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**THE RELATIONSHIP BETWEEN
THE GALACTIC MATTER DISTRIBUTION,
COSMIC RAY DYNAMICS,
AND GAMMA RAY PRODUCTION**

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THE RELATIONSHIP BETWEEN THE GALACTIC MATTER DISTRIBUTION,
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ABSTRACT

Theoretical considerations and analysis of the results of γ -ray astronomy suggest that the galactic cosmic rays are dynamically coupled to the interstellar matter through the magnetic fields, and hence the cosmic ray density should be enhanced where the matter density is greatest on the scale of galactic arms. This concept has been explored in a galactic model using recent 21 cm radio observations of the neutral hydrogen and 2.6 mm observations of carbon monoxide, which is considered to be a tracer of molecular hydrogen. The model assumes: (1) cosmic rays are galactic and not universal; (2) on the scale of galactic arms, the cosmic ray column (surface) density is proportional to the total interstellar gas column density; (3) the cosmic ray scale height is significantly larger than the scale height of the matter; and (4) ours is a spiral galaxy characterized by an arm to interarm density ratio of about 3:1. The second assumption implies that the γ -ray emission is proportional to the square of the mass on the scale of galactic arms. The theoretical predictions for γ -rays produced by matter--cosmic ray interactions in this model show a good correlation with the galactic γ -ray observations, not only in terms of the absolute intensities along

the galactic plane, but also in terms of the positions of specific galactic features near longitudes 315° , $330-335^\circ$, $340-345^\circ$, 0° , 25° , and 35° .

A constant cosmic ray density, as might be expected in the simplest concept of a universal cosmic ray model, gives too small a ratio between the γ -ray intensity in the central region and the general anticenter region and does not give rise to significant peaks along galactic spiral arm features in the galactic γ -ray data.

With regard to the galactic center itself, whereas there may be a small additional component, such as Compton scattering from a high photon density, there is quite reasonable agreement between the observed γ -ray distribution and that predicted on the basis of cosmic ray nucleons and electrons interacting with the current best estimate of the interstellar matter.

Finally, for the future, the theoretical picture developed here makes a specific prediction on a finer level, particularly with regard to the ratio of the γ -rays from the interstellar (principally molecular) clouds to that from the intercloud regions, namely that it should be proportional to the mass of the matter, not the square of the mass as is the prediction and apparent situation when the galactic arm segments and interarm regions are compared.

Subject Headings: γ -Rays, Cosmic Rays, Galactic Structure,
Interstellar Medium

INTRODUCTION

Because the solar system is buried deep within our Galaxy, the picture of the overall structure of the Galaxy is relatively poor compared to that of other galaxies. This is true in spite of the substantial progress that has been made at several wavelengths, particularly surveys of the 21 cm line of atomic hydrogen and recent studies of the 2.6 mm emission line of CO, a tracer of molecular hydrogen. The very new field of γ -ray astronomy ultimately offers the potential of adding significantly to our knowledge of the galaxy because of the unique properties of these photons. It has been known for over two decades (e.g. Hayakawa, 1952; Hutchinson, 1952) that the interaction of cosmic rays with interstellar matter would lead to diffuse galactic γ -ray emission which could be used in the study of the galactic matter distribution and the cosmic ray gas, responsible for what is believed to be the most dynamic of the expansive pressures in the Galaxy. Now that the first results from high energy γ -ray astronomy are available (Kraushaar et al., 1972; Fichtel et al., 1975a, 1975b; and Thompson et al., 1976), it is seen that the most striking feature of the celestial sphere when viewed in the frequency range of high-energy γ -rays is indeed the emission from the galactic plane, which is particularly intense in the galactic longitudinal region from about 300° to 50° . This enhancement corresponds in longitudinal extent to that seen at 21 cm, but the γ -ray emission shows relatively more contrast compared to regions away from the galactic center direction.

When examined more closely, the longitudinal and latitudinal distributions appear generally correlated with galactic structural

features, with maxima occurring at galactic longitudes of about 315° , $330-335^\circ$, $340-345^\circ$, 0° , 25° , and 35° (Fichtel et al., 1975a, Thompson et al., 1976), in general agreement, for example, with the galactic center itself and locations of tangents to arm segments in Simonson's (1976) picture of the galaxy based on 21 cm measurements and the density wave theory. On the basis of the interpretation of the γ -ray data (e.g. Bignami and Fichtel, 1974; Paul et al., 1974; Schlickeiser and Thielheim, 1974b; Bignami et al., 1975; Paul et al., 1975; Stecker et al., 1975; Schlickeiser and Thielheim, 1976; Puget et al., 1976; Paul et al., 1976), there are good reasons for believing that the cosmic ray density is enhanced where the matter density is greatest, and this concept of coupling is supported by theoretical considerations (Parker, 1966, 1969). Thus, γ -ray astronomy ultimately promises to provide a high contrast view of galactic features -- a picture which will not be blurred by absorption and scattering effects since a high energy γ -ray passing through even the diameter of the central plane of the galactic disk has only about a 1% chance of interacting.

