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ON THE IONIZATION OF HYDROGEN AND HELIUM BY HYDROMAGNETIC SHOCK WAVES

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RESUMEN

Se calculan las condiciones de salto en frentes de choque hidromagnéticos con velocidades en el intervalo de 10 a 200 km s^{-1}, incluyendo el efecto de campos magnéticos perpendiculares al flujo con valores entre 0 y 1×10^{-4} gauss. Nuestros resultados para velocidades menores que 16 km s^{-1} coinciden con los de Field *et al.* (1968).

Cuando el campo magnético es nulo y la velocidad está comprendida entre 30 km s^{-1} y 60 km s^{-1} el hidrógeno se ioniza parcial o totalmente, mientras el helio permanece neutro. Cuando el campo magnético es no nulo el rango de velocidades para el cual el hidrógeno se ioniza, sin ionizarse el helio, se desplaza hacia valores más altos.

Se discute la importancia de estos resultados para algunos problemas astronómicos. En particular se ve que es fácil explicar la ausencia de helio ionizado en tres regiones H II que están cerca del núcleo de nuestra galaxia si la ionización se debe a ondas de choque hidromagnéticas.

ABSTRACT

Hydromagnetic shock waves in the 10 to 200 km s^{-1} range including the effect of a magnetic field in the 0 to 1×10^{-4} gauss range perpendicular to the flow, have been computed. Our results for $v_0 \leqq 16$ km s^{-1} are in very good agreement with those of Field *et al.* (1968).

It is found that in the case of there being no magnetic field and for v_0 in the 30 to 60 km s^{-1} range a large fraction of the hydrogen atoms is ionized while most of the helium atoms remain neutral. In the presence of a magnetic field the range in which hydrogen is ionized while helium remains neutral, is shifted to higher velocities.

The relevance of our results to some astronomical problems is briefly discussed. In particular the lack of ionized helium in three H II regions near the nucleus of our galaxy can be easily explained if the ionization is due to hydromagnetic shock waves.

Key words: SHOCK WAVES — NEBULAE — GALACTIC NUCLEI.

I. INTRODUCTION

The existence of three H II regions near the nucleus of our galaxy where $N(He^+ + He^{++})/N(H^+) < 0.03$ (Churchwell and Mezger 1973; Huchtmeier and Batchelor 1973) has led several astronomers to propose ionization mechanisms that, permitting a normal or even a helium rich composition, could explain the low ratio of ionized helium to hydrogen. Preferential absorption by small dust particles of photons capable of ionizing helium rather than those capable of ionizing hydrogen (c.f. Jura and Wright 1974; Churchwell, Mezger and Huchtmeier 1974) and a different initial mass function in the nucleus of our galaxy, in the sense that the mass of the most massive objects is smaller in the nucleus than in the solar neighborhood (Rodríguez, Torres-Peimbert and Peimbert 1974) have been proposed to explain the lack of ionized helium.

Evidence in favor of supersonic velocities in the direction of the center of our galaxy has been presented by Kaifu, Kato and Iguchi (1972) Scoville (1972) and Mezger (1974). Furthemore Chaisson (1973) finds that the velocity dispersion of G 0.7 − 0.0, one of the three H II regions where ionized helium is deficient, is in the 35 to 45 km s^{-1} range. These observations indicate the presence of hydromagnetic shock waves in the 30 to 150 km s^{-1} range in the nucleus of our galaxy. Minkowski and Osterbrock (1959), after studying the elliptical galaxy NGC 1052, suggested the possibility that a considerable fraction of the ionization in NGC 1052 is produced by energy supplied by the degradation of turbulent energy. The large [O I]/[O II] line intensity ratios in the nuclei of M51 and M81 (Peimbert 1968) also suggest the presence of shock waves in these objects. Moreover, there are several observations indicating non-circular motions in the 30 to 150 km s^{-1} range in and near the nuclei of several normal galaxies (c.f. Goad 1974) which again indicate the presence of shock waves.

These results led us to study shock waves as a source of ionization in galactic nuclei in this paper. In particular we will derive the helium and hydrogen degree of ionization to see if it is possible by this mechanism to explain the lack of ionized helium in the nucleus of our galaxy. We decided to compute hydromagnetic shock waves in the 16 to 70 km s^{-1} velocity range, which might be important in the study of nuclei of normal galaxies. In § II we present the shock wave computations and in § III we discuss the relevance of our results to several astronomical problems, as well as the conclusions.

