γ-RAYS FROM DISCRETE RADIO SOURCES

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ABSTRACT

The fluxes of low energy ($\sim$100 MeV) and high energy ($\sim 5 \times 10^{12}$ eV) γ-rays from intense radio sources have been calculated under the hypothesis that radio electrons are continuously produced through nuclear collisions. The effect of expansion of the source which gives rise to a decrease in production rate with time has been taken into account in these calculations. It is found that the fluxes expected from nuclear collision process are generally higher than the fluxes from other processes like bremstrahlung and inverse compton scattering by factors of 10 or more. While the calculated fluxes of γ-rays of energy $>$100 MeV are less than the observed upper limits for all the processes, the fluxes calculated for nuclear collision process for $E > 5 \times 10^{12}$ eV, exceed the experimental upper limits for Crab, Cas A and the jet in Virgo A. More sensitive experiments should be able to decide whether the nuclear collision process is ruled out for low energies as well: in this respect Cas A seems to be the most promising source.

1. INTRODUCTION

IT is well known that radio emission from many discrete sources is due to the synchrotron radiation of high energy electrons in ambient magnetic fields. The origin of these high energy electrons is, at present, unknown. The idea that these electrons are secondary in origin, *viz.*, they are continuously produced through pion production in collisions of protons and heavy nuclei with the ambient gas has been proposed by Burbidge.[1] Under these conditions, one also expects a flux of γ-rays from these sources, the expected fluxes being related to the number of electrons in the source. Several experiments[2–11] have been undertaken to detect γ-rays in the MeV and TeV (1 TeV = 1000 GeV) ranges from several discrete sources. So far, these experiments have been able to give only upper limits, though it may soon be possible to increase their sensitivity and observe definite fluxes. In this context it will be interesting to compute the expected γ-ray fluxes from various radio sources. Several estimates have so far been given.[12-15] These estimates have not fully considered two important factors, *viz.*, the expansion of the source and the leakage of charged particles from the source volume. The general procedure is to relate the production rate of γ-rays to the production rate of electrons. The latter is generally taken to be the uniform rate given by dividing the total number of electrons present in the source (derived from radio data) by the lifetime of the source. However, if the source is an expanding one, the production rate is not uniform in time; the rate decreases with time since the matter density decreases due to expansion. Hence, the assumption of a uniform rate of production of electrons results in an overestimate for the present rate of production of γ-rays. This effect is especially important for low energy ($\sim$ 100 MeV) γ-rays since the electrons of corresponding energy have half-life against synchrotron radiation much higher than the lifetime of the source and hence are stored over the entire lifetime of the source. In this paper, we will take into account the variation in density due to expansion while calculating the γ-ray fluxes. As for the leakage of charged particles from the source volume we will show that this does not affect the results if the leakage rate is independent of energy. This arises due to the fact that both the electrons and the nuclear particles that produce the electrons and γ-rays leak at the same rate.

We will present results for the fluxes of γ-rays from four intense discrete radio sources, *viz.*, Crab, Cas A, Cygnus A and the jet in Virgo A. These fluxes will be compared with fluxes expected from other processes like bremstrahlung and inverse compton scattering. The results will be discussed in relevance to the observed experimental upper limits.

2. ASSUMPTIONS

(1) It is assumed that all the electrons result from nuclear collisions and no direct acceleration takes place.

(2) The leakage of charged particles is characterised by a leakage time τ which is independent of energy and is the same for electrons and nuclear particles.

(3) If the source is an expanding one, the rate of expansion is assumed to be uniform so that the matter density in the source at any time t can be represented as

$$n(t) = n_0 t^{-3}$$

(4) Relative production of pions of different charges is given by charge independence; thus, the γ-ray multiplicity is the same as electron positron* multiplicity.

