Primary γ-Rays [and Discussion]

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Primary γ-rays

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Within our Galaxy, cosmic rays can reveal their presence in interstellar space and probably in source regions by their interactions with interstellar matter which lead to γ-rays with a very characteristic energy spectrum. From the study of the intensity of the high energy γ radiation as a function of galactic longitude, it is already clear that cosmic rays are almost certainly not uniformly distributed in the Galaxy and are not concentrated in the centre of the Galaxy. The galactic cosmic rays appear to be tied to galactic structural features, presumably by the galactic magnetic fields which are in turn held by the matter in the arm segments and the clouds. On the extra-galactic scale, it is now possible to say that cosmic rays are probably not at the density seen near the Earth. The diffuse celestial γ-ray spectrum that is observed presents the interesting possibility of cosmological studies and possible evidence for a residual universal cosmic-ray density, which is much lower than the present galactic cosmic-ray density.

1. 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 interstellar matter leading to high energy γ-rays mostly arising from π^0 mesons formed in the interactions. The high energy γ radiation formed in this way is distinguishable by its unique energy spectrum which has a maximum intensity at 70 MeV. Further, the intensity of the radiation from the galactic plane (Kraushaar *et al.* 1972; Kniffen, Hartman, Thompson & Fichtel 1973), is great enough so that it stands out clearly from the diffuse background, which also has a very different energy spectrum (Fichtel, Hartman & Kniffen 1973). Thus, γ-ray astronomy can provide information on the product of the galactic cosmic-ray intensity and the interstellar matter.

Another only slightly older field of astronomy, namely radio astronomy, has provided considerable insight into the distribution of matter, and especially of atomic hydrogen in the Galaxy through the study of the 21 cm line. Together with radio and other related data, γ-ray astronomy can then ultimately provide a picture of the distribution of cosmic rays in the Galaxy both on a broad scale, within arm segments and clouds, and around sources of cosmic rays, as well as helping to define the principal galactic features. At present, γ-ray astronomy is in its earliest stages of development, but already some galactic features are becoming apparent.

In this paper, after a short summary of the general considerations related to the production of γ-rays by galactic cosmic rays and the present experimental results, the specific galactic models currently being proposed to explain the galactic radiation are discussed to understand what is presently known and what future γ-ray observation could be expected to reveal.

Beyond the Galaxy, γ-ray astronomy may be providing information on cosmic rays in the intergalactic region, although the interpretation of the diffuse γ radiation observed by OSO-III (Kraushaar *et al.* 1972) and SAS-II (Fichtel *et al.* 1973) is ambiguous and will remain so until much more detailed information is available on the spatial distribution to test the uniformity, and the precise energy spectrum is measured. None the less, the present data on this diffuse celestial radiation are strongly suggestive that the γ radiation may provide insight into cosmology and possible ancient cosmic rays in the Universe. Regardless of the ultimate resolution of that problem, the diffuse radiation deserves attention here because the observed level sets an upper limit on the product of the cosmic-ray density and the intergalactic matter density at the present time.

2. Cosmic rays and galactic γ radiation

(*a*) *General*

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

$$\Phi = (1/4\pi) \int SKg\,(r, \mathrm{d}\Omega)\, n(r, \mathrm{d}\Omega)\, \mathrm{d}r\,\mathrm{d}\Omega, \tag{1}$$

where S is the number of γ-rays produced on the average for one interstellar nucleus/second 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 $1.5 \times 10^{-25}\ \mathrm{s}^{-1}$.

It is worth mentioning at this point that the principal contribution to the high energy γ radiation from the cosmic-ray interactions with interstellar matter comes in the cosmic-ray energy range from a few tenths of a GeV to a few tens of GeV. Below that energy range the parent π^0 mesons are not produced, and at higher energies the contribution is very small because the cosmic-ray energy spectrum is decreasing much faster with energy $(\sim E^{-\frac{5}{2}})$ than the pion production is increasing $(\sim E^{\frac{1}{4}})$. Hence, when cosmic rays are mentioned here, the energy range mentioned above is implied.

(*b*) *Present γ-ray experimental picture*

High energy γ radiation was first seen to be arriving from the galactic plane by Kraushaar *et al.* (1972) with the OSO-III experiment. More recently, the results from the SAS-II γ-ray telescope, which are currently being analysed, are providing information of improved angular accuracy and statistical weight (Kniffen *et al.* 1973). For background information a short description of the SAS-II experiment will be given in the next paragraph before presenting the experimental results.

A schematic diagram of the γ-ray telescope flown on SAS-II is shown in figure 1. The spark chamber assembly consists of 16 spark chamber modules above a set of four central plastic scintillators and another 16 modules below these scintillators. Thin tungsten plates, averaging 0.03 radiation lengths thick, are interleaved between the spark chamber modules, which have an active area of approximately 640 cm². The large number of thin tungsten plates and spark chambers serve a dual purpose, first to provide material for the γ-ray to be converted into an electron pair which can then be clearly identified and from which the arrival direction of the γ-ray can be determined, and, secondly, to provide a means of determining the energy of the electrons in the pair by measuring the Coulomb scattering. The energy threshold is about

30 MeV. The energy of the γ-ray can be measured up to about 200 MeV, and the integral flux above 200 MeV can be determined. A more complete discussion of the SAS-II γ-ray telescope is given by Derdeyn *et al.* (1972). The calibration and data analysis are similar to those used for previous balloon γ-ray digitized spark chambers (Fichtel, Kniffen & Ogelman 1969; Kniffen 1969; Fichtel, Hartman, Kniffen & Sommer 1972; Thompson, 1973). The SAS-II satellite is capable of being pointed in any direction, and normally viewed the same region of the sky for a period of about a week. The orbit is nearly equatorial at an altitude ranging from about 440 to 610 km.