II. COMPUTATIONS

Since shock fronts can appear at supersonic flow velocities and internal degrees of freedom (such as excitation and ionization of atoms) can be excited when gas flows through a shock front, the absence of helium recombination lines could be attributed to the absence of ionized helium rather than to a low helium abundance. It is of interest then to inquire whether passage of neutral gas through a shock front can lead to the ionization of hydrogen but not of helium.

This requires that the post-shock temperature of the gas be less than 25 000°K approximately, which can be achieved at low flow velocities even when the shock is already strong, or at large flow velocities if the shock is weak. For large flow velocities the presence of a magnetic field can weaken the discontinuity (see for instance Field *et al.* 1968) and produce the latter condition.

To describe the change in the flow parameters across a shock, we use the one dimensional steady state hydromagnetic equations:

$$\frac{\partial}{\partial x}(\rho v) = 0$$

$$\frac{\partial}{\partial x}[p + \rho v^2 + B^2/8\pi] = 0 \qquad (1)$$

$$\frac{\partial}{\partial x}\left[\rho v\left(\frac{1}{2}v^2 + U + p/\rho\right) + \frac{B^2}{4\pi}v\right] = q\rho$$

where ρ is the mass density, v is the velocity, B is the magnetic field (assumed perpendicular to the flow), U is the internal energy per unit mass and q is the energy loss per unit mass per unit time.

If we consider a gas of hydrogen and helium only we have:

$$\rho = m_H n\left(1 + \frac{N_{He}}{N_H}\,\frac{m_{He}}{m_H}\right)$$

and

$$p = nKT\left(1 + \frac{N_{He}}{N_H} + \xi^H + \frac{N_{He}}{N_H}\xi^{He}\right)$$

where T is the temperature, m_H is the hydrogen atom mass, $m_{He} = 4\,m_H$ is the helium atom mass, N_{He}/N_H is the helium to hydrogen abundance ratio by number, n is the hydrogen particle density, ξ^H is the fractional ionization of hydrogen and ξ^{He} is the fraction of helium that is once ionized. We have taken $U = \frac{3}{2}p/\rho$, and we have neglected the mass of the electrons.

To compute the ionization structure of the gas we take

$$\xi = \frac{\alpha_I/\alpha_R}{1 + \alpha_I/\alpha_R}$$

where

$$\alpha_I = 1.3 \times 10^{-8}[T(°K)]^{½}\ \zeta F\, I_{(eV)}^{-2}\, e^{-I/KT}\ cm^3\ s^{-1}$$

is the collisional ionization coefficient given by Cox and Tucker (1969) and where the parameters ζ, I and F for hydrogen and helium are given in Table 1,

$$\alpha_R = 2.07 \times 10^{-11} Z^2 [T(°K)]^{-½} \left(0.4288 + \frac{1}{2}\ln\beta + 0.469\,\beta^{-⅓}\right) cm^3\ s^{-1}$$

is the radiative recombination coefficient (Cox and Tucker 1969) for hydrogen-like ions. Here $\beta = I/KT$. For both H and He we take $Z = 1$, that is, we consider as an approximation, that the recombination of He^+ is hydrogen-like.

TABLE 1

	$I_{(eV)}$	ζ	F
H	13.6	1	0.83
He	24.6	2	0.63

We integrate Equations (1) across the shock and obtain

$$\rho_1 v_1 = \rho_0 v_0 \qquad (2)$$

$$p_1 + \rho_1 v_1^2 + B_1^2/8\pi = p_0 + \rho_0 v_0^2 + \frac{B_0^2}{8\pi} \qquad (3)$$

$$\frac{1}{2}v_1^2 + U_1 + \frac{p_1}{\rho_1} + B_1^2/4\pi\rho_1 + A = \frac{1}{2}v_0^2 + U_0 + p_0/\rho_0 + B_0^2/4\pi\rho_0 \qquad (4)$$

$$B_1/\rho_1 = B_0/\rho_0 \qquad (5)$$

where the subscript "0" indicates pre-shock values and the subscript "1" post-shock values, and

$$A = \int \frac{q\rho dx}{\rho_0 v_0} = \int q dt$$

$$= (\xi_1^H - \xi_0^H)\frac{I_H}{m_H\left(1 + \frac{N_{He}}{N_H}\frac{m_{He}}{m_H}\right)} + \frac{N_{He}}{N_H}(\xi_1^{He} - \xi_0^{He})\frac{I_{He}}{m_H\left(1 + \frac{N_{He}}{N_H}\frac{m_{He}}{m_H}\right)} \qquad (6)$$

is the energy lost per unit mass across the shock due to ionization of hydrogen and single ionization of helium.

