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Galactic γ-ray Lines Resulting from Interactions Between Low Energy Cosmic Rays and the Interstellar Medium

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Abstract

Calculated spectral profiles and galactic distributions are presented for γ-ray lines resulting from interactions between low energy cosmic rays and the interstellar gas and dust. Calculated local intensities are also presented for γ-ray lines from discrete sources such as supernova remnants and dense interstellar gas clouds. The γ-ray lines from excited dust nuclei (which have long mean lifetimes) are sharp, having widths of the order of a few keV; the lines from excited gas nuclei are relatively narrow, having widths of the order of 100 keV; and the lines from excited cosmic ray nuclei are broad, having widths of the order of 1 MeV. The longitudinal distribution of γ-ray lines in the galactic plane shows a significant concentration toward the galactic centre, and a rapid falloff beyond $l \geqslant 50°$. The most intense γ-ray lines arise from positron annihilation (0·511 MeV) and the deexcitation of $^{12}C^*$ (4·439 MeV) and $^{16}O^*$ (6·131 MeV). In the direction of the galactic centre, these lines have estimated intensities of the order of 10^{-5} photons cm^{-2} s^{-1} rad^{-1}, and so they may be resolved from the diffuse γ-ray background there by observing with a high resolution Ge(Li) detector. In the direction of several strong discrete sources, the estimated fluxes are generally lower: $\sim 10^{-6}$ photons cm^{-2} s^{-1} for the Crab Nebula and the Vela pulsar, $\sim 10^{-8}$ photons cm^{-2} s^{-1} for the interstellar dense cloud ρ Oph, but $\sim 10^{-5}$ photons cm^{-2} s^{-1} for the ring cloud around the galactic centre. The calculated intensities of various other γ-ray lines are compared with available experimental data, and their detectability is considered. The implication of the galactic distribution of low energy cosmic rays for the gas density of the interstellar space through which the cosmic rays propagate is also discussed.

Introduction

Gamma-ray line astronomy is a new branch of astronomy, and takes its place alongside radio, IR and high energy X-ray astronomy as an important research field for investigating the nature of the Galaxy. As has been recognized for some time, low energy cosmic rays ($E \leqslant 100$ MeV per nucleus) interact with the interstellar medium and give rise to nuclear γ-ray lines, primarily via the deexcitation of excited nuclei or by positron–electron pair annihilation. The prime candidates for suitable excited nuclei are $^{12}C^*$, $^{14}N^*$, $^{16}O^*$, $^{20}Ne^*$, $^{24}Mg^*$, $^{28}Si^*$ and $^{56}Fe^*$. Positron annihilation produces a characteristic line at 0·511 MeV.

The spectral features of the γ-ray lines produced by nuclear deexcitation will vary widely, depending on whereabouts in the Galaxy the excited nuclei reside. Those contained within the interstellar dust have long mean lifetimes and will produce a sharp line spectrum; those contained within the interstellar gas, owing to their low recoil velocities, will produce a relatively narrow line spectrum; while those in the form of cosmic rays will, due to their high velocities, produce a strongly Doppler-broadened line spectrum.

Galactic γ-ray line observations should provide a suitable tool for investigating the galactic distribution of low energy cosmic rays, whose intensity in interstellar space essentially remains unknown owing to the effects of solar modulation. They should also provide an appropriate means for determining the composition and galactic distribution of the interstellar gas and dust. Low energy galactic cosmic rays are important not only for studying the origin and propagation of cosmic rays in general, but also for studying the structure of the Galaxy. Since low energy cosmic rays have a high ionization loss rate, they will contribute to the heating of the interstellar medium and to the nucleosynthesis of light elements by mechanisms which are not yet understood. Although the composition and galactic distribution of the interstellar gas have been studied by radio, IR and high energy γ-ray observations, those of the interstellar dust have not been so well studied. The sharp γ-ray line feature resulting from the deexcitation of excited nuclei within the interstellar dust nuclei should provide a tool for such a study. In addition, γ-rays are suitable for studying certain discrete objects, such as very dense interstellar clouds, because of their high penetrating power when compared with radio and IR radiation.

Gamma-ray line astronomy is at present only in the exploratory phase. Several theoretical studies of line production have been made, and the observability of various lines has been discussed, but few positive detections have been made; an example of a positive detection being the balloon observations by Haymes *et al.* (1975). The major experimental obstacles to the detection of many γ-ray lines are associated with extracting them from the high background of low energy γ rays.

Hayakawa *et al.* (1964) first estimated the line emission intensity, and Fowler *et al.* (1970) the combined line emission intensity, of γ rays with energies greater than 1 MeV, as a possible limitation on the production of Li, Be and B nuclei in the interstellar medium by low energy cosmic rays. Ramaty *et al.* (1970) drew attention to the existence of low energy positrons emitted from unstable β-particle decaying nuclei that result from interactions between low energy cosmic rays and the interstellar medium. They also calculated the flux of the γ-ray line arising from positron annihilation at $0 \cdot 511$ MeV. Rygg and Fishman (1973) examined a large number of nuclear excitations in the 1–2 MeV range, but they considered only the direct excitation of low energy cosmic ray nuclei by interstellar hydrogen and ignored the broadening of excited cosmic ray emission lines. Meneguzzi and Reeves (1975) and Yoshimori (1975) distinguished two line components in the galactic γ-ray spectrum and calculated some individual line fluxes: a broad component resulting from the deexcitation of excited cosmic ray nuclei and a narrow component resulting from the deexcitation of excited interstellar gas nuclei. Recently, Lingenfelter and Ramaty (1976, 1978) have made a detailed evaluation of the production rates of γ-ray lines, making comparisons with the reported γ-ray line fluxes. They also presented a study of the origin and observability of diffuse γ-ray line emission from our Galaxy. In particular, they pointed out the existence of a hitherto unknown component of very narrow lines due to the interstellar dust, and they suggested that measurements of such lines could provide information on the composition, size and spatial distribution of the interstellar dust.

There have been a few observations of galactic γ-ray lines. Haymes *et al.* (1975) first detected γ-ray lines at $0 \cdot 511$, $1 \cdot 2$–$1 \cdot 6$ and $4 \cdot 6$ MeV in the direction of the galactic centre with a balloon-borne NaI(Tl) scintillation detector. Recently, Leventhal *et al.* (1978) confirmed the 0·511 MeV line observation of Haymes *et al.* The traditional NaI(Tl) scintillation detector is now being replaced by the high resolution Ge(Li) detector for the measurement of weak γ-ray lines, the latter having an energy resolution that is some 20–30 times better. The first observation of a cosmic source with a Ge(Li) detector was made in 1967 (Jacobson 1968; Peterson and Jacobson 1970); however, measurements of the Crab Nebula continuum failed to reveal any statistically significant features. Shortly afterwards, a second Ge(Li) detector was flown by balloon to observe the quiet Sun (Womac and Overbeck 1970), but no solar lines were detected although upper limits were established for the 0·511 and 2·2 MeV lines. Since then, large-area Ge(Li) detectors have been flown by balloon (Nakagawa *et al.* 1971; Jacobson *et al.* 1975; Alberhne and Vedrenne 1976; Leventhal *et al.* 1977; Ling *et al.* 1977*a*). The first satellite-borne Ge(Li) detector was launched by the military (Nakano *et al.* 1974), and was used to search for γ-ray lines.

Recently, in addition to the 0·511 MeV positron annihilation line, a 400 keV line from the Crab Nebula has been reported by Leventhal *et al.* (1977). Also a 20 minute burst of γ-ray lines has been reported by Jacobson *et al.* (1978) using balloon-borne Ge(Li) detectors. An interpretation of this exciting event has been given by Lingenfelter *et al.* (1978).

In the present paper, a systematic study is made of the γ-ray lines resulting from interactions between low energy cosmic rays and the interstellar medium. A detailed evaluation of the γ-ray source function is made, and the spectral profiles and galactic distributions of several γ-ray lines are calculated under specified assumptions. In addition, estimates are made of the intensities of the γ-ray lines from the Crab Nebula, the Vela pulsar, ρ Oph and the galactic centre, and these are compared with the measurements obtained from balloon and satellite observations. Finally, the galactic distributions of low energy cosmic rays and the interstellar medium are discussed.

Prediction of γ-ray Lines from Excited Nuclei

γ-ray Source Functions

Theoretical studies of nuclear γ-ray lines resulting from interactions between low energy cosmic rays and the interstellar medium have been made by several investigators. Typical γ-ray deexcitation lines, together with their deexcitation processes, excitation reactions and mean lifetimes, are listed in Table 1.

The γ-ray source function is defined as the rate of production of γ-ray lines at the source per unit of volume, time and solid angle (cm^{-3} s^{-1} sr^{-1}). It is given by

$$S_{ij}(\varepsilon_k, \boldsymbol{r}) = \int \mathrm{d}E\, n_i^{\mathrm{G}}(\boldsymbol{r})\, I_j(E, \boldsymbol{r})\, \sigma_{ij}(E, \varepsilon_k)\,, \tag{1}$$

where $\boldsymbol{r}$ is the position vector from the detector to the source volume element, E is the cosmic ray kinetic energy per nucleon, $n_i^{\mathrm{G}}(\boldsymbol{r})$ is the density of interstellar gas nuclei of type i, $I_j(E, \boldsymbol{r})$ is the differential energy spectrum of cosmic rays of type j, and $\sigma_{ij}(E, \varepsilon_k)$ is the cross section for the interaction between nuclei of types i and j producing an excited nucleus which at rest emits a γ ray of energy ε_k.