In view of these considerations, it seems valuable to attempt to develop a galactic model based on the most current theoretical ideas and data concerning the interstellar matter distribution and compare the predictions of such a model to the γ -ray data. Following the suggestion by Kniffen et al. (1973) that the bulk of the galactic γ -rays might originate in the galactic structural features of the inner galaxy, Bignami and Fichtel (1974) developed a cylindrically-symmetric model

involving strong coupling between the cosmic rays and the interstellar matter on the scale of galactic arms. Bignami et al. (1975) extended this concept of matter-cosmic ray coupling to a model using a spiral structure of the type proposed by Simonson (1976) on the basis of 21 cm observations and the density wave theory. Since the time of this work, there have become available improved information about the atomic hydrogen and measurements on the 2.6 mm CO line which have been interpreted in terms of molecular hydrogen densities. In addition, the high energy galactic γ -ray data from SAS-2 now exist in nearly final form. Hence, more definitive statements can now be made in relating γ -ray astronomy to the questions of the galactic cosmic ray pressure and the structure of the galaxy.

Other approaches have been taken by various authors to the problem of γ -rays and galactic structure. Schlickeiser and Theilheim (1974 a,b) and Theilheim (1975) have noted that the cosmic rays should be coupled to some portion of the matter through the galactic magnetic fields. Assuming a power law dependence between the magnetic field strength and the product of the cosmic ray and matter densities and using the spiral magnetic field model of Theilheim and Langhoff (1968), they determined that reasonable agreement with the γ -ray observations is obtained using a third to fourth power dependence of this product on the magnetic field. Paul et al. (1976) have noted that similarities in the observed spatial variations of the high energy γ -rays and 150 MHz radio emission and radio observations of M31 suggest a proportionality between the cosmic ray density, the gas density and the square of the

magnetic field strength. A spiral model of the galaxy was developed which gives a good fit to existing observations.

Fuchs et al. (1976) used the preliminary estimates of the galactic molecular hydrogen distribution of Scoville and Solomon (1975) and found that no power law relationship between cosmic rays and gas density gave a particularly good agreement with the γ -ray observations. Stecker et al. (1975) used the same CO measurements to deduce the shape of the molecular hydrogen distribution, but normalized the actual density using infrared and X-ray absorption measurements. Taking the scale height of the molecular hydrogen to be the same as that of the neutral hydrogen, they concluded that the best fit to the γ -ray distribution is obtained with cosmic rays proportional to the 0.3 power of the gas density. Using this same matter distribution, Stecker (1975), as an alternate explanation, assumed that the supernova distribution obtained by Kodaira (1974) represents the galactic cosmic ray distribution. This model again gives reasonable agreement with the observations and supports the concept of a supernova origin for cosmic rays. Both the Stecker et al. (1975) and Stecker (1975) models require a significant contribution to the γ -ray production from inverse Compton scattering by cosmic ray electrons on an enhanced starlight density assumed to exist near the galactic center.

Puget et al. (1976) considered the effects of local concentrations of matter in the galaxy. They found that these were not responsible for the major features appearing in the γ -ray data. Using recent HI and CO surveys, they computed the cosmic ray distribution needed to

account for the γ -ray results and found that it must be 1.9 to 4.8 times the value of the solar system in a region about 5 kpc from the galactic center.

The principal goal of this paper will be to develop a model of the galactic matter and cosmic ray distributions using the best available theoretical and observational information, especially the galactic γ -ray results. The key assumptions which will enter into the primary model are: (1) cosmic rays are galactic in origin and not universal; (2) on the scale of galactic arms, the cosmic ray column density is proportional to the total interstellar gas column density; (3) the cosmic ray scale height is significantly larger than the scale height of the matter; and (4) ours is a spiral galaxy characterized by an arm to interarm density ratio of about 3:1. Alternate models in which one or more of these assumptions are violated are discussed and shown to give poorer agreement with the γ -ray observations than the primary model. In general, these results demonstrate the insight that γ -ray astronomy can ultimately give to the study of the galactic structure and cosmic ray - matter coupling.

II. BASIC CONCEPTS

Under the assumption that the cosmic rays and magnetic fields are primarily galactic and not universal, the fields and cosmic rays can only be constrained to the galactic disk by the gravitational attraction of the matter through which the magnetic fields penetrate (Bierman and Davis, 1960; Parker, 1966, 1968, 1969). The local energy density of

the cosmic rays is about the same as the estimated energy density of the magnetic field and that of the kinetic motion of matter. Together the total expansive pressure of these three effects is estimated to be approximately equal to the maximum that the gravitational attraction can hold in equilibrium. Assuming the solar system is not in an unusual position in the galaxy, these features suggest that the cosmic ray density throughout the galaxy may generally be as large as could be contained under near-equilibrium conditions. Further theoretical support is given to this concept by the calculated slow diffusion rate of cosmic rays (e.g. Parker, 1969; Lee, 1972; Wentzel, 1974) in the magnetic fields of the galaxy, the small cosmic ray anisotropy, and the likely high-production rate of cosmic rays. The above considerations lead to the postulate that the energy density of the cosmic rays is larger where the matter density is larger on the scale of galactic arms. The specific assumption made in this work is that on the scale of galactic arms the number of cosmic rays is directly proportional to the matter to which they are coupled, and it will be seen that the results suggest that the cosmic rays are coupled to all the gaseous matter, atomic and molecular.