We have neglected the loss of energy due to radiative cooling within the discontinuity since

$$\frac{t_I}{t_c} \sim \frac{4\mathcal{L}}{\frac{1}{2}m_H v_0^2 \sigma v_0}\left[1 + \frac{3\sigma v_0}{4\alpha_I}\right] \sim \frac{16}{v_6^3}[1 + 1.8 \times 10^{-2} v_6] < 1$$

for $v_6 > 4$, which is required for hydrogen to be ionized after the shock ($v_0 = v_6 \times 10^{+6}$ cm s^{-1}).

Here $t_c = \frac{\frac{1}{2}m_H v_0^2}{4\mathcal{L} n_0}$ is the cooling time, where we have taken the emissivity $\mathcal{L}$ to be 10^{-22} erg cm^3 s^{-1}, typical of a gas in equilibrium at $T \sim 5 \times 10^4$ °K (Cox and Daltabuit 1971). This is certainly an overly generous estimate of the cooling efficiency since this emissivity is due to electron-ion collisions and not, as in our case, to atom-atom collisions which are known to be less efficient. (See for instance Zel'dovich and Raizer 1966). This means that the real cooling time is much longer than the one considered here. In the above formula $t_I = t_t + t_A$ is the ionization time where t_t is the thermalization time and t_A is the ionization time due to atom-atom collisions. $\sigma = 2.5 \times 10^{-17}$ cm^2 is the geometrical cross section for hydrogen atoms and α_I is the hydrogen collisional ionization coefficient for $T \sim 5 \times 10^4$ °K.

Equations (2)-(6) were solved numerically using a two-stage Newton-Raphson method. In the first stage a solution is found for $B_0 = 0$ by solving (2) and (3) for v and substituting in (4). The resulting equation is solved by a standard Newton-Raphson procedure for one variable. In the second stage small magnetic field steps are taken until the desired value is reached. Each step is solved as before, and the solution provides the starting point for the Newton-Raphson solution of the next step. The solutions obtained conserve mass, momentum and energy to 1 part in 10^4.

In Figure 1 the post-shock temperature and the hydrogen and helium fractional ionizations are shown as functions of the flow velocity in the absence of

