Journal of the Arkansas Academy of Science

Volume 48 | Article 14

1994

Gamma Ray Emissions from Binary Pulsar Systems

Tony A. Hall
Arkansas State University

Andrew T. Sustich
Arkansas State University

Gamma Ray Emissions From Binary Pulsar Systems

Tony A. Hall and Andrew T. Sustich
Arkansas State University
Department of Physics
State University, AR 72467

Abstract

A method is developed for estimating the gamma ray flux impinging upon the earth from production in binary pulsar systems. We calculate production of the 6.13 MeV gamma ray line characteristic of ^{16}O. These are produced by protons emitted by the pulsar interacting with ^{16}O atoms at the surface of the companion. We examine different types of companion stars and estimate the gamma ray flux at the earth as a function of proton emission from the pulsar and distance from the earth. Prospects for detection from earth are discussed.

Introduction

A binary star system consists of two gravitationally bound stars, orbiting a common center of mass. A pulsar is a rapidly rotating neutron star, which, due to its intense magnetic field, emits a wide energy spectrum of charged particles and electromagnetic waves into narrow cones about each of its magnetic poles. In binary pulsar systems in which at least one of the stars is a pulsar, protons emitted from the pulsar can strike the surface of the companion star, where they interact to produce nuclear excitations (see Zeilik et al., 1992). Gamma rays are emitted in the de-excitation process, and theses gamma rays travel outward from the system until they may ultimately be detected at the earth.

In spectra from solar flare bursts, the most prominent gamma ray lines are the 4.43 MeV line from ^{12}C followed by the 6.13 MeV line from ^{16}O (Chupp et al., 1984). Since others have already focused on the 4.43 MeV line from ^{12}C in previous solar flare work (Lang et al., 1987; Werntz et al., 1990), we study the 6.13 MeV line from ^{16}O in this article.

Model and Methods

Gamma rays are produced when a proton scatters inelastically off a target ^{16}O nucleus. The ^{16}O nucleus is left in an excited state and emits a gamma ray upon de-excitation,

$$p + {}^{16}O \rightarrow p' + {}^{16}O^*$$

$$^{16}O^* \rightarrow {}^{16}O + \gamma(6.13 \text{ MeV}). \tag{1}$$

The probability that a proton of energy E'_p, in traversing a thickness dx of the target at distance x into the target, will excite an ^{16}O nucleus to the appropriate excitation level is given by

$$dP(x) = \sigma(E'_p)\, n_a(x)\, dx\,. \tag{2}$$

where $\sigma(E'_p)$ is the production cross section for the gamma ray line in question and $n_a(x)$ is the number density of target nuclei (^{16}O).

In most laboratory experiments, the target number density n_a is constant, and the target is so thin that the proton does not lose any appreciable amount of energy in traversing the target. In this case, an integration over the thickness t of the target yields the thin-target approximation for the probability of interaction (and production of a gamma ray),

$$P(E'_p) = \sigma(E'_p)\, n_a\, t\,. \tag{3}$$

In our situation, the protons continually lose energy as they penetrate into the companion star and we must employ a thick-target approximation. The probability of interaction in a thickness dx at a distance x into the companion is

$$dP(x) = \sigma(E_p(x, E'_p))\, n_a(x)\, dx\,, \tag{4}$$

where E(p) is the energy of the proton of initial energy E'_p after traversing the distance x. We change to an integration over initial proton energy

$$dx = dE'_p \left[\frac{dE'_p}{dx}\right]^{-1} \tag{5}$$

where $dE'_p/dx \leq 0$ is the stopping power of the target material.

As the gamma rays are produced at increasing depth into the companion star, their probability of escaping out of the companion material decreases exponentially. As a first approximation, we assume that all gammas produced within one attenuation length of the companion surface escape with 100% probability, and all those produced further in than one attenuation length are completely absorbed before escaping. Hence, for a given proton energy E'_p, we allow it to lose up to the energy loss at one attenuation length $\Delta(E'_p)$. Beyond that point, the proton cannot produce a gamma which will escape. Our gamma ray production probability is then

$$P(E'_p) = \int_{E'_p}^{E'_p+\Delta'(E'_p)} dE_p\, \sigma(E_p)\, n_a \left[\frac{dE_p}{dx}\right]^{-1} . \qquad (6)$$