The nonthermal continuum radiation in the galaxy, which is generally attributed to the synchrotron radiation from cosmic ray electrons interacting with the galactic magnetic fields (e.g. Ginzburg and Syrovatskii, 1964, 1965) has a scale height which is large compared to that of either the galactic atomic or molecular hydrogen. Baldwin (1967, 1976) estimates the equivalent disk thickness to be about 750 pc, and some analyses have suggested it is even larger. Significant non-thermal emission is

even seen as high as 2 kpc above the plane. Clearly, these results give support to the concept of the cosmic rays and magnetic field extending to substantially greater heights than the matter distribution. The non-thermal radiation is, of course, directly related only to the cosmic ray electrons and not the protons; however, assuming those electrons which are not direct secondaries of the cosmic ray protons have the same origin as the cosmic ray protons, there is no reason to expect them to separate although their ratio as a function of energy would be expected to vary somewhat due to the different energy loss processes. Support of this concept is given by the generally good correlation of the distribution of non-thermal radio emission as a function of galactic longitude to that of the high energy galactic γ -rays (Paul et al., 1976). Recent cosmic ray results also suggest that the cosmic rays spend a significant fraction of their lifetime in the halo, where the matter density is very much smaller than that in the galactic disk (Jokipii, 1976). Thus, in the primary model to be developed here the cosmic ray scale height will be assumed to be substantially larger than that of the matter. As will be seen, the results are not sensitive to the exact scale height as long as it is clearly larger than (\geq twice) that of the matter.

If the Galaxy is examined on a smaller scale than that of the galactic arms, the problem is a very dynamic one because the pressures of the interstellar gas, magnetic fields, and cosmic rays create an unstable situation over dimensions of the order of 500 pc along the magnetic field (Parker, 1976). Further, in this concept, the dynamical

instability is the major factor in the formation of the large cloud complexes, and bulging magnetic bubbles in between. The bulges are inflated by the cosmic rays, and the inflation, at whatever rate it may occur, provides the escape of cosmic rays from the disk of the galaxy. At the same time, the thermal gas tends to move along the magnetic lines of force, away from the raised, low intensity portion of the field along the lines of force into the lower regions nearer the galactic plane. This diminishes the overburden of the raised portion, permitting the field and cosmic-ray gas to expand upward there, causing further slipping of the thermal gas downward along the lines of force. The net result of these considerations is that the interstellar gas exists mainly in widely separated discrete clouds, many of which have masses which are too small to maintain the cloud in equilibrium by self-gravitation alone. More recently, Rasmussen and Peters (1975) have proposed a model of long cosmic ray life with little cosmic ray escape. Whereas there would be expected to be relatively few magnetic bubbles in this model (Parker, 1976), the scale height of the cosmic ray distribution relative to the plane of the galaxy is still large compared to that of the matter distribution.

III. INTERSTELLAR GAS DISTRIBUTION

The question of the galactic gas distribution divides naturally into three levels: the general density distribution as a function of galactic radius, the concentration into spiral arms, and on the finest scale the formation of clouds. With regard to the first level, the

atomic hydrogen distribution is generally estimated from measurements on the 21 cm line. For this paper, the recent large scale galactic survey of this line by Gordon and Burton (1976) will be used. Generally the atomic hydrogen density is felt to be reasonably well known with the principal qualifications being that the column density is difficult to estimate in regions where it becomes large such as the galactic center region and along the major inner spiral arms and that the interpretation particularly of the spiral pattern is complicated by uncertainties in the knowledge of the differential galactic rotation.

The molecular hydrogen density and distribution is less well known. A rather high density (comparable or larger than the atomic hydrogen density) was suspected for many years (e.g. Gould, Gold, and Salpeter, 1963) on the basis of general galactic gravitational considerations. An indirect method of estimating the molecular hydrogen density currently receiving substantial attention is based on 2.6 mm radio measurements of the CO emission line (Scoville and Solomon, 1975; Burton et al., 1975; and Gordon and Burton, 1976) based on the hypothesis (Scoville and Solomon, 1974; Goldreich and Kwan, 1974) that the most important source of CO excitation in galactic clouds is the collision of CO with H₂. Using the cylindrically-symmetric Schmidt model of galactic rotation, it is concluded that the molecular hydrogen density at $b = 0^\circ$ is relatively large in the region from 4 to 8 kpc from the galactic center, with the maximum density between 5 and 6 kpc where it is about 6 times the HI density in the same region. The actual normalization is uncertain, but the values quoted by Gordon and Burton will be used in

this work. It must, in general, be remembered that, whereas recent CO line observations are of very considerable importance, a number of approximations and assumptions are involved in proceeding from the CO measurements to the deduced molecular densities.

The limited data which exist on disk thicknesses indicate that the molecular hydrogen, with a scale height of about 50 pc, is more closely confined to the disk (Burton and Gordon, 1976) than is the neutral atomic hydrogen which has a scale height of 120 pc inside the solar circle, increasing linearly beyond the sun to about twice this value at about 15 kpc (Baker and Burton, 1975). These scale heights somewhat reduce the dominance of the molecular hydrogen at small galactic radii. Beyond the solar circle, the atomic hydrogen dominates.