Gamma-ray lines are emitted by excited nuclei, whose excitation may result from any of the following three excitation interactions:

$$\textit{Interaction I:} \qquad \mathrm{CR} + \mathrm{ISG} \rightarrow \mathrm{ISG}^*, \tag{2a}$$

$$\textit{Interaction II:} \qquad \mathrm{CR} + \mathrm{ISG} \rightarrow \mathrm{CR}^*, \tag{2b}$$

$$\textit{Interaction III:} \qquad \mathrm{CR} + \mathrm{ISD} \rightarrow \mathrm{ISD}^*, \tag{2c}$$

where CR, ISG and ISD denote cosmic rays, interstellar gas and interstellar dust grains respectively, while an asterisk is used to indicate an excited state. The line widths of the resulting γ rays vary widely, depending on which of the above forms the excited nuclei are in. If the excited nuclei were at rest with respect to the observer, the energy spectrum of the γ-ray emission would be essentially a series of δ functions at energies ε_k. However, because the nuclei are generally in motion with respect to the observer, the observed γ-ray emission will be Doppler shifted, and the γ-ray energy ε will be given by

$$\varepsilon = \varepsilon_k / \{\gamma - (\gamma^2 - 1)^{\frac{1}{2}} \cos\theta\}, \tag{3}$$

where γ is the Lorentz factor of the excited nucleus in the rest frame of the observer and θ is the angle between the direction of the velocity of the excited nucleus and the line of sight.

Table 1. Properties of γ-ray deexcitation lines

E_γ (MeV)	Deexcitation process	Excitation reaction	Mean life (s)
0·847	^{56}Fe*(0·847) → g.s.	^{56}Fe(p, p′)^{56}Fe*(0·847)	$9{\cdot}7 \times 10^{-12}$
1·369	^{24}Mg*(1·369) → g.s.	^{24}Mg(p, p′)^{24}Mg*(1·369)	$1{\cdot}75 \times 10^{-12}$
1·632	^{14}N*(3·945) → ^{14}N*(2·313)	^{14}N(p, p′)^{14}N*(3·945)	$3{\cdot}1 \times 10^{-15}$
1·634	^{20}Ne*(1·634) → g.s.	^{20}Ne(p, p′)^{20}Ne*(1·634)	$1{\cdot}2 \times 10^{-12}$
1·779	^{28}Si*(1·779) → g.s.	^{28}Si(p, p′)^{28}Si*(1·779)	$6{\cdot}8 \times 10^{-13}$
2·313	^{14}N*(2·313) → g.s.	^{14}N(p, p′)^{14}N*(2·313)	$8{\cdot}5 \times 10^{-14}$
4·438	^{12}C*(4·439) → g.s.	^{12}C(p, p′)^{12}C*(4·439)	$5{\cdot}6 \times 10^{-16}$
6·129	^{16}O*(6·131) → g.s.	^{16}O(p, p′)^{16}O*(6·131)	$2{\cdot}4 \times 10^{-11}$
6·917	^{16}O*(6·919) → g.s.	^{16}O(p, p′)^{16}O*(6·919)	$\ll 1{\cdot}2 \times 10^{-14}$

For the excitation interaction I (equation 2a), the observed γ-ray source function $S^{\mathrm{I}}_{ij}(\varepsilon, \boldsymbol{r})$ is given by

$$S^{\mathrm{I}}_{ij}(\varepsilon, \boldsymbol{r}) = \int \mathrm{d}E\, n_i^{\mathrm{G}}(\boldsymbol{r})\, I_j(E, \boldsymbol{r})\, \sigma_{ij}(E, \varepsilon_k)\, f_{ij}(E, \varepsilon), \tag{4}$$

where $f_{ij}(E, \varepsilon)$ is the observed distribution of γ-ray energies for γ rays emitted by excited interstellar gas nuclei of type i which have interacted with cosmic ray nuclei of type j, having an energy E per nucleon (interaction I). If the excited nucleus emits γ rays isotropically (i.e. if γ rays are emitted with equal probability in all directions in the rest frame of the nucleus) then the normalized angular distribution function for them is given by

$$F(\theta')\, \mathrm{d}\theta' = \tfrac{1}{2} \sin\theta'\, \mathrm{d}\theta', \tag{5}$$

where θ' is the transformed value of θ in the rest frame of the nucleus. Since the observed γ-ray energy ε is

$$\varepsilon = \gamma\varepsilon_k\{1+(1-\gamma^{-2}\cos\theta')^{\frac{1}{2}}\}, \tag{6}$$

the observed γ-ray distribution function becomes

$$F(\varepsilon)\,\mathrm{d}\varepsilon = \frac{F(\theta')\,\mathrm{d}\varepsilon}{\mathrm{d}\varepsilon/\mathrm{d}\theta'} = \frac{\mathrm{d}\varepsilon}{2\varepsilon_k(\gamma^2-1)^{\frac{1}{2}}}, \tag{7}$$

where $F(\varepsilon)$ is a uniform distribution between

$$\varepsilon_{\min} = \varepsilon_k\{\gamma-(\gamma^2-1)^{\frac{1}{2}}\} \qquad \text{and} \qquad \varepsilon_{\max} = \varepsilon_k\{\gamma+(\gamma^2-1)^{\frac{1}{2}}\},$$

these being the limiting energies which the excited nucleus may have in order that the γ-ray's energy ε_k may be Doppler shifted to ε. If the probability that the interaction between nuclei of types i and j, having an energy E, results in an excited nucleus with a Lorentz factor of γ at the time of deexcitation is given by $P_{ij}(E,\gamma)$ then the distribution of γ-ray energies $f_{ij}(E,\varepsilon)$ for interaction I takes the form

$$f_{ij}(E,\varepsilon) = \int_{\gamma_{\min}}^{\infty} \mathrm{d}\gamma\; P_{ij}(E,\gamma)/2\varepsilon_k(\gamma^2-1)^{\frac{1}{2}}. \tag{8}$$

The probability $P_{ij}(E,\gamma)$ may be deduced from the experimental results for proton and α-particle inelastic scatterings by several nuclei (Satchler 1955; Levinson and Banerjee 1957; Clegg and Satchler 1961; Baxter *et al.* 1964). The minimum Lorentz factor $\gamma_{\min}$ which the excited nucleus must have in order that the γ-ray energy ε_k be Doppler shifted to ε is given by

$$\gamma_{\min} = \tfrac{1}{2}(\varepsilon\varepsilon_k^{-1}+\varepsilon^{-1}\varepsilon_k). \tag{9}$$

For the excitation interaction II (equation 2b), the observed γ-ray source function $S_{ij}^{\mathrm{II}}(\varepsilon,\boldsymbol{r})$ is similarly given by

$$S_{ij}^{\mathrm{II}}(\varepsilon,\boldsymbol{r}) = \int \mathrm{d}E\; n_i^{\mathrm{G}}(\boldsymbol{r})\,I_j(E,\boldsymbol{r})\,\sigma_{ij}(E,\varepsilon_k)\,g_{ij}(E,\varepsilon), \tag{10}$$

where $g_{ij}(E,\varepsilon)$ is the observed energy distribution for γ rays emitted by excited cosmic ray nuclei of type j which have interacted with interstellar gas nuclei of type i (interaction II). The distribution of γ-ray energies for interaction II takes the form

$$g_{ij}(E,\varepsilon) = \int_{\gamma'_{\min}}^{\infty} \mathrm{d}\gamma'\; Q_{ij}(E,\gamma')/2\varepsilon_k(\gamma^2-1)^{\frac{1}{2}}, \tag{11}$$

where $Q_{ij}(E,\gamma')$ is the probability that the excited cosmic ray nucleus will have a Lorentz factor γ' at the time of deexcitation. The Lorentz factor $\gamma'_{\min}$ is defined in a similar way to $\gamma_{\min}$, while $Q_{ij}(E,\gamma')$ is deduced from the experimental data cited in the previous paragraph.

For the excitation interaction III (equation 2c), the line width depends on the mean lifetime of the level and on the size and composition of the dust grains. Unlike excited nuclei in interstellar gases, which retain most of their recoil energy for times much longer than the lifetimes of the excited levels, excited nuclei in interstellar dust grains may conceivably lose all of their recoil energy before they emit the γ rays. The only line broadening will then be due to the bulk motion of the dust grains. The existence of such a very narrow line component was originally pointed out by Lingenfelter and Ramaty (1977), who discussed its detectability.