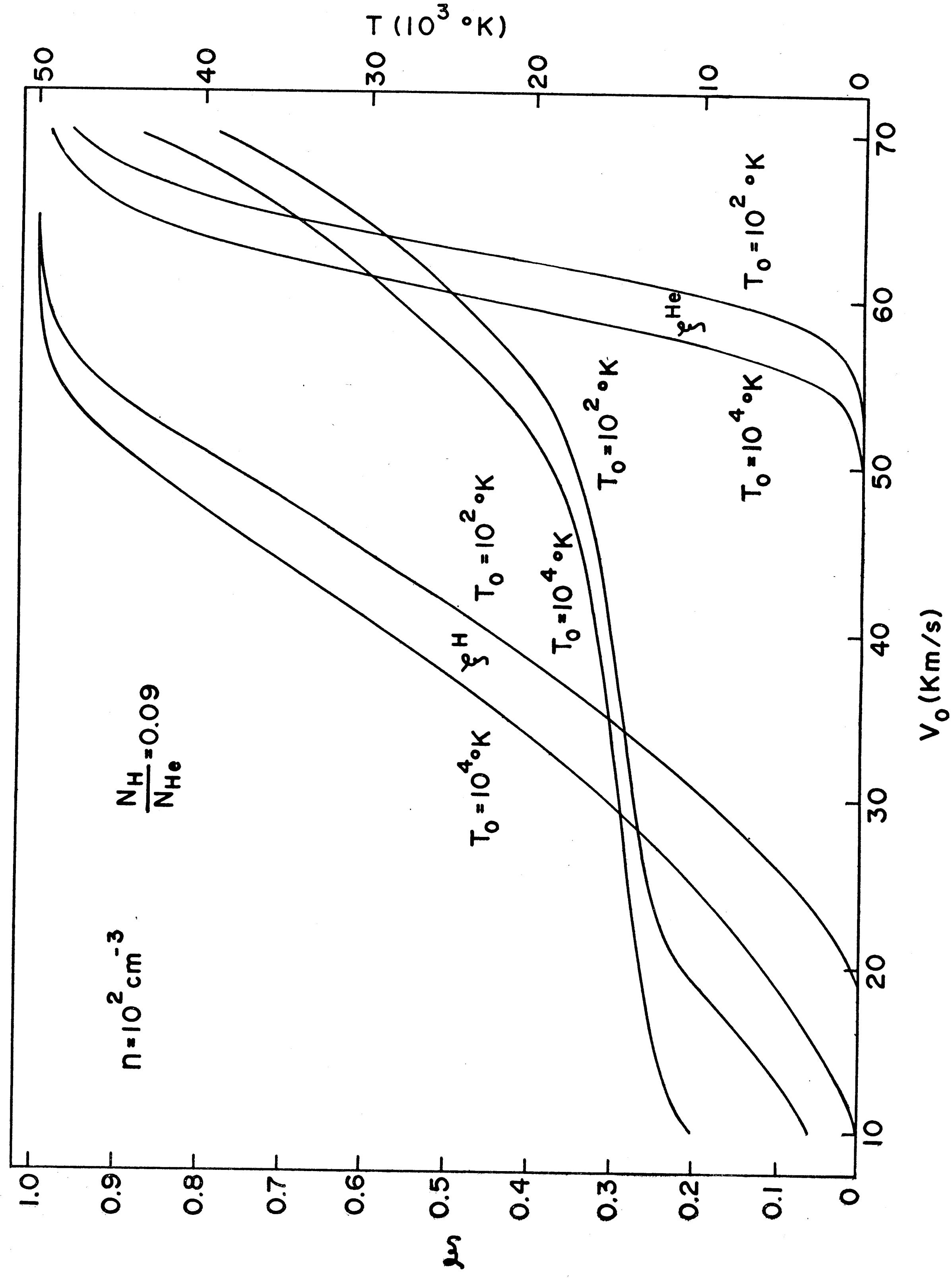

FIG. 1. The post shock temperature, hydrogen ionizationand helium ionization as functions of velocity for $B_o = 0$.