The spiral structure of external galaxies is defined by the distributions of young stars, HII regions, 21 cm radiation, and in some cases continuum radio emission. In our galaxy, however, the necessary observations are complicated by the fact that the solar system is immersed in the galactic structure, and so the existence and nature of spiral arms is a more open question. The distributions of continuum radiation (Landecker and Wielebinski, 1970; Price, 1974), γ -radiation (Bignami et al., 1975), HII regions (Georgelin and Georgelin, 1976), supernova remnants (Clark and Caswell, 1976), pulsars (Seiradakis, 1976), infrared emission (Hayakawa et al., 1976), and 21 cm neutral hydrogen emission (Burton, 1976) are all consistent with the existence of spiral structure in the galaxy. In particular, Simonson (1976) has used the 21 cm measurements, the density wave theory, and an arm-to-interarm

density ratio of 3:1 to construct a model of the overall spiral pattern of our Galaxy. In the above-mentioned observations which cover both sides of the galactic center, the spiral arm features in the 270° to 360° longitude quadrant appear more pronounced than those in the 0° to 90° quadrant. At present, the CO observations which are related to molecular hydrogen densities exist only for 0° to 180° (Scoville and Solomon, 1975; Burton et al., 1975). Although these measurements do not show conclusive evidence of spiral structure, it is not clear whether this effect is the result of the relatively limited observations. As more CO observations are made, this component should become a very useful probe of spiral structure. In part because the matter in molecular form appears to show the same overall kinematics as the atomic hydrogen (Burton, 1976), and in part for the practical purpose of having a galaxy-wide model of interstellar gas, it will be assumed here that all the matter in the galaxy exhibits spiral structure, although the relative contributions of atomic and molecular hydrogen will vary considerably with galactocentric radius. The galactic spiral arm model has been applied to the recent observations of the interstellar constituents. The data have been interpreted in terms of the Simonson (1976) model of galactic structure, which was also used in the earlier paper (Bignami et al., 1975). The arm densities are estimated by modulating the radial distribution of both atomic and molecular hydrogen given by Gordon and Burton (1976). The modulation is chosen to provide a 3 to 1 arm to interarm contrast with a peak at the galactocentric radius of the arm and with an average value consistent with the radial distributions obtained from the surveys. Thus,

for the portions of the plane where CO observations ($270 \leq l \leq 360$) do not exist, the densities in the extensions of a given arm were adjusted by 20 percent to reflect the changing galactocentric distances. The height dependence of each constituent is taken to be a gaussian with the scale heights given by Baker and Burton (1975) and Gordon and Burton (1976).

γ -Ray astronomy has not yet progressed to the point where it is meaningful to speak of observations of individual galactic clouds, although the asymmetry of the high energy (> 100 MeV) galactic latitude distributions in the center and anticenter do suggest local effects possibly correlated with Gould's Belt, as first noted by Fichtel et al. (1975a). However, the question of the degree to which the cosmic rays are dynamically coupled to the clouds by the magnetic fields has been raised. Among others, two quite different positions have been suggested. One is that these clouds are relatively independent of the general cosmic ray--matter coupling, and the other is that they do couple strongly to the field. In the former case, the molecular hydrogen would play very little role in the cosmic ray dynamic balance problem. In the latter case, which is the one being pursued here, the field lines converge in the regions of the clouds and then diverge rapidly outside. The molecular hydrogen is then dynamically coupled and thereby increases the total number of cosmic rays that can be held by the gravitational attraction; however, the cosmic rays are not preferentially contained in the clouds (The possibility that the cosmic rays are preferentially in the clouds is a third alternative, which will be

discussed in the next paragraph.), but rather move freely along the lines of force passing through the molecular clouds with their density being reasonably uniform over the entire magnetic field configuration. Thus, in this case the great majority of the cosmic rays are normally in the less dense region in the intermolecular cloud region, even though the total number of cosmic rays will be proportional to the total matter in any arm segment. Specifically, on the average, the total number of cosmic rays integrated over a unit column perpendicular to the galactic plane will be proportional to the matter integrated over the same column. Thus, in this picture the cosmic ray density is related to the average matter density in the galactic arm as a whole even though the matter distribution has a finer structure.

As noted in the last paragraph, there is a third extreme wherein the coupling of the cosmic rays to the mass occurs on the scale of clouds not arms. This would imply that the sources of the cosmic rays are necessarily in the clouds, they do not have a major perturbing effect on the magnetic field configuration of the cloud when they are created or subsequently, and that the cosmic rays and magnetic fields on the scale of galactic arms do not play a major role in cloud formation. The major arguments against this extreme position appear to be the wide galactic latitude distribution of the radio synchrotron radiation, the general distribution of the synchrotron radiation, and considerations of the expansion pressure effects of the cosmic rays. A clear experimental test will be whether, when the finer angular resolution, higher sensitivity γ -ray data is available, the γ -rays from these clouds compare

to the intercloud region in accordance with the second power of the matter, as they would if the cosmic rays are coupled to the matter on the scale of clouds, or the first power as they would if the coupling is primarily on the scale of arm segments, as proposed in this work.

In considering the γ -rays produced by the interaction of cosmic rays and matter, it is possible in the model being used here to take the average matter density in an arm segment if the smallest scale of interest is a galactic arm. This approach would not be possible if the cosmic rays were primarily confined to the cloud regions since then the γ -rays would have a quadratic dependence on mass on the scale of clouds (as they do on the scale of arms in the picture here), and a much more detailed calculation requiring assumptions on cloud size and distribution would be required. It is worth noting that the γ -ray source strength between the clouds and the inter-cloud regions varies approximately as the first power of the matter density, not quadratically as in the arm to interval comparison, and, hence, the contrast is smaller for the same mass ratio, although the density in the clouds may in fact often be quite high.

