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THE GALACTIC THERMAL PRESSURE GRADIENT

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RESUMEN. El cociente 6717/6731 del [S II], tal como se observa en restos de supernova de gran tamaño, presenta un gradiente negativo como funciōn de la distancia galactocēntrica. Este gradiente puede ser al menos parcialmente debido a un gradiente negativo en la densidad de la componente tibia del medio interestelar. Esta hipōtesis es verificada al analizar el tamaño māximo que alcanzan los restos de supernova como funciōn de la distancia galactocēntrica, observāndose objetos mayores a mayores distancias del centro galāctico. Un gradiente negativo en la presiōn tērmica de esta componente es obtenido cuando combinamos el gradiente de densidad con el gradiente tērmico que ha sido obtenido a partir de observaciones de radio en regiones H II. La forma del gradiente de densidad y del gradiente de presiōn es similar a la forma en la cual se distribuyan las nubes moleculares y la emisiōn en H166α. Esta similitud es probablemente debida a que en puntos interiores al Sol, la presiōn externa excede una presiōn crītica a partir de la cual es posible la conversiōn de nubes difusas en nubes moleculares.

ABSTRACT. The [S II] line ratio 6717/6731 observed in large galactic supernova remnants (SNR's), has a negative gradient as a function of galactocentric distance. This gradient may be at least partially due to a negative density gradient in the warm component of the interstellar medium. This hypothesis is verified by galactocentric distribution of maximum sizes of radio SNR's, where the largest objects are seen at greatest distances from the galactic center. A negative thermal pressure gradient is obtained when this density gradient and the temperature gradient obtained from radio observations of H II regions are combined. The shape of the density and pressure gradient is similar to the way in which molecular clouds and H166α are distributed. This similarity is probably due to the fact that at points interior to the solar galactocentric distance, the external pressure exceeds a critical pressure beyond which the conversion of diffuse into molecular clouds is possible.

Key words: GALAXY-STRUCTURE — INTERSTELLAR-SUPERNOVAE REMNANTS

I. INTRODUCTION

The thermal pressure of the interstellar medium is a quantity of some importance, insofar as it is one of the parameters regulating the transformation of diffuse into molecular clouds (Cox and Franco 1986) and, consequently, the star formation process. On the other hand, as it is determined by the gravitational potential in the Z-direction, it may reveal the value of the latter. Thermal pressure in the gaseous component of the interstellar medium can be explored only where self-gravity is not important. We are thus compelled to direct our attention to either the warm or hot component of the interstellar medium. In this work we explore the thermal pressure in the warm component, using supernova remnants (SNR's) in order to inquire on the particle density and H II regions so as to obtain the temperature.

II. THE DENSITY GRADIENT

In a recent paper Fesen, Blair and Kirshner (1985) (henceforth FBK) investigated the behaviour of several optical line ratios in SNR's whose diameters are larger than 20 parsec. They plotted the S^+ line ratio 6717/6731 as a function of galactocentric distance (Figure 1), and found it to increase as the remnant is further away from the galactic center. As the ratio is very nearly constant within each SNR (in the mean, standard deviations within each object are ∿8%), they concluded that the behaviour of this line ratio as a function of galactocentric distance reflects a real galactic trend. Since 6717/6731 is a function of the electron density (n_e) in the recombination region of SNR's, being larger when n_e is smaller, we must inquire into which can be the reasons as to why n_e is larger amongst those objects that are closer to the galactic center.

A possible explanation is that the ambient particle density is a decreasing function of galactocentric distance. It has been known for some time that n_e and the preshock density (n_o) are related through a very simple expression. For shock velocities (Vs) larger than about 70 km s^{-1}, Bohigas et al. (1983) showed that magnetic pressure is dominant in the recombination region of a SNR, in which case,

$$n_o = \left[\frac{n_e^2 B_o^2}{8\pi m_H \mu V_s^2}\right]^{1/3} \qquad (1)$$

where B_o is the magnetic field of the surrounding medium, m_H is the hydrogen mass and μ is the mass per particle (in units of m_H) in the ambient medium. When applied to SNR's, this equation leads to preshock densities of the order of 1 cm^{-3}, typical of the warm component of the interstellar medium, as expected from the analysis carried out by Kafatos et al. (1980) on the effect of pre-shock density on the observability of these objects. Thus, equation (1) indicates that a decreasing value of n_e can be accounted for with a negative galactocentric gradient on the density of the interstellar medium, if all other things (V_s, B_o and μ) remain constant.