3. CALCULATION

3.1. *Low Energy γ-Rays* ($\sim 100\ MeV$)

If $N_p(E')$ be the number of nuclear particles initially, the number at time t is $N_p(E')\,e^{-t/\tau}$. Let k_e be the mean fraction of primary energy received by an electron in the collision of a nuclear particle of energy E′ with ambient gas. Let q_e be the mean electron multiplicity. The number of electrons of energy $E = k_e E'$ produced at time t in an interval dt is given by

$$p_e(E, t) = N_p(E')\,e^{-t/\tau}\,\sigma\,q_e\,n(t)\,c\,dt \qquad (1)$$

where σ is the pion production cross-section and c, the velocity of light. Number of electrons that survive up to the present time T is then $p_e(E, t)\,e^{-(T-t)/\tau}$. Here, the loss of electrons due to synchrotron radiation has been neglected since for electrons of energy ~ 100 MeV, the half-life against synchrotron radiation in a magnetic field of $\sim 10^{-4}$ gauss is about 80 million years which is much larger than the lifetime of sources to be considered. Total number of electrons present in the source at present time T is

$$N_e(T, E) = N_p(E')\,e^{-T/\tau}\,q_e\,n_0\sigma \int_{t_0}^{T} t^{-3}\,dt \qquad (2)$$

where we have substituted $n(t) = n_0 t^{-3}$ and t_0 is the time when pion production begins, *i.e.*, the time when nuclear particles of energy above the threshold for the pion production are injected.

We can write,

$$N_e(T, E) \quad n_p(E')\quad e^{-T/\tau}\,\frac{\sigma c q_e n_0}{2t_0^2} \quad \text{for } T \gg t_0 \qquad (3)$$

Rate of production of γ-rays of energy $k_\gamma E'$ at present time T is given by

$$p_\gamma(T, k_\gamma E') = N_p(E')\,e^{-T/\tau} q_\gamma\,\sigma c\,n(T) \qquad (4)$$

where k_γ is the mean fraction of primary energy received by a γ-ray and q_γ is the γ-ray multiplicity. If d is the distance of the source from the earth, the flux of γ-rays at earth is $F_\gamma = p_\gamma/4\pi d^2$. Comparing equations (3) and

* We will refer to them simply as 'electrons' in the rest of the paper.

(4) and using $q_e = q_\gamma$, we get

$$F_\gamma(T, p\,E) = 2\,\frac{N_e(T, E)}{4\pi\, d^2\, T}\left(\frac{t_0}{T}\right)^2 \tag{5}$$

where $p = k_\gamma / k_e$. $N_e(T, E)$ is the total number of electrons present in the source at present time and the quantity $N_e(T, E)/4\pi\, d^2$ can be computed from the radio spectrum observed at the earth for any assumed magnetic field in the source. It is seen that expression (5) is independent of τ and hence the γ-ray flux derived from radio flux is independent of leakage of charged particles from the source. If there is no expansion in the source, the production rate is uniform and expression (5) reduces to

$$F_\gamma(T, pE) = \frac{N_e(T, E)}{4\pi\, d^2\, T}. \tag{6}$$

Expression (5) can be rewritten in another way. If X is the matter traversed in gm./cm.^{2} from time t_0 onwards

$$X = \int_{t_0}^{\infty} c\, m_p \frac{n_0}{t^3}\, dt = c\, m_p \frac{n_0}{2 t_0^2}. \tag{7}$$

Hence substituting for t_0 in terms of X and putting $n_0 = nT^3$, where n is the present matter density, we get

$$F_\gamma(T, pE) = \frac{c\, n\, m_p}{X}\,\frac{N_e(T, E)}{4\pi\, d^2} \quad \text{photons/cm.}^2\,\text{sec.} \tag{8}$$

3.2. *High Energy γ-Rays* ($\sim 10^{12}\, eV$)