IV. GAMMA RAY PRODUCTION

The principal contribution to the high energy ($\geq 10^2$ MeV) γ -radiation comes from the cosmic ray nuclear interactions with interstellar matter--principally from the nucleon component of the cosmic rays in the energy range from a few-tenths of a GeV to a few tens of GeV (e.g. Cavallo and Gould, 1971; Stecker, 1971; Fichtel and Kniffen, 1974). The contributions from the cosmic ray electrons, principally bremsstrahlung, become

particularly important at lower energies, although bremsstrahlung radiation is not negligible for $E > 100$ MeV. The values of the local galactic source functions for the processes most likely to contribute to the 10-30 MeV and the > 100 MeV galactic γ -radiation are given by Fichtel et al. (1976), and these will be used here except for the cosmic ray nucleon-matter interaction source function, for which 1.04×10^{-26} photons ($E > 100$ MeV) $\text{cm}^{-3}\text{s}^{-1}\text{ster}^{-1}$ will be used. This value, which is slightly larger than the equivalent value used by Fichtel et al., is basically taken from the work of Stecker (1973); however, two partially compensating corrections have been applied. These are an increase relative to the value quoted by Stecker of about 27% to reflect the more current estimate of the proton spectrum after accounting for solar demodulation and a decrease of about 16% to reflect the current best estimate of the interstellar cosmic ray helium spectrum. The electron bremsstrahlung source function is 0.28×10^{-26} , and so this contribution amounts to about one-fourth of the total γ -ray emission above 100 MeV.

The electron spectrum used by Fichtel et al. (1976) was deduced in part on the basis of the solar modulation required to reproduce the observed cosmic ray positron spectrum from that calculated to exist in interstellar space on the basis of the positrons being secondaries from cosmic ray interactions. Consistency is obtained with the high energy observations where the modulation is generally believed to be small. As noted earlier, Rasmussen and Peters (1975) have recently reexamined a

closed-galaxy model for cosmic rays and shown that, under certain assumptions, it can explain the observed nuclear composition and flux of cosmic rays near the earth. One interesting prediction of this model is that the cosmic ray electron bremsstrahlung would be larger relative to the cosmic ray nucleon π^0 γ -ray flux because of a relatively higher predicted interstellar electron flux than in the more currently popular model wherein there is significant cosmic-ray leakage from the galaxy. An accurately measured γ -ray energy spectrum can clearly help to resolve the question of whether this alternate theory is correct.

In galactic γ -ray production, cosmic ray--mater interactions dominate over other source mechanisms locally, and this feature should remain true throughout the galaxy except for regions where the starlight photon/interstellar gas density ratio, $N_{\text{ph}}(r,\ell,b)/N(r,\ell,b)$, is much larger than the value in the solar vicinity. If such high photon densities exist at all, they should occur only in the galactic center where the presence of a highly enhanced starlight density might lead to a significant γ -ray intensity from Compton scattering of energetic cosmic-ray electrons by these photons. The photon density in this region is inaccessible to direct observation in our own galaxy and estimates of its magnitude are highly uncertain. The presence of a small peak in the γ -ray data near $\ell = 0^\circ$ may support the existence of a Compton component, but there is substantial disagreement over just what the contribution is (Shukla and Paul, 1976; Cowsik and Voges, 1975; Fichtel, 1975; Paul, Casse, and Cesarsky, 1976; Stecker, 1976).

The calculation for the γ -ray flux from both electrons and nucleons in a given direction is discussed in depth in the papers by Bignami et

al. (1975) and Fichtel et al. (1976) and will not be repeated in detail here. The highly dominant energy component of the cosmic rays, the nucleons, is assumed to vary with total mass as indicated before. The primary electron component is assumed to have the same source as the protons; however, since a part of the electron component is of secondary origin and the energy loss functions are quite important, the cosmic ray electron energy spectrum and flux relative to that of the protons varies with position in a manner calculated in detail by Fichtel et al. (1976), who have shown that the primary cosmic ray electrons contribute to the γ -ray production approximately in proportion to the square of the matter density times a function which decreases the strength of the dependence to some degree. At the same time the secondary cosmic ray electrons contribute as the cube of the matter density times a term which somewhat decreases the strength of the dependence. Hence, the secondaries become somewhat more significant in high density regions, but remain a minority contribution within the range of densities considered here. The net result is that for the range of matter densities believed to exist the ratio of the total source function for both primary and secondary electrons to that for cosmic ray nucleons remains nearly constant throughout the galaxy if the cosmic ray electrons and protons, in turn, are assumed to have the same source.

V. RESULTS

Following the procedure described in the previous sections, the γ -ray intensity distribution was calculated using the interstellar gas

distribution of Gordon and Burton (1976) modulated according to the spiral pattern deduced by Simonson (1976) with the integral of the cosmic ray density over a column perpendicular to the galactic plane being proportional to the equivalent integral over the total gas density. The scale height for the cosmic rays was taken to be 400 pc, and the density at the galactic plane was normalized to the local value used in calculating the local γ -ray source function. As noted earlier, the results are not sensitive to the scale height of the cosmic ray density distribution as long as it is larger than that of the matter distribution and the density is normalized to the local value. The value chosen is consistent with both the non-thermal radio emission data and the total cosmic ray pressure that can be expected to be contained by the existing matter. Figure 1 indicates the longitudinal distribution calculated for this model compared to two alternatives which will be discussed shortly. In Figure 2, this same distribution with a .9 normalizing factor for the molecular hydrogen density is compared to the experimental data. The deviation of this normalization factor from 1.0 is quite small compared to the uncertainty in the molecular hydrogen density. As can be seen, the major features are generally reproduced very well in position and intensity, especially when the uncertainty in the matter density is considered. Assuming the agreement is not fortuitous, it implies that the cosmic rays are in fact coupled to the matter to essentially the same degree as locally since proportionality was assumed in the calculation, and, in view of the fact that the cosmic ray density seems to be about the maximum that can be held, a nearly full dynamic coupling between the cosmic rays and the mass seems to be a reasonable conclusion.