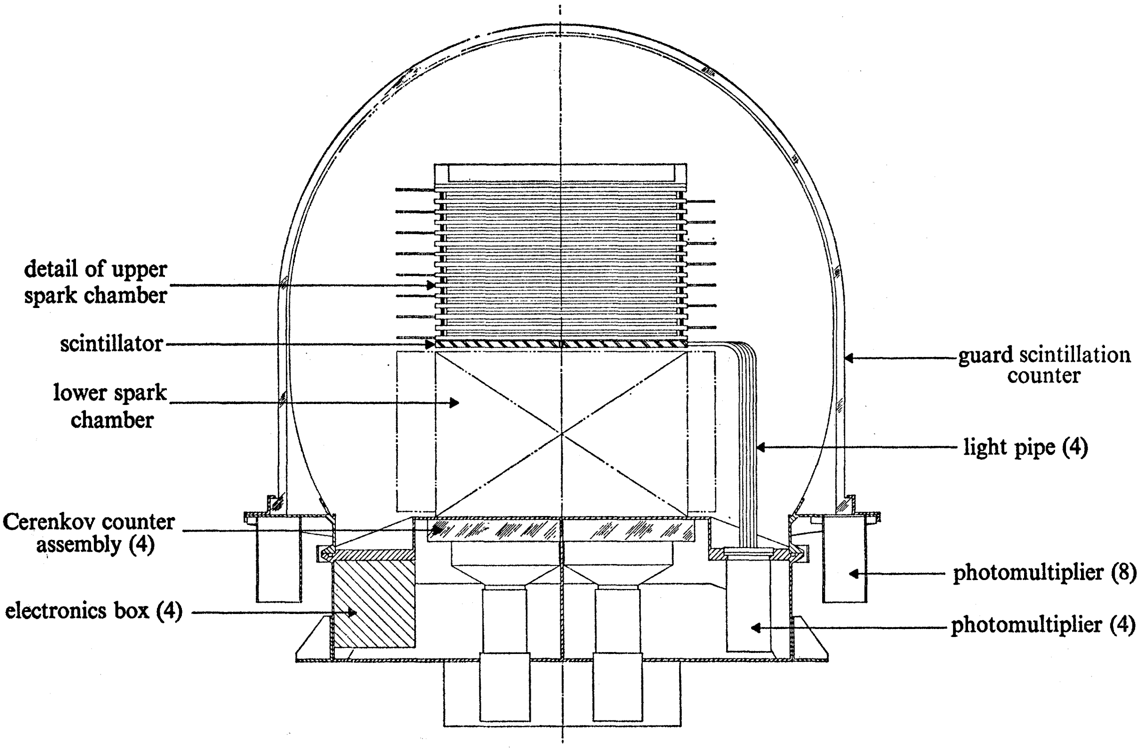

FIGURE 1. Schematic diagram of the SAS-II γ-ray experiment (Derdeyn *et al.* 1972).

Relative to the general background celestial diffuse radiation, an enhanced flux of high energy (> 30 MeV) γ-rays is observed along the entire galactic plane. The region ($320^\circ < l^{\mathrm{II}} < 40^\circ$) is particularly intense, as seen in figure 2, which shows the intensity of γ-rays above 100 MeV summed from $b^{\mathrm{II}} = -10^\circ$ to $b^{\mathrm{II}} = +10^\circ$ and plotted as a function of galactic longitude (Kniffen *et al.* 1973). Notice specifically that the radiation from the galactic centre is not more intense than the rest of the interval of about 60° in l^{II} around the galactic centre. This lack of a peak in the γ-ray distribution at the centre negates any theory which tries to explain the general enhancement in the region ($320^\circ < l^{\mathrm{II}} < 40^\circ$) in terms of a strong source reaching a maximum in the galactic centre region.

Summing the radiation for $E_\gamma > 100$ MeV into bins with a width in b^{II} of 2.5° in the region ($330^\circ < l^{\mathrm{II}} < 30^\circ$), the distribution in figure 3 is obtained. The one σ half-width is 4.5°. With the current uncertainties in the knowledge of the pointing direction, and the known accuracy for determining the arrival directions of the individual γ-rays, a pure line source would be broadened to have a σ of $3.5 \pm 0.5^\circ$. Hence, the uncertainty of angular resolution in the preliminary data is still a significant factor in the angular distributions. However, from the above results, it can be concluded that the 2σ line width is probably not more than about 6° on the average for the 60° interval ($330° < l^{II} < 30°$).

The energy spectrum for the γ radiation in the region ($330° < l^{II} < 30°$, $-10° < b^{II} < 10°$) is shown in figure 4. Notice that the energy spectrum is quite flat, especially as compared to the very steep energy spectrum of the diffuse radiation (Fichtel *et al.* 1973). If it is assumed that the diffuse radiation pervades the galactic plane region also, then the contribution from the galactic plane alone is obtained by subtracting the diffuse spectrum from the total. This result is shown