No correlation between shock velocity and galactocentric distance is found. On the other hand Paul, Cassé and Cessarsky (1976), investigating the distribution of synchrotron radiation and γ-rays of energy larger than 100 MeV, found that

$$B_o = a\, n_o^{\frac{1}{2}} \qquad (2)$$

which leads to,

$$n_o = \frac{a}{(8\pi m_H)^{\frac{1}{2}}\, V_s}\ \frac{n_e}{\mu^{\frac{1}{2}}} \qquad (3)$$

and, since the shock velocity is not a function of galactocentric distance,

$$\frac{n_o}{(n_o)_\odot} = \frac{n_e/\mu^{\frac{1}{2}}}{(n_e/\mu^{\frac{1}{2}})_\odot} \qquad (4)$$

The electron density is found from 6717/6731, whereas μ can be found from the work of Peimbert, Torres-Peimbert and Rayo (1978) to be approximately given by,

$$\mu \approx 1.739 - 0.028\, R_G \qquad (5)$$

where R_G is the galactocentric distance in units of kiloparsec.

The results are plotted in Figure 2. A linear fit for data points beyond 5 kpc (within this galactocentric distance the distribution of H_2 exhibits and abrupt change in the gas properties (Burton 1976)), and excluding RCW86, which is the young remnant of the 185 AD supernova event (Clark and Stephenson 1977), leads to

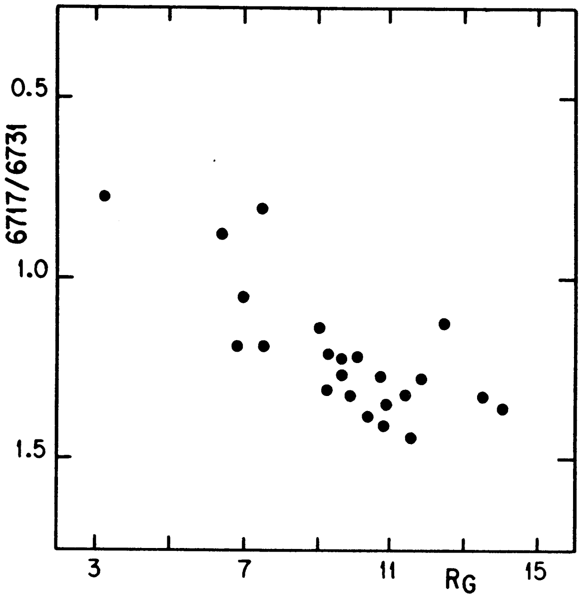

Fig. 1. The S^+ line ratio 6717/6731 in large SNR's as a function of galactocentric distance (R_G, in kiloparsec).

$$\frac{n_o}{(n_o)_\odot} = 4.08(\pm\ 1.28) - 0.308(\pm\ 0.08)R_G \qquad (6)$$

with a correlation coefficient of 0.64. Thus, the gradient in 6717/6731 may be revealing a real interstellar density gradient.

But a density gradient is not the only possible explanation for the galactocentric gradient in 6717/6731. A selection effect has been proposed by FBK in order to explain the behaviour of 6717/6731. They argue that observation towards the galactic center will occlude the faintest SNR's, and only the densest (brightest) SNR's will be observed in this direction. Consequently, a gradient in the interstellar density can not be deduced by the observed gradient in 6717/6731. A more extensive discussion on the significance of selection effects will be given in a forthcoming paper. But it is evident that if we are to confirm or dismiss the hypothesis regarding a galactocentric density gradient, we have to explore other sources of information regarding this question.

Figure 3, also taken from FBK, is a plot of SNR's radio diameter as a function of galactocentric distance for all those objects given by Clark and Caswell (1976). It is well known that these objects are strong radio sources during all their lifetime (except may be for the first hundred years, according to Brown and Marscher 1978), so that it is not surprising that the diagram is practically full. Yet, it is interesting to observe that there is a well defined upper bound for the diameters, indicating the maximum size at which a SNR disappears as such. Furthermore, this upper bound is not random, but shows a tendency to increase with galactocentric distance. The radius (R_{10} in units of 10 parsec) of a SNR in the radiative phase is given by (Chevalier 1974),

$$R_{10} = 1.30\ E_{50}^{0.32}/V_7^{0.45}\ n_o^{0.36} \qquad (7)$$

Where E_{50} is the energy of the supernova explosion in 10^{50} erg and V_7 is the shock velocity in 100 km s^{-1}. Since the shock velocity is not a function of galactocentric distance, and since it would be quite ourprising if E_{50} were, it follows that any variation in the largest possible size of a SNR is likely to be due to the density in the surrounding medium.

