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ASTRONOMY
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Letter to the Editor

Determination of Cooling Rates in the Interstellar Medium

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ABSTRACT

The cooling in most interstellar 'clouds' is due to fine-structure line emission by C^+. An estimate of the cooling rate can be obtained from the measurement, in the ultraviolet, of the column density $N(C^+\,{}^2P_{3/2})$ relative to $N(H^o+H^+)$. We discuss the measurement of these column densities for eight interstellar 'clouds', sometimes using new observations. In equilibrium the cooling rate equals the heating rate. The rate we obtain is too high to be explained either by the ionization of C by the interstellar radiation field or by ionization of H by low-energy cosmic rays. Photo-electric emission from 'dust' could explain the observed heating rate.

Key words: interstellar medium, heating, dust, cosmic rays.

I. Introduction

Neither the heating nor the ionization of the interstellar medium is well understood. All of the ionization mechanisms that have been suggested also provide energy to the interstellar medium, but not all of the suggested heating mechanisms cause ionization of the interstellar medium.

In equilibrium, the heating rate can be calculated from the cooling rate. The cooling rate can be determined with good accuracy once the ultraviolet spectrum is known. We present a determination of the cooling rate in this Letter and demonstrate that it has important consequences for a determination of the heating mechanism.

II. Energy loss from the interstellar gas

In the general interstellar medium, the primary energy-loss mechanism is collisional excitation of the low-lying energy levels of the more abundant atoms and ions (e.g. see Spitzer 1978, and Dalgarno and McCray 1972) followed by radiation in the infrared. The main ions involved in this process are C^+, 0^o, Si^+, N^+, C^o, and Fe^+. Possibly the H_2 molecule also plays a role. The column density (or at least an upper limit) in the upper (emitting) level in a cloud can be determined from the absorption line from that level, usually observed in the ultraviolet region of the spectrum. In almost every 'cloud' we find that the energy loss is greatest in C^+ emission line, i.e. the product $h\nu\, N(C^+\,{}^2P_{3/2})\, A_{ul}$ is greater than the corresponding quantity for any of the other fine-structure levels, where $h\nu$ is the energy of the infrared transition, A_{ul} is the spontaneous transition rate, and $N(C^+\,{}^2P_{3/2})$ is the column density of the excited level.

The reason for the predominance of C^+ as the cooling agent is probably the high abundance of this ion and the relative ease of collisional excitation. An illustration of this is given by Morton (1975) for the case of ζ Oph where the H_2 plays a larger (but still minor) role than in the other cases considered here. The atom 0^o, which may be somewhat less abundant than C^+, is also more difficult to excite.

We have determined the C^+ and hydrogen column densities by using a curve-of-growth determined for each cloud from the Fe II lines. Enough of these iron lines are observed with sufficient accuracy to well define the curve. The f-values used are those summarized by Morton and Smith (1973); for the λ 1608 line of Fe II we have used $f = 4.5 \times 10^{-2}$. Extrapolation of the curves-of-growth to higher values of the equivalent width is not necessary, since the lines we are dealing with do not represent very high column densities.

The results are shown in Table 1. Half of the measurements were taken by the IUE, supplemented by Copernicus observations (ζ Oph: Morton 1975; ζ Pup: Morton 1978; α Vir: York and Kinahan 1979; ρ Leo: Smeding and Pottasch 1979). For some of the stars more than one component ('cloud') is seen in the interstellar-line spectrum: this component is identified in the table by its LSR velocity.

The column density $N(C^+\,{}^2P_{3/2})$ is given in the second row of the table. The third row gives the column density of the neutral hydrogen $N(H^o)$, as derived from the Lyman α absorption line (some from Bohlin et al. 1978). To account for the possibility that some of the hydrogen along the line-of-sight may be ionized, we calculate the total hydrogen in another way. Most of the sulphur is in the form of S^+. S^o is present in only negligible amounts and S^{++}, while present in most of the 'clouds' listed in Table 1, never exceeds more than 20% of the total sulphur abundance. If we assume that the sulphur abundance in the interstellar gas is solar ($\frac{S}{H} = 1.2 \times 10^{-5}$), and the available evidence points in the direction (e.g. Morton, 1975, 1978), we may calculate the total hydrogen column density from the S^+ density. These last two quantities are given in the fourth and fifth rows of Table 1. It is interesting to compare the values of $S^+(\frac{S}{H})^{-1} = H^o + H^+ + 2\,H_2$ determined in this way with the values of H^o determined from the Lyman α absorption. The agreement is within the observational error except in two cases. In the case of α Vir, York and Kinahan (1978) find the difference significant and conclude that there is as much ionized hydrogen as neutral hydrogen along the line of sight. In the case of ζ Oph there is a substantial difference, which, considering the good agreement in the other 'clouds' is worthy of comment. Two possibilities exist: 1) the S is underabundant in only this case, or 2) the H_2 is formed in a separate 'cloud' with such a low-velocity dispersion that the S^+ contribution from the 'cloud' is a very narrow line that is almost unseen on top of the wider S^+ line. In this case the measured column density of S^+ represents only the 'cloud' in which the H^o exists. This interpretation is supported by the fact that the Lyman α absorption gives a column density $\log N(H^o) = 20.7$, in excellent agreement with the value derived from $N(S^+)$ and given in row five of the table. If this second possibility is true, the contribution of the H_2 'cloud' to the measured C^+ $({}^2P_{3/2})$ column density will likewise be small and we need not consider this 'cloud' further.

