GALACTIC ARM STRUCTURE AND GAMMA RAY ASTRONOMY

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ABSTRACT

In an attempt to explain the observed unexpectedly high energy gamma radiation over a broad region of the galactic plane in the general direction of the galactic center, a model is proposed wherein the galactic cosmic rays are preferentially located in the high matter density regions of galactic arm segments, as a result of the weight of the matter in these arms tieing the magnetic fields and hence the cosmic rays to these regions. The presently observed galactic gamma ray longitudinal distribution can be explained with the current estimate of the average galactic matter density, if the average arm to interarm matter ratio is five to one for the major arm segments toward the galactic center from the sun, and if the cosmic ray density normalized to its local value is assumed to be directly proportional to the matter density.

I. INTRODUCTION

Gamma ray astronomy is emerging as another rewarding avenue of astronomical research into the nature of our galaxy. As has been recognized for some time, cosmic rays in the galaxy interact with the intergalactic matter leading to high energy gamma rays mostly arising

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from the π° mesons formed in the interactions. Further, the intensity of this radiation (Kraushaar et al., 1972 and Kniffen et al., 1973) is great enough so that it stands out clearly from the diffuse celestial background, which also has a very different energy spectrum (Fichtel et al., 1973). Thus, gamma ray astronomy can provide information on the product of the galactic cosmic ray intensity and the intergalactic matter.

Independently, radio astronomy has provided considerable insight into the distribution of atomic hydrogen in the galaxy through the study of the 21 cm line. It has been noted, however, by Kraushaar et al. (1972) that, even when careful consideration is given to the angular resolution function of the gamma ray detectors, the gamma ray intensity as a function of galactic longitude is not consistent with that predicted from the 21 cm data assuming a uniform cosmic ray density. Most strikingly the radiation from the general vicinity of the galactic center is too high by a factor of three to four, whereas in the general anticenter direction the predicted intensity is close to the observed value without any normalizing. Wolfendale et al. (1973) have made somewhat different assumptions leading to a cosmic ray intensity which is also smooth on a galactic scale, but rises in intensity toward the galactic center. This theory, as well as the recent proposal of Stecker et al. (1973) which involves Fermi acceleration of cosmic rays in a one kpc ring around the galactic central region, requires a relatively high cosmic ray energy density over the broad central region of the galaxy or at least a portion of it.

In pursuing the problem of galactic gamma radiation it is important to realize that the one-dimensional full width angular resolution of the high energy gamma ray detectors flown thus far has been either several degrees, in the case of SAS-II, or about 25°, in the case of OSO-III. Thus, the observed intensity of a feature with a thickness comparable to the disc of the galaxy will decrease approximately as one over the distance once it is more than 2 kps away for SAS-II (and closer for OSO-III) and faster if it is also small in extent within the plane. Hence, more distant regions of the galaxy would have to be substantially more intense than local ones to explain an observed intensity of gamma rays in any given direction. This consideration together with the geometrical distribution of the intense high energy gamma radiation, particularly the broad flat distribution of the gamma radiation in galactic longitude over 60° to 90° in the central region of the galaxy (Kniffen et al., 1973) has suggested to us that the source of the enhancement is possibly predominantly diffuse radiation from the spiral arm segments closest to the sun in the direction of the galactic center.

In this letter the reasons for proposing enhanced gamma radiation from arm segments due to the interaction of cosmic rays with the matter in the arms will be discussed. Second, the specific model will be presented and it will be seen that, with the non-uniform matter distribution proposed, the observed gamma radiation is consistent with current estimates of the galactic matter density, and the local galactic cosmic ray energy density.

II. THE THEORETICAL MODEL

The number and energy spectrum of the gamma rays produced by cosmic rays interacting with intergalactic matter has been calculated in detail for the case of the cosmic radiation in intergalactic space by several authors (e.g. Stecker, 1970; Cavallo and Gould, 1971). The flux of gamma rays with energies greater than E at a distance r is given by the expression

$$\Phi(E) = \int d\Phi(E,r) = \frac{1}{4\pi}\int S\, Kg(r,d\Omega)\; n(r,d\Omega)\; dr\, d\Omega \qquad (1)$$

where S is the number of gamma rays produced on the average for one interstellar nucleus/sec and a cosmic ray energy density and spectrum equal to that near the earth, n is the intergalactic proton density, g has been introduced here to represent the ratio of the cosmic ray density to that in the vicinity of the solar system, and K (assumed here to be 1.5) has been introduced to account for the molecular hydrogen density. Following Stecker (1973) S is taken to be $1.5 \cdot 10^{-25}$/sec.

