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Possible origin of cosmic γ ray flux from pulsars

Sushen Kumar Saha
Indian Association for the Cultivation of Science, Calcutta-32, India

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Abstract. The flux of celestial γ rays has been calculated from neutron stars (pulsars) on the basis of the model of neutron stars as developed by Tsuruta and Cameron and the cooling rate calculated by Raychaudhuri taking into account neutrino emission according to the photon–neutrino coupling theory. The result is found to be in good agreement with the experimental results as obtained in OSO III experiments.

Hutchinson (1952) and later on Morrison (1958) suggested that certain astronomical objects might emit a measurable flux of γ rays. By the middle of the last decade much theoretical work had been done on the flux to be expected from neutral pion decay, inverse Compton collisions and bremsstrahlung (Hayakawa *et al* 1964, Garmire and Kraushaar 1965, Ginzburg and Syrovatskii 1965, Gould and Burbridge 1967, Fazio 1967). The important experiments to measure the γ ray emission flux were conducted by Clark *et al* (1968), Frye and Wang (1969) and Browning *et al* (1972). The intensity measured in the experiment by Clark *et al* (1968) was higher by more than an order of magnitude than the value calculated for the decay of neutral pions produced in the collision of the primary cosmic radiation with interstellar hydrogen (Pollack and Fazio 1963) and stimulated a search for alternative production mechanisms. Among these were inverse Compton scattering of cosmic ray electrons by a high density (13 eV cm^{-3}) of infrared photons (Cowsik and Pal 1969, Shen 1969, O'Connell and Varma 1969, Maraschi and Treves 1970, Ipavich and Lenchek 1970) and the superposition of point sources (Ogelman 1969). Other investigators (Stecher and Stecker 1970, Cavallo and Gould 1970) have calculated that production on interstellar hydrogen can explain the disc γ rays for the peak in the direction of the galactic centre where an additional source is required. Pinkau (1970) showed that high γ ray flux values of OSO III follow from the expected correlation of cosmic ray sources with regions of large hydrogen density. So it is very interesting to observe the growing controversy on this problem, and we want to add a few words in this connection.

If supernovae produce cosmic rays then they are most probably injected into space within a very short time interval. This is also true of cosmic rays considered to be accelerated in pulsars (Ostriker and Gunn 1969). Thus γ rays may be helpful to learn about the intensities of distant cosmic ray sources. We are interested in calculating the γ ray flux due to the release of cosmic rays into interstellar space by different events.

Raychaudhuri (1971) has shown that x rays and probably γ rays also come from neutron stars. A neutron star is assumed to be formed through the free fall collapse of a supernova. This means that such a star does not arrive easily at its stable configuration. Large dynamical velocities are developed during the infall of a remnant and a stable configuration cannot be formed until the dynamical oscillations that occur about the stable configuration have been damped away. The associated energies are very large since the dynamical speeds are much less than that of light, say $\frac{1}{3}c$ (for the situation in which the dimensions of the equilibrium structure are not much greater than the critical Schwarzschild radius), giving a value of 10^{20} erg g^{-1}. The total energy for a remnant of mass $1\, M_\odot$ is approximately 2×10^{53} erg for example. Since a neutron star is a remnant core of a supernova explosion its surface composition is likely to be the same as the equilibrium composition of for example Fe.

The table 1 below from Raychaudhuri (1971) gives the results for the neutron star model. The star is taken to have mass $0{\cdot}6\, M_\odot$ with magnetic field strength $H = 10^{14}$ G, L_{ph} and L_ν denote the photon and neutrino luminosity, E_T is the total thermal energy, t is the cooling time and T_c and T_e the core and surface temperatures.

Table 1. Neutrino luminosity and cooling time for a neutron star having mass $0{\cdot}6\, M_\odot$ and magnetic field strength 10^{14} G. Calculations have been done on the basis of photon–neutrino weak coupling theory.