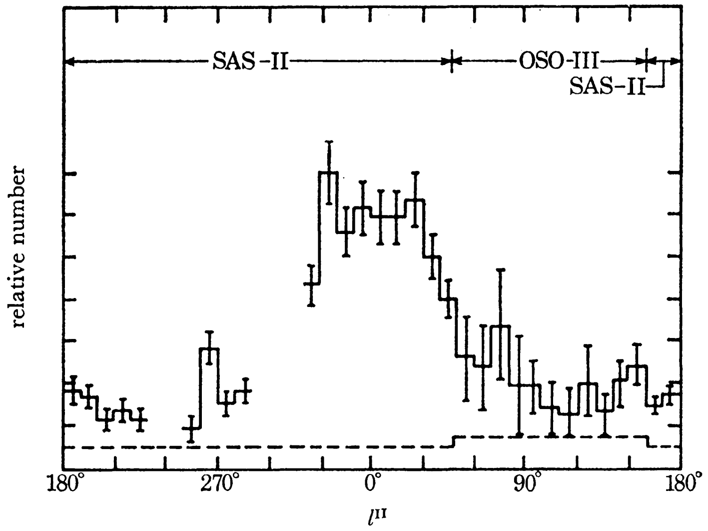

FIGURE 2. Distribution of high energy (> 100 MeV) γ-rays along the galactic plane. The data marked OSO-III are those of Kraushaar, *et al.* (1972), and those marked SAS-II, of Kniffen *et al.* (1973), and Thompson *et al.* (1974). The diffuse background level is shown by a dashed line. It is higher in the case of OSO-III than SAS-II because the OSO-III is summed from $b^{II} = -15°$ to $b^{II} = +15°$ and the SAS-II data from $b^{II} = -10$ to $b^{II} = +10$. The ordinate scale is approximately in units of $10^4 \times$ photons cm^{-2} rad^{-1} s^{-1}.

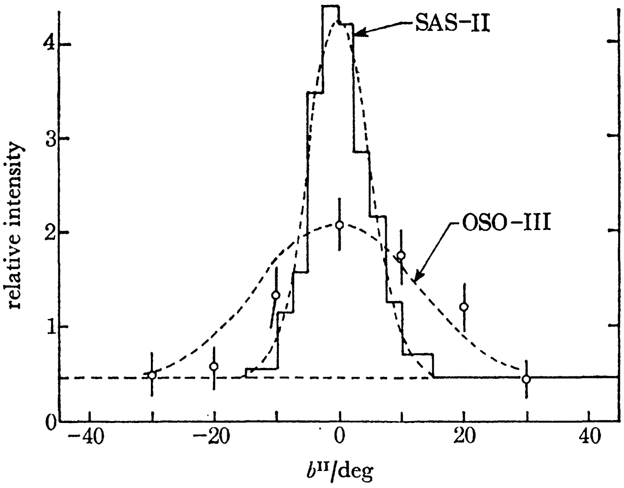

FIGURE 3. Distribution of high energy ($E_\gamma > 100$ MeV) γ-rays summed from $l^{II} = 330°$ to $l^{II} = 30°$ as a function of b^{II}. The OSO-III data are those of Kraushaar *et al.* (1973). The dashed curve through the SAS-II data (Kniffen *et al.* 1972) is a gaussian distribution with $\sigma = 4.5°$. As indicated in the text, this distribution still includes a substantial experimental angular uncertainty, so the real distribution of γ-rays is probably somewhat narrower.

as the dashed line in figure 4. It is seen that, whereas there is almost no effect on the spectrum above 100 MeV, the contribution of the diffuse background at about 40 MeV is quite significant. The integral flux above 100 MeV is $(1.1 \pm 0.3) \times 10^{-4}$ photon cm^{-2} sr^{-1} s^{-1}, where the errors include uncertainties due to the fact that the analysis of the calibration data is not yet complete. Within present uncertainties, the energy spectrum is consistent with a π^0-decay spectrum from cosmic-ray interstellar matter interactions or a mixture of this spectrum and a spectrum formed by Compton radiation from cosmic-ray electrons. The intensity of the radiation in the anticentre direction is much lower, averaging about 0.2×10^{-4} photons cm^{-2} rad^{-1} s^{-1}).

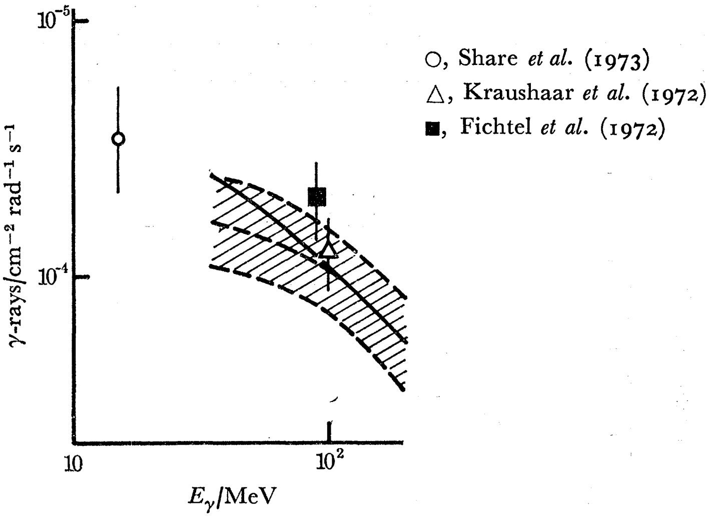

FIGURE 4. Energy spectrum for γ-rays from the region $(-10^\circ < b^{\mathrm{II}} < 10^\circ, 330^\circ < l^{\mathrm{II}} < 30^\circ)$, as determined by SAS-II. The solid curve is the best estimate of the total spectrum and the dashed curve represents the contribution after the diffuse background has been subtracted.

An enhancement relative to the plane flux in the surrounding region is seen in the interval $260^\circ < l^{\mathrm{II}} < 270^\circ$ (Thompson *et al.* 1974). This enhancement is centred around $b^{\mathrm{II}} = -3\,(\pm 1)^\circ$ rather than $b^{\mathrm{II}} = 0^\circ$. The excess has a hard spectrum, similar within statistics to that of the galactic plane itself. Possible explanations of this specific feature will be discussed after a discussion of some of the current models to explain the galactic radiation.

