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SOURCES OF EXCITATION OF THE INTERSTELLAR GAS AND GALACTIC STRUCTURE

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ABSTRACT

The excitation of the interstellar gas is discussed in the light of recent evidence from γ-ray, molecular, and 21-cm line observations. Previous studies of the excitation of the interstellar gas have not taken into account the substantial density contrast that exists between spiral arms and interarm regions. We examine the role played by the galactic distribution of three sources of excitation (supernovae, OB stars, and ultraviolet stars) in determining the physical state of the interstellar gas in arm and interarm regions.

Subject headings: Galaxy, the — gamma rays — interstellar matter

I. INTRODUCTION

Theories of the ionization and heating of the interstellar gas have tended to favor a particular source of excitation. At present, at least three known sources (supernovae, OB stars, and ultraviolet stars) are believed to be important contributors. In this paper we take an eclectic point of view and discuss how each of these sources is likely to affect the observed physical state of the interstellar gas. We emphasize the role played by the galactic distribution of both sources and interstellar gas in determining the excitation of the interstellar gas. Since these known sources are consistent with a time-dependent rather than a steady-state model for the interstellar gas, it is important for us to discuss the observational evidence against the steady-state theory.

Theories of the excitation of the interstellar gas can be classified as steady-state or time-dependent. In the steady-state theory the implicit assumption is made that the average time interval between exposures of the gas to heating and ionization is very short compared with the characteristic time scale for the gas to cool or recombine. In practice the cooling time scale is relevant since for $T \gtrsim 100°$ K it is shorter than the corresponding recombination time scale. On the other hand, if the exposure time scale is greater than or about equal to the cooling time, we have a time-dependent situation (Gerola, Kafatos, and McCray 1974).

The original steady-state theory (Field, Goldsmith, and Habing 1969) assumed a pervading source (low-energy cosmic rays) of heating and ionization even in relatively dense regions. As pointed out by O'Donnell and Watson (1974), the observations of HD and D/H by the *Copernicus* satellite yield a low total ionization rate in interstellar clouds ($< 10^{-16}$ s^{-1}). These results indicate that low-energy cosmic rays are not a suitable ionization source and require that the ionization rate must vary between cloud and intercloud regions of the interstellar medium (cf. Silk 1973).

In contrast to the time-dependent model, the steady-state model makes the definite prediction of a cloud-intercloud density contrast of approximately 100:1. There is no indication that 100:1 is the favored density contrast (cf. Gerola *et al.* 1974); in fact, the available evidence from 21-cm measurements (Falgarone and Lequeux 1973) points to a cloud-intercloud density contrast of about 2:1 unless the scale size of the cloud is much smaller than 10 pc.

A stronger argument against the steady-state theory comes from the ultraviolet absorption-line measurements in the direction of γ Sco (Rogerson *et al.* 1973). These measurements show that the highest ionization stages of the heavy elements (e.g., C III, N III) are much less populated than one would predict from any steady-state theory. This conclusion is correct irrespective of whether the observed C I comes from the intercloud medium or from a circumstellar shell as assumed by Weisheit and Tarter (1973). Ionization rates less than 10^{-17} s^{-1} and high depletion factors that are required by the steady-state theory are simply not observed in the *intercloud* medium where these anomalously low ionization rates would yield ionized fractions of hydrogen that are in conflict with what is implied from the dispersion measures of nearby pulsars (cf. Kafatos *et al.* 1974). We feel that the above arguments constitute strong evidence that the steady-state theory is not correct.

II. EVIDENCE FOR ARM-INTERARM DENSITY CONTRAST

On the basis of the density wave theory (Lin and Shu 1964), one infers that large-scale galactic shocks occur at the inner edge of the spiral arms. The rapid compression of the gas in these shocks to perhaps 5 to

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10 times their original density may be responsible for triggering star formation.

In the two-armed spiral picture the pattern diminishes as one goes outward radially from about 11 kpc. Thus it is expected that the gas compression will be smaller in this region than in the 5 kpc region. It has been suggested that the gas compression produced by the two-armed spiral shock pattern increases monotonically with decreasing radius from about 5 in the 11 kpc region to 8–9 in the 3–4 kpc region (Roberts 1970).