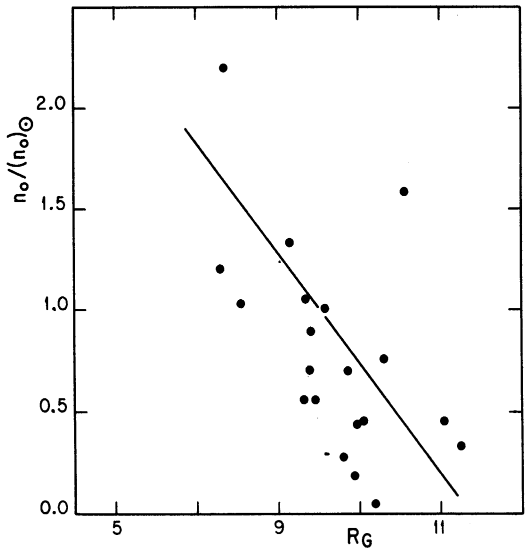

Fig. 2. The behaviour of the density of the warm component of the interstellar medium ($n_O/(n_O)_\odot$) as a function of galactocentric distance (R_G, in kiloparsec), as found from the S^+ line ratio 6717/6731 (equation (4)).

Thus, equation (7) can be used to explore a possible density gradient in the warm component of the interstellar medium from the maximum possible size (Rm) of SNR's through

$$\frac{n_O}{(n_O)_\odot} = \frac{(Rm)_\odot^{2.79}}{Rm^{2.79}} \qquad (8)$$

We divided galactocentric distances in 1 kpc bins, and looked for the largest SNR's in each bin and within 100 pc of the galactic plane using the list of Clark and Caswell (1976). The result of this inspection is shown in Figure 4, where the quantity $(Rm)_\odot^{2.79}/Rm^{2.79}$ is plotted. It is evident that there is a real gradient, and a linear fit to data points beyond 5 kpc (for the reason above mentioned) leads to,

$$\frac{n_O}{(n_O)_\odot} = 2.81(\pm\ 0.23) - 0.181(\pm\ 0.025)\ R_G \qquad (9)$$

with an excellent correlation coefficient of 0.95. Notice that equation (6) prescribes a gradient that is 1.7 times larger than the one given by equation (9), indicating that a selection effect is indeed operating when the sulphur line ratio is considered. It is interesting to observe that at 4.7 kpc, a point not included in the correlation, there is a noticeable drop in the interstellar density, a feature that coincides with the observed distribution of H_2. Interstellar density seems to rise again at 3.8 kpc, suggesting that there is another major change in the properties of the interstellar medium at approximately this galactocentric distance.

III. THE TEMPERATURE GRADIENT

We would also like to obtain a temperature gradient from SNR's, but no such thing is found from the temperature sensitive line ratio (4068+4076)/(6717+6731) of S^+ or 5007/4363 of O^{+2}, since the recombination region is dominated by magnetic pressure. There are other sources of information, such as H II regions (Peimbert, Torres-Peimbert and Rayo 1978, Mezger et al. 1979; Shaver et al. 1985; and, also for a review, Azcárate, Cersósimo and Colomb 1985) and planetary nebulae (Maciel and Faundez-Abans 1986). A distinct positive galactocentric

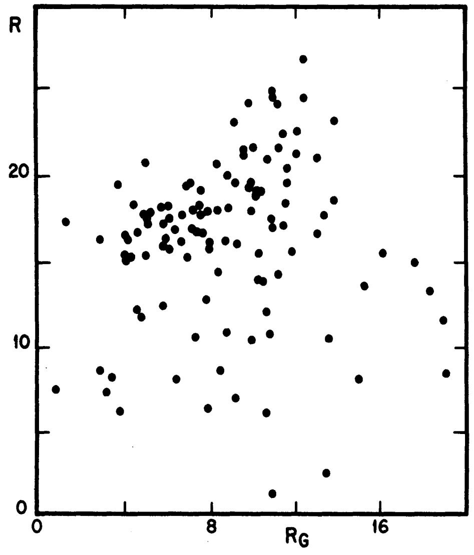

Fig. 3. Distribution of the radius of SNR's (R, in parsec) as a function of galactocentric distance (R_G, in kiloparsec).