T_e (K)	lg L_{ph} (erg s^{-1})	lg L_ν (erg s^{-1})	lg T_c (K)	lg E_T (erg)	lg t (yr)
10^8	40·56	39·88	10·40	50·24	2·10
5×10^7	39·36	39·13	10·08	49·60	2·54
2×10^7	37·77	38·20	9·68	48·74	2·90
10^7	36·56	37·23	9·26	47·88	3·07
5×10^6	35·36	36·37	8·90	47·17	3·26
2×10^6	33·77	35·42	8·47	46·30	3·37
10^6	32·56	34·42	8·04	45·51	3·58
5×10^5	31·36	33·32	7·57	44·60	3·78

We shall consider here γ rays produced by neutron stars. Raychaudhuri (1971) has shown that the energy requirement for the generation of γ rays ($\geqslant 50$ MeV) at the rate of 10^{44} erg s^{-1} is met by a neutron star within 1 to 3 years of its formation. Pollack and Fazio (1963) have calculated a source strength of $9{\cdot}7 \times 10^{-27} n$ quanta cm^{-3} s^{-1} sr^{-1} produced by the average cosmic rays on interstellar hydrogen of density n cm^{-3}. The average cosmic ray energy density is about 10^{-12} erg cm^{-3}. Following Pinkau (1970) we assume that the γ ray yield is proportional to the energy density. Thus $9{\cdot}7 \times 10^{-15} n$ quanta/erg s sr are produced. If W(erg) is the energy input per source into cosmic rays, then this source produces a flux of $F_i = 9{\cdot}7 \times 10^{-15}\, Wnr_i^{-2}$ quanta cm^{-2} s^{-1}. r_i is the distance of the ith source from the Earth. We shall take here, according to Raychaudhuri's model discussed above, the energy input per source W to be approximately $1{\cdot}2 \times 10^{53}$ erg. Indeed, this can be taken to be the maximum energy that can be propagated from a pulsar (Raychaudhuri 1971). Taking the usual hydrogen density n cm^{-3} as 10^{-2} cm^{-3} we get $Wn = 1{\cdot}2 \times 10^{51}$ erg cm^{-3}. Using these values we can calculate the value of F_i for different pulsars. The independent estimates of their distances r_i and their periods p are available.

Let us consider the extent of the sources in the sky. If R_i is the radius of the volume filled by cosmic rays from the ith event, a typical angular dimension will be given by

R_i/r_i. If $\Delta\Omega$ sr is the size of the angular resolution of any γ ray astronomical instrument, then the reduced counting rate F_i', of the order of

$$F_i' = \frac{F_i \, \Delta\Omega}{\pi(R_i/r_i)^2},$$

is recorded. This equation is to be applied only if $\Delta\Omega \leqslant (R_i/r_i)^2$.

In this model of neutron stars, the frequency of pulsation ω can be taken to be given by

$$\omega = \frac{2\pi}{p} = \frac{9{\cdot}5}{10^8} T_c$$

where T_c is the core temperature from Raychaudhuri's model. So we can calculate T_c from this relation; the periods p for pulsars are known from the table. From table 1 we can obtain the corresponding value of t_i, the age of the pulsars. We shall have to obtain a relation between R_i and t_i. For this we can apply the usual diffusion picture of the cosmic rays. Here $R_i = (\lambda c t_i)^{1/2}$ where $\lambda \simeq 3$ pc is the diffusion mean free path (Jokipii and Parker 1969). Then we get $R_i(\text{pc}) \simeq t_i(\text{yr})^{1/2}$.

Recently Ramaty *et al* (1970) have advanced a value of $\lambda \simeq 3 \times 10^{-2}$ pc and this would result in a relation $R_i \simeq 0{\cdot}1 t_i^{1/2}$. We may take these two values $\lambda = 3$ pc and $\lambda = 3 \times 10^{-2}$ pc as symbolizing the range of expansion velocities that we may expect. Table 2 contains values of F_i for these two laws of expansion and for a value of $\Delta\Omega = 10^{-2}$ sr corresponding to an angular resolution of about 3°.