For computing the flux of γ-rays of energy $\sim 10^{12}$ eV, it is necessary to consider the loss of electrons due to synchrotron radiation. If we assume the nuclear particles have a power law spectrum $N(E) = AE^{-\alpha}$, the production spectrum of electrons is

$$\begin{aligned} P_e(E, t) &= N_p(k_e E)\, q_e \sigma\, c\, n(t) \\ &= A k_e^{(\alpha-1)} E^{-\alpha} q_e \sigma\, c\, n(t). \end{aligned} \tag{9}$$

It can then be shown[16] that the number of electrons of energy E at time T is

$$N_e(E, t) = q_e \sigma\, c\, n_0 \frac{k_e^{(\alpha-1)}}{E^\alpha} \int_0^{1/bE} (1 - b\,Et)^{\alpha-2} (T - t)^{-3}\, dt \tag{10}$$

where b is the coefficient of synchrotron energy loss term given by $dE/dt = -bE^2$. It is seen that contribution to electrons comes only over a period $1/bE$; for $H = 10^{-4}$ gauss, $E = 5 \times 10^{12}$ eV, we have $1/bE = 150$ years which is generally much smaller than the lifetime of source. Hence, matter density can be treated as constant at an average value given by

$$\langle n \rangle = bE \int_0^{1/bE} n_0 (T - t)^{-3} \, dt.$$

Expression (10) then reduces to

$$N_e(E, T) = q_e \sigma c \frac{k_e^{(\alpha-1)}}{E^\alpha} \times \frac{1}{(\alpha - 1) bE} \langle n \rangle. \tag{11}$$

The photon production rate at time **T** is

$$P_\gamma(E, T) = q_\gamma \sigma c n(T) \frac{k_\gamma^{+(\alpha-1)}}{E^\alpha}.$$

Hence,

$$F_\gamma(E, T) = \frac{N_e(E, T)}{4\pi d^2} \frac{n}{\langle n \rangle} p^{(\alpha-1)} (\alpha - 1) bE \tag{12}$$

The γ-ray flux does not depend on the actual value of matter density since only $n/\langle n \rangle$ is involved in expression (12). It also does not critically depend on the expansion of the source since $n/\langle n \rangle$ is not much less than unity.

4. Application to Specific Sources

We will consider four intense radio sources Crab, Cas A, Cygnus A and the jet in Virgo A. Data on the relevant parameters like distance, magnetic field, matter density and lifetime are summarised in Table I. The distances

Table I

Source	Distance	H gauss	Lifetime years	Density atoms/c.c.
Crab ..	1·1 Kpc	10^{-4}	915	10
Cas A ..	3·4 Kpc	10^{-4}	260	50
Cygnus A ..	220 Mpc	5×10^{-5}	5×10^5	10^{-3}
Jet in Virgo A	13·2 Mpc	10^{-4}	10^6	10

and lifetimes are those given by Kardashev.[17] The matter density in Cygnus A is taken as 10^{-3} atoms/c.c., a value about 100 times smaller than the usually assumed density in our galactic halo. For the other sources, the values given are those generally used by many authors.

For γ-rays of energy ~ 100 MeV, the information on the electron content of the source is directly derived from the observed radio emission as tabulated by Howard and Maran[18] by making use of the well-known synchrotron radiation formulae.[19] The expected fluxes of γ-rays of energy > 200 MeV, and the experimental upper limits are shown in Table II. The value of p, the ratio of the fraction of primary energy received by the γ-ray

TABLE II

Flux of γ-rays in units of photons/cm.^{2} sec.