For an isothermal shock,

$$\rho_2/\rho_1 = v_1{}^2/v_2{}^2 \qquad (1)$$

where ρ_1 and ρ_2 are the density before and after the compression, respectively; v_1 is the infall speed of the gas; and v_2 the sound speed in the compressed region. For a sound speed of 10 km s^{-1} and a material speed of 30 km s^{-1} a compression of 9 is obtained. These large density contrasts, however, occur only over a very narrow region on the inside of the spiral arm. Thus over a broad region of the spiral arm (1 kpc) the density contrast is smaller.

Normally the density contrast between the arm and the interarm regions, $\rho_{\max}/\rho_{\min}$, is specified as one of the model parameters in the density wave theory. As no direct observations of $\rho_{\max}/\rho_{\min}$ have been made, this parameter is not well known. Roberts and Yuan (1970) find that for most places in the galactic plane a density contrast of 3:1 to 4:1 is consistent with both the linear and nonlinear density wave theories. A density contrast of about 3:1 seems to be well accepted by other authors (Yuan 1970; Burton 1971; Simonson 1974). However, although 21-cm line measurements are consistent with appreciable density contrast between the arm and interarm regions, strong evidence for a density contrast has only recently become available as a result of γ-ray observations.

Recently Bignami and Fichtel (1974) have attempted to relate the observed galactic γ-radiation to the structure of the Galaxy. The γ-ray flux in units of photons cm^{-2} sr^{-1} s^{-1} is given by

$$\Phi(E) = \frac{1}{4\pi}\int SKg(r, \Omega)n_{\mathrm{H}}(r, \Omega)drd\Omega \qquad (2)$$

for an energy E and distance r. The interstellar neutral hydrogen is given by n_{H}, and K is the total hydrogen content divided by n_{H}. S is the number of γ-rays produced per second for one hydrogen nucleus. Stecker (1973) has calculated S for γ-ray production from π^0 decay and finds a value of 1.5×10^{-25}. This result is in good agreement with the value of 1.6×10^{-25} s^{-1} found by Kraushaar *et al.* (1972). In equation (2), g represents the ratio of cosmic-ray density to that in the solar neighborhood. Bignami and Fichtel assume that the cosmic-ray density is proportional to the matter density. It follows that their computed γ-ray flux is proportional to $n_{\mathrm{H}}{}^2$. Bignami and Fichtel (1974) use Simonson's (1974) model of the Galaxy. The arm-interarm spacings, with the addition of the 4 kpc dispersion ring, are from Kerr and Westerhout (1965). Assuming that the arm-interarm density contrast for the inner galactic arms is 5:1, $K = 1.5$, and $g \propto n_{\mathrm{H}}$, Bignami and Fichtel are able to reproduce the SAS-2 γ-ray observations of Kniffen *et al.* (1973). Bignami and Fichtel suggest that the steplike appearance of the observations results from looking through regions of varying density (i.e., arm and interarm). It is clear that the γ-ray observations cannot be reproduced by a model of uniform density in the plane, but are explainable only in terms of a density contrast between the galactic arms and interarms.

The γ-ray flux is critically dependent upon the total amount of hydrogen (neutral and molecular). Jenkins and Savage (1974) find an average neutral-hydrogen density of ~ 0.6 atoms cm^{-3} within 1 kpc of the Sun. They estimate that the total hydrogen density (protons, atoms, and molecules) is ~ 1.5 cm^{-3}. Since there is little ionized hydrogen, it follows that there is at least as much molecular hydrogen as neutral hydrogen within 1 kpc of the Sun. Consequently, the value of K in equation (2) is more likely equal to 2 than 1.5 (although it may vary as one goes toward the galactic center). This upward revision to $K = 2$ implies that lower neutral-hydrogen densities are required to explain the observed γ-ray flux.

The amount of hydrogen above the galactic plane is also important in determining the γ-ray flux (assuming $p_{\mathrm{CR}} + p_{\mathrm{Gal}} \rightarrow \pi^0 \rightarrow \gamma + \gamma$). In their model Bignami and Fichtel assume that the hydrogen density drops off as a quasi-Gaussian (Schmidt 1956). This is true for several hundred parsecs above the plane but probably not true over distances of kiloparsecs. The drop may be more like an exponential one after several hundred parsecs. Thus, assuming an indefinite Gaussian dropoff would underestimate that amount of hydrogen above the plane. Also recent determinations of the hydrogen thickness between half-density points (Jackson and Kellman 1974) are larger than the values used by Bignami and Fichtel. These minor modifications of their model would indicate that their equatorial densities may be too large.