The most important γ-ray lines that may be expected to exhibit the very narrow component are those produced by relatively long-lived nuclear levels in relatively abundant heavy nuclei which have large excitation cross sections. Mean lives of suitably long-lived nuclear levels may be found in Table 1. For proton-induced reactions, the excitation cross sections of these levels peak at proton energies of approximately 10 MeV. Nuclear kinematics arguments show that suitable heavy nuclei have recoil energies of a few tens of keV per nucleon. In dust grains of density of about 1 g cm^{-3}, such excited nuclei are stopped by the grains over a time scale of the order of 10^{-12} s (Northcliffe and Schilling 1970; Winterbon 1975). From a comparison of this time scale with the lifetimes of the excited levels (Table 1) we see that the 6·129 MeV line of ^{16}O, the 1·634 MeV line of ^{20}Ne, the 1·369 MeV line of ^{24}Mg, the 1·779 MeV line of ^{28}Si and the 0·847 MeV line of ^{56}Fe should exhibit the very narrow component, but that the 4·438 MeV line of ^{12}C, the 1·632 MeV and 2·313 MeV lines of ^{14}N, and the 6·917 MeV line of ^{16}O should not.

It should be noted that the interstellar dust grains should have linear sizes that are larger than the stopping distances of the recoiling nuclei in order that the γ-ray deexcitation lines exhibit the very narrow component. The average stopping distances are estimated to be about 1 μm. Since observations of the reddening and obscuration of starlight by interstellar dust grains are consistent with an equilibrium grain-size distribution of the form

$$N(a) = N_0 \exp(-a/a_0),$$

where the characteristic radius a_0 is of the order of 0·1 μm (Wickramasinghe 1967; Aannestad and Purcell 1973), it is expected that a significant fraction of the excited nuclei come to rest within the dust grains. However, such a value for a_0 (although appropriate to a diffuse cloud) may not be representative of most grains, since the bulk of the interstellar grain mass may well be contained in dense dark clouds. Finally we note that those nuclei which escape from the dust grains will not contribute to the very narrow line component.

For the excitation interaction III, the observed γ-ray source function $S_{ij}^{\mathrm{III}}(\varepsilon, \boldsymbol{r})$ is given by

$$S_{ij}^{\mathrm{III}}(\varepsilon, \boldsymbol{r}) = \int \mathrm{d}E\, n_i^{\mathrm{D}}(\boldsymbol{r})\, I_j(E, \boldsymbol{r})\, \sigma_{ij}(E, \varepsilon_k)\, h_{ij}(E, \varepsilon), \qquad (12)$$

where $n_i^{\mathrm{D}}(\boldsymbol{r})$ is the density of interstellar dust nuclei of type i and $h_{ij}(E, \varepsilon)$ is the observed energy distribution for γ rays emitted by excited interstellar dust nuclei of type i which have interacted with cosmic ray nuclei of type j (interaction III). In order to determine $h_{ij}(E, \varepsilon)$, the following three factors must be taken into consideration: the stopping time of the excited dust nucleus, the mean lifetime of the excited level and the grain size distribution.

The total γ-ray source function $S_{ij}(\varepsilon, \boldsymbol{r})$ may now be obtained by summation:

$$S_{ij}(\varepsilon, \boldsymbol{r}) = S_{ij}^{\mathrm{I}}(\varepsilon, \boldsymbol{r}) + S_{ij}^{\mathrm{II}}(\varepsilon, \boldsymbol{r}) + S_{ij}^{\mathrm{III}}(\varepsilon, \boldsymbol{r}). \qquad (13)$$

The resulting γ-ray intensity observed along the line of the sight as a function of the galactic coordinates (l, b) is

$$I(\varepsilon; l, b) = \int \mathrm{d}\boldsymbol{r}(l, b)\, S_{ij}(\varepsilon, \boldsymbol{r})\,. \tag{14}$$

In particular, the galactic plane will be a strong source of γ-ray lines. The longitudinal distribution of the γ-ray line intensity in the galactic plane $|b| < 10°$ is given by

$$I(\varepsilon; l, |b| < 10°) = \int_{-10°}^{10°} \mathrm{d}b \int_0^{h \cot b} \mathrm{d}r\, S_{ij}(\varepsilon, s)\,, \tag{15}$$

where h is the half-thickness of the galactic plane, taken to be 100 pc in the inner Galaxy, and s is the galactocentric distance, which is given by

$$s = (s_\odot^2 + r^2 - 2s_\odot r \cos l)^{\frac{1}{2}}\,, \tag{16}$$

where $s_\odot$ is the distance between the galactic centre and the solar system.

Excitation Cross Sections

The energy-dependent excitation cross sections used in the present calculations are taken from measurements of the excitation of the 4·439 MeV level in ^{12}C (Reich *et al.* 1956; Strauch and Titus 1956; Peele 1957; Tyren and Maris 1957; Nagahara 1961), of the 6·131 MeV level in ^{16}O (Hornyak and Sherr 1955; Tyren and Maris 1957; Kobayashi 1960) and of the 2·313 and 3·945 MeV levels in ^{14}N and the 1·634 MeV level in ^{20}Ne (Oda *et al.* 1960). In addition, the review papers by Audouze *et al.* (1967), Lingenfelter and Ramaty (1967) and Ramaty *et al.* (1975), together with the cross sections measured by Mitchel and Ophel (1964) and Zobel *et al.* (1968), are referred to.

Galactic Distribution of Interstellar Medium

The distribution of the interstellar gas in the galactic plane has been extensively studied. The picture that has emerged is rapidly changing and has important implications for galactic structure theory. Earlier studies of the interstellar gas distribution depended on information obtained from diffuse optical light, the radio continuum and the 21 cm atomic hydrogen line. Recently, the large-scale distribution of molecular hydrogen in the galactic plane has been inferred from galactic surveys of the 2·6 mm radio line emission ($J = 1 \rightarrow 0$ transition) of CO molecules (Burton *et al.* 1975; Scoville and Solomon 1975; Burton and Gordon 1976; Gordon and Burton 1976) and of high energy γ-rays (Fichtel *et al.* 1975; Bennett *et al.* 1977). Solomon and Stecker (1974) noted that the galactic distribution of high energy γ-ray emission bears a strong similarity to the distribution of molecular clouds within the Galaxy. This similarity, coupled with the lack of sufficient gas in atomic form to explain the high energy γ-ray observations, led to the supposition that molecular hydrogen is far more abundant in the inner Galaxy than atomic hydrogen, and that molecular hydrogen plays the major role in producing galactic high energy γ rays. The radial distribution of interstellar atomic and molecular hydrogen has been described by Gordon and Burton (1976), who found that the number density of molecular hydrogen is 2 cm^{-3} in the 5–6 kpc region and that it decreases dramatically for distances less than 4 kpc and also within the outer Galaxy. At 10 kpc, at least half of the interstellar gas is probably in atomic form, and there is a negligible amount of molecular hydrogen in the outer regions of the Galaxy. The abundances of elements in the interstellar gas are assumed here to be identical with those in the solar system and are taken from the review paper by Cameron (1973).

The distribution of ionized hydrogen in the galactic plane has been studied by detecting the H166α and H109α radio recombination lines, and these distributions have been compared with that of the neutral hydrogen atom (Lockman 1976). The density ratio of ionized to neutral hydrogen atoms is less than 10^{-2}, and there is no simple connection between the radial distribution of neutral and ionized hydrogen. In the present calculations, the distribution of ionized hydrogen is not taken into consideration.

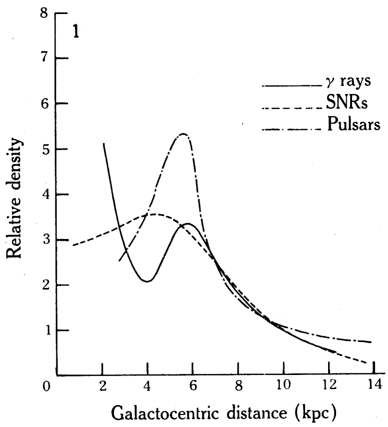
In addition to the interstellar gas, there exists the dust component of the interstellar medium. That the diffuse IR flux from the galactic plane is due to thermal radiation by dust particles was proposed by Stein (1966) and Pipher (1973). Recent IR observations have provided new information on the galactic distribution and the composition of the dust. Hayakawa *et al.* (1976) found a positive correlation between the 2·4 μm IR flux and CO emission on a galactic scale, while Fazio and Stecker (1976) predicted a similar galactic distribution for the diffuse far-IR (100–300 μm) emission originating in molecular clouds. In the present calculations it is assumed that the ratio of total gas to dust is roughly the same as that in the more diffuse atomic clouds (Ryter *et al.* 1975) and that the physical properties of the dust are roughly uniform throughout the Galaxy. The mass of dust is assumed to be 10^{-2} of the total mass of the interstellar medium. The elemental abundances in the dust, taken from Morton (1975), indicate that the matter in the dust is composed predominantly of heavier elements.

Galactic Distribution of Cosmic Rays

The galactic distribution of cosmic rays can be predicted from the distribution of the products that originate from interactions between cosmic rays and the ambient medium and ambient radiation field, as well as from their source distribution. It is well known that the galactic distribution of cosmic ray electrons far from the solar system should be studied by observing the celestial nonthermal background radio emission which is due to synchrotron radiation from relativistic electrons gyrating in the interstellar magnetic field. The radial distribution of cosmic ray electrons in the galactic plane predicted from radio emission observations at 408 MHz is fairly uniform within 8 kpc of the galactic centre but decreases rapidly beyond 8 kpc (Baldwin 1976). Although Paul *et al.* (1976) have suggested that the density of cosmic ray nuclei is proportional to the electron density throughout the Galaxy, such proportionality has not been confirmed.