The γ rays from Earth provide a calibration source for comparison between different observations. The result presented by Clark *et al* (1968) indicates a flux of $(6{\cdot}4 \pm 1{\cdot}3) \times 10^{-3}$ cm^{-2} s^{-1} sr^{-1} for observations at magnetic latitudes less than 20°. This can be compared with $(1{\cdot}5 \pm 0{\cdot}45) \times 10^{-3}$ cm^{-2} s^{-1} sr^{-1} observed by Explorer XI (Kraushaar *et al* 1965). The discrepancy is about a factor of four. An apparent isotropic background intensity of $(1{\cdot}1 \pm 0{\cdot}2) \times 10^{-4}$ cm^{-2} s^{-1} sr^{-1} has been observed. It may be added that the later recalibration of the apparatus has resulted in lower intensities such as $(1{\cdot}2^{+0{\cdot}4}_{-0{\cdot}5}) \times 10^{-4}$ photons cm^{-2} s^{-1} rad^{-1} from the galactic disc towards the galactic centre and $(3^{+1}_{-1{\cdot}2}) \times 10^{-4}$ in the anticentre region (Clark *et al* 1971).

From our calculation we observe that perhaps there are numbers of discrete γ ray sources which cannot be regarded as point sources nor diffuse background but rather represent clouds of varying angular diameter. Of these PSR 0950 seems to be the prominent source. We find an average flux of $2{\cdot}5 \times 10^{-3}$ cm^{-2} s^{-1} sr^{-1} from this pulsar which agrees well with the observations. It can be pointed out in this respect that PSR 0950 is a very significant pulsar as it is the youngest of the nearest pulsars. Lingenfelter (1969) also speculated that PSR 0950 might have a role in increasing the cosmic ray activity on Earth. We think that in measuring the cosmic ray flux the role of PSR 0950 should be stressed. From table 2 other prominent sources are CP 0808, PSR 1133, PSR 1929, PSR 1642, PSR 1451, etc. The total average γ ray flux that we get from the table agrees well with the experimental results presented by OSO III experimenters. It can be remarked that the maximum detectibility is reached if the counts are integrated over the angular dimensions of the sources.

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Table 2. Summary of typical parameters of a few potential γ ray sources, their angular dimensions and their flux values for the two cases of rapid and slow expansion respectively. Here we take the neutron star model

Source	γ_i(pc)	p	t_i(yr)	Total flux integrated over source $F_i \times 10^7$ ($cm^{-2} s^{-1}$)	Rapid expansion $R_i = t_i^{1/2}$ Half angle of cloud R_i/r_i (deg)	Rapid expansion $R_i = t_i^{1/2}$ Flux from within $\Delta\Omega = 10^{-2}$sr $F_i' \times 10^7$ ($cm^{-2} s^{-1}$)	Slow expansion $R_i = 0{\cdot}1 t_i^{1/2}$ Half angle of cloud R_i/r_i (deg)	Slow expansion $R_i = 0{\cdot}1 t_i^{1/2}$ Flux from within $\Delta\Omega = 10^{-2}$ sr $F_i' \times 10^{-7}$ ($cm^{-2} s^{-1}$)
Crab PSR 0531	1700	0·033	992	4·48	1	4·48	0·1	4·48
MP 0736	370	0·375	$2{\cdot}9 \times 10^3$	94·4	8	14·77	0·8	94·4
Vela PSR 0833	410	0·0892	$1{\cdot}85 \times 10^3$	76·9	5·8	23·0	0·58	76·9
MP 1240	1100	0·388	$3{\cdot}03 \times 10^3$	10·7	2·8	10·7	0·28	10·7
PSR 1451	250	0·264	$2{\cdot}53 \times 10^3$	207	11·2	16·5	1·12	207
PSR 1642	160	0·388	$3{\cdot}03 \times 10^3$	505	19·1	14·0	1·91	505
PSR 1929	140	0·227	$2{\cdot}36 \times 10^3$	660	19·2	18·0	1·92	660
PSR 0950	60	0·253	$2{\cdot}4 \times 10^3$	3900	—	—	4·23	2179
PSR 1133	130	1·190	$5{\cdot}01 \times 10^3$	765	27·7	10	2·77	765
CP 0808	130	1·29	$5{\cdot}25 \times 10^3$	765	28·0	10	2·8	765

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