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Cosmic Rays in the Galactic Centre

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Abstract

The cosmic ray flux in the galactic centre region is predicted from the observed data for high energy γ rays, γ-ray lines and massive molecular clouds. The predicted cosmic ray fluxes above 1 GeV and below 100 MeV are two and four orders of magnitude respectively larger than the value in the neighbourhood of the solar system. The corresponding energy density of cosmic rays is estimated to be $100\,\mathrm{eV\,cm^{-3}}$. Such a concentrated stream of cosmic rays could accelerate the dense and massive molecular clouds by transfer of their momentum.

1. Introduction

The high energy γ-ray observations by the SAS–2 and COS–B satellites have revealed that the galactic centre has an enhanced γ-ray emission (Bennett *et al.* 1977; Fichtel *et al.* 1977). These observations are of great interest because the presence of the γ rays allows a direct determination of the high energy cosmic ray flux (>1 GeV) in the galactic centre region. Strong γ-ray line emissions from the galactic centre also have been detected by Haymes *et al.* (1975) and Leventhal *et al.* (1978) with balloon-borne γ-ray spectrometers, and these observations provide important information on the low energy cosmic ray flux (<100 MeV) in the galactic centre region.

Molecular line observations of interstellar matter in the galactic centre region have revealed the existence of dense and massive molecular clouds. Recently, the gas motion near the galactic nucleus and the nuclear activity have been studied by observation of molecular emission lines, and the results show that the Sgr A, Sgr B2, $+100\ \mathrm{km\,s^{-1}}$ and Bridge clouds in the galactic nucleus are massive molecular clouds. The observations have enabled estimates to be made of the size, density and total mass of these clouds (e.g. Fukui *et al.* 1977).

Since high energy γ rays and γ-ray lines result from high and low energy cosmic ray interactions respectively with the interstellar matter, cosmic ray fluxes can be predicted from the observed distribution of interstellar matter and the γ-ray data described above. In the present paper, the cosmic ray fluxes above 1 GeV and below 100 MeV in the galactic centre region are predicted and the corresponding energy density of cosmic rays is compared with the value in the neighbourhood of the solar system. The possible acceleration of massive molecular clouds by transfer of momentum to them from significantly high flux cosmic rays is considered.

2. Observed Data for Galactic Centre Region

(*a*) *Gamma Ray Emissions*

A pronounced excess of high energy γ-rays from the galactic centre was first reported by Clark *et al.* (1968). This enhancement has since been verified in later experiments: The observations of Fichtel *et al.* (1977) revealed that the general region surrounding the galactic centre was significantly more intense than the rest of the plane, the γ-ray intensity being $(9 \pm 1) \times 10^{-5}$ photons $\mathrm{cm^{-2}\,s^{-1}\,rad^{-1}}$ (>100 MeV). Bennett *et al.* (1977) studied the spatial, energy and time characteristics of high energy γ rays, and the trapezoidal profile of the γ-ray emission that they obtained was in good agreement with the result of Fichtel *et al.* The observed intense emission in the galactic centre was narrow and exhibited significant fine structure. The γ-ray intensity found was $(7 \cdot 0 \pm 0 \cdot 5) \times 10^{-5}$ photons $\mathrm{cm^{-2}\,s^{-1}\,rad^{-1}}$ (>100 MeV), integrated over the latitude range $|b| < 6°$.

Haymes *et al.* (1975), using a balloon-borne NaI(Tl) scintillator detector, observed γ-ray lines at 0·53 and 4·6 MeV with intensities of $(8 \cdot 0 \pm 2 \cdot 3) \times 10^{-4}$ and $(9 \cdot 5 \pm 2 \cdot 7) \times 10^{-4}$ photons $\mathrm{cm^{-2}\,s^{-1}}$ respectively. These lines could be associated with positron annihilation and with the nuclear decay of $^{12}C^*$. Several overlapping lines in the 1·2–2·0 MeV energy interval also were detected. Leventhal *et al.* (1978), using a balloon-borne high resolution Ge(Li) spectrometer, have confirmed the existence of a positron annihilation line from the galactic centre, their measured intensity of $(1 \cdot 21 \pm 0 \cdot 22) \times 10^{-3}$ photons $\mathrm{cm^{-2}\,s^{-1}}$ being in agreement with the result of Haymes *et al.* within the experimental errors.

(*b*) *Massive Molecular Clouds*

The interstellar hydrogen in the galactic centre region has been extensively studied in various ways. It occurs partly in atomic form, in which it can be observed in the 21 cm line, but a large fraction is molecular and is concentrated in dense clouds. Although the H_2 molecules in these clouds have not been observed directly, their existence has been deduced from observations of the emission or absorption lines of other molecules such as CO, OH or H_2CO that always accompany H_2 (Scoville *et al.* 1974; Bania 1977; Liszt *et al.* 1977).