gradient is found in all cases, and no relation is found between the value of this gradient and the method used in order to derive it. There is, however, a relation between the zero point and the line observed as temperature in the high density gas is systematically larger than at the low density gas, a trend that might be due to the inhibiting effect of collisional deexcitation on the cooling of dense regions (Garay and Rodríguez, 1983). As for the cause producing the gradient, three basic hypothesis have been put forward, an increase on the dust content of H II regions closer to the galactic center, an effective temperature gradient in the exciting stars and a heavy element abundance gradient. Several inconveniences have been found in relation to the first two possible explanations (see Lichten, Rodríguez and Chaisson 1979; Maciel and Faundez-Abans 1986; Peimbert, Torres-Peimbert and Rayo 1987), and it seems that the most likely cause for the temperature gradient is the well known abundance gradient that has been observed in our galaxy, as well as in many others. Thus, the temperature gradient is not the result of some localized cause, but of a general feature of the interstellar medium. Amongst all the possible determinations of the temperature gradient we selected the one obtained by Lichten, Rodríguez and Chaisson (1979), for the only reason that their data leads to the highest correlation coefficient amongst all regressions (0.82). For galactocentric distances ranging from 5 to 13 kpc, they found that

$$T = 4700 + 380\ R_G \qquad (10)$$

IV. THE PRESSURE GRADIENT

From the previous discussion, it follows that it is sensible to derive the thermal pressure gradient of the interstellar medium by simply combining the density determined by the observed maximum size of SNR's and the temperature gradient expressed by equation (10). The results are given in Figure 5, where the pressure is given in absolute units and not in terms of its value in the solar environment. To do so we used the atomic density obtained by Falgarone and Lequeux (1973) for the solar vicinity, and calculated the temperature from equation (10). The two points interior to 5 kpc were calculated in this way, a procedure that is not entirely correct since equation (10) is strictly valid for galactocentric distances larger than 5 kpc. Yet, regressions applied to observations at H109α (Churchwell et al. 1978), H76α (Wink, Wilson and Bieging 1983) and H166α (Azcárate, Cersósimo and Colomb 1985), all with good correlation coefficients (0.73, 0.7 and 0.6 respectively), indicate that the gradient extends down to 4 kpc. This is very close to our most interior point, which is at 3.8 kpc. A second order fit to data points beyond 5 kpc leads to the following equation for the thermal pressure (P_T),

$$P_T(10^{-12}\mathrm{dyn\ cm}^{-2}) = 1.6(\pm0.63) - 0.143(\pm0.146)R_G + 0.004(\pm0.008)R_G^{\ 2} \qquad (11)$$

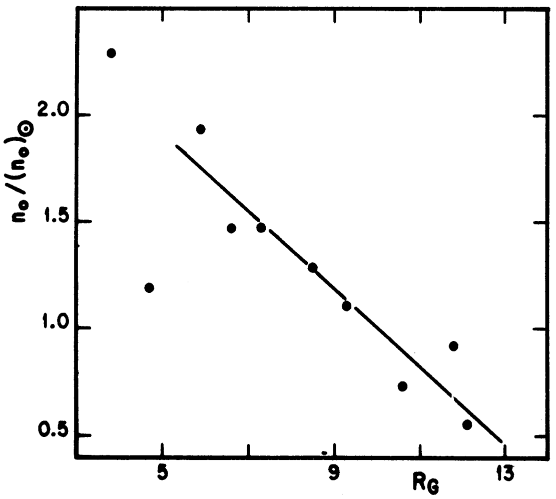

Fig. 4. The behaviour of the density of the warm component of the interstellar medium ($(n_o/n_o)_\odot$) as a function of galactocentric distance (R_G, in kiloparsec), as found from the maximum size of SNR's (equation (8)).

with a correlation coefficient of 0.91. The thermal pressure is represented by a continuous line in Figure 5.