With regard to the cosmic ray distribution, the assumption is made here that the cosmic rays and magnetic fields are galactic and not universal. Then, as shown by Bierman and Davis (1960) and Parker (1966) in more detail, a magnetic field can only be contained by the weight of the gas through which it penetrates, and hence it is tied to the matter. The magnetic field lines then have their greatest density where the matter density is greatest, and tend to diverge in less dense regions. This picture is supported by the synchrotron emission measurements from M51 by Mathewson et al. (1971) at Westerbrok as well as by the density wave theory as applied to the spiral arm structure by Roberts and Yuan (1970). The galactic cosmic rays are primarily contained by the magnetic fields, and indeed their energy density cannot substantially exceed that of the magnetic fields, or the cosmic ray pressure will push a bulge into the fields ultimately allowing the cosmic rays to escape. The local energy density of the cosmic rays is about 1 eV/cm^3, which is also approximately the estimated energy density of the average magnetic field. This feature together with source and lifetime considerations suggests that the magnetic fields are nearly saturated with cosmic rays and that the cosmic ray density may generally approach the limit the magnetic fields can contain. As a working hypothesis, it will, therefore, be assumed that the energy density of the cosmic rays is at or near its saturation value, and, therefore, higher, in general, where the matter is denser and better able to contain the magnetic fields. This hypothesis is applied, and indeed is most relevant on the scale of galactic arms. As gamma ray astronomy improved in angular resolution, it can also be tested on the scale of clouds. (The possible importance of local clouds as gamma ray emitties has been noted by Black and Fazio, 1973.) A reasonable trial assumption, which shall be used here, is that the cosmic ray density is proportionate to the matter density. If this is correct, the fluctuations in matter density are quite important in determining the expected gamma ray intensity calculated by eq. (1) since the gamma radiation becomes proportional to n^2.

The density distribution of interstellar matter has generally been estimated from 21 cm radio data with corrections in the form of multiplying factors to include lesser amounts of ionized and molecular hydrogen. Some problems associated with the direct interpretation of the 21 cm data are discussed for example, by Simonson (1970) in his review of the "Spiral Workshop" held at the University of Maryland in 1970. First, there is clearly significant absorption of the 21 cm line over a band in galactic longitude about the galactic center, and also in those directions which are approximately along spiral arm segments. Second, the interpretation of the observed intensity in the 21 cm line in terms of density depends on the velocity assumed for the parent matter, and there is increasing reason to believe the velocity pattern is not as simple as assumed in the earliest models. It is actually this latter problem which is of greater concern here because it affects the peak valley ratio of the matter density distribution.

It seems plausible, relying again both on measurements from external galaxies and on the density wave theory for the spiral pattern, to assume this ratio to be five to one at least for the inner galactic arms, (e.g. Roberts and Yuan, 1970). In constructing the hydrogen density distribution n_H $(\ell^{II}, b^{II}, \rho)$ model we have made the following assumptions. Between the Sun (at R = 10 kpc) and the galactic center there are three main arms, the 4 kpc dispersion ring, the Norma Scutum, and the Sagittarius. The Sun itself is located on the inner side of a "local" arm of lesser density than the three previous ones. Outside the local arm (R > 11 kpc) no well defined feature is placed, but rather a smooth decrease up to 16 kpc. Table 1 summarizes the density values adopted on the equatorial plane as a function of the galactocentric distance.

Table I

Galactocentric distance (kpc)	0-.7	.7-3.5	3.5-4.5	4.5-5.	5.-6.	6.-7.3	7.3-8.5
Equatorial density (cm^{-3})	2.0	.40	2.0	.40	2.0	.40	2.0
(kpc)	8.5-9.7	9.7-11.	11.-12.	12.-13.3	13.3-14.6	14.6-16.	
(cm^{-3})	.40	.60	.52	.38	.28	.14	

For simplicity, a cylindrical symmetry is assumed so that the equatorial distribution n_H (R,0) is invariant for galactocentric longitude. This is equivalent to approximating the arm segments with arcs of circles and may of course lead to small displacements in the position of the maxima of emission.

The vertical hydrogen distribution, $n_H(z)$, is computed as a quasi-gaussian decrease from the equatorial value as in Schmidt (1965). The half-width-half-maximum of the distribution is 110 pc up to the Sun's radius, 150 pc up to 11 kpc and 200 outwards.

The density distribution $n_H(R,z)$ thus obtained is transformed into heliocentric galactic coordinates $n_H(\ell^{II}, B^{II}, \rho)$ squared since $g \sim n$, then integrated over ρ in steps of 100 pc and over b^{II} in steps of 1°.

The result is then introduced in equation (1) to yield the gamma-ray line flux. In comparing the calculated value to the experimental data, a normalization factor of 1.1 was required. The difference between 1.1 and 1.0 is small compared to the combined uncertainty of the parameters used in the theory, such as the S and K factors in equation (1) and experimental normalization errors. Figure 1 shows the available SAS II data together with the result of our computations, both integrated between $\pm$ 10° b^{II}. However, 2° interval points are also shown for the model to present the arm structure in more detail and to give an idea of what could be seen with a gamma-ray telescope of better angular resolution and better statistics. Also presented is the contribution from the Sagittarius arm alone and from the Sagittarius and the Norma-Scutum arm. Note that, in the symmetry of the model, two small but significant peaks are present at the intermediate longitudes of 90° and 270°. These represent the contribution of our local arm and their longitude value does suffer most from the circular approximation being bound to shift outwards (e.g., towards 260°) in a picture closer to reality.* Although a very satisfactory agreement is obtained between the SAS II data (Kniffen et al., 1973) and the OSO III data of Kraushaar et al., (1972) in terms of absolute flux measurements, no detail comparison is shown here because of the different characteristics of the two experiments in angular resolution and statistics.