(c) *Galactic cosmic ray – matter models*

In the first attempts to compare the observed high energy γ-ray intensity with calculated values, it was assumed (e.g. by Kraushaar *et al.* 1972) that the cosmic-ray density was uniform throughout the Galaxy so that g could be taken outside the integral in equation (1), and was usually set equal to one. Using the 21 cm data to estimate columnar hydrogen density (Kraushaar *et al.* 1972) showed that whereas the calculated intensity was fairly close to that expected in the anticentre direction when the expected intensity was integrated over the solid angle of the detector (which had a gaussian angular sentivitity with 1σ of about 15°), the observed intensity in the galactic centre region was about four times the calculated value. Thus, the galactic longitudinal dependence was clearly inconsistent with this model, and it could, therefore, not be brought into agreement by assuming a uniformly higher value of the cosmic-ray density or by assuming that the total matter density was uniformly much higher because a significant portion of the interstellar hydrogen was in molecular form, for example.

More recently, Strong, Wdowczyk & Wolfendale (1973), have assumed that the cosmic-ray density has a smooth distribution, but one which increases towards the galactic centre according to the equation:

$$g \propto \{Z \exp\left(-Z^2/Z_0\right) \exp\left(-\tfrac{1}{100}R^2\right) \left[1-\exp\left(-\tfrac{1}{4}R^2\right)\right] \left[1+4\cos^2\left(\phi-\phi(R)\right)\right]\}^n. \qquad (2)$$

In this relation Z is the height above the galactic plane, $Z_0 = 175$ pc and R = distance to galactic centre in kpc. The choice of this form was based on this expression representing the mean magnetic field ($n = 1$) or the square of the mean magnetic field ($n = 2$), in accordance with the work of Thielheim *et al.* (1971). The results were in better agreement with the centre–anticentre ratio, but do not agree in detail with more recent SAS-II results. This work, however, is important as one of the papers breaking with the traditional constant density cosmic-ray concept.

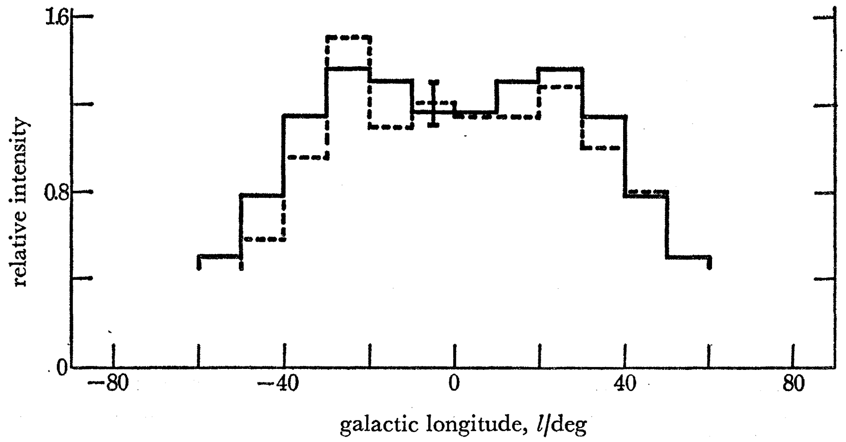

Figure 5. Comparison of the longitudinal distribution of galactic γ radiation observed on SAS-II (– – –) with the distribution given by the theoretical model of Stecker *et al.* (1974) (——).

Stecker, Puget, Strong & Bredekamp (1974), have proposed that the galactic cosmic-ray flux varies with the radial distance from the galactic centre and is about an order of magnitude higher than the local value in a toroidal region between 4 and 5 kpc. They further suggest that this enhancement can be plausibly accounted for by Fermi acceleration caused by a hydrodynamic shock driven by the expanding gas in the '3 kpc' arm and invoked in some versions of galactic structure theory. This theory does provide a possible explanation of the general enhancement in the central region as shown in figure 5, but possibly not some of the fine details now beginning to appear. There is, of course, also the question of whether or not the Fermi acceleration exists. If it does, then, clearly, the accelerated cosmic rays could play a very important role.

In pursuing the problem of galactic γ radiation, it is important to realize that the one-dimensional full-width angular resolution of the high-energy γ-ray detectors flown thus far has been either several degrees, in the SAS-II, or about 25° in the case of OSO-III. Thus, the observed intensity of a feature with a thickness comparable to the disk of the Galaxy will decrease approximately as the reciprocal of the distance once it is more than 2 kpc away from 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 γ-rays in any given direction with the present instruments. This consideration, together with the geometrical distribution of the intense high energy γ radiation, particularly the broad, relatively flat distribution of the γ radiation in galactic longitude over 60 to 90° in the central region of the Galaxy, suggested to Kniffen *et al.* (1973), and Bignami & Fichtel (1974), 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 centre.

Bignami & Fichtel (1974) have proceeded further and proposed that in general the cosmic rays are enhanced where the matter is greatest; namely, in the arm segments and clouds. This hypothesis is supported by the following considerations: First, it is assumed that the cosmic rays and magnetic fields are galactic and not universal. Then, as shown by Bierman & Davis (1960) and Parker (1966) in more detail, magnetic fields and cosmic rays can only be contained by the mass of the gas through which the magnetic fields penetrate; and, hence, they are tied to the matter. The magnetic field lines would tend to have their greatest density where the matter density is greatest. This picture is supported by the synchrotron emission measurements from M51 by Mathewson, Van der Kruit & Brown (1971), at Westerbroc, as well as by the density wave theory, as applied to the spiral arm structure by Roberts & Yuan (1970).