Recent observations of the galactic distribution of molecular clouds (Solomon and Scoville 1974) show that the amount of matter in such clouds peaks at distances of 5–6 kpc from the galactic center. The above authors use these observations to argue that the density of molecular hydrogen in the inner arms of our Galaxy may be as high as $n_{\mathrm{H}_2} \simeq 3$–5, which is significantly higher than previously assumed. We have calculated the γ-ray flux with lower neutral-hydrogen densities than assumed by Bignami and Fichtel. In carrying out our calculations we have assumed that $K = 2$ in equation (2) and $n \simeq 1.5$ in the inner arms. Our galactic half-thicknesses were taken from Jackson and Kellman (1974). If, however, molecular-hydrogen densities as high as those suggested by Solomon and Scoville are present in the inner arms, the neutral-hydrogen density would have to drop even more. It follows that the observed galactic γ-ray flux may be explained without assuming that the cosmic-ray flux is proportional to the interstellar gas density, contrary to what Bignami and Fichtel postulated.

One can conclude that although the exact neutral-hydrogen densities for the inner galactic arms may be smaller than they suggest, the model of Bignami and Fichtel gives reasonably good agreement with the observed galactic γ-radiation. These results indicate the presence of a density contrast between the galactic arms and interarms which may be as high as 5:1.

III. EFFECT OF ARM-INTERARM DENSITY CONTRAST

a) *Supernova Models*

We have argued above that there is evidence for significant arm-interarm density contrast. It is important to estimate the effect of this contrast on supernova models for the interstellar medium. Although there is some debate as to whether the local region of the Galaxy is part of a proper spiral arm or the spur of an arm, we consider it an arm since density contrast rather than the global structure of the Galaxy is the important factor in this discussion.

Time-dependent models for the interstellar medium require that we specify the density of the interstellar gas. OAO-2 observations of Lα absorption in the direction of early B-type stars (Macchetto and Panagia 1973) yield a mean density of the diffuse interstellar atomic hydrogen of $n_{\rm H} = 0.35\ {\rm cm}^{-3}$. When one takes into account the stars that have dense clouds in front of them, the density becomes $n_{\rm H} \simeq 0.6\ {\rm cm}^{-3}$. Macchetto and Panagia point out that there are no systematic variations of the hydrogen density with distance. Therefore, these values are appropriate up to distances of 450 pc along the galactic plane. Since most of the clouds are accounted for out to distances of 450 pc, it is unlikely that the total density will be much above $0.6\ {\rm cm}^{-3}$. On the other hand, the high-resolution 21-cm absorption results of Hughes, Thompson, and Colvin (1971) and Radhakrishnan and Goss (1972) indicate that about half of the mass is in the cold component, which has a mean temperature of about 70° K. Radhakrishnan *et al.* (1972) estimate that the mean density of the cold component in the galactic plane is about $0.3\ {\rm cm}^{-3}$. It follows that the 21-cm and OAO observations give consistent mean densities for the local arm.

Our supernova models were computed in a manner similar to that described in Gerola *et al.* (1974). Average quantities obtained are shown in table 1.

TABLE 1

SUPERNOVA MODEL RESULTS
$E_{\rm SN} = 7 \times 10^{50}$ ergs, $\epsilon_{\rm X} = 150$ eV

Parameter	Arm ($n = 0.5\ {\rm cm}^{-3}$, $\tau_{\rm SN} = 50$ yr)	Interarm ($n = 0.1\ {\rm cm}^{-3}$, $\tau_{\rm SN} = 150$ yr)
$\langle n_{\rm H}/T \rangle$	1.3×10^{-2}	1.3×10^{-3}
$\langle T^{-1} \rangle^{-1}$	37	71
$\langle T \rangle$	530	1200
Percent of the gas with $T <$ 500° K	86	75
$\langle n_e \rangle$	7.3×10^{-3}	4.4×10^{-3}
$\langle n_e^2/T^{3/2} \rangle$	4.7×10^{-7}	5×10^{-8}
$\langle n_e^2/T^{1/2} \rangle$	2.9×10^{-5}	3.9×10^{-6}

