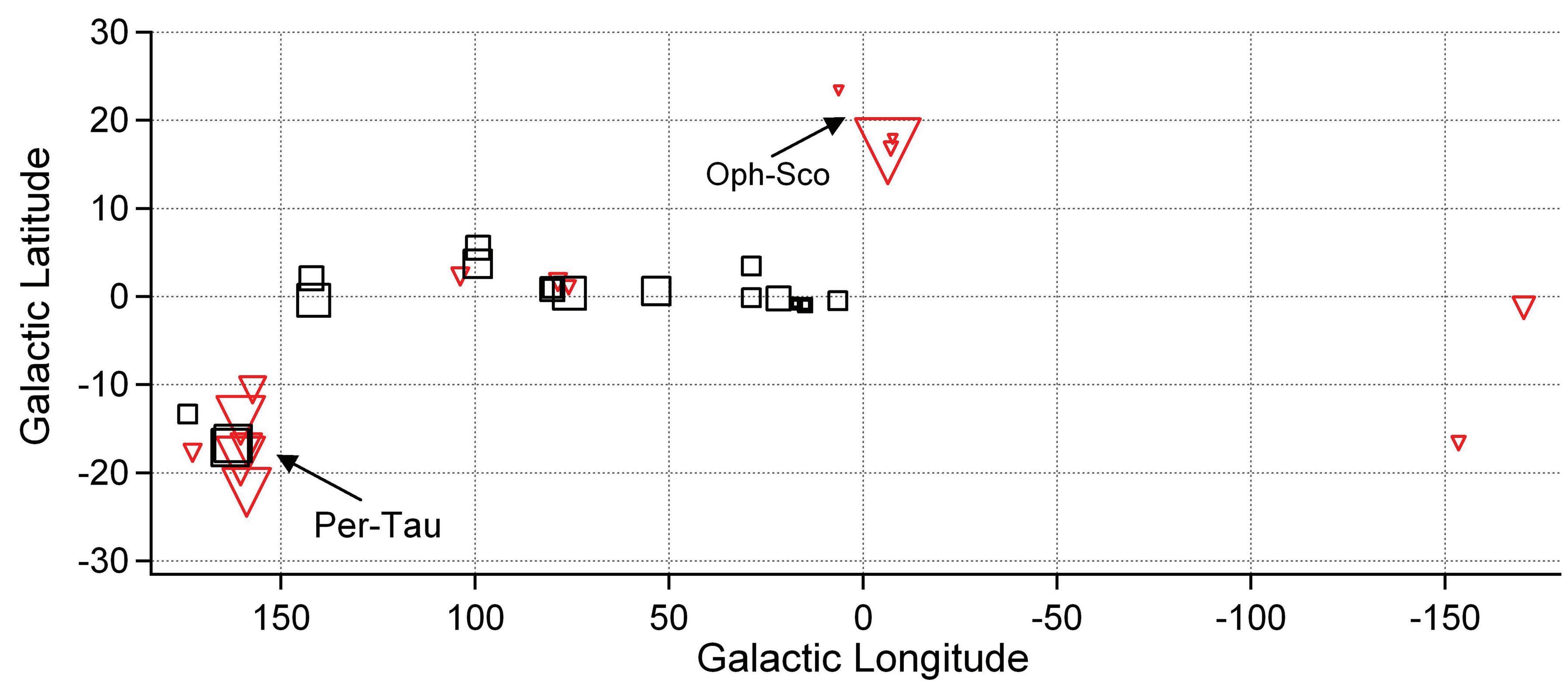
### Cosmic-Ray Ionization Rate vs. Hydrogen Column Density Per Cloud




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 $H_3^+$, and so $N_H$ has been scaled accordingly. Red triangles are derived from 3σ upper limits on the $H_3^+$ 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 $10^{21}$ $cm^{-2}$ before losing all of their energy (Cravens & Dalgarno 1978).