The corresponding method of predicting the galactic distribution of cosmic ray nuclei is to observe high energy π^0 decay γ rays resulting from interactions between cosmic rays and the interstellar medium. Since the radial distribution of interstellar hydrogen in the galactic plane has been fairly well deduced, the radial distribution of cosmic ray nuclei can be predicted. The predicted distribution of cosmic ray nuclei, normalized to unity at 10 kpc (i.e. at the distance of the solar system), is illustrated in Fig. 1.

Another method of predicting the galactic distribution of cosmic ray nuclei is to study that of the cosmic ray sources (i.e. supernova explosions). We therefore may assume that there exists a strong correlation between the galactic distribution of supernova remnants and pulsars on the one hand and cosmic rays on the other.



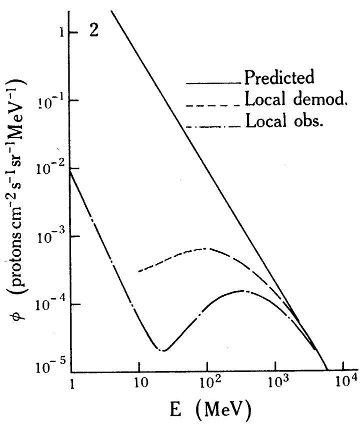


Fig. 1 (*left*). Comparison of predicted forms for the radial distribution of cosmic ray nuclei within the Galaxy. The forms correspond to the observed distributions of: (full curve) high energy γ rays; (dashed curve) supernova remnants; (dot–dash curve) pulsars. The full curve is here taken to be representative of cosmic rays in general.

Fig. 2 (*right*). Comparison of predicted and experimental forms for the energy spectrum of interstellar cosmic ray protons, showing the dependence of the proton flux density ϕ upon proton energy E. The forms correspond to: (full curve) theoretical proton spectrum based on considerations described in the text; (dashed curve) the observed local proton spectrum corrected according to the solar modulation theory of Urch and Gleeson (1973); (dot–dash) curve the observed local proton spectrum. The full curve is here taken to be representative of cosmic rays in general.

Table 2. Elementary abundances for interstellar gas and cosmic ray nuclei

Element	Relative abundance in interstellar gas	Relative abundance in cosmic rays	Element	Relative abundance in interstellar gas	Relative abundance in cosmic rays
H	$1\cdot00$	$1\cdot00$	Ne	$1\cdot08\times10^{-4}$	$2\cdot66\times10^{-4}$
C	$3\cdot71\times10^{-4}$	$1\cdot72\times10^{-3}$	Mg	$3\cdot37\times10^{-5}$	$3\cdot30\times10^{-4}$
N	$1\cdot18\times10^{-4}$	$4\cdot66\times10^{-4}$	Si	$3\cdot14\times10^{-5}$	$2\cdot30\times10^{-4}$
O	$6\cdot76\times10^{-4}$	$1\cdot48\times10^{-3}$	Fe	$2\cdot61\times10^{-5}$	$1\cdot16\times10^{-4}$

The radial distribution of supernova remnants in the galactic plane has been studied by Pimley (1975) and that of pulsars by Seiradakis (1976). Relative distributions of supernova remnants and pulsars are also included in Fig. 1, their densities also being normalized to unity at 10 kpc. The radial distribution for supernova remnants is probably unreliable near the galactic centre (where they are obscured by the prevailing strong optical and radio background) and it should be regarded as a lower limit there. This conclusion is supported by McCarthy's (1973) observation that the distribution of supernovae increases rapidly for radial distances less than 3 kpc from the galactic centre. The radial distribution of pulsars also shows a marked decrease away from the galactic centre. Although no pulsar has been

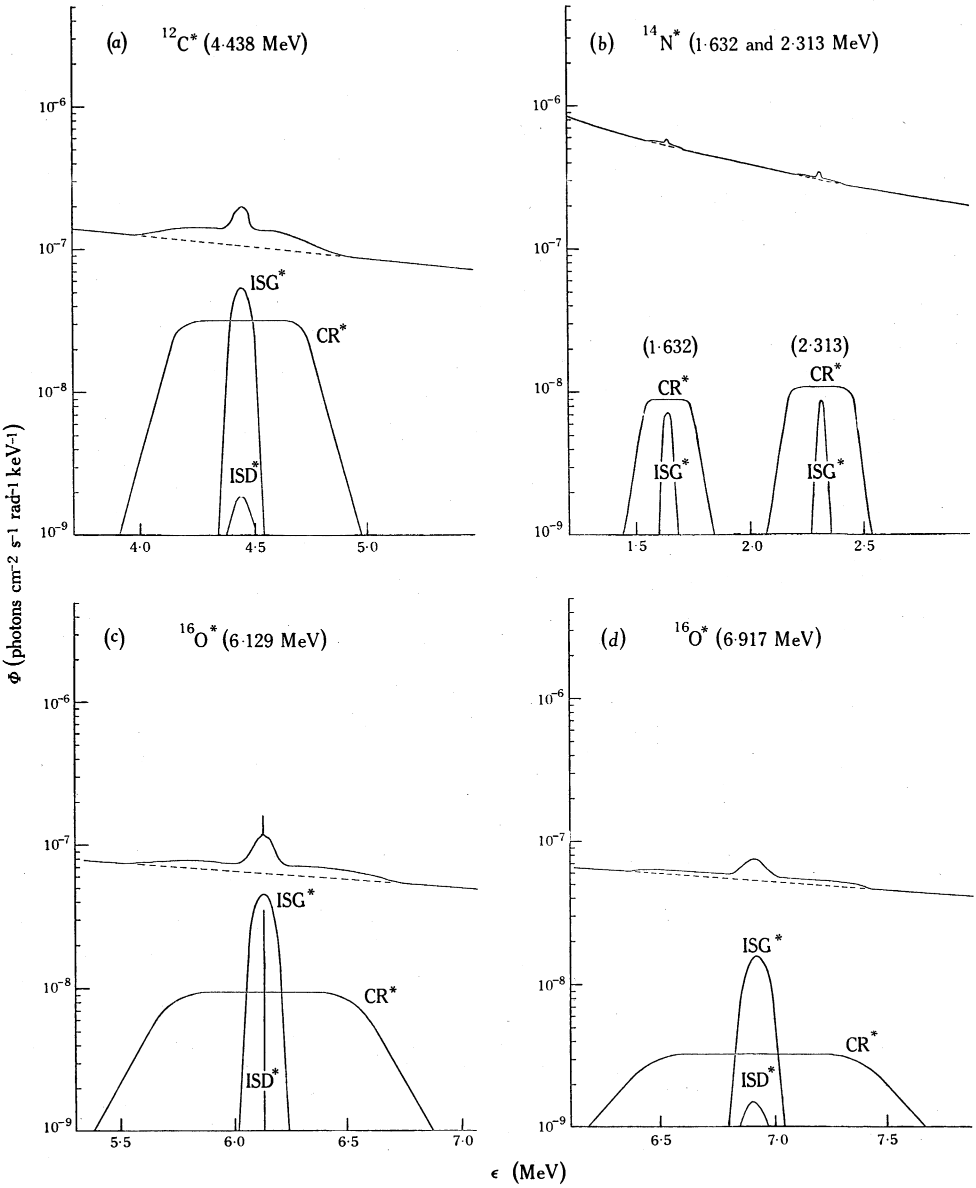
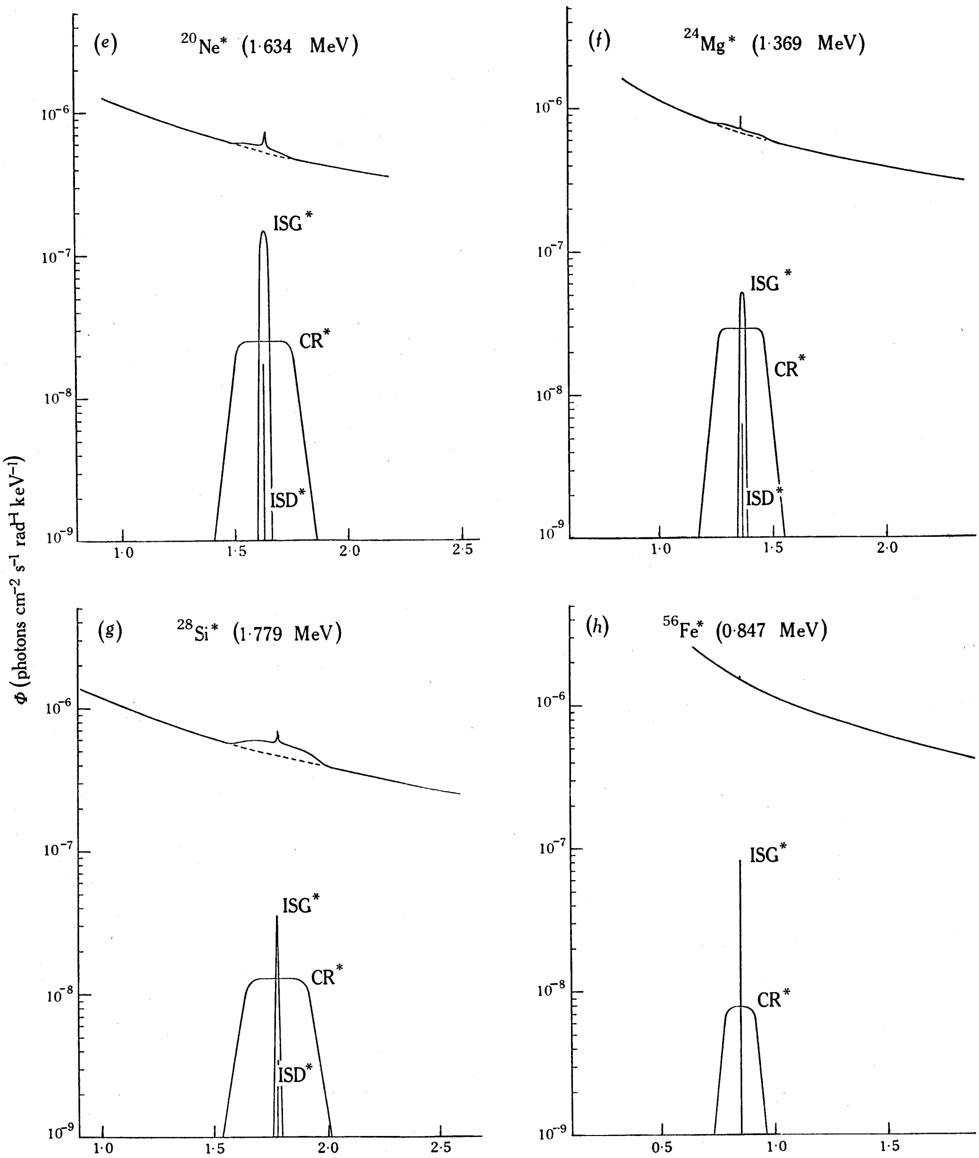