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*Note that such enhancements are very sensitive to the local matter distribution, since they are relatively close, and could be much larger than indicated here.

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FIGURE CAPTION

Fig. 1. Longitudinal distribution of galactic gamma-flux integrated in $\pm 10°$ b^{II}. SAS-II points are given together with their error bars. Thick line represents the model smoothed in 10° of ℓ^{II}. Thin line represents the model in 2° intervals. Dotted line (---) gives the contribution of the Sagittarius and Norma-Scutum arms and dash-dot (-.-.) the contribution of the Sagittarius arm alone.

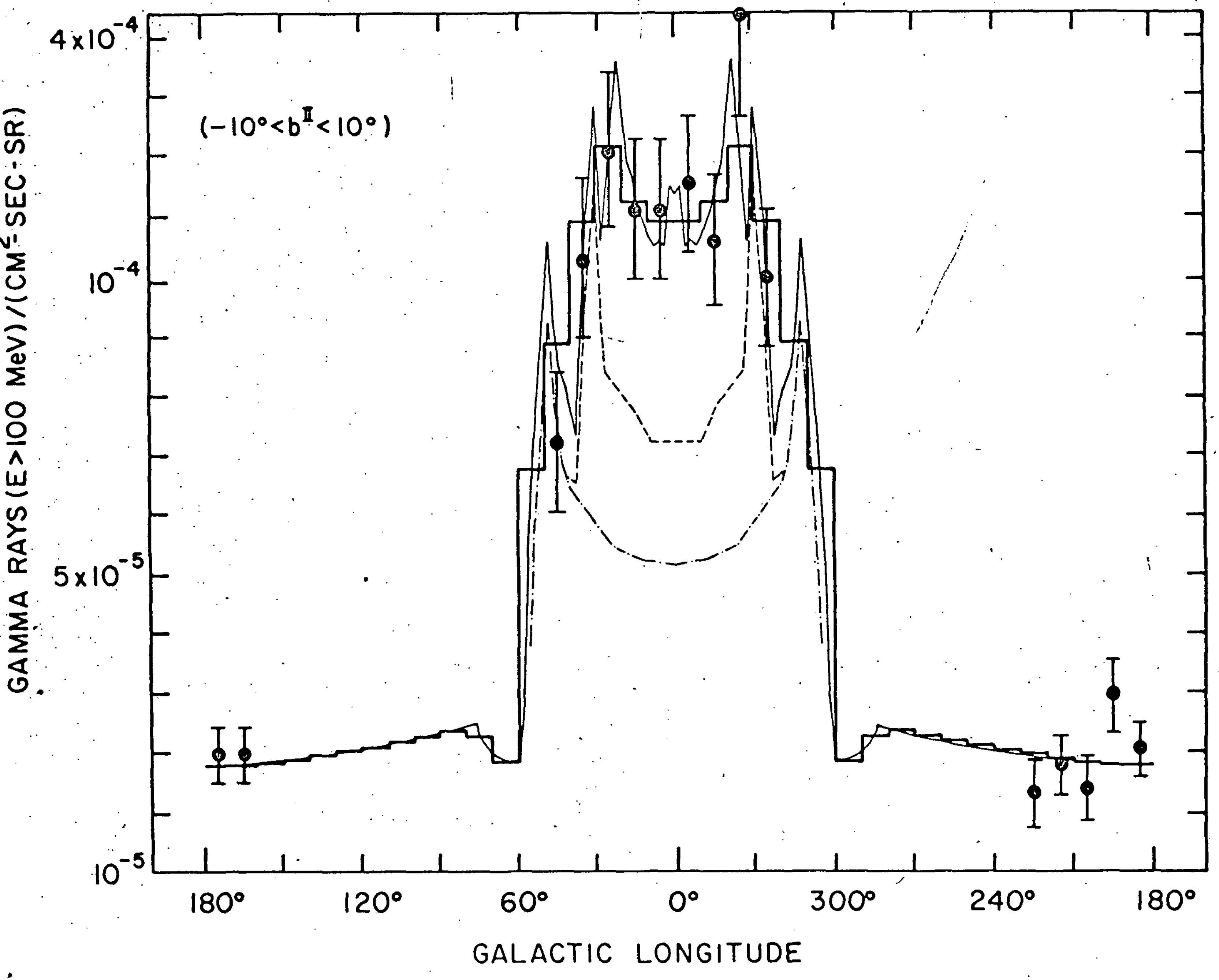
4x10^-4
(-10°<b^II<10°)
10^-4
5x10^-5
10^-5
GAMMA RAYS (E>100 MeV)/(CM^2-SEC-SR)
180° 120° 60° 0° 300° 240° 180°
GALACTIC LONGITUDE

Figure 1