Supernovae in the arm and interarm regions are assumed to emit energies of 7×10^{50} ergs in the form of 150 eV soft X-rays. Observational evidence which supports our assumed soft X-ray supernova model has been discussed recently by Cornett and Hardee (1974). They point out that the observed H I shells surrounding the supernova remnant W44 can be explained as gas set in motion by pressure gradients resulting from soft X-ray heating. The harmonic mean temperature $\langle T^{-1} \rangle^{-1}$ is defined by the relationship $\langle T^{-1} \rangle^{-1} \equiv \langle n_{\rm H} \rangle / \langle n_{\rm H}/T \rangle$. The units of T and n_e are ° K and ${\rm cm}^{-3}$. The last two quantities in the table, $\langle n_e^2/T^{3/2} \rangle$ and $\langle n_e^2/T^{1/2} \rangle$, are relevant for the calculation of low-frequency absorption, radio recombination-line emission, and diffuse Hα and Hβ line emission, respectively. We chose a 5:1 density contrast between arm and interarm regions. Type II supernovae, which are the most frequent ones, are likely to originate in the arms because of their apparent association with massive stars. Therefore, we chose a 3:1 ratio in the frequencies of occurrence. The results show that the electron density contrast between arm and interarm regions is much smaller than that predicted for neutral hydrogen absorption, free-free absorption or Hα–Hβ emission. We emphasize that our models refer to a region that is within about 1 kpc of the Sun.

One of the few observed discrete γ-ray sources is in the direction of the Vela pulsar (Thompson *et al.* 1974). These authors assume that the hydrogen density in the vicinity of the Vela supernova remnant is $1.5\ {\rm cm}^{-3}$ and estimate that a cosmic-ray energy of 3×10^{50} ergs would be required to account for the observed γ-ray flux. However, estimates for the number density in the region of the Vela supernova remnant range from about 0.1 to $0.3\ {\rm cm}^{-3}$ (Alexander *et al.* 1971; Gorenstein *et al.* 1974; Grewing *et al.* 1973). It follows that the required cosmic-ray energy is $1.5\text{–}4.5 \times 10^{51}$ ergs. It is interesting to note that if one assumes 15 eV per ionization, then an energy of approximately this amount is required to explain the ionization of the Gum Nebula (cf. Brandt *et al.* 1971). Although these observed energies are higher than usually assumed for a supernova outburst, energies of this amount were observed in the explosion of SN 1972 in NGC 5253. The observations of this supernova indicate a *UBV* energy of about 3×10^{50} ergs (Ardeberg and de Groot 1973). The estimated bolometric emission is 1.3×10^{51} ergs. This latter estimate is likely to be a lower limit.

It is important to understand how our calculations depend on the assumed interstellar density. The effect of varying the density while holding both the total energy in the supernova outburst, the frequency of the outbursts, and the energy of the photons constant has been estimated. As the assumed density is increased, free-free absorption ($\langle n_e^2/T^{3/2} \rangle$) and H$\alpha$ and Hβ emission ($\langle n_e^2/T^{1/2} \rangle$) increase while the relevant temperatures $\langle T \rangle$ and $\langle T^{-1} \rangle^{-1}$ decrease. For a particular model ($\tau_{\rm SN} = 50$ yr, $E_{\rm SN} = 7 \times 10^{50}$ ergs, $\epsilon_{\rm X} = 150$ eV) 96 percent of the gas is at a temperature less than 500° K if the assumed number density is $n = 1.0\ {\rm cm}^{-3}$. The quantity $\langle n_e \rangle$ decreases very slowly with increasing density. Because the matter density is higher toward the galactic center, it follows that our calculations predict enhanced free-free absorption, radio recombination-line emission, Hα and Hβ emission, and free-free continuum emission in the inner regions of the Galaxy. There is observational evidence to support this prediction (Gerola *et al.* 1974; Silk 1973). Unlike previous interpretations (cf. Silk 1973), which required rates of ionization (ζ) about an order of magnitude higher toward the galactic center, our interpretation does not require an increase in ζ but rather reflects an increase in density. This follows because in the time-dependent theory the average ζ is proportional to $(n\tau)^{-1}$.