The dependence on target density n_a is really artificial here. We assume the target density to be given by the nuclear number density times a typical ^{16}O stellar abundance. The stopping power dE_p/dx is also proportional to the nuclear number density, so that our result is independent of the density of the companion. This production probability is then folded with the proton spectrum $N_p(E'_p)$ from the pulsar which strikes the companion star to obtain the number of gamma rays per second produced,

$$N_\gamma = \int_{E_t}^{\infty} dE'_p\, N_p(E'_p) \int_{E'_p}^{E'_p+\Delta'(E'_p)} dE_p\, \sigma(E_p)\, n_a \left[\frac{dE'_p}{dx}\right]^{-1} , \qquad (7)$$

where E_t = 6.52 MeV is the threshold energy for production of the 6.13 MeV gamma ray. The proton spectrum is assumed to obey a power law and is normalized to N_p protons per second,

$$N_p(E'_p) = N_p \hat{N}_p(E'_p) = N_p K (E'_p)^{-\alpha} , \qquad (8)$$

so that normalization constant K is determined from

$$\int_{E_t}^{\infty} dE'_p\, \hat{N}_p(E'_p) = 1 . \qquad (9)$$

By inverting the order of integration and performing one integral analytically, we obtain

$$N_\gamma = \int_{E_t}^{\infty} dE_p \frac{n_a N_p}{(E_t)^{1-\alpha}} \sigma(E_p) \left[\frac{dE_p}{dx}\right]^{-1} \left\{ (E_p)^{-\alpha+1} - (E_p+\Delta(E_p))^{-\alpha+1} \right\} \qquad (10)$$

Data for the gamma production cross section are compiled from the literature (Dyer et al., 1981; Lang et al., 1987; Lesko et al., 1988). An analytic fit to stopping power data has been provided to us (Lang, 1993). The cross section peaks in the 10-15 MeV range and falls slowly with energy (See Fig. 1). The energy loss over one attenuation length is obtained from the stopping power

$$\Delta(E_p) = \int_0^{x_\gamma} dx \left[\frac{dE'_p}{dx}\right] , \qquad (11)$$

where the attenuation length x_γ is obtained by assuming a purely hydrogen composition for the companion (Zombeck, 1990).

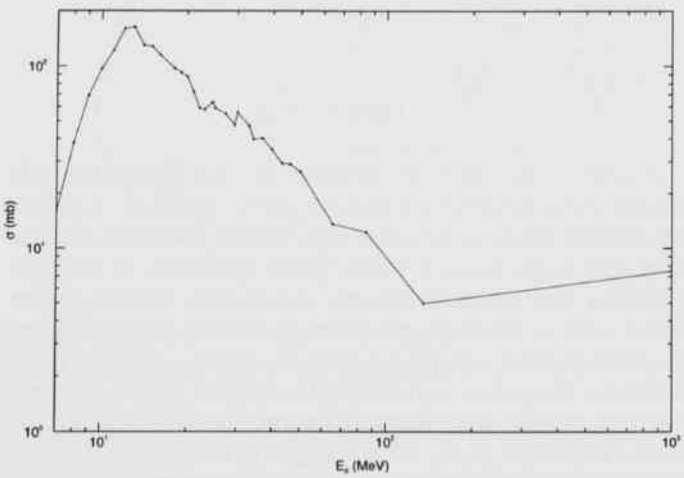

Fig. 1. Cross section for production of 6.13 MeV gamma rays by protons on ^{16}O.

Results and Discussion

The resulting integral is integrated numerically to obtain the number of gamma rays per second produced. We take the power factor for the proton spectrum to be a = 2. A proton influx of $N_p = 10^{41}/sec$ is taken as a baseline. This is an upper limit estimate for the Crab Pulsar based on the luminosity of the surrounding nebula (Zombeck, 1990).

The gamma ray production per unit energy of the incoming protons [the integrand of equation (10)],

$$\frac{dN_\gamma}{dE'_p} = Np(E'_p)\, P(E'_p) , \qquad (12)$$

shows a peak behavior similar to the gamma ray production cross section and 90% of the gamma rays are due to protons with energies $E'_p \leq 50$ MeV (See Fig. 2).