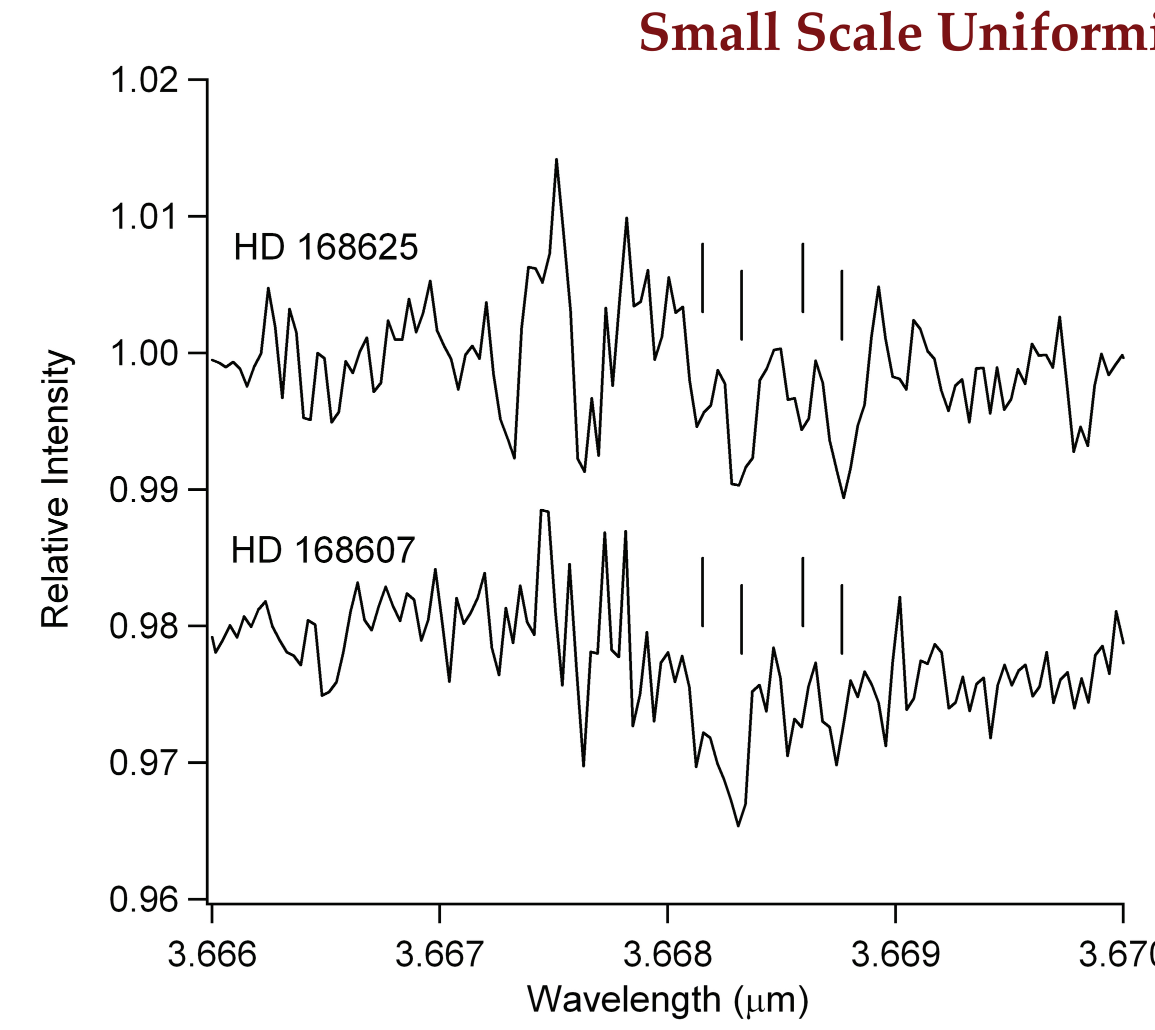
## SPATIAL VARIABILITY

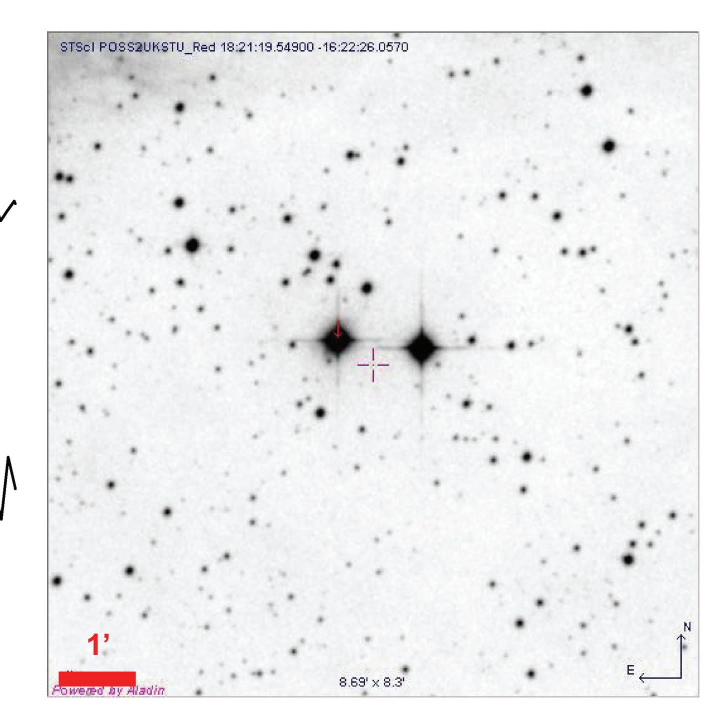
### Variation in the Ionization Rate with Respect to Galactic Coordinates




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. At present, it seems that we are more likely to detect $H_3^+$ in the Galactic plane. It is interesting that most of the sight lines in the Oph-Sco region have spectra with S/N ≥ 400 and yet show no evidence of $H_3^+$ absorption. However, unreduced data toward multiple sight lines in the Per OB2 association may soon change this preliminary finding.

### Small Scale Uniformity




These two spectra (above left) show the $R(1,1)^u$ and $R(1,0)$ absorption lines of $H_3^+$ toward HD 168625 and HD 168607. These stars are separated by about 1 arcminute on the sky (above right; image from the Digitized Sky Survey), which corresponds to 0.4 pc at a distance of 1400 pc. As a result, we expect both sight lines to probe similar material and conditions. Both spectra indicate 2 cloud components in velocity space, although these features are much clearer in the HD 168625 spectrum. The derived ionization rates for these two sight lines are consistent with each other within the calculated uncertainties. On small spatial scales then, it would appear that the cosmic-ray ionization rate may be relatively constant.

## 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

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