b) *OB Stars*

O and early B-type stars contribute to the heating and ionization of the interstellar medium. Since these stars have lifetimes of about 3×10^6 years, they are located predominantly along the inner edges of spiral arms where they are formed. Torres-Peimbert, Lazcano-Araujo, and Peimbert (1974) have computed the fraction of O and early B-type stars that lie outside dense H II regions. They define a dense H II region as one that is detectable on the Palomar *Sky Survey*. The total percentage of the Galaxy (within about 1 kpc) occupied by diffuse H II regions due to O and early B-type stars can be estimated from their number density, luminosity, the percentage of these stars that lie outside observable H II regions, and an assumed mean interstellar density. For a mean interstellar density of 0.3 cm^{-3}, we estimate that 30 percent of the low-density medium can be kept ionized by these stars. For lower densities n we find that this percentage varies as $(0.3/n)^2$. The greatest single contribution is made by O5 stars, and fully 70 percent of the total contribution is made by O5–O7 stars. B-type stars later than B0 make a negligible contribution to heating and ionization even though they are more numerous than stars of earlier spectral type. The H II regions that are formed by stars in the low-density region can easily account for the pulsar dispersion measures and the Hβ emission seen in the solar neighborhood. However, a statistical theory, which would take into account the evolution of the Strömgren spheres after the parent star has moved off the main sequence, is needed to determine the amount of neutral hydrogen absorption and free-free absorption in this low-density medium. Although strictly speaking these results refer only to the solar neighborhood, we can apply them as an approximation to other arm regions. We estimate that in spiral arms OB stars are more important than supernovae in producing $\langle n_e \rangle$ and diffuse hydrogen line emission unless the mean density is higher than about 0.6 cm^{-3}.

c) *Ultraviolet Stars*

Stellar evolutionary calculations predict that most stars should evolve through a very hot stage before they become white dwarfs. The spatial distribution of ultraviolet stars is expected to be similar to that of long-period variables and planetary nebulae and consequently they should be distributed more uniformly in space than OB stars. This circumstance implies that most ultraviolet stars are located in regions of low interstellar density and therefore their initial Strömgren spheres should be larger than OB stars of comparable luminosity. As discussed by Hills (1972) and Rose and Wentzel (1973), the Strömgren spheres of ultraviolet stars are likely to play a significant role in determining the physical state of the interstellar gas. The predicted volume of the Strömgren spheres should be sufficient to fill about one-third of the volume of regions whose mean density is equal to 0.1 cm^{-3}. In regions of somewhat different density n the fraction of space occupied by H II regions should vary as $(0.1/n)^2$. It follows that ultraviolet stars should be important sources of heating and ionization at high galactic latitudes. Density wave theory and γ-ray measurements make it clear that an interarm region must exist. The mean density of interarm regions cannot be much less than 0.1 cm^{-3}. Pulsar dispersion measures provide evidence for a mean electron density of $n_e \simeq 0.03 \text{ cm}^{-3}$ in interarm regions. We estimate that in interarm regions ultraviolet stars are more important than supernovae in producing $\langle n_e \rangle$ and diffuse hydrogen line emission unless the interarm density is greater than about 0.6 cm^{-3}. This point may be of considerable significance because OB stars are located predominantly along spiral arms and Type II supernovae are likely to exist in spiral arms. There is no reason to believe that supernovae are required to explain the heating and ionization of the interarm regions.

IV. CONCLUSIONS

We have discussed how the galactic distribution of known sources of heating and ionization influence the excitation of the interstellar gas. The observed galactic γ-rays, which appear to originate primarily from spiral arms, give evidence for substantial density contrasts between arms and interarms. Following Bignami and Fichtel (1974) we have recalculated the predicted γ-ray flux using new determinations of the galactic half-thickness and recent estimates of the molecular hydrogen abundance. We find that the observed γ-ray flux can be explained without postulating high *neutral* hydrogen densities in the inner spiral arms. If the amount of molecular hydrogen is as high as some recent estimates indicate g, the ratio of cosmic-ray density to local cosmic-ray density, may not increase as fast as the gas density.

We have calculated statistical time-dependent models for arm and interarm regions using realistic neutral-hydrogen densities and plausible supernova rates. We find that the spiral arms contribute more to free-free and neutral-hydrogen absorption than the interarm regions. However, the interstellar electron densities that are deduced from pulsar dispersion measures are predicted to arise about equally from both regions. Moreover, we predict that higher densities (rather than a higher ζ) cause the enhanced free-free absorption, radio recombination-line emission, and Hα emission that are observed toward the galactic center. In addition, we have used the recent observations of Torres-Peimbert *et al.* (1974) to make new estimates of the effect of OB stars on the interstellar gas. We find that the H II regions produced by OB stars in intercloud regions can account for the pulsar dispersion measures and Hβ emission observed in the solar neighborhood. It has been previously argued that ultraviolet stars should be important sources of heating and ionization at high galactic latitudes. In this paper, we argue that recent evidence for substantial density contrasts between arm and interarm regions indicates that ultraviolet stars are the most likely source of excitation in interarm regions.

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