Source	N_e (>100 MeV)	Calculated flux of γ-rays (E>200 MeV)			Experimental upper limits*		
	$4\pi d^2$	p—p	Brem-strahlung	Inv. compton on 3° K photons	Energy MeV	Flux	Reference
Crab	$3{\cdot}1 \times 10^6$	$5{\cdot}4 \times 10^{-7}$	$4{\cdot}3 \times 10^{-8}$	$2{\cdot}3 \times 10^{-6}$	> 100	$3{\cdot}1 \times 10^{-5}$	(10)
					30–500	$1{\cdot}9 \times 10^{-4}$	(9)
					>1000	$1{\cdot}2 \times 10^{-5}$	(11)
Cas A	$4{\cdot}3 \times 10^7$	$3{\cdot}8 \times 10^{-5}$	$5{\cdot}4 \times 10^{-7}$	$4{\cdot}85 \times 10^{-8}$	>1000	$1{\cdot}5 \times 10^{-5}$	(11)
					> 50	5×10^{-4}	(8)
Cygnus A	$2{\cdot}7 \times 10^8$	$4{\cdot}85 \times 10^{-9}$	$6{\cdot}45 \times 10^{-11}$	$1{\cdot}56 \times 10^{-9}$	>1000	$2{\cdot}1 \times 10^{-5}$	(11)
					30–500	$1{\cdot}8 \times 10^{-4}$	(9)
Jet in Virgo A	$6{\cdot}45 \times 10^7$	$2{\cdot}14 \times 10^{-6}$	$1{\cdot}6 \times 10^{-7}$	$6{\cdot}2 \times 10^{-11}$	> 50	$2{\cdot}7 \times 10^{-4}$	(8)

* Only the best upper limits available are given.

to that of the electron has been taken as 2. The value of X, the matter traversed in the source, is a quantity which is not known very well. It must be remembered that the grammage referred to here is the matter traversed by particles trapped in the source. Its value depends on the time of injection of high energy nuclear particles. For example, in the Crab if we assume uniform expansion, particles present from a period of 50 years from the origin to the present would have traversed 3 gm./cm.^{2} of matter. If relativistic particles were present even earlier, X can be larger. We have calculated the flux values for an assumed value of $X = 3$ gm./cm.^{2}; hence, the calculated fluxes may represent upper limits. For the jet in Virgo A, no expansion has been assumed[17] and hence the flux has been calculated from equation (6).

For γ-rays of energy 5×10^{12} eV, we need information on the electron spectrum in the region of 10^{12} eV. For Crab, the optical spectrum observed in the region of 10^{14}–10^{15} c/s is assumed to be the synchrotron loss modified spectrum and hence the electron spectrum computed. In case of Virgo A, Bless[20] gives an index of $-2\cdot 56$ for the optical spectrum. On the other hand, Felten[21] is of the view that the spectrum right from the radio to X-ray region may be a single power law with exponent equal to $-2/3$. Since there is a gap in experimental information in the infra-red region and since the optical data of different workers do not agree with each other, one cannot decide in favour of either of the spectra. Hence we have calculated the results for both spectra of Bless[20] and Felten.[21] For Cas A and Cygnus A, no direct information exists in optical range. However, if we assume the injected spectrum to be the same as the spectrum extrapolated from low energies, the electron density around 10^{12} eV and hence γ-ray fluxes can be computed. The computed values are shown in Table III.

TABLE III

Fluxes of γ-rays ($E > 5\times 10^{12}$ eV) in units of photons/cm.^{2} sec.

Source	Calculated flux			Experimental upper limits	
	Nuclear collision	Bremstrahlung	Inv. Compton on 3° K photons	Flux	Reference
Crab	$1\cdot 0\times 10^{-8}$	$1\cdot 1\times 10^{-13}$	$2\cdot 5\times 10^{-13}$	5×10^{-11}	(5)
Cas A	$2\cdot 1\times 10^{-10}$	$1\cdot 6\times 10^{-14}$	$2\cdot 7\times 10^{-13}$	1×10^{-10}	(6)
Cygnus A	$1\cdot 2\times 10^{-11}$	$5\cdot 4\times 10^{-21}$	$5\cdot 7\times 10^{-15}$	5×10^{-11}	(5)
Virgo A*	$9\cdot 7\times 10^{-11}$ ($2\cdot 5\times 10^{-11}$)	$9\cdot 7\times 10^{-16}$ ($1\cdot 5\times 10^{-18}$)	$6\cdot 5\times 10^{-13}$ ($4\cdot 0\times 10^{-20}$)	5×10^{-11}	(5)

* Values given in paranthesis refer to the spectrum of Bless[(20)] while the others are for the case of Felten's[(21)] spectrum.