The interstellar density decreases considerably inwards from 4 kpc and remains low until the edge of the nuclear disc at 750 pc (Gordon and Burton 1976). Then at a few hundred parsecs from the galactic centre a third radial change occurs: the density greatly increases and the hydrogen is almost entirely in the molecular state, mostly concentrated in massive and dense clouds whose motions deviate widely from the rotation of the nuclear disc. These clouds lie close to the galactic plane and are quite thin. The complete survey of CO emission from the galactic centre region has revealed that the molecular clouds are almost wholly concentrated in a region within about 250 pc, and the density and total mass within this distance have been estimated to be of the order of $10^3\ \mathrm{cm^{-3}}$ and $10^8\ M_\odot$ respectively (Gordon and Burton 1976).

Recently Fukui *et al.* (1977) have observed the galactic nucleus in the HCN emission line, and they have mapped precisely the molecular cloud near Sgr A. Their results have revealed the entire picture of this molecular cloud, and its estimated typical density and total mass are $>3 \times 10^3\ \mathrm{cm^{-3}}$ and $>3 \times 10^6\ M_\odot$, if the size of the cloud is assumed to be $90 \times 20 \times 20$ pc. The mass of the core part is estimated to be less than 15% of the total. Certainly there seem to be a high particle density and a large total mass in the cloud. An apparent anticorrelation with the radio continuum distribution is found for this cloud, while there is rather good agreement with the distributions of the far and near infrared radiations.

The Sgr B2 molecular cloud is separated from Sgr A by about 130 pc in the projected distance. This cloud is extended with a size of about 45 pc diameter, and its average density and total mass are estimated to be about 5×10^3 cm^{-3} and $3 \times 10^6 M_\odot$ (Scoville and Solomon 1975); that is, values comparable with those found for the Sgr A molecular cloud.

3. Estimation of Cosmic Ray Flux in Galactic Centre Region

High energy γ rays and γ-ray lines from the galactic centre could result from cosmic ray interactions with gas in the dense and massive molecular clouds. The γ-ray intensity coming from the galactic centre then may be expressed as

$$I_\gamma = qnV/4\pi R^2, \tag{1}$$

where q is the emissivity, n the target gas density, V the volume of the molecular cloud and R the distance from the galactic centre to the Earth, namely 10 kpc. Since high energy γ rays result from the decay of π^0 mesons produced in cosmic ray interactions with hydrogen, cosmic ray protons with energies above 1 GeV could contribute to π^0 meson production. The high energy γ-ray emissivity q_{HG} would then be given by

$$q_{\mathrm{HG}} = \int J(E)\,\sigma(E)\,\mathrm{d}E, \tag{2}$$

where $J(E)$ is the cosmic ray proton flux in the galactic centre region and $\sigma(E)$ the production cross section of π^0 meson from proton–proton interactions. Equation (2) may be rewritten as

$$q_{\mathrm{HG}} = \int \big(J(E)/J_\odot(E)\big)\,J_\odot(E)\,\sigma(E)\,\mathrm{d}E = fq_\odot, \tag{3}$$

with

$$f \equiv J(E)/J_\odot(E), \qquad q_\odot \equiv \int J_\odot(E)\,\sigma(E)\,\mathrm{d}E,$$

where $J_\odot(E)$ is the cosmic ray flux in the neighbourhood of the solar system and $q_\odot$ is the high energy γ-ray emissivity in the solar system. Stecker (1975) estimated $q_\odot$ to be $1\cdot3 \times 10^{-25}$ s^{-1}, and, with this value, equation (3) is reduced to

$$q_{\mathrm{HG}} = 1\cdot3 \times 10^{-25} f. \tag{4}$$

Since, as noted in Section 2*a*, the high energy γ-ray intensity is around 7×10^{-5} photons cm^{-2} s^{-1}, nV is of the order of 10^{65} and R = 10 kpc, f becomes of the order of 10^2.

This implies that the cosmic ray flux above 1 GeV in the galactic centre region is about two orders of magnitude larger than the value in the neighbourhood of the solar system.