We are now in a position to compute the average energy loss per H atom (neutral plus ionized). This is given by

$$\frac{h\nu\, N(C^+\,{}^2P_{3/2})\, A_{21}}{N(H^o+H^+)}\ \mathrm{erg\ s^{-1}}\ \text{per H atom.}$$

The column densities are taken from rows 2 and 5 of Table 1, $A_{21} = 2.4 \times 10^{-6}\ s^{-1}$, and the frequency corresponds to $\lambda = 156\,\mu m$. The results are given in the bottom row of Table 1.

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TABLE 1

ENERGY LOSS IN DIFFERENT INTERSTELLAR CLOUDS

	units	HD 164794	(+2 km s^{-1}) HD 175754	(-77 km s^{-1}) HD 175754	HD 164816	ζ Oph	ζ Pup	α Vir	(-59 km s^{-1}) ρ Leo	HD 191877
log N (C^+ $^2P_{3/2}$)	cm^{-2}	15.22	15.00	13.38	15.22	15.4	15.8	14.16	14.93	15.00
log N (H^0)	cm^{-2}	20.87	20.57		20.61	20.72 21.13*	20.00	19.00	20.26	20.64
log N (S^+)	cm^{-2}	15.84	15.60	14.07	15.54	15.95	15.23	14.51	15.54	15.77
log N ($H^0 + H^+ + 2H_2$)☆	cm^{-2}	20.76	20.52	18.79	20.46	20.87	20.15	19.43	20.46	20.69
ENERGY LOSS PER H Atom	erg s^{-1}	0.7 x 10^{-25}	0.8 x 10^{-25}	1.2 x 10^{-25}	1.2 x 10^{-25}	1.0 x 10^{-25}	3.2 x 10^{-25}	1.6 x 10^{-25}	1.2 x 10^{-25}	0.7 x 10^{-25}

* Includes H_2

☆ from $(H^0 + H^+ + 2H_2) = S^+ \left(\frac{H}{S}\right)$

III. Discussion

The striking result shown in Table 1 is that the energy loss per H atom has a relatively high value, and that it is almost constant for the different 'clouds' considered. The errors involved in the determination of the column densities, will be discussed but they are probably large enough to conclude that the energy loss per H atom may be constant. Assuming an equilibrium situation, this value of the energy loss is also the energy gain per H atom.

A. Discussion of column density determination

This energy loss rate depends on the accuracy of the determination of the column density of excited C^+. The uncertainties in this quantity are small (less than a factor 2) if one accepts that the curve-of-growth used (derived from the Fe^+ lines) is valid. This is correct if all the lines are formed in the same 'cloud' or in clouds of similar physical condition. If, however, the excited C^+ were formed in a region of entirely different physical conditions than the Fe^+ regions a much larger error could result. An example which should be considered is that the excited C^+ is formed in an HII region surrounding the observed star while the Fe^+ is in a neutral 'cloud' not related to the HII region. While we cannot completely exclude this possibility, it seems unlikely for the following reasons:

1) The stars against which the interstellar lines have been observed vary in spectral type from B1 to O4. If the excited C^+ were formed primarily in an HII region surrounding the star, one would expect the N ($C^+{}_{3/2}$) to be strongly correlated with the spectral type. In fact, no such effect is observed (see Table 1), the column density N ($C^+{}_{3/2}$) being about the same for the O4 star HD 164794 and the B1 star HD 191877.