If relativistic electrons are present in sources, they can also produce photons by bremstrahlung and inverse compton scattering. The flux of γ-rays due to bremstrahlung depends only on the electron spectrum and the matter density. The fluxes of γ-rays of energy > 200 MeV and $> 5\times 10^{12}$ eV calculated by using the formulae given by Garmire and Kraushaar[13] are also shown in Tables II and III. The γ-ray spectrum arising from inverse compton scattering of electrons on synchrotron photons (process 1) has been calculated by Gould[22] for the Crab. The spectrum due to inverse compton scattering on microwave photons corresponding to the 3° K universal black-body radiation (process 2) has been calculated by Apparao.[23] Both these processes give a flux of 10^{-6} photons/cm.^{2} sec. for γ-rays of energy > 100 MeV; for $E > 5\times10^{12}$ eV process 1 gives a flux of 4×10^{-12} photons/cm.^{2} sec. The γ-ray fluxes from process 1 is inversely proportional to the energy density of photons in the source. Hence, the γ-ray fluxes due to process 1 from other sources which have steeper spectra and also have photon density less than that of Crab are much smaller than that for Crab and hence not calculated. To produce γ-rays of energy 5×10^{12} eV by process 2, we need electrons of energy 4×10^{13} eV; for this the electron spectrum extrapolated from $\sim 10^{12}$ eV has been used. The γ-ray fluxes for $E > 200$ MeV and $E > 5\times10^{12}$ eV from process 2 are shown in Tables II and III.

5. Discussion

It is seen from Table II that flux of γ-rays of energy > 200 MeV from nuclear collision process is higher by a factor of 10 or more than that from other processes for all the sources excepting Crab. For the Crab, the inverse compton scattering is the most effective process. It is also seen that the calculated fluxes are much less than the observed experimental upper limits. The highest expected value is for Cas A and it is about 10 times less than the observed upper limit. Even this calculated value may be an upper limit; the value of $X = 3$ gm./cm.^{2} corresponds to the injection taking place when Cas A was 22 years old. If the injection had taken place at the 10th year, X would have been about 5 times higher and the present γ-ray flux 5 times lower.

The effect of expansion is to lower the γ-ray flux expected from the nuclear collision process by a factor $\frac{1}{2}(T/t_0)^2$ as compared to the flux for the case of no expansion. As a result of this, younger sources like Cas A are better candidates for low energy (~ 100 MeV) γ-ray astronomy than older sources like Cygnus A. Even for Cas A, the reduction factor is about 100 or more. If there had been no expansion, the expected γ-ray flux for $E > 200$ MeV would have been 2×10^{-3} photons/cm.^{2} sec. This is well above the experimental upper limit and would have, but for the expansion, ruled out nuclear collision process as an effective mechanism for the production of γ-rays. For γ-rays of energy $> 5 \times 10^{12}$ eV, while the fluxes from bremstrahlung and inverse compton scattering are less than the observed upper limits, the fluxes calculated for nuclear collision process exceed the upper limits. The only uncertain parameter in the latter process is the magnetic field assumed. But the dependence of γ-ray flux on H is through the term $H^{(1-\alpha)}$ which is a rather weak dependence for values of α in the region of unity. Hence, it is seen that the observed upper limits rule out nuclear collisions as an effective process for high energy γ-rays.

If the sensitivity of experiments can be increased in the low energy region (~ 100 MeV) it will be possible to decide whether or not nuclear collision process is effective at low energies also. In this respect Cas A seems to be the most promising source, since the expected flux is only a few times lower than the present upper limit.

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