Nuclear γ-ray lines are emitted by excited nuclei resulting from interactions of low energy cosmic rays (< 100 MeV) with gas in dense massive molecular clouds, and observations of these lines give a valuable guide to the composition of the clouds. In addition, observations of the positron–electron annihilation line from the galactic centre are of particular interest since they allow a direct determination of the positron production rate from cosmic rays, which can then be related to the cosmic ray flux and the matter density. With a reliable assumption for the matter distribution, the positron annihilation line is therefore a good probe for estimating cosmic ray intensity. Cosmic ray positrons are produced from the β decay of unstable ^{11}C, ^{13}N and ^{15}O nuclei resulting from nuclear interactions of low energy cosmic rays with gas in the massive molecular clouds. Since nuclear interactions producing β-unstable carbon, nitrogen and oxygen nuclei involve relatively low threshold energies of the order of 10 MeV, the β-decay positrons have maximum energies of the order of 1 MeV. These positrons will be readily decelerated by ionization collisions and they will be annihilated to emit two 0·511 MeV γ-rays. Hence, the 0·511 MeV line will have a very narrow width of a few keV.

The emissivities q_{LG} of the positron–electron annihilation line at 0·511 MeV and of the $^{12}C^*$ line at 4·43 MeV are estimated to be $1\cdot83\times10^{-26}f(0\cdot511)\ s^{-1}$ $(H\ atom)^{-1}$ and $2\cdot35\times10^{-23}f(4\cdot43)\ s^{-1}\ (C\ atom)^{-1}$ respectively. The abundance ratio of carbon to hydrogen atoms in the molecular clouds is assumed to be $3\cdot71\times10^{-4}$, the same as the value in the solar system (Cameron 1973). Since the lines at 0·511 and 4·43 MeV are found to have fluxes of $1\cdot21\times10^{-3}$ photons $cm^{-2}\ s^{-1}$ (Leventhal *et al.* 1978) and $9\cdot5\times10^{-4}$ photons $cm^{-2}\ s^{-1}$ (Haymes *et al.* 1975), the respective values for $f(0\cdot511)$ and $f(4\cdot43)$ become 8×10^3 and $1\cdot3\times10^4$. These values imply that the cosmic ray flux below 100 MeV in the galactic centre region is about four orders of magnitude larger than the flux in the neighbourhood of the solar system.

4. Discussion

As we have seen, the recent γ-ray observations suggest that the cosmic ray flux in the galactic centre region is very large compared with the value in the neighbourhood of the solar system: in order to explain the observed γ-ray data, the cosmic ray fluxes above 1 GeV and below 100 MeV need to be about 10^2 and 10^4 times larger respectively. These predicted fluxes give an energy density for the cosmic rays of 100 eV cm^{-3}, which is two orders of magnitude larger than that in the neighbourhood of the solar system.

Such high flux cosmic rays may play an important role in the motion of the massive molecular clouds in the galactic centre. Liszt *et al.* (1977) have demonstrated that the distribution and motion of the Sgr A, Sgr B2, +100 km s^{-1} and Bridge clouds deviate significantly from dynamical equilibrium. The radial velocity of each outgoing molecular cloud is about 100 km s^{-1} and the total energy in the clouds is estimated to be $>10^{53}$ erg (10^{46} J), a magnitude which could not be provided by a supernova explosion. In order to explain this result, a matter ejection model was proposed by Oort (1974), Whiteoak *et al.* (1974) and Fukui *et al.* (1977).

In this model the characteristic distribution and motion of the molecular clouds are determined by matter ejection from the galactic nucleus. However, there is also a possibility that high flux cosmic rays could accelerate the outgoing molecular clouds. Observations show that the radial velocity of the clouds is nearly independent of their distance from the galactic nucleus, despite the strong gravitational field. This implies that the molecular clouds were ejected with some initial velocity and thereafter have been continuously accelerated in the outward direction.

Although at first sight it seems that it would be very difficult to accelerate highly dense and low-temperature clouds, a sufficiently concentrated stream of cosmic rays could do so by transfer of their momentum. A theory for the diffusion of cosmic rays through a medium such as a molecular cloud, which takes into account the effect of hydromagnetic waves, has been put forward by Lerche (1967), Wentzel (1969), Kulsrud and Pearce (1969) and Tademaru (1969). These authors have shown that a small drift of cosmic rays, relative to the background interstellar plasma, of the order of the Alfvén velocity can produce an instability which increases the amplitude of the hydromagnetic waves, but this increase in amplitude is countered by a decrease due to friction between the ionized and neutral portions of the molecular cloud. Overall, the cosmic rays become coupled to the cloud and tend to drag it along and, as a result, the cloud is heated and accelerated. A rough approximation shows that the cosmic ray flux necessary to accelerate a molecular cloud is two orders of magnitude larger than the value in the neighbourhood of the solar system. This value is consistent with the flux predicted above from the observed data of high energy γ rays. Hence, it seems quite possible that a concentrated stream of cosmic rays could contribute to the acceleration of the massive molecular clouds in the galactic centre region.

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