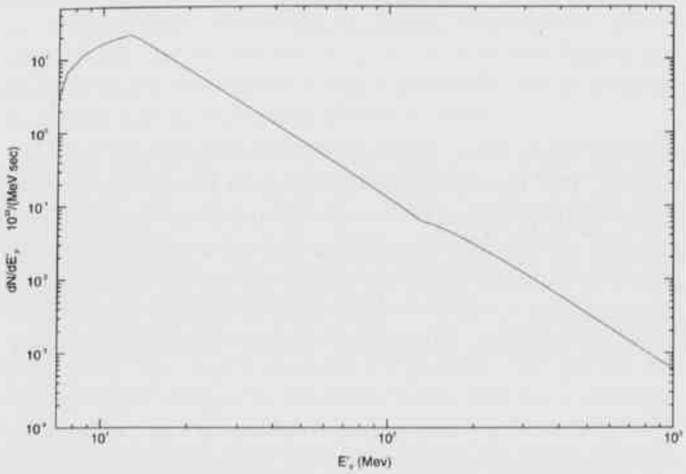

Fig. 2. Production rate of 6.13 MeV gamma rays as a function of energy of incoming protons from the pulsar.

The gamma ray flux at the Earth is obtained by dividing the gamma ray production rate by $4\pi d^2$ where d is the distance to the pulsar. Using 1000 light-years as the distance to the nearest pulsar we obtain

$$\phi_{6.13\gamma} = 2.4 \times 10^{-8}\ (cm^2\ sec)^{-1} \ . \quad (13)$$

In order to determine if this flux is detectable from Earth, we need to consider the background signal which it must compete against. The observed energy flux from continuum gamma rays from the Crab Nebula is (Zombeck, 1990)

$$\frac{d\phi_E}{dE} = 10^2\ \frac{eV}{cm^2 sec MeV} \quad (14)$$

At a gamma ray energy of 6.13 MeV, this provides a gamma ray flux of approximately

$$\frac{d\phi_\gamma}{dE} = \frac{d\phi_E/dE}{E\gamma} = 1.7 \times 10^{-5}\ (cm^2 sec\ MeV)^{-1} \ . \quad (15)$$

We take this to represent a typical background signal. Since the 6.13 MeV gamma ray line from ^{16}O has a full width at half maximum of about 0.1 MeV, the flux from the line has a maximum of approximately

$$\frac{d\phi_{6.13\gamma}}{dE} = \frac{\phi_{6.13\gamma}}{0.1 MeV} = 2.4 \times 10^{-7}\ (cm^2 sec\ MeV)^{-1} \ . \quad (16)$$

Conclusions

We have found the flux of 6.13 MeV gamma rays to be about two orders of magnitude smaller than an estimated background signal. This is probably an order of magnitude below detection threshold. However, more effort needs to be devoted to investigating the proton flux and energy spectrum from pulsars and the calculation of the background signal before their detection is ruled out.

Acknowledgements

The authors are indebted to Dr. Carl Werntz and Dr. Fred Lang for introducting them to this problem and for much useful discussion regarding its solution. The hospitality of Dr. Carol Jo Crannell and the Solar Physics Branch of NASA-Goddard Space Flight Center during visits to NASA-Goddard is gratefully acknowledged. This work has been supported by NASA grant NAG8-277, Arkansas Space Grant Consortium grant NL-3013S, SILO Undergraduate Research Fellowship, and NASA-Goddard Space Flight Center NSF-REU Program.

Literature Cited

Chupp, E.L., D.J. Forrest, P.R. Higbie, A.N. Suri, C. Tsai and **P.P. Dunphy.** 1973. Solar gamma ray lines observed during the solar activity of August 2 to August 11, 1972, Nature 241:333-335.

Dyer, P., D. Bodansky, A.G. Seamster, E.B. Norman and **D.R. Maxson.** 1981. Cross sections relevant to gamma-ray astronomy: proton induced reactions, Phys. Rev. C 23:1865-1882.

Lang, F.L., C.W. Werntz, C.J. Crannell, J.I. Trombka and **C.C. Chang.** 1987. Cross sections for production of the 15.10-MeV and other astrophysically significant gamma-ray lines through excitation and spallation of ^{12}C and ^{16}O with protons, Phys. Rev. C 35:1214-1227.

Lang, F.L. 1993. Private communication.

Lesko, K.T., E.B. Norman, R.-M. Larimer, S. Kuhn, D.M. Meekof, S.G. Crane and **H.G. Bussel.** 1988. Measurements of cross sections relevant to gamma-ray line astronomy, Phys. Rev. C 37:1808-1817.

Werntz, C., F.L. Lang and **Y.E. Kim.** 1990. Solar flare gamma-ray line shapes, Ap. J. Suppl. 73:349-357.

Zombeck, M.V. 1990. Handbook of Space Astronomy and Astrophysics, Cambridge Press, New York, 440 pp.

Zeilek, M., S.A. Gregory and **E.V.P. Smith.** 1992. Introductory Astronomy and Astrophysics. Harcourt Brace Jovanovich, Orlando, 504 pp.