Note in Figure 2 that the galactic center region from $l = 310^\circ$ to $l = 40^\circ$, five of the six maxima in the predicted distribution fit well in position with the experimental data. The peak to valley ratio for the Scutum, Norma, and 4-kpc arms (longitude ranges of 310° - 320° , 330° - 335° , and 340° - 345°), as well as the central region, seem to be more pronounced in the experimental data than in the calculated results. The simplified approach to the matter density distribution within the arms used in the calculation, i.e., a constant value over the width of the arm, rather than a rise to a maximum at the ridge from the sides, tends to make the peaks less pronounced than a more realistic model. Both the density wave theory (e.g. Roberts and Yuan, 1970) and measurements of external galaxies (e.g. Mathewson, van der Kruit, and Brown, 1972; Guibert, 1974) indicate that the density within an arm decreases outward from the high-compression region of maximum density near the inner side.

The small peak near $l = 0^\circ$ in the calculation results from the assumption of a mass concentration near the galactic center, with a total mass equal to that calculated from the CO data (Scoville, Solomon, and Jefferts, 1974). Whereas there seems to be reasonable agreement with the experimental data, especially in view of the mass distribution in the galactic center region not being well known, the peak in the center region might also be due in part to another source mechanism such as inverse Compton scattering, since the photon density in the galactic center region is even less well known. Thus, while a Compton component is not ruled out by the data or the present calculation, it

seems clear that a large Compton contribution is not necessary to an understanding of the γ -ray emission from this region.

The galactic latitude distribution calculated here for the γ -radiation from the anticenter region has a full width half maximum value of about 12° , which is consistent within uncertainties with the distribution observed by SAS-2 (Fichtel et al., 1975a), when the angular resolution function of the instrument (small compared to 12°) is included. In the galactic center region the agreement is poorer in that although the total intensity is correct and a narrow central peak is seen, the experimental data of SAS-2 (Fichtel et al., 1975a) and COS-B (Bennett et al., 1976) have a more significant broad component. This difference can be traced immediately to the narrow latitude distribution assumed for molecular hydrogen throughout the galaxy in the model as opposed to the much broader one for atomic hydrogen which dominates outside the solar circle. The results here suggest that the effective scale height of molecular hydrogen may be larger than the assumed value of 50 pc in the region beyond 7 or 8 kpcs from the galactic center. A small part of the broad latitude component which is observed appears to result from the interactions of cosmic rays with the local matter distribution known as Gould's Belt, as discussed by Fichtel et al. (1975a), Puget et al. (1976), and Thompson et al. (1976). These local clouds should be prime areas for future study with γ -ray instruments of improved sensitivity and angular resolution.

It must also be kept in mind that point sources not yet identified may be contributing to the galactic emission. Discrete sources might, for example, explain the observed excesses above the calculation in the $\sim 37^\circ < \ell < 45^\circ$ and $270^\circ < \ell < 290^\circ$ regions. This is a particularly likely possibility for the former case, in that there are at least ten radio pulsars in the galactic longitude range from $\sim 37^\circ$ to 45° , all within 4° of $b = 0^\circ$, and four radio pulsars have already been identified as γ -ray sources (Kniffen et al., 1974; Thompson et al., 1975; Ügelman et al., 1976). A combination of uncertainties in the pulsar period derivatives and limited statistics in the SAS-2 γ -ray data have thus far prevented a definitive statement being made with regard to the contribution due to pulsar emission in this longitude interval. Ügelman et al. (1976) have noted, however, that pulsars are not expected to be a major contributor to the total galactic emission.

For comparison, the distribution expected for a model in which the galactic cosmic rays have the same scale height as the matter is also shown in Fig. 1. As expected, the difference is relatively small and the deviation is well within uncertainties in the parameters used in the calculation. It should, however, be remembered that the broader cosmic ray distribution is also supported by the non-thermal radio emission.

The γ -ray longitude distribution expected for a model in which the cosmic rays are constant throughout the galaxy with a value equal

the data. In the center region, however, the γ -ray intensity for the constant cosmic ray model is substantially below the observations, and the individual peaks and valleys show almost no contrast. Since the matter distribution in the center region is dominated by the molecular hydrogen, which is characterized by relatively large uncertainties, the general γ -ray intensity in the center might be explained by the molecular hydrogen densities being somewhat over twice as high as the current best estimates. Simply increasing the assumed matter density, however, cannot reproduce the individual galactic structural features which appear in the data, and so the constant cosmic ray assumption still would not give a good fit. The failure of this type of model, particularly with regard to its low contrast for galactic features, would appear to offer evidence against the concept of a constant cosmic ray density throughout the galaxy and hence against the universality of cosmic rays.