The galactic cosmic rays are tied to the matter 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 0.5 eV/cm^3, which is also approximately the estimated energy density of the average magnetic field and the estimated maximum of about 1 eV/cm^2 that matter can hold. This feature suggests that the cosmic-ray density may generally approach the limit the matter can contain. This concept is given some theoretical support by the expected slow diffusion rate of cosmic rays in the magnetic fields of the Galaxy and the very possibily high production rate of cosmic rays, which together also suggest that in general the cosmic rays should be plentiful in a given region and should not move quickly to less dense regions. Therefore, it was assumed that the energy density of the cosmic rays is at or near its saturation value, and hence, higher, in general, where the matter is denser and better able to contain the magnetic fields. As a trial assumption, Bignami & Fichtel (1974) let the cosmic-ray density be proportional to the matter density. The fluctuations in matter density are then quite important in determining the expected γ-ray intensity calculated by equation (1), since the γ 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 centre, and also there are indications of high optical depth along spiral arm segments. Secondly, the interpretation of the observed intensity in the 21 cm line in terms of density depends on the assumed galactic velocity field, 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 (e.g. Roberts & Yuan 1970), to assume at least for the inner galactic arms that this ratio is five to one. In constructing the hydrogen density distribution n_{H} (l^{II}, b^{II}, ρ) model, Bignami & Fichtel have made the following assumptions: between the Sun (at $R = 10$ kpc) and the galactic centre 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. The intervals in galactocentric distance are based on those of Westerhout (1970), except for the introduction of the 4 kpc dispersion ring. The densities for distances less than 10 kpc are adjusted to reflect the 5:1 arm to interarm ratio assumed here.

Table 1

galactocentric distance/kpc	0–0.7	0.7–3.5	3.5–4.5	4.5–5	5–6	6–7.3	7.3–8.5
equatorial density/cm^{-3}	2.0	0.40	2.0	0.40	2.0	0.40	2.0
galactocentric distance/kpc	8.5–9.7	9.7–11	11–12	12–13.3	13.3–14.6	14.6–16	
equatorial density/cm^{-3}	0.40	0.60	0.52	0.38	0.28	0.14	

For simplicity, a cylindrical symmetry was 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.

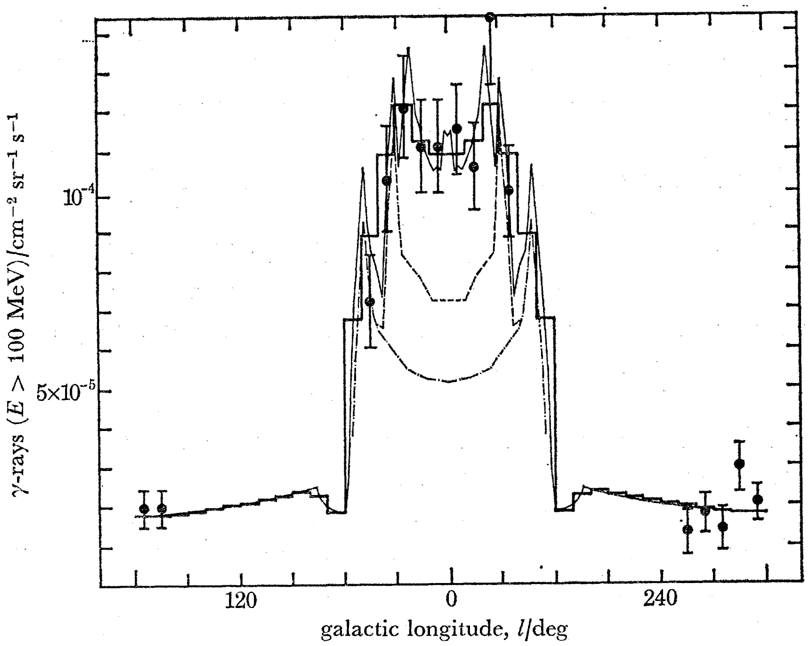

Figure 6. Longitudinal distribution of galactic γ-flux integrated over ± 10° in b^{II}. SAS-II points are given together with their error bars. The thick line represents the model of Bignami & Fichtel (1974) smoothed in 10° l^{II} intervals. The thin line represents the model in 2° intervals. The dotted line (----) gives the contribution of the Sagittarius and Norma-Scutum arms and dash-dot (–·–·), the contribution of the Sagittarius arm alone.

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 100 pc up to the Sun's radius, 150 pc up to 11 kpc, and 200 outwards.

The result is then introduced in equation (1) to yield the γ-ray line flux. Figure 6 shows the available SAS-II data in 10° l^{II} intervals together with the computations, both integrated between $\pm 10°$ in b^{II}. 2° l^{II} 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 γ-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. Further, the intensity depends very critically on the mass and cosmic-ray density.

The experimental data in figure 2 show a peak in the region between 260 and 270°, which deserves special attention. First, to see more clearly the significance of this peak, the intensity of γ-rays above 100 MeV is summarized in table 2 in 10° intervals along the plane and within a 7.5° interval on each side of the plane (Thompson, Bignami, Fichtel & Kniffen 1974). The large intensity in the interval $(260° < l^{II} < 270°, -7.5° < b^{II} < 0)$ is seen to be three times the level in surrounding intervals; hence, the intensity is 3.0 γ-rays $\mathrm{cm^{-2}\,sr^{-1}\,s^{-1}}$, slightly over seven standard deviations above the average level of approximately 0.95 ± 0.26. The intensities in the other regions given in table 2 are similar to those in the galactic plane anticentre direction (Kniffen *et al.* 1973).

TABLE 2

l^{II}	250°		260°		270°		280°		290°
$-7.5° < b^{II} < 0°$		0.8 ± 0.3		3.0 ± 0.5		1.08 ± 0.26		1.15 ± 0.36	
$0° < b^{II} < 7.5°$		0.5 ± 0.3		0.95 ± 0.26		0.83 ± 0.23		1.04 ± 0.35	

It is possible to relate this enhancement to the large-scale galactic structure in that region, especially in view of the 'hat brim' effect of the galactic plane at those longitudes wherein the radiation tends to come from south of the galactic plane. Although the Milky Way in the region $l^{II} \approx 260$–$270°$ has not been studied as thoroughly as other regions, the 21 cm radio data does point to a maximum of emission in that region (Kerr, Harten & Ball 1974; Hindman & Kerr 1970; Goniadski & Jech 1970), resulting possibly from the super-position of three arm segments as seen in figure 7 (Simonson 1974).