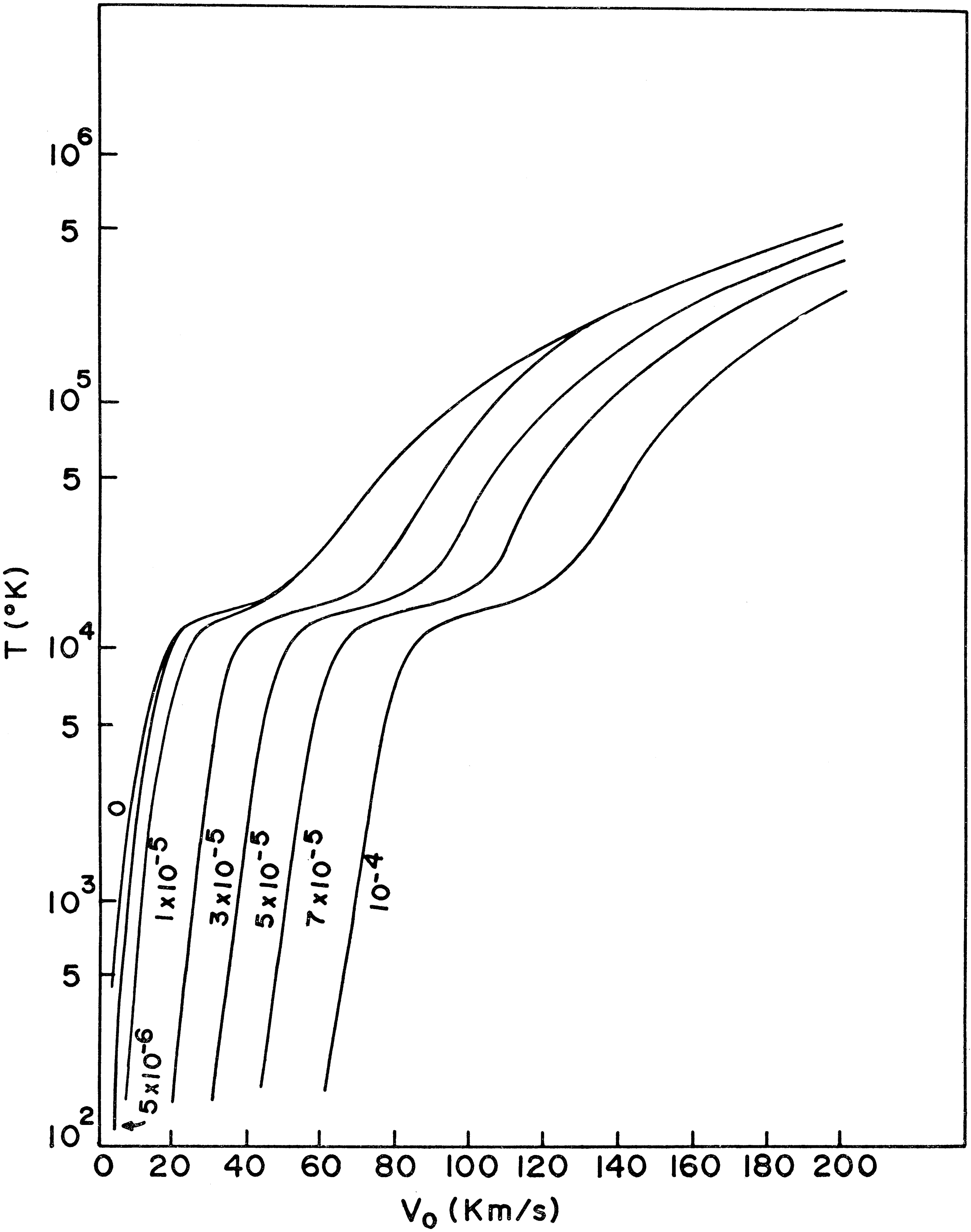

FIG. 2. The post shock temperature as a function of velocity for several values of the pre-shock magnetic field. Each curve is labeled by the pre-shock magnetic field measured in gauss.

a magnetic field. The pre-shock density was taken to be 10^2 cm^{-3}, the helium abundance considered was 0.09 and two pre-shock temperatures were used, 10^2°K and 10^4°K. It is apparent that for flow velocities between 40 km s^{-1} and 60 km s^{-1} the hydrogen is ionized while the helium remains neutral. Notice also that while hydrogen becomes ionized when the velocity increases, the post-shock temperature remains almost constant. This of course is due to excitation of internal degrees of freedom.

The effects of a magnetic field are shown in Figure 2. The pre-shock conditions are $n_0 = 10^2$ cm^{-3}, $T_0 = 10^2$°K, $\frac{N_{He}}{N_H} = 0.09$. The curves for $B_0 = 0$, 5×10^{-6}, 10^{-5} gauss correspond to those given by Field *et al.* (1968) for $v_0 \leq 16$ km s^{-1} since under these conditions ionization does not occur. The flattening of the temperature curves at about 15 000°K is again due to the effects of ionization. At high velocities the effects of magnetic fields of these strengths become less important. At a given pair of values of the pre-shock temperature and magnetic field there is a minimum flow velocity, the magnetosonic velocity, below which there is no discontinous solution (see for instance Field *et al.* 1968). This cutoff is not shown in Figure 2.

In Figure 3, we show the flow velocity that for a given magnetic field, will result in post-shock values:

$$T_1 \sim 15\,000\ °K,\ \xi_1^{H} \sim 0.5 \quad \text{and} \quad \xi_1^{He} \sim 10^{-4}.$$

We did not consider in our program the effect of the ionizing recombination radiation on the material ahead of the shock. Since about 40% of the hydrogen recombinations are to the first level and half of the ionizing photons will go to ionize the material ahead of the shock it follows that for $v_0 = 35$ km s^{-1} and $T_0 = 100$ °K, (see Figure 1) $\xi^H = 0.32$ and about 6.5% of the hydrogen atoms will be ionized before entering the shock. This is equivalent to assuming that after the shock we have an additional energy of ~ 0.8 eV per particle. In Figure 1 the effect of adding approximately 0.9 eV ($T_0 = 10^4$ °K) per particle is shown. Since for $v_0 > 35$ km s^{-1}, ξ^H is higher, the pre-ionization effect will be more important. In any case the maximum