V. SUMMARY

In this paper, the concept that on the scale of galactic arm segments, the cosmic ray density is related to the matter to which they are dynamically coupled through the magnetic fields has been explored particularly with regard to γ -ray astronomy. It is found that with the present data there is a good correlation between the observed γ -ray intensity and that predicted on the basis of essentially complete coupling of the cosmic rays to the best estimate of the atomic and molecular hydrogen in the galaxy. Further, if it is assumed that all the matter, atomic and molecular, is modulated in the galactic spiral arm segment pattern deduced by Simonson (1976), the individual maxima observed in the γ -radiation from the central region are well correlated with those predicted to result from spiral arm tangents at

315°, 330°-335°, 340°-345°, 25°, and 35°. Further, the intensity at the center is reproduced, and the general ratio between the anti-center region and the central ($l \leq 40^\circ$) region of the galaxy is well explained.

A constant cosmic ray density, as might be expected in the simplest concept of a universal cosmic ray model, gives too small a ratio between the γ -ray intensity in the central region and the general anticenter region and does not give rise to significant peaks along galactic spiral arm features in the galactic γ -ray data.

With regard to the galactic center itself, whereas there may be a small additional component, such as Compton scattering from a high photon density, there is quite reasonable agreement between the observed γ -ray data and that predicted on the basis of cosmic ray nucleons and electrons interacting with the interstellar matter as best it can be determined at this time. Also, here as elsewhere, the possible contribution of point sources not yet identified must be kept in mind until future data become available.

Finally, for the future, the theoretical picture developed here makes a specific prediction on a finer level, specifically with regard to the ratio of the γ -rays from the interstellar (principally molecular) clouds to that from the intercloud regions, namely that it should be proportional to the mass of the matter, not the square of the mass as is the prediction and apparent situation when the galactic arm segments and interarm regions are compared. This specific prediction, as well as more detailed comparisons on arm to interarm regions, can be tested when γ -ray data of much greater sensitivity and somewhat better

angular resolution are available and more complete and exact information is available on the molecular hydrogen distribution. Clearly, these results can have a significant bearing on our understanding of cosmic ray containment, propagation, and pressure.

FIGURE CAPTIONS

Fig. 1: The solid line shows the longitude distribution of γ -ray emission above 100 MeV summed from -10° to $+10^\circ$ in galactic latitude, for the primary model calculation described in the text. The dot-dashed line shows the longitude distribution for a variation of the model in which the scale height of the cosmic ray distribution is assumed to be the same as that of the matter distribution. The dashed line gives the longitude distribution which would be expected if the cosmic ray density in the galaxy were uniform with an intensity equal to that measured in the solar system.

Fig. 2: Comparison of the calculated longitude distribution of γ -rays with energy above 100 MeV with the SAS-2 results. The calculation has been normalized by assuming that the molecular hydrogen density in the galaxy is approximately 10 percent smaller than the nominal values of Gordon and Burton (1976). For regions of the plane where localized sources have been reported, the open circles give the intensities as observed, while the filled circles give the residual intensities after subtraction of the point source component. These point sources are the Crab (including PSR 0531+21), γ 195+5, Vela (including PSR 0833-45), PSR 1818-04, PSR 1747-46, and Cygnus X-3. The experimental results in the Vela region represent a more complete analysis of the data than has been reported previously.

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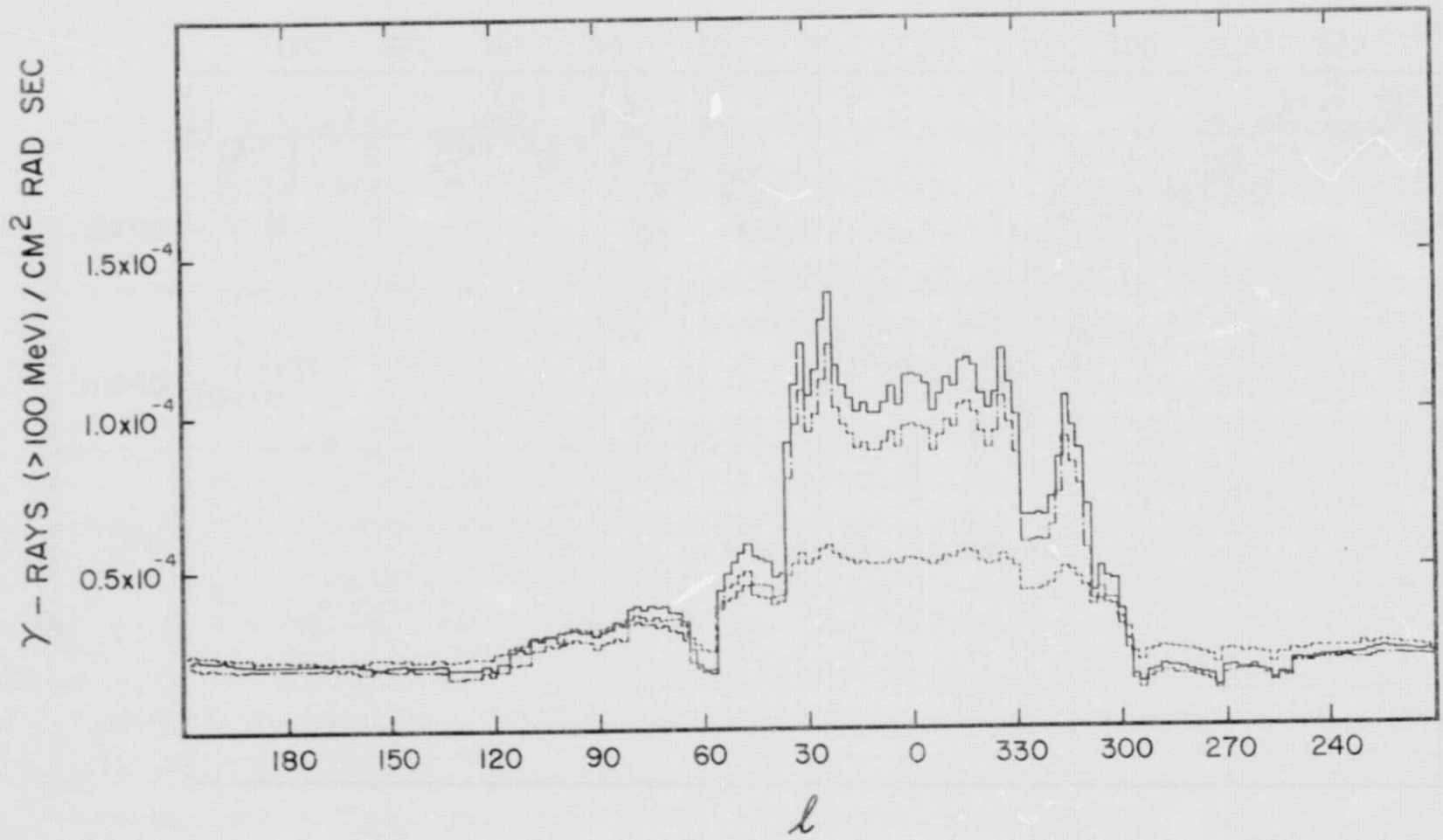