It should also be noted, however, that near the centre of the region of the γ-ray excess lies the Vela X supernova remnant (centred at $\alpha = 130.5°$ and $\delta = 45.0°$), which contains the second fastest pulsar known, PSR 0833-45 (period ≈ 84.2 ms) at $\alpha = 128.8°$ and $\delta = -45.0°$. The best estimate of the centre of the γ-ray excess is $\alpha = 129.5 \pm 1°$ and $\delta = -(46 \pm 1)°$. The Vela object has a complex non-thermal radio source geometry (Milne 1968), emits both soft and hard continuum X-rays (Seward *et al.* 1971; Bunner 1971; Kellogg *et al.* 1973), and has been observed to have a pulsating hard X-ray component (Harnden, Johnson & Haymes 1972; Harnden & Gorenstein 1973), which, however, accounts for only about 6% of the total radiation in the X-ray interval. An extrapolation of the spectrum to the γ-ray region lies well below the results presented here, indicating that some new production mechanism would be required.

Such a mechanism could be the π^0-producing interactions of the expanding cosmic-ray cloud of the supernova remnant. This hypothesis would be in agreement with the observed γ-ray energy spectrum. Assuming the excess γ radiation to be due to cosmic rays associated with the Vela supernova, assuming the supernova remnant to be 460 pc away, and assuming the matter density to be about 1.5 protons/cm^3, 3×10^{43} J of energy would be in the form of cosmic rays from this supernova. This is a number in the energy range, 10^{42}–10^{44} J needed if supernovae are to be the main source of galactic cosmic rays and is also in the range predicted by Colgate (1968) for the supernova hydrodynamic shock theory.

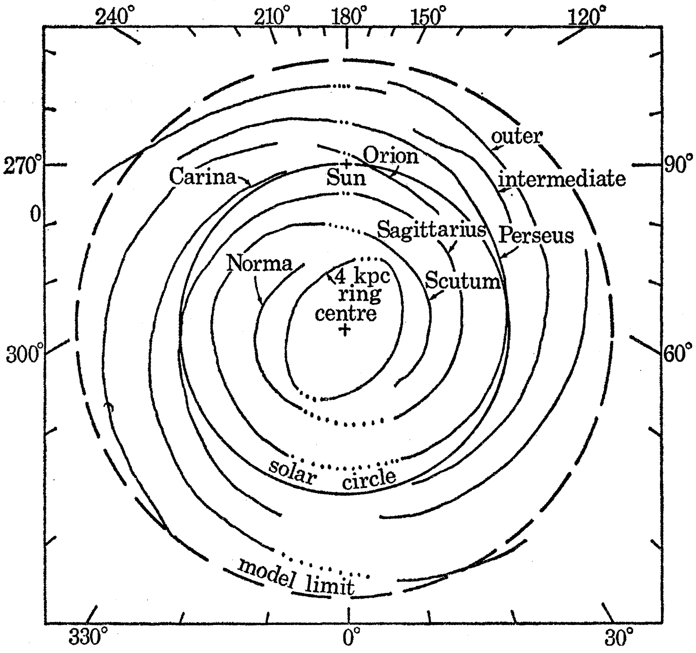

FIGURE 7. A smoothed spatial diagram of the locations of matter density deduced from 21 cm HI line measurements, and the density-wave theory by Simonson (1974).

For the moment, the question of which explanation (the latter or a sum of contributions from cosmic rays in one or several arm segments) accounts for most of the Vela excess must remain open, although the distribution of γ-rays seems to favour the more compact supernova remnant explanation.

As the SAS-II data analysis proceeds further, some additional features should become apparent; however, as the large, high-sensitivity γ-ray telescopes of the future examine the Galaxy with finer angular resolution, the distribution of cosmic rays and matter in the arm segments, and even the clouds will become apparent in detail. At that time, the dynamic pressures imposed by the cosmic-ray gas should be seen clearly, both as the cosmic rays expand about their source and as they apply pressure with the magnetic fields to the galactic features in which they are being held.

3. EXTRAGALACTIC COSMIC RAYS

High energy γ radiation can contribute to the study of extragalactic cosmic rays in two ways; first, in setting constraints on current theoretical models proposing that the cosmic rays pervade a local cluster or supercluster of galaxies at approximately the level observed in our own

Galaxy, and, secondly, in speaking to cosmological models involving ancient cosmic rays. Again, the discussion will begin with the current experimental situation.

The γ-ray experiment on OSO-III of Kraushaar *et al.* (1972), first observed a finite, apparently constant diffuse flux for regions of the sky which were far enough from the galactic plane that no portion of the relative wide angle of the OSO-III detector (*ca.* 35°) overlapped the galactic plane. An integral value of $(3.0 \pm 0.9) \times 10^{-5}$ cm^{-2} sr^{-1} s^{-1} was quoted for the intensity above 100 MeV, but essentially no energy spectral information was obtained. SAS-II has now also observed a finite, diffuse flux of γ-rays with a steep energy spectrum in the energy region from 35 to 200 MeV in several regions with $|b^{\mathrm{II}}| > 15°$ (Fichtel *et al.* 1973). Representing the energy spectrum by a power law of the form $\mathrm{d}J/\mathrm{d}E = AE^{-\alpha}$ over this energy range, α is found to be $2.7^{+0.4}_{-0.7}$, and the integral flux above 100 MeV is $\left(2.8^{+0.9}_{-0.7}\right) \times 10^{-5}$ photon cm^{-2} sr^{-1} s^{-1}. Combining this result with existing low energy γ-ray data yields an energy spectrum