Fig. 3. Calculated γ-ray line spectral profiles for γ-ray lines arising from deexcitation of the indicated nuclei in the direction of the galactic centre, showing the dependence of the photon flux density Φ upon photon energy ε. Individual line components are shown singly, labelled according to the location of the excited nucleus: ISG*, interstellar gas; ISD*, interstellar dust; CR*, cosmic rays. The composite line profile is also shown superposed on the diffuse γ-ray background.

observed closer to the galactic centre than 3 kpc, the possibility that the pulsar density is also quite high there cannot be excluded. In addition, there seem to be indications of the presence of a galactic spiral structure in the pulsar distribution.

The three deduced distributions for cosmic rays shown in Fig. 1 are not inconsistent within the experimental errors if the densities of supernova remnants and



Figs 3*e*–3*h* (*see caption opposite*)

pulsars are assumed to increase rapidly near the galactic centre. For the present calculations, the galactic distribution of cosmic rays deduced from the observation of high energy γ rays is employed.

Energy Spectrum of Interstellar Low Energy Cosmic Rays

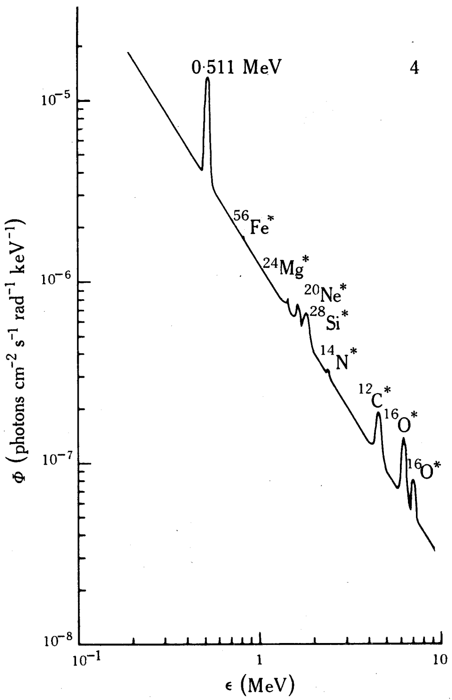
The energy spectrum of low energy cosmic rays observed in the vicinity of the Earth seems to be significantly different from that which holds in interstellar space, owing to the effects of solar modulation. Since the solar modulation mechanism is not completely understood, the energy spectrum of low energy cosmic rays in interstellar space cannot be readily deduced.

The interstellar energy spectrum for cosmic ray protons may be derived from considerations regarding the energy density of cosmic rays, the ionization rate of interstellar hydrogen and the abundance ratios of stellar light elements (see Yoshimori 1975). The resulting energy spectrum is shown in Fig. 2 (full curve). The proton spectrum observed near the Earth (dot–dash curve) and that deduced from the solar modulation theory (dashed curve) of Urch and Gleeson (1973) are compared with it in Fig. 2 also. We here assume that the energy spectrum for interstellar cosmic ray heavy nuclei follows that for the protons, and we take the abundance ratios of cosmic ray nuclei from the observations of Garcia-Munoz *et al.* (1975). The abundance ratios of interstellar gas nuclei (Cameron 1973) and cosmic ray nuclei (Garcia-Munoz *et al.* 1975) used in the present calculations are shown in Table 2, where the abundances are expressed relative to that for hydrogen.

Spectral Profiles and Galactic Distribution of γ-ray Line Emissions

The calculated γ-ray line profiles from deexcitation of cosmic ray nuclei, interstellar gas nuclei and interstellar dust nuclei are shown in Figs 3*a*–3*h*, together with their superposition on the diffuse γ-ray background. The spectral profiles are for: (*a*) the 4·438 MeV line from $^{12}C^*$, (*b*) the 1·632 and 2·313 MeV lines from $^{14}N^*$, (*c*) the 6·129 and (*d*) the 6·917 MeV lines from $^{16}O^*$, (*e*) the 1·634 MeV line from $^{20}Ne^*$, (*f*) the 1·369 MeV line from $^{24}Mg^*$, (*g*) the 1·779 MeV line from $^{28}Si^*$ and (*h*) the 0·847 MeV line from $^{56}Fe^*$ emitted from the galactic centre direction ($|l| < 30°$). Although the very narrow line cannot be emitted for the 4·438, 1·632, 2·313 and 6·917 MeV lines arising from the deexcitation of levels with mean lives $\leqslant 10^{-12}$ s (Figs 3*a*, 3*b* and 3*d*), the other profiles show the very narrow line emission of a few keV width which results from excited interstellar dust nuclei, while all profiles show the relatively narrow emission of $\sim$100 keV width which results from excited interstellar gas nuclei, and the broad emission of $\sim$500 keV width which results from excited cosmic ray nuclei. The widths of the very narrow lines are assumed to be 3 keV (FWHM). All of the γ-ray spectral profiles are shown collectively in Fig. 4, superposed on the diffuse γ-ray background. Since the intensities of the γ-ray lines are much smaller than that of the diffuse γ-ray background, a precise observation is needed to detect them. The strongest line is the 4·438 MeV line from $^{12}C^*$ whose intensity is estimated to be $1 \cdot 4 \times 10^{-5}$ photons $cm^{-2} s^{-1} rad^{-1}$.

Fig. 5 shows the calculated longitude distribution for the 4·438 MeV line emission from excited interstellar dust and gas $^{12}C^*$ nuclei in the galactic plane ($|b| < 10°$). The corresponding longitude distribution for the 4·438 MeV line emission from excited cosmic ray $^{12}C^*$ nuclei is not included because of its broad spectral profile. The calculated longitude distributions for the other γ-ray lines follow a similar distribution to that for the 4·438 MeV line. The rapid increase in intensity near $l = 40°$ (apparent in Fig. 5) can be explained by the enhancements in the distributions of interstellar hydrogen and cosmic ray nuclei in the 5–6 kpc region. The high intensity peak toward the galactic centre results from the increased cosmic ray and interstellar medium densities there. The longitude distribution of high energy γ rays observed by the SAS-2 satellite is included in Fig. 5 also for comparison, and is seen to be in rough agreement with the calculated distribution.



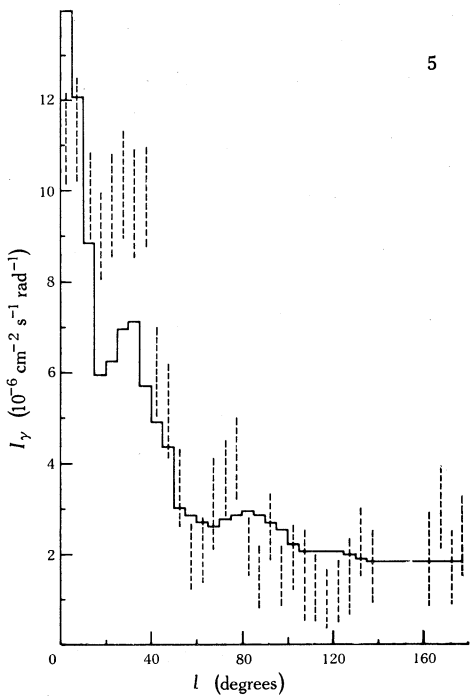


Fig. 4 (*left*). Calculated γ-ray spectrum from the galactic centre direction, showing the dependence of the photon flux Φ upon photon energy ε. Emission lines from the deexcitation of the indicated nuclei, together with the positron annihilation line, are superposed on the continuum γ-ray background.