Fig. 1

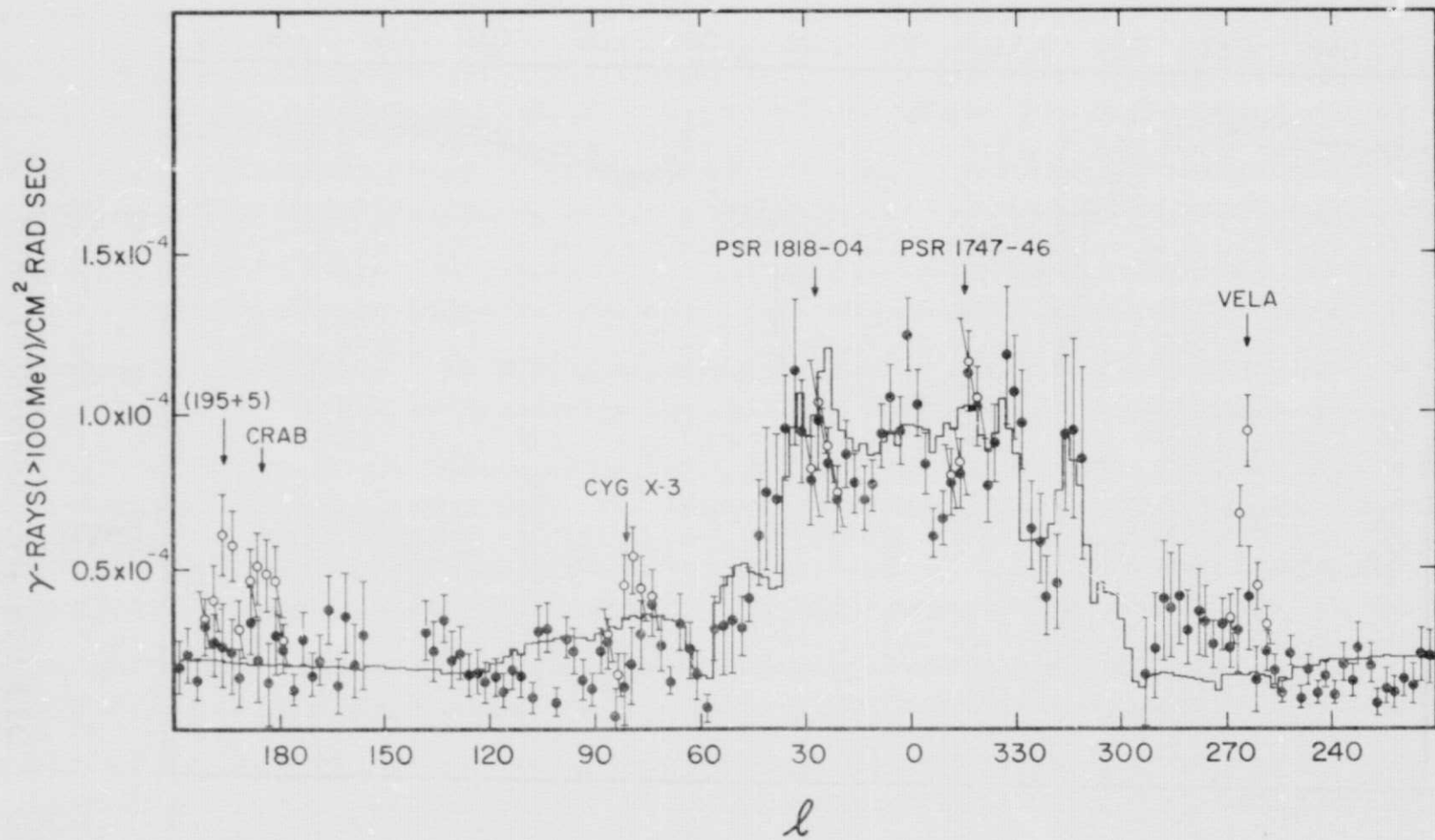


FIG. 2