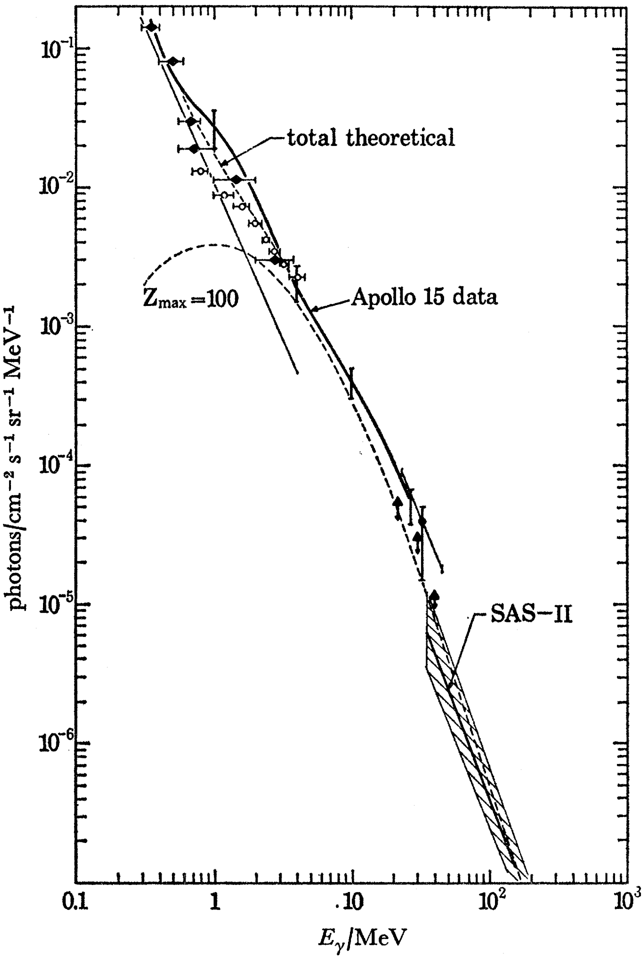

FIGURE 8. Diffuse celestial radiation observed by several experiments (the data marked SAS-II refers to Fichtel *et al.* 1973). Also shown are the straight line extrapolation of the X-ray data (solid line) and the curve predicted by the cosmic-ray-intergalactic matter interaction cosmological model with $Z_{\max} = 100$ (Stecker 1969) discussed in the text (dashed line). ▲, Share *et al.* (1974); ◆, Golenetskii *et al.* (1971); ○, Vedrenne *et al.* (1971); ●, Mayer-Hasselwander *et al.* (1972); Apollo 15 data, Trombka *et al.* (1973), SAS-II, Fichtel *et al.* (1973).

which is not a simple power law in energy, as in the X-ray region, but which demonstrates first an increase and then a decrease in slope, as shown in figure 8.

If it is to be assumed that cosmic rays pervade the entire Universe, a specific cosmological model must be selected before any conclusions can be drawn. However, the relatively low intensity observed in the 100–170 MeV region can put constraints on the distance to which cosmic rays at the density observed in the vicinity of the Earth may extend, as will be seen, since the limit is sufficiently close in distance to avoid major cosmological effects. Using the γ-ray measurements mentioned in the last paragraph, and using the values $K = 1.1$, $g = 1$ and $S = 1.5 \times 10^{-25}$, the limiting radius is about 50 Mpc for an interstellar density of $10^{-5}/\text{cm}^3$ and 500 Mpc for a density of $10^{-6}/\text{cm}^3$. (If a non-closed theory of the Universe is used, the density could be lower and the limiting radius correspondingly larger.) Future γ-ray observations at higher energies could further restrict this limit, unless of course, a π^0-like spectrum is seen at these higher energies instead of the steep spectrum seen at 30 to approximately 170 MeV.

It is also instructive to consider the possible origin of the diffuse radiation, since at least one explanation relates to primordial cosmic rays. First of all, there is the possibility that the diffuse radiation is the sum of many weak discrete or extended sources of unknown origin. Only future experimental results can clarify the picture with regard to that possibility. There are, however, at least two other possibilities; one that the radiation comes from diffuse electrons interacting with matter, photons, or magnetic fields, and the other is that the γ-rays are of cosmological origin.

With regard to the diffuse electron possibility, bremsstrahlung seems unlikely. In an energy region, 1–10 MeV, where an increased slope would be expected due to an increasing rate of energy loss, the opposite is observed. For both synchrotron and Compton radiation, the observed photon spectrum would imply a similarly shaped parent electron spectrum which would have even very much sharper spectral features. Further, for all three cases, the intensity seems high to be consistent with reasonable estimates of the interstellar parameters.

Of the pure γ-ray cosmological hypotheses, there are three, of which I am aware, that seem to be possible candidates. They are the cosmic-ray-interstellar matter interaction model, the particle-antiparticle annihilation in the baryon symmetry steady-state model, and the cosmic-ray-black-body interaction model. In all theories, the resulting γ-ray spectrum is red-shifted substantially by the expansion of the Universe.

In an expanding model of the Universe, the density of matter is much greater in the cosmological past than it is observed to be in the present. However, since the γ radiation produced in interactions of cosmic rays with matter in the distant past reaches us from large distances, the energy of these photons is degraded by the cosmological redshift caused by the expansion of the Universe. One curve developed by Stecker (1969) involving red-shifts up to about 100 is shown in figure 8. The theoretical curve is seen to agree with experimental data reasonably well. If the maximum red-shift is at least 50, as the data imply, then the density of cosmic rays in intergalactic space is 10^{-4} of the local galactic value for an intergalactic matter density of $10^{-5}/\text{cm}^3$.