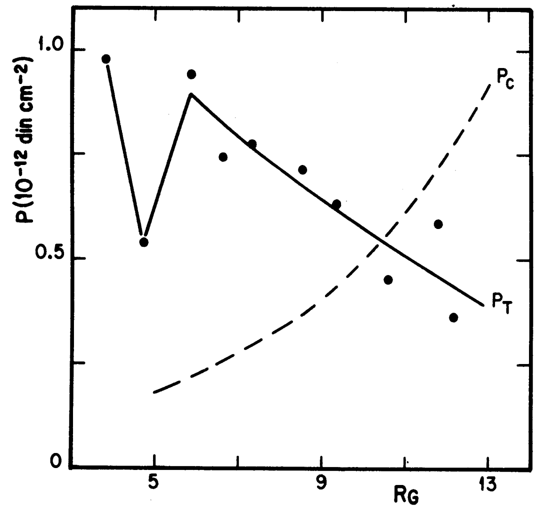

Fig. 5. The thermal pressure of the warm component of the interstellar medium (P_T) is given by a continuous line. The critical pressure (P_c) by the dashed line.

It must be pointed out that the pressure distribution is remarkably similar to the H166α and molecular hydrogen distribution (shown in Figure 6, taken from Burton 1976). The cause for this coincidence may be connected to those processes responsible for the transformation of diffuse into molecular clouds. According to Cox and Franco (1986) two conditions should be met in order to assure this conversion; first, the optical depth of the diffuse cloud should be large enough so as to shield the molecules that are being formed within it and, secondly, the external pressure should be large enough so as to direct the diffuse cloud into the self-gravity regime. Both conditions lead to a critical external pressure (P_c) given by,

$$P_c(10^{-12}\text{dyn cm}^{-2}) \cong 0.5(Z_\odot/Z)^2 \qquad (12)$$

where Z is the ambient metallicity. P_C is represented by a disjoint line in Figure 5. If the external pressure (P_T) is larger than the critical pressure (P_C), the transformation of diffuse into molecular clouds is viable, otherwise it will be restricted to the action of some unpredictable agent. As we see from Figure 5, the condition for the conversion of diffuse into molecular clouds is satisfied for galactocentric distances smaller than approximately 10 kpc, but not beyond this point. Furthermore, the density distribution (see Figure 4) indicates that more material is available for the formation of molecular clouds as we move down to 5 kpc, in agreement with the steep rise observed in the H_2 distribution. Finally, the drop in the density of the warm component of the interstellar medium at 5 kpc, is well correlated to the observed distribution of molecular hydrogen.

V. FINAL REMARKS

It is evident that the pressure distribution is a consequence of the structure of the galactic potential in the Z-direction. This relation can enable us to explore the pressure, density and magnetic field distribution in the Z-direction for various galactocentric distances. The mass distribution in the galaxy will produce a specific pressure gradient. This, in turn, will determine in which regions of the galaxy will take place the transformation of diffuse into molecular clouds and, consequently, the star formation process. As the ambient medium is seeded with metals, the temperature in the region (as well as the critical pressure) will tend to decrease. If the thermal pressure stays constant, and it will if the mass distribution remains essentially fixed, the gas density will increase as the temperature rises. Thus, the galaxy has probably evolved towards steeper gradients in the temperature, critical pressure and density in the gas and, consequently, towards an increasingly larger concentration of molecular clouds in the those regions where the thermal pressure is largest. A more detailed discussion on these questions will be presented in a forthcoming paper.

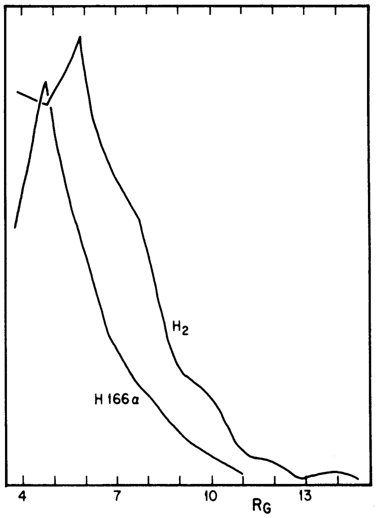

Fig. 6. Galactocentric distribution of molecular hydrogen (H_2) and H166α emission. The vertical line is arbitrary.

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