Fig. 5 (*right*). Calculated longitude distribution of the strongest γ-ray deexcitation line, the 4·438 MeV line from excited interstellar gas and dust $^{12}C^*$ nuclei in the galactic plane ($|b| < 10°$), showing the dependence of the γ-ray line intensity I_γ on galactic longitude l. The high energy γ-ray data (vertical bars) observed by the SAS-2 satellite are included for comparison.

0·511 MeV Positron Annihilation Line

Cosmic ray positrons are produced by two processes: the decay of π^+ resulting from interactions between high energy cosmic ray protons and interstellar hydrogen and the β-particle decay of unstable C, N and O nuclei resulting from nuclear interactions between low energy cosmic rays and the interstellar gas. Since interactions producing unstable C, N and O nuclei involve relatively low threshold energies of the order of 10 MeV, the β-decay positrons will dominate the π^+-decay positrons. Moreover, the β-decay positrons have maximum energies of the order of 1 MeV, whereas the spectrum of the π^+-decay positrons has a maximum at about 35 MeV and decreases rapidly toward lower energies. Hence, it is much more likely for β-decay positrons to stop and annihilate within the Galaxy to produce the 0·511 MeV γ rays than for the π^+-decay positrons. Typical reactions leading to the production of β-particle emitting nuclei, together with their decay modes and maximum positron energies, are listed in Table 3.

The positron production from C, N and O β-particle decaying nuclei has been calculated by Verma (1969) and Ramaty *et al.* (1970). However, the galactic distributions of the cosmic ray nuclei and the interstellar medium were not taken into consideration in their calculations.

Table 3. Properties of β-particle emitting reactions

Production reaction	Decay mode	Maximum positron energy (MeV)
$^{12}C(p, pn)^{11}C$, $^{14}N(p, 2p2n)^{11}C$, $^{16}O(p, 3p3n)^{11}C$	$^{11}C \rightarrow {}^{11}B + \beta^+ + \nu$	0·97
$^{14}N(p, pn)^{13}N$, $^{16}O(p, 2p2n)^{13}N$	$^{13}N \rightarrow {}^{13}C + \beta^+ + \nu$	1·19
$^{14}N(p, n)^{14}O$	$^{14}O \rightarrow {}^{14}N + \beta^+ + \nu$	1·86
$^{16}O(p, pn)^{15}O$	$^{15}O \rightarrow {}^{15}N + \beta^+ + \nu$	1·73

The source function $S_b(E_b, \boldsymbol{r})$ for β-particle emitting nuclei is given by

$$S_b(E_b, \boldsymbol{r}) = \sum_{ij} \int dE \, n_i(\boldsymbol{r}) \, I_j(E, \boldsymbol{r}) \, \sigma_{ij}(E) \, k_{ij}(E, E_b), \tag{17}$$

where $\boldsymbol{r}$, $n_i(\boldsymbol{r})$ and $I_j(E, \boldsymbol{r})$ are defined in accordance with our above-established practice, $\sigma_{ij}(E)$ is the interaction cross section for production of a β-particle emitting nucleus, and $k_{ij}(E, E_b)$ is the distribution function for production of a β-particle emitting nucleus with energy E_b given an interaction energy E. Since ^{11}C, ^{13}N, ^{14}O and ^{15}O contribute most significantly to positron production, only nuclear reactions for production of these β-particle emitting nuclei are taken into consideration here. The relevant cross sections are taken from Audouze *et al.* (1967), Lingenfelter and Ramaty (1967) and Ramaty *et al.* (1975). The distribution function $k_{ij}(E, E_b)$ is in general unknown. It is assumed that the kinetic energy per nucleon is equally distributed among all of the secondary nuclei produced, so that we have

$$k_{ij}(E, E_b) = E_b - (A_i E - Q_{ij})/(A_i + A_j), \tag{18}$$

where A_i and A_j are the mass numbers of the incident and target nuclei respectively, and Q_{ij} is the Q value for the nuclear reaction. Since the lifetimes of C, N and O β-particle emitting nuclei are short and the angular distribution of positrons in the rest frame of β-particle emitting nuclei is nearly isotropic, the Lorentz factor distribution of positrons in the galactic rest frame can be obtained from the source function by taking into account the kinematics of the decay (Stecker 1971).

It is assumed that positrons in the interstellar medium have reached a quasi-equilibrium condition by leakage from the Galaxy, electron annihilation and energy loss from ionization. Since ionization loss predominates for interstellar positrons resulting from β decay, energy losses from bremsstrahlung and Compton collisions may be neglected. The total number $S_T(\boldsymbol{r})$ of positrons annihilating at or near rest per cm^3 is given by

$$S_T(\boldsymbol{r}) = \int_1^\infty d\gamma \, S_{\beta^+}(\gamma, \boldsymbol{r}) \exp\left\{ - \int_1^\gamma \frac{d\gamma}{d\gamma/dt} \left(\frac{1}{\tau_a} + \frac{1}{\tau_L} \right) \right\}, \tag{19}$$

where γ is the Lorentz factor for a positron in the galactic rest frame, $S_{\beta^+}(\gamma, \boldsymbol{r})$ is the Lorentz factor distribution for positrons, $d\gamma/dt$ is the energy loss rate from ionization in hydrogen, $\tau_a(\gamma)$ is the annihilation time and $\tau_L(\gamma)$ is the leakage time. Values for $d\gamma/dt$, $\tau_a(\gamma)$ and $\tau_L(\gamma)$ were obtained from Stecker (1971).

Positrons stopping in the interstellar gas can in principle either annihilate from the free state an electron bound in an interstellar gas atom or first capture an electron to form a hydrogen-like positronium atom prior to annihilation. Stecker (1971) and Leventhal (1973) pointed out that positronium formation was important in astrophysics. In fact the cross section for free annihilation with the emission of two antiparallel 0·511 MeV γ rays is about seven orders of magnitude smaller than the positronium formation cross section, and hence free annihilation may be neglected. Positronium may be formed with its component spins aligned antiparallel (the singlet-para state with total spin 0) or with its component spins aligned parallel (the triplet-ortho state with total spin 1). On a statistical basis, the ortho state is expected to be formed three times as often as the singlet state. Singlet positronium annihilates in $1 \cdot 3 \times 10^{-10}$ s and yields two antiparallel 0·511 MeV γ rays, while triplet positronium annihilates in $1 \cdot 4 \times 10^{-7}$ s and yields three γ rays in a plane. The triplet positronium annihilation does not form a line spectral profile but instead forms a continuum spectrum below 0·511 MeV. Hence, on the average, only one 0·511 MeV γ ray is produced for every two positrons that annihilate, and so the intensity of 0·511 MeV γ rays observed along the line of sight as a function of the galactic coordinates is given by

$$I_{0\cdot 511}(l, b) = \tfrac{1}{2} \int d\boldsymbol{r}(l, b)\, S_T(\boldsymbol{r}) \,. \tag{20}$$

The calculated longitudinal distribution of 0·511 MeV γ-ray line emission in the galactic plane is similar to that for nuclear deexcitation line emission (as exemplified in Fig. 5 by the 4·438 MeV line from $^{12}C^*$). Also, the intensity of the 0·511 MeV line in the galactic centre direction, $2 \cdot 4 \times 10^{-5}$ photons $cm^{-2}\, s^{-1}\, rad^{-1}$, is comparable with those for the 4·439 MeV line and the diffuse γ-ray background. The width of the 0·511 MeV line is sharp.

γ-ray Lines from Supernova Remnants and Dense Interstellar Clouds

The SAS-2 and COS-B satellites have detected strongly excessive high energy γ-ray emission from 13 discrete sources, which have been identified with the Crab Nebula, the Vela pulsar and other active astronomical objects. In these γ-ray sources, low energy cosmic rays may also exist at appreciably high densities and, in such cases, a strong γ-ray line emission is to be expected from them.

The γ-ray line intensity from a discrete source is given by

$$I_i = (1/4\pi R^2) \int J_p(E)\, n_i\, V\, \sigma(E)\, dE \,, \tag{21}$$

where R is the distance from the discrete source to the Earth, $J_p(E)$ is the energy spectrum of cosmic ray protons in the confinement region of the source, n_i is the density of type i target nucleus, V is the volume of the cosmic ray confinement region and $\sigma(E)$ is the cross section for production of γ-ray lines. The spectral distribution $J_p(E)$ is assumed to be identical with the interstellar proton spectrum of power law type (shown in Fig. 2), while the abundance ratios of target nuclei are assumed to be identical to those in the solar system. In the present calculations, the broad component resulting from deexcitation of cosmic ray nuclei is excluded from the γ-ray line component.

Supernovae have long been considered as leading candidates for the origin of cosmic rays. Consequently we assume that the cosmic ray densities associated with supernova remnants are appreciably higher than those found in the interstellar medium. If it is assumed that an energy W of the order of 10^{50}–10^{51} erg is released at a supernova explosion in the form of cosmic ray nuclei, the energy density of cosmic ray nuclei in the resulting supernova remnant would be W/V. The corresponding energy spectrum $J_p^{SNR}(E)$ of cosmic ray protons would be

$$J_p^{SNR}(E) = (W/V)w^{-1} J_p^{IS}(E), \tag{22}$$

where $J_p^{IS}(E)$ is the interstellar cosmic ray proton spectrum shown in Fig. 2 and w is the energy density of interstellar cosmic rays, which is of the order of 10^{-12} erg cm^{-3}.