2) For several stars (HD 175754, ρ Leo) at least two cloud components are present and easily separable. At most only one can correspond to an HII region surrounding the star. However in both cases, the excited C^+ absorption is seen in both 'clouds', and in each case the same high value of energy loss is found. Thus there are indisputably cases where the stellar HII region has no effect.

3) The fact that the cooling rate per H atom, computed for nine clouds in different directions and at different distances, can be so similar, indicates that the method is unlikely to be far wrong. The fact that this cooling rate has a reasonable explanation, strengthens this argument.

B. Energy input in the ISM

We now consider the various energy input mechanisms in more detail to see which of these can produce the energy gain we have determined.

Consider first the energy input due to photo ionization of C^+ This can be written as

$$\frac{\Gamma N (C^0) \Delta E}{N (H^0 + H^+)} \text{ erg s}^{-1} \text{ per H atom}$$

where Γ is the photo-ionization rate for C^0 and ΔE is the average excess energy of the ionizing photons. We have used a value of $\Gamma = 3.6 \times 10^{-10}$ s^{-1}, which is 3 times the value given by De Boer, Koppenaal and Pottasch (1972), to account for the present (e.g. summary by Draine, 1978) estimate that the interstellar radiation field is 3 times as intense as estimated by Habing (1969). The value of 1.5 eV for ΔE was used. The observed values of N (C^0) are always less than 10^{14} cm^{-2} (except ζ Oph) and the value of energy input due to photo ionization of C^0 is always less than 2×10^{-28} erg s^{-1} per H atom (except ζ Oph which is 5×10^{-27} erg s^{-1} per H atom). This is much smaller than the required 10^{-25} erg s^{-1} per H atom, given in Table 1.

Consider next the energy input due to cosmic rays. Following Spitzer and Tomasko (1968), Spitzer (1978) this can be written as

$$5.4 \times 10^{-12}\ \zeta \text{ erg s}^{-1} \text{ per H atom}$$

where ζ is cosmic-ray ionization-rate coefficient. There are different ways to estimate this coefficient. Spitzer and Jenkins (1974) have summarized the different observational determinations which indicate a value $\zeta \simeq 10^{-16}$ s^{-1} or somewhat less. If this value is correct, cosmic rays fail by orders of magnitude to provide the necessary energy input.

Finally we consider the heating of the gas by photo-electron emission from dust (Watson, 1972). Although the detailed nature of the dust is not known, the properties of many likely materials are similar so that a general discussion can be given. The most important parameters are: the yield (number of electrons emitted per absorbed photon), which is a strong function of the photon energy; the energy of the photo-electron; and the average charge of the dust grains which in turn is a function of the electron density in the gas. According to De Jong (1977) and Draine (1978), photoelectric heating is largest when the grain charge is close to zero, which occurs when $n_e \gtrsim 10^{-1}$ cm^{-3} using 3 times the Habing radiation field. Draine (1978) and De Jong (1977) suggest using yields of 10 to 20%. If these yields occur for photons of as low as 6 eV to 8 eV, heating rates of from 4×10^{-26} to 10^{-25} erg s^{-1} per H atom are predicted, at least for values of T_e $\leq$ 6000 K. It may be noted that De Jong (1978) has also suggested that the threshold for this process must occur at values as low as 6 eV.

This heating rate is slightly less, but quite close, to the heating rates observed. When $n_e < 10^{-1}$ cm^{-3} the heating rate will be substantially reduced. This argues that n_e must be of the order of 10^{-1} cm^{-3} or greater in all these interstellar 'clouds'. This does not conflict with the average value of $\bar{n}_e$ of about 3×10^{-2} cm^{-3} deduced from pulsar dispersion measurements since the 'clouds' cover only a part of the line of sight.

Our most important conclusion is that the heating rate does not vary substantially from one cloud to the other, even though the clouds considered undoubtably have very different physical conditions (density, temperature, and ionization state). This must mean that the process causing the heating is always proportional to n(H) but does not depend on n_e or T_e.

This means that heating by ionization of C is unimportant but this conclusion has been reached earlier (Morton, 1975; Black and Delgarno, 1977; De Jong, 1977). We also conclude that cosmic rays cannot contribute significantly to the observed 'heating' rate. On the other hand, photoelectric emission from dust appears en effective way of converting the starlight energy between 1600 Å and 912 Å into interstellar gas energy. However, the high value of the observed heating rate requires that the dust has a high photoelectric yield, that it effectively absorbs photons of relatively low energy (~ 6 eV), and that it is neutral. Further the gas T_e must be less than about 6000 K.

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