The Cosmic-Ray Ionization Rate

STEPHEN LEPP
University of Nevada, Las Vegas
Physics Department
4505 Maryland Parkway
Las Vegas, NV 89154 USA

ABSTRACT. A wide variety of molecules have been observed in the interstellar clouds. They are believed to be formed by reaction networks which begin with ionization by cosmic-rays. Cosmic-rays are also an important heating mechanism for many astrophysical regions. In this paper I shall review the methods used to infer the cosmic-ray ionization rate and the values which have been measured.

1 Introduction

Cosmic-rays are very high energy charged particles which stream throughout the galaxy. They are composed mostly of protons and alpha particles with about 1% heavier nuclei, electrons and positrons. The relatively high abundance of heavy elements suggests the origin of cosmic-rays are from regions with highly processed material such as supernova or pulsars (Cowsik and Price 1971).

There is a large excess of lithium,-beryllium-boron group elements compared to other cosmic objects. If these are assumed to be spallation products from collisions of the heavier nuclei cosmic-rays with normal matter then the cosmic-rays must pass through about 3 grams/cm^2 of material. This gives path lengths in the galactic disc of about $5 \times 10^5 pc$ (Spitzer 1968).

2 Chemistry of Cosmic Rays

In interstellar clouds cosmic-rays primarily ionize hydrogen and helium

$$\begin{aligned} \mathrm{Cosmic-Ray} + \mathrm{H_2} &\rightarrow \mathrm{H_2^+} + \mathrm{e} && (1) \\ &\rightarrow \mathrm{H^+} + \mathrm{H} + \mathrm{e} && (2) \\ \mathrm{Cosmic-Ray} + \mathrm{He} &\rightarrow \mathrm{He^+} + \mathrm{e}\,. && (3) \end{aligned}$$

The electrons are energetic and cause additional ionizations and heating of the gas. The H_2^+ reacts quickly with molecular hydrogen to form H_3^+

$$\mathrm{H_2^+} + \mathrm{H_2} \rightarrow \mathrm{H_3^+} + \mathrm{H} \qquad (4)$$

P. D. Singh (ed.), Astrochemistry of Cosmic Phenomena, 471–475.

which rapidly reacts with other atoms and molecules in the gas

$$H_3^+ + O \rightarrow OH^+ + H_2 \quad (5)$$
$$H_3^+ + CO \rightarrow HCO^+ + H_2 \quad (6)$$
$$H_3^+ + N \rightarrow NH_2^+ + H \quad (7)$$

usually by transferring a proton. These proton transfer reactions with H_3^+ are the initial reactions in the ion-molecule reactions networks which have been proposed to explain the molecular abundances. For example the OH^+ produced in reaction 3 goes on to form both OH and H_2O.

Prasad and Tarafdar (1983) pointed out that the fast electrons created by cosmic-ray ionization also produce ultraviolet photons by exciting the Lyman and Werner bands of H_2. Calculations of molecular dissociation and ionization rates by these cosmic-ray induced photons may be found in Sternberg, Lepp and Dalgarno (1987) and Gredel, Lepp and Dalgarno (1989).

3 Cosmic-ray Flux Measurements Near Earth

Measurements of the cosmic-ray flux at the earth allow one to infer a lower limit to the cosmic-ray ionization rate of $\xi = 6.8 \times 10^{-18}\, s^{-1}$ (Spitzer 1968). This represents a lower limit as the lowest energy cosmic-rays don't penetrate the solar wind into the earths orbit. More recently Cecchi-Pestellini and Aiello (1992) have used Voyager data and an some assumptions about the extrapolation to lower energies to estimate a cosmic-ray ionization rate of $4 \times 10^{-17} s^{-1}$ for the solar neighborhood.

4 Recombination Lines

Another method for inferring the cosmic-ray ionization rate is to compare high lying recombination lines with neutral hydrogen absorption measurements (Shaver 1976). The absorption measurements of neutral hydrogen allow one to identify cold gas along the line of sight. The ratio of recombination line optical depth to 21 cm neutral hydrogen optical depth is only a weak function of density and temperature times the cosmic-ray ionization rate. The measurements of ionization rate along various lines of sight by this method are summarized in table 1.

Table 1: Ionization rate: recombination lines

Authors	ξ (s^{-1})
Shaver (1976)	$\leq 2 \times 10^{-17}$
Shaver, Pedlar and Davies (1976)	$\leq 3 \times 10^{-17}$
Casse and Shaver (1977)	$< 2 \times 10^{-17}$
Payne, Salpeter and Terzian (1984)	$\leq 2 \times 10^{-17}$

The rates are upper limits when the recombination line is not observed. Hydrogen charge transfer to oxygen followed by the formation of molecules could lead to an effective recombination rate up to five times larger for high molecular fractions (Shaver et al 1976, Glassgold and Langer 1976). This means the rates listed in table 1 could be low by up to a factor of five.