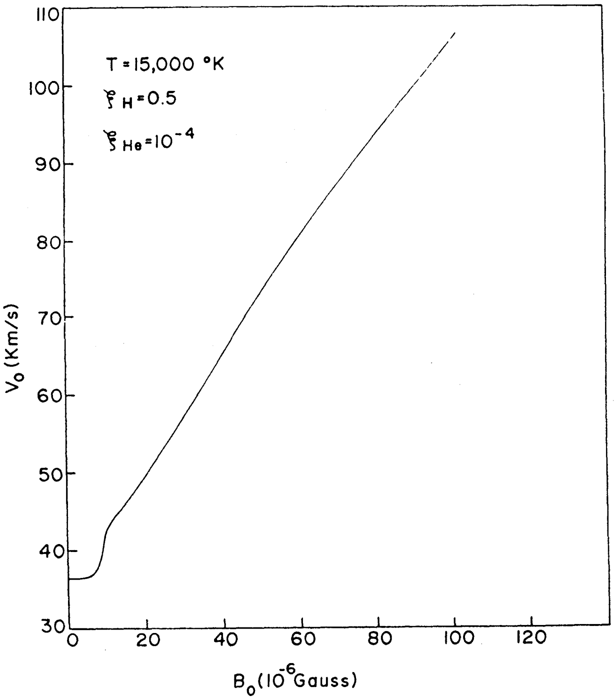

FIG. 3. The shock velocity that will produce a 50% ionization of hydrogen as a function of the pre-shock magnetic field. The post shock temperature is 15 000 °K and the ionization of helium is approximately 10^{-4}.

hydrogen pre-ionization will be of about 20% and helium will not be preionized for $v_0 < 50$ km s^{-1}.

III. DISCUSSION

From the computations presented in §II, it is found that for a considerable range in shock velocities, hydrogen is ionized while helium remains neutral. This property can be used to differentiate, at low shock velocities, the shock wave mechanism from the ionization due to early type main sequence O stars, since these stars ionize helium throughout the H II region.

Since the characteristic cooling time is at least an order of magnitude smaller than the recombination one it follows that the size of the H II region behind the shock is given by

$$l \sim v_1 \frac{5KT_1}{n_1 \mathcal{L}(T_1)}, \tag{7}$$

where $\mathcal{L}(T_1)$ is the emissivity of the gas given by Cox and Daltabuit (1971). Equation (7) is obtained by integrating equation (1.c). This result implies that the emission measure of this H II region for $T_1 \sim 1.5 \times 10^4$ °K is given by E.M. $\sim 10^{-7}$ v_1 ξ^H n_1 pc cm^{-6} where v_1 is given in cm s^{-1}. Notice that if kinetic energy is being degraded in a turbulent region the estimate of the emission measure should be multiplied by the number of shocks along the line of sight.

We do not know what is the amount of kinetic energy that is being degraded through ionization in the nucleus of our galaxy. However, it is clear that if the turbulent velocities are in the 30 to 60 km s^{-1} range (or somewhat higher in the presence of a magnetic field) and if the ionization is due to shock waves, it is possible to explain the lack of ionized helium in some regions near the nucleus of our galaxy.

Our results might apply to other nuclei of galaxies. For example in the nucleus of M82, where an explosion took place about $1 - 2 \times 10^6$ years ago, about half of the helium atoms are neutral and the [O I]/[O II] line intensity ratio is somewhat higher than in normal H II regions (Peimbert and Spinrad 1970).

From observations of the Copernicus Satellite (Morton *et al.* 1973; Rogerson *et al.* 1973) it follows that the degree of ionization in the low density interstellar medium (intercloud medium) is very low and that a large fraction of the helium atoms is neutral (Torres-Peimbert, Lazcano and Peimbert 1974). Therefore from the results presented in §II we can rule out the possibility of supernovae being responsible for most of the ionization of the intercloud medium. However, there might be a small contribution from very old SN remnants with velocity of expansion smaller than 60 km s^{-1}. Other possible sources of heating and ionization of the low density interstellar medium which imply degradation of turbulent energy are provided by Mira stars (Carrasco and Grasdalen 1972), high velocity clouds falling to the galactic plane (Oort 1970), and planetary nebulae. In the case of planetary nebulae the ejected shells show velocities of expansion in the 15 to 50 km s^{-1} range with a typical velocity of about 25 km s^{-1} (Wilson 1950). Most planetary nebulae belong to the disk population and show moderate velocities with respect to the gas near the plane of the galaxy. We will discuss elsewhere the contribution of planetary nebulae to the heating and ionization of the low density interstellar medium.

The study of sources of energy and ionization mechanisms in the nuclei of galaxies is very important and is in its early stages. It is clear that accurate observations of the $N(He^+ + He^{++})/N(H^+)$ ratio in and near the nuclei of other galaxies, coupled with information on turbulent velocities, are needed to evaluate the importance of the mechanism suggested in this paper.

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