The intensities of the γ-ray lines from typical supernova remnants such as the Crab Nebula and the Vela pulsar can now be estimated. Radio, optical, X-ray and γ-ray emissions from these supernova remnants have been observed, and the total cosmic ray energy, the hydrogen density and the volume of the cosmic ray confinement region can be deduced from these data. The Crab Nebula and Vela pulsar lie at a distance of 2 kpc and 500 pc from the Earth respectively. The observations indicate that the Crab Nebula has $W \approx 10^{50}$ erg and $n_H \approx 10$ cm^{-3} (see e.g. Apparao 1973) and that the Vela pulsar has $W \approx 10^{51}$ erg and $n_H \approx 2$ cm^{-3} (see e.g. Ramaty *et al.* 1971). The predominant γ-ray lines to be expected from these sources are those arising from positron annihilation (0·511 MeV) and the deexcitation of $^{12}C^*$ (4·439 MeV), $^{16}O^*$ (6·131 MeV) and $^{20}Ne^*$ (1·634 MeV). Their estimated fluxes are given in Table 4, which shows that the fluxes of γ-ray lines emitted from the Crab Nebula are expected to be of the order of 10^{-7} photons cm^{-2} s^{-1} and those from the Vela pulsar to be of the order of 10^{-6} photons cm^{-2} s^{-1}.

Table 4. Predicted intensities of γ-ray lines from discrete sources

E_γ (MeV)	Estimated line flux (photons cm^{-2} s^{-1}) from: Crab Nebula	Vela pulsar	ρ Oph	galactic centre
0·511	$5 \cdot 0 \times 10^{-7}$	$1 \cdot 6 \times 10^{-6}$	$1 \cdot 5 \times 10^{-8}$	$3 \cdot 0 \times 10^{-5}$
4·439 ($^{12}C^*$)	$2 \cdot 4 \times 10^{-7}$	$7 \cdot 7 \times 10^{-7}$	$7 \cdot 3 \times 10^{-9}$	$1 \cdot 4 \times 10^{-5}$
6·131 ($^{16}O^*$)	$2 \cdot 2 \times 10^{-7}$	$7 \cdot 0 \times 10^{-7}$	$6 \cdot 8 \times 10^{-9}$	$1 \cdot 3 \times 10^{-5}$
1·634 ($^{20}Ne^*$)	$1 \cdot 4 \times 10^{-7}$	$4 \cdot 5 \times 10^{-7}$	$4 \cdot 4 \times 10^{-9}$	$8 \cdot 4 \times 10^{-6}$

Dense interstellar clouds may also prove to be detectable localized sources of γ-ray line emission arising from interactions between low energy cosmic rays and the vast amount of gas they contain. Recently, near- and far-IR observations of several dense dark clouds have yielded new information on their densities, their sizes and their celestial positions. These observations indicate that many dark clouds are more massive than was previously believed, owing to the presence of large amounts of heretofore unobservable molecular hydrogen.

The dark cloud south of the star ρ Oph is perhaps the largest and densest molecular cloud in the vicinity of the solar system. It is also one of the best-observed clouds at IR wavelengths (Vrba *et al.* 1975; Fazio *et al.* 1976) and in microwave line emission (Encrenaz *et al.* 1975). These observations indicate that the cloud's density is $\sim 10^4\ \mathrm{cm}^{-3}$, the extent of the cloud is ~ 3 kpc, its total mass is $\sim 4\times 10^3\ M_\odot$ and the distance to the cloud is ~ 190 pc. The fluxes of γ-ray lines from such a cloud are estimated to be of the order of 10^{-8} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, if the energy density of cosmic rays is assumed to be $10^{-12}\ \mathrm{erg\,cm}^{-3}$. Such low intensities cannot be detected with any presently available apparatus. However, the possibility that an appreciable flux of high intensity cosmic rays may exist in the dense cloud is suggested by the COS-B data (Strong 1977). If that is the case, this dark cloud also becomes a strong candidate for a source of eventually detectable γ-ray lines.

Recent observations of molecular lines from OH, H_2CO and CO have revealed the presence of numerous massive gas clouds in the immediate vicinity of the galactic centre. A group of these molecular clouds forms a ring around the galactic centre of radius ~ 270 pc, which moves radially outwards. The hydrogen density in this cloud ring must be of the order of 10^3–$10^4\ \mathrm{cm}^{-3}$ to be able to excite the observed CO and NH_3 emission lines. The total mass of the cloud ring is estimated to be between $10^8\ M_\odot$ and $10^9\ M_\odot$, corresponding to a volume of $\sim 10^{62}\ \mathrm{cm}^3$. This should be compared with estimates of the total mass of gas contained within the Galaxy, namely $\sim 4\times 10^9\ M_\odot$ (Gordon and Burton 1976). The cosmic ray proton intensity in the cloud ring is deduced to be some 10–10^2 times higher than that found in the vicinity of the solar system (the distance of the solar system from the galactic centre is ~ 10 kpc). The γ-ray line fluxes expected from the cloud ring are here estimated to be of the order of 10^{-5} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, as shown in Table 4. Lingenfelter and Ramaty (1976) adopted a cosmic ray intensity that was 30 times larger than this in order to explain the 4·438 MeV line intensity observed by Haymes *et al.* (1975).

Discussion

We now consider the above-made predictions of γ-ray line emission intensities from various proposed sources in relation to the available experimental data. Trombka *et al.* (1973), using NaI(Tl) scintillation detectors on board Apollos-15, -16 and -17, observed the diffuse γ-ray background in the energy range 0·2–20 MeV, and obtained upper limits for the intensities of γ-ray lines from positron annihilation (0·511 MeV) and from the nuclear decay of $^{12}C^*$ (4·439 MeV) of $(3\cdot 0\pm 1\cdot 5)\times 10^{-3}$ and $(4\cdot 4\pm 1\cdot 4)\times 10^{-4}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ respectively. Ling *et al.* (1977*b*), using a balloon-borne Ge(Li) detector, obtained an upper limit for the 0·511 MeV line intensity of $9\cdot 2\times 10^{-3}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ in the galactic anticentre direction. Yoshimori *et al.* (1979, present issue pp. 375–82), also using a balloon-borne Ge(Li) detector, made long-duration measurements on γ-ray lines from the galactic plane between longitudes 50° and 200°, and obtained upper limits of $4\cdot 0\times 10^{-3}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{rad}^{-1}$ for the intensity of the 0·511 MeV line and values of the order of 10^{-3} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{rad}^{-1}$ for the intensities of the following nuclear γ-ray lines: $^{14}N^*$ (1·632 MeV), $^{20}Ne^*$ (1·634 MeV), $^{24}Mg^*$ (1·369 MeV), $^{28}Si^*$ (1·779 MeV) and $^{56}Fe^*$ (0·847 MeV). Walraven and Haymes (1976) reported the possible detection of a 1·16 MeV γ-ray line at a flux level of $(3\cdot 4\pm 1\cdot 5)\times 10^{-3}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ from a point in the galactic plane (l = 345°, b = 5°). Imhof and Nakano (1977) made a galactic survey with the first satellite-borne Ge(Li) detector and demonstrated the possible presence of γ-ray line emission at 1·116 and 1·369 MeV from the galactic plane over the galactic longitude interval 255°–328°, having upper limits of $(1\cdot52\pm0\cdot49)\times10^{-2}$ and $(1\cdot4\pm0\cdot49)\times10^{-2}$ photons $cm^{-2}\,s^{-1}$ respectively. However, better statistics are needed to firmly establish the existence of these lines.

The above observations provide upper limits to the 0·511 MeV and $^{12}C^*$ (4·439 MeV) line intensities in regions away from the galactic centre. However, the calculated intensities for these lines in regions away from the galactic centre are 4×10^{-6} and 2×10^{-6} photons $cm^{-2}\,s^{-1}\,sr^{-1}$ respectively, and are thus two to three orders of magnitude smaller than the observed upper limits. This is probably due to the high background flux of both atmospheric γ rays and secondary γ rays produced by cosmic ray interactions in the detector and surrounding material. Since the intensity of the diffuse γ-ray background observed by Trombka *et al.* (1973) is 4×10^{-5} photons $cm^{-2}\,s^{-1}\,sr^{-1}\,keV^{-1}$ at 0·511 MeV and 1×10^{-6} photons $cm^{-2}\,s^{-1}\,sr^{-1}\,keV^{-1}$ at 4·438 MeV, these background intensities are one order of magnitude larger than the calculated 0·511 MeV and 4·438 MeV line intensities. Thus a 3σ deviation of the 0·511 MeV line intensity above the diffuse background will be detected if γ-ray line observations using a 100 cm^2 area Ge(Li) detector are made for 160 hours.