5 Dense Clouds

In dense clouds the OH abundance is proportional to the H_3^+ abundance (Lepp, Dalgarno and Sternberg 1987). This could be combined with model assumptions about the H_3^+ destruction rate to determine an ionization rate. The fractionation of HCO^+ is a measure of the H_3^+ destruction rate because the fractionation in H_3^+ is passed along to HCO^+. The upper limit on the H_3^+ destruction allows one to infer a upper limit to the electron abundance for clouds with $DCO^+/HCO+$ measurments (Wooten et al 1982, Langer 1984 and Dalgarno and Lepp 1984). The combination of the fractionation measurment and the proportionality of H_3^+ and OH allow one to infer upper limits to the cosmic ray ionization rates for those clouds with both fractionation and OH measurments. The upper limits are $\xi > 4 \times 10^{-18}\, s^{-1}$ for L134N and $\xi > 8 \times 10^{-18}\, S^{-1}$ for B335 (Lepp, Dalgarno and Sternberg 1987). The rates are insensitive to the H_3^+ recombination rates as the H_3^+ is primarily removed by charge transfer reactions.

Each cosmic-ray ionization of a hydrogen molecule converts one molecule into two hydrogen atoms. The atoms reform into molecules on grain surfaces at a rate $k_g r$ so the cosmic-ray ionizion rate is given by

$$\xi n_{H_2} \times 2 \approx n_H n_{H_2} k_g r \quad (8)$$

$$\xi \approx n_H k_g r/2 \quad (9)$$

Fukui and Hayakawa (1981) proposed using this to infer a cosmic-ray ionization rate for a measured hydrogen abundance, they infer the very low value of $\xi \approx 0.7 \times 10^{-18} s^{-1}$. Although this inferred rate is quite low in fact one might expect it to be an upper limit as atomic hydrogen may also be formed by photodissociation near the edges of the cloud.

6 Diffuse Clouds

In diffuse clouds OH is produced by reaction sequences initiated either by cosmic ray ionization of H or H_2 and the OH abundance is proportional to the cosmic-ray ionization rate (Black and Dalgarno 1973, Hartquist, Black and Dalgarno 1978). The OH is removed by photodissociation and so the rate inferred is dependent on the assumed rate. Recent quantum calculations (van Dishoeck and Dalgarno 1984) have shown the photodissociation cross section is larger then previously assumed and van Dishoeck and Black (1986) have rederived rates for several diffuse clouds. The inferred rates are also sensitive to the assumed rate constant for H_3^+ dissociative recombination. Table 2 shows the inferred cosmic ray ionization rates for some diffuse clouds for both slow ($< 10^{-8}\, cm^3\, s^{-1}$) and fast ($\approx 10^{-7}\, cm^3 s^{-1}$) values for the H_3^+ recombination rate.

Table 2: Ionization Rate: Diffuse Clouds

Cloud	ξ (s^{-1}) fast H_3^+ recombination	ξ (s^{-1}) slow H_3^+ recombination
ζ Per	2×10^{-16}	6×10^{-17}
ζ Oph	4×10^{-16}	1×10^{-16}
o Per	8×10^{-16}	2×10^{-16}

[1] from van Dischoek and Black (1986)

7 Conclusions

The cosmic-ray ionization rate may be different for different parts of the interstellar medium. The average ionization rate is probably a $few \times 10^{-17}\, cm^3\, s^{-1}$. In some regions the infered rate is sensitive to the rates of reactions such as dissociative recombination of H_3^+ or the branching between OH and H_2O in the dissociative recombination of H_3O^+. In particular if the recent measurements of rapid dissociative recombination of H_3^+ stand up then their is a puzzle as to why the OH in diffuse clouds leads to such a high inferred rate.

8 References

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QUESTIONS AND ANSWERS

L.Blitz: Why can't you just use the gamma-ray data to get the cosmic ray ionization rate?

S.Lepp: The gamma-rays track the high energy portion of the cosmic-rays whereas the ionization is mainly from the low energy.

W.Langer: It has been suggested that cosmic rays scatter Alfven waves in clouds and could be attenuated somewhat. Wouldn't this lead to variations in CR ionization rate in dense cores versus diffuse clouds?

S.Lepp: That's right.

E.van Dishoeck: (comment) The cosmic ray ionization rates derived from diffuse cloud models quoted in your talk are very high and refer to the case that the H_3^+ dissociative recombination is high. If that rate is low, we find $\zeta \approx 7 \times 10^{-17}\ s^{-1}$.

S.Lepp: Yes, the second column on my view graph had the rates assuming H_3^+ recombination is slow.

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