An alternate attempt to explain the γ radiation through red-shifted γ-rays from π° decay arises from the big bang theory of cosmology with the principle of baryon-symmetry. Harrison (1967) was one of the first to propose a model of this type. Omnes (1969), following Gamow (1948), considered a big bang model in which the Universe is initially at a very high temperature and density, and then shows that, if the Universe is baryon-symmetric, a separation of matter from anti-matter occurred at $T > 30$ MeV. The initial phase separation of matter and anti-matter leads ultimately to regions of pure matter and pure anti-matter of the size of galaxy clusters. Stecker, Morgan & Bredekamp (1971) have predicted the γ-ray spectrum which would be expected from annihilation at the boundaries of such clusters from the beginning of their existence to the present. This spectrum is very similar (essentially indistinguishable) to the one in figure 8 in the energy range for which data exists, and is not included in the figure for that reason. The final model involves cosmic-ray interactions with the early black-body radiation; it will be discussed by Wolfendale (1974) at this meeting.

4. Summary

As the previous sections have indicated, although celestial γ-ray research is just emerging as the newest branch of astronomy, it is already providing results which are of considerable importance in the study of the Galaxy and the Universe. Because of the close relation between γ-rays and cosmic rays, its development should be of special interest to cosmic-ray physicists. In §2, it was seen that cosmic rays are almost certainly not uniformly distributed in the Galaxy and are not concentrated in the centre of the Galaxy. The galactic cosmic rays are more probably tied to structural features by magnetic fields, which are in turn held by the matter in the arm segments and clouds. However, the detailed study of the dynamic influence of the cosmic rays in source regions and the study of their diffusion in the Galaxy will have to wait for a γ-ray telescope twenty times or more as sensitive as SAS-II and one with somewhat better angular resolution even than SAS-II.

On an extragalactic scale, it was seen in §3, that it is possible to say that the cosmic-ray density seen near the Earth is not universal; at present it is not possible, on the basis of the diffuse γ-ray data, to exclude the possibility that the cosmic rays pervade the local supercluster. However, the apparent non-uniform distribution of cosmic rays in the Galaxy, if firmly established, would be a difficulty for this latter concept. The diffuse celestial γ-ray spectrum that is observed presents the interesting possibility of cosmological studies and possible evidence for a residual universal cosmic-ray density, which is much lower than the present galactic cosmic rays. Again, a future γ-ray instrument of much larger sensitivity with modest energy and angular resolution can answer many of these questions.

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Discussion

T. Gold (*Space Sciences Building, Cornell University, Ithaca, New York* 14850 *U.S.A.*). It seems to be commonly believed that there is some limit to the energy content in fast particles that a magnetized cloud can contain, and that this limit is given by an equality of the particle energy and the magnetic field energy. This is not so, and one cannot see any reason for comparing these two energies. For the case of a magnetized gas the effect of the additional fast particles is to increase the internal pressures in the cloud leading to expansion. So long as the magnetic field strength is enough to make the radius of gyration of each energetic particle small compared with the dimensions of the cloud, this field merely serves to communicate the pressure represented by the fast particles to the ambient gas cloud whose currents maintain that field. The resulting expansion of the ambient gas cloud will depend upon this pressure, represented by the fast particles as well as the other pressures – the gas pressure and the magnetic field pressure. The only way that the magnetic field strength enters into this problem is in fact not in preventing but in assisting expansion. Equipartition has no particular significance and the only limit to the amount of high speed gas that can be held in the cloud is given by the inertia of the ambient gas resisting expansion.

If one wishes to picture the process in more detail, one may consider that the conducting cloud merely maintains the same magnetic field, however many energetic particles are supplied. Each energetic particle represents the addition of a diamagnet, and this implies that the currents in the cloud will increase so as to maintain the same field nevertheless. The forces of expansion on the ambient gas are of course due to the cross-products of the currents in the magnetic fields, and these products will increase as the currents increase required to maintain the same fields. The force of expansion is therefore communicated from the fast particles to the cloud through the fact that they cause the ambient currents to increase.

This situation is of course quite different from the case where the currents responsible for the field are in one domain and the fast particles in another (the case of the Earth, of the radiation belts, for example). It is in those cases the comparison of the two energy densities is indeed significant.

So far as one can see, the distribution of the γ-rays from the Galaxy may well fit the distribution of the massive stars. It would then equally fit the distribution of supernova remnants or any other product of massive star evolution.

C. E. Fichtel. The basic assumption of Bignami & Fichtel (1974) is that, on the average, the cosmic ray density is proportional to the matter density since the gravitional force of the matter is the only known attractive force counterbalancing the expansive pressures of the cosmic rays, the magnetic fields, and the kinetic motion of the particles. It is certainly possible in local regions, for example around supernovae, for the cosmic ray pressure to be relatively large leading to a fast expansion. The Vela supernova remnant discussed here may be an example.

J. L. Osborne (*University of Durham*). What is the effective energy range of cosmic rays that produce your observed galactic γ-rays?

C. E. Fichtel. A few tenths of a GeV to a few tens of GeV.

F. G. Smith, (*Nuffield Radio Astronomy Laboratories, University of Manchester, Jodrell Bank, Macclesfield, Cheshire*). The comparison of γ-ray brightness and neutral hydrogen density seems to show that the γ-ray emissivity is proportional to a power of the density. Is this close to the square of the density? Does the computation depend much on the angular resolution of the γ-ray detector?

The γ-ray brightness distribution does not resemble any other distribution; for example both supernova remnants and pulsars are more widely distributed through an arc 180° wide. There is, however, a large ratio between centre and anti-centre regions for both, as for the γ-ray brightness.

C. E. Fichtel. By assuming the cosmic ray density to be proportional to the matter density, the γ ray emissivity becomes proportional to the square of the density. To compare the predicted intensity with that observed, proper account must be taken of both the distance and the angular resolution of the detector. (For these preliminary data, the full width, half maximum one-dimensional angular resolution is 6°.) Within the framework of the present data there seems to be reasonable agreement with this theoretical hypothesis.