Regarding γ-ray lines from the galactic centre direction, we have the balloon-borne NaI(Tl) scintillation detector measurements by Haymes *et al.* (1975) for the 0·511 and 4·438 MeV line fluxes of $(8\cdot0\pm2\cdot3)\times10^{-4}$ and $(9\cdot5\pm2\cdot7)\times10^{-4}$ photons $cm^{-2}\,s^{-1}$. In addition, Haymes *et al.* found a group of γ-ray lines in the energy range 1·2–2·0 MeV with fluxes of $(2\cdot6\pm0\cdot6)\times10^{-3}$ photons $cm^{-2}\,s^{-1}$. These lines could be associated with a combination of the 1·369 MeV line from $^{24}Mg^*$, the 1·634 MeV line from $^{20}Ne^*$ and the 1·779 MeV line from $^{28}Si^*$. The data of Haymes *et al.* indicate that the energy production rate is 8×10^{36} erg s^{-1} for the 0·511 MeV line and 7×10^{37} erg s^{-1} for the 4·438 MeV line in the galactic centre region. The energy production rate for the 4·438 MeV line is enormously large, and is comparable with the radio emission rate from the galactic centre. Recently, Leventhal *et al.* (1978), using a balloon-borne Ge(Li) detector, observed the 0·511 MeV line in the galactic centre direction to have a flux of $(1\cdot21\pm0\cdot22)\times10^{-3}$ photons $cm^{-2}\,s^{-1}$. Measurements of the 2·2 and 4·4 MeV lines in the galactic centre direction, reported from the HEAO-1 observation, confirm the presence of low energy cosmic rays of appreciably high intensity in the galactic centre region.

The calculated fluxes of the 0·511 MeV and 4·438 MeV lines from the dense massive cloud in the immediate vicinity of the galactic centre are $3\cdot0\times10^{-5}$ and $1\cdot4\times10^{-5}$ photons $cm^{-2}\,s^{-1}$ respectively. These fluxes are at least one order of magnitude smaller than those observed by Haymes *et al.* (1975). Their observation indicates that the cosmic ray energy density in the galactic centre is 10^{-10} erg cm^{-3}, which is two orders of magnitude larger than that in the vicinity of the solar system.

For γ-ray lines from supernova remnants, we have experimental upper limits to the 0·511 MeV line flux in the Crab Nebula of $1\cdot1\times10^{-3}$ and $4\cdot6\times10^{-3}$ photons $cm^{-2}\,s^{-1}$ obtained by Walraven *et al.* (1975) and Ling *et al.* (1977*a*) respectively. Leventhal *et al.* (1977) reported evidence for a line feature at 400 keV. This line appears to be a gravitationally redshifted positron annihilation line emanating from the surface of the Crab Nebula pulsar; its flux is $(2\cdot24\pm0\cdot65)\times10^{-3}$ photons $cm^{-2}\,s^{-1}$. Ling *et al.* (1977*b*) also searched for this line feature, but could not find it. Hence, the data remain inconclusive as to whether the 400 keV line is emitted from the Crab Nebula pulsar or not. The estimated intensity of the 0·511 MeV line from the Crab Nebula itself is three orders of magnitude smaller than the observed upper limits.

High energy γ-ray observations by the SAS-2 and COS-B satellites show that the Crab Nebula and the Vela pulsar are strong sources of γ rays, with fluxes of the order of 10^{-5}–10^{-6} photons $cm^{-2}\,s^{-1}$ for energies above 100 MeV. These observations suggest that the cosmic ray energy density is six orders of magnitude larger than that in the vicinity of the solar system. If so, the resulting γ-ray line fluxes will be of the order of 10^{-6} photons $cm^{-2}\,s^{-1}$, which is in fact comparable with the theoretical estimate. Thus a 3σ deviation of the 0·511 MeV line intensity above the diffuse γ-ray background will be detected if γ-ray line observations using a 100 cm^2 area and 0·05 sr solid-angle Ge(Li) detector are made for 150 hours.

No observations have yet been made of γ-ray lines from dense interstellar clouds. As was shown in the previous section, the expected γ-ray line emission from ρ Oph is considered to be unobservable with currently available detectors. However, there still remains the possibility that a large number of γ-ray lines may be emitted by this dense interstellar cloud. The strong γ-ray point source CG 135+1 discovered by the COS-B satellite is regarded as the identified object W3, which is an O-star association in a very early evolutionary stage and contains 10 IR sources and 4 condensed centimetre-wavelength sources. The component W3(A) consists of a compact dense shell of ionized gas surrounded by a dense shell of neutral gas of density $\sim 10^4\,cm^{-3}$, which the 1 mm observations suggest has an H_2 mass of $10^3\,M_\odot$. The reported high energy γ-ray intensity is four orders of magnitude larger than the interstellar one, thus indicating that this dense interstellar cloud could contain an appreciable flux of high intensity cosmic rays and so be a strong γ-ray line source.

Paul *et al.* (1976) have derived a simple model which accounts satisfactorily for the observed galactic radio and high energy γ-ray radiations, and they have concluded that there exists a good correlation between the large-scale radial distributions of the interstellar gas and cosmic rays. This high correlation is also confirmed by the present calculations, since the radial distribution of cosmic rays, deduced from those for high energy γ-rays, supernova remnants, pulsars and the interstellar gas (primarily molecular hydrogen clouds in the inner Galaxy), peaks in a region between 5 and 6 kpc from the galactic centre. The stellar distribution within the Galaxy has a significant radial dependence, increasing rapidly in density toward the galactic centre, where appreciable γ-ray emission resulting from the inverse Compton process may be expected. Moreover, since the stellar distribution peaks in a region between 5 and 6 kpc, just as does the molecular hydrogen distribution, it is highly likely that this region contributes strongly to protostar formation.

Recently, the isotopic composition of cosmic ray beryllium has been determined by Garcia-Munoz *et al.* (1977) and Webber *et al.* (1977), and a lifetime of $1 \cdot 7 \times 10^7$ years for the leakage of cosmic rays from the Galaxy has been derived on the basis of the ^{10}Be abundance measurements. However, the measured abundance ratio of cosmic ray light nuclei (Li, Be and B) to medium-weight nuclei (C, N and O) is found to be in agreement with calculations based on a steady-state model for the interstellar propagation of cosmic ray nuclei having an exponential path length distribution and a 6 $g\,cm^{-2}$ leakage mean free path. Hence, the gas density of the interstellar space through which the cosmic rays propagate is deduced to be 0·2 cm^{-3}, which is substantially less than the traditionally accepted average interstellar gas density of 1 cm^{-3}. This suggests that cosmic rays may not be spending the major part of their lifetime in the galactic plane, but rather that they spend it in the galactic halo or else in specific regions of the galactic plane of low gas density. But this suggestion is inconsistent with the observed results that the high energy γ-ray emission concentrates in the galactic plane and that the radial distribution of γ-ray emission in the galactic plane closely mirrors that of the interstellar gas. This inconsistency is probably due to a large ambiguity in the estimation of the cosmic ray leakage lifetime. It is difficult to determine a precise ^{10}Be abundance, because ^{10}Be cannot be accurately separated from ^{9}Be with available isotope detectors. Indeed, Garcia-Munoz *et al.* (1977) obtained an abundance ratio $^{10}Be/Be = 0 \cdot 028 \pm 0 \cdot 03$, whereas Webber *et al.* obtained $^{10}Be/Be = 0 \cdot 08 \pm 0 \cdot 03$. Moreover, an interpretation of the ^{10}Be abundance ratio in terms of the cosmic ray leakage lifetime is dependent on the solar modulation theory. Thus, even with improved measurements of the ^{10}Be abundance, the astrophysical interpretation of the data remains open because of our lack of understanding of the solar modulation phenomenon. Webber *et al.* derived a cosmic ray leakage lifetime of 1×10^{7} years and an average density for the interstellar gas traversed by the cosmic rays of $0 \cdot 8^{+0 \cdot 5}_{-0 \cdot 3}$ cm^{-3}. Their data seem to favour a galactic plane confinement, but the errors are large enough to encompass models in which the cosmic rays spend a considerable time in a galactic halo where the density is $\lesssim 0 \cdot 1$ cm^{-3} as well. In order to determine the interstellar gas density through which the cosmic rays traverse, it is really necessary to obtain statistically better determinations of the ^{10}Be abundance.

Although a number of galactic γ-ray lines have been observed with high resolution Ge(Li) detectors, a significant increase in both exposure times and sensitivity is needed to detect the numerous weak γ-ray lines. At present [mid 1978] two satellite experiments are being prepared: The first is another military mission (the second so far) to be launched in late 1978, comprising two independent systems, each with a 75 cm^3 high purity Ge(Li) detector in a polyscintillator shield of NaI(Tl) (Nakano *et al.* 1976). The second is the largest and most sensitive high resolution experiment built for the third mission of the HEAO, and is to be launched in 1979. It consists of a cluster of four high purity Ge(Li) detectors with a total volume of 300–400 cm^3 in a CsI(Na) shield. It will have a sensitivity of the order of 10^{-5} photons cm^{-2} s^{-1} for various kinds of γ-ray sources. This HEAO-C observation represents at least two orders of magnitude improvement over the experiments thus far conducted. A precise all-sky survey, together with point source observations, are to be undertaken by the HEAO-C.

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