NASA-CR-193262

Final Report for Grant NAG 2-765
LIMITS ON NEUTRINO RADIATIVE DECAY FROM SN1987A *

ANDREW H. JAFFE
Enrico Fermi Institute and Department of Astronomy & Astrophysics, University of Chicago, 5640 S. Ellis Ave., Chicago, IL 60637-1433, USA

ED FENIMORE
MS D436, Los Alamos National Laboratory, Los Alamos, NM 87544, USA

and

MICHAEL S. TURNER†
Enrico Fermi Institute and Departments of Physics and Astronomy & Astrophysics, University of Chicago, 5640 S. Ellis Ave., Chicago, IL 60637-1433, USA
and
NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510-0500, USA

ABSTRACT

We calculate limits on the properties of neutrinos using data from gamma-ray detectors on the Pioneer Venus Orbiter and Solar Max Mission satellites. A massive neutrino decaying in flight from the supernova would produce gamma rays detectable by these instruments. The lack of such a signal allows us to constrain the mass, radiative lifetime, and branching ratio to photons of a massive neutrino species produced in the supernova.

1. Introduction

The occurence of Supernova 1987a in the Large Megellanic Cloud has proven to be among the most fruitful experiments in the heavenly laboratory for the confirmation of "known" physics and the constraining of new physics. Aside from its obvious impact upon the study of the late stages of stellar evolution in general and upon supernova physics in particular, models for SN87a have become an industry for the study of the couplings of light particles (neutrinos, axions) to ordinary matter. In this work, we discuss limits upon the properties of neutrinos independent of specific model for the supernova.

When a supernova occurs, the bulk of the binding energy of the progenitor star ($\sim 3\times10^{53}$ erg) is released in neutrinos, a fact predicted by theory and confirmed by the

*The NASA Technical Officer for this grant is L. Lasher, NASA Ames
†Principal Investigator

observation of a neutrino burst from the supernova, with a characteristic temperature of about $T_\nu \approx 4.5$ MeV. If at least one species of neutrinos is unstable and if it couples to the photon, then some of these neutrinos will decay to photons en route, which are potentially detectable as MeV gamma rays. At the time of the supernova burst's arrival at earth and environs, there were several satellites operating in the solar system capable of detecting the decay photons in the course of their watch for gamma ray bursts. Analyses of the data from one of these detectors, on board the Solar Max Mission (SMM) satellite, has already been presented.[1-4] Here, we examine the data from Gamma Burst Detector on the Pioneer Venus Orbiter (PVO).

2. Expected Gamma-Ray Signal

We assume that 1/3 of the total supernova energy is released in a species of massive neutrinos. These neutrinos then decay in flight into a photon and a light neutrino (*e.g.*, an electron neutrino). Typically, the decay products will each have energies of $1/2 \times 3 \times T_\nu \approx 7$ MeV.

We will consider decays of the form $\nu \rightarrow \nu' + \gamma$. We expect that the parent neutrino will be a massive exotic neutrino, while the daughter neutrino will be a member of a light family such as ν_e. In particular, this decay allows two possibilities: the helicity of the daughter neutrino may either be flipped or the same with respect to the parent as the photon takes away a unit of spin (assuming both neutrinos are relativistic). From quantum mechanics, then, we know that the distribution of the photon in the rest frame of the parent will be proportional to either $\cos^2(\bar{\phi}/2)$ or $\sin^2(\bar{\phi}/2)$, where $\bar{\phi}$ is the rest-frame angle between the directions of the parent neutrino and the photon.

At a given time at the detector, photons are received that resulted from neutrinos decaying on the surface of an ellipsoid defined such that the sum of the time between the supernova and the neutrino decay and the time between the decay and the detection of the photon is equal to the time of detection. Actually, this is only approximately true—there is an additional delay incurred due to the finite mass of the parent neutrino. Furthermore, due to the relativistic beaming of the decay products into the forward direction, many more photons are received from long, skinny ellipsoids (corresonding to short delay times) than from others (corresponding to longer delays). Thus, the relativistic delay will play a correspondingly larger role in these events.

From relativistic kinematics, the angular distribution of daughter photons in turn determines the distribution of photon energies as a function of neutrino energy, for each of the two possible decays (flip or no flip). The time delay is determined by the energy of the neutrino and the decay ellipsoid above. Thus, the photon spectrum as a function of time is determined. It is given by

$$\begin{aligned} dN &= B_\gamma \frac{L_\#(E)}{4\pi D^2} \frac{e^{-t_d/\gamma\tau}}{\gamma\tau} f_i(E,\mu)\, dt\, dt_d\, dE\, d\mu \\ &\quad \times \delta\left(t - t_d\left\{1 - v\mu + \frac{D}{t_d}\left[\sqrt{1 - \left(\frac{vt_d}{D}\right)^2 (1-\mu^2)} - 1\right]\right\}\right) \end{aligned} \tag{1}$$

where B_γ is the branching ratio of the parent neutrino to photons, N is the neutrino number flux at the detector, $L_\#$ is the differential number luminosity as a function of

E, the parent neutrino energy, $D = 1.7 \times 10^{23}$cm is the distance to the supernova, t_d is the time of the neutrino's decay, v is the neutrino's velocity and $\gamma = E/m_\nu$ is the relativistic factor, τ is the neutrino lifetime, t is the time of the photon's arrival at the detector, μ is the cosine of the "lab-frame" decay angle between the parent neutrino's direction and the photon, and $f_i(E,\mu)$ is the distribution of angles as a function of neutrino energy for each of the two helicity possibilities. The Dirac δ function enforces the arrival ellipsoid. In this paper, we will concentrate on the limit of short decay times, $t_d \sim \gamma\tau \ll D$, so the delta function becomes $\delta(t - t_d(1 - v\mu))$.

Changing variables from μ to the photon energy k, and integrating over the decay time t_d gives

$$dN = B_\gamma \frac{L_\#}{4\pi D^2} e^{-2kt/m_\nu\tau} \frac{2k}{m_\nu\tau} f_i(E,k)\, dk\, dE\, dt, \tag{2}$$

where $f_i(E,k)$ now gives the distribution of photon energies as a function of parent neutrino energy:

$$f(E,k) = \begin{cases} 2k/E^2 & \text{no flip} \\ 2(E-k)/E^2 & \text{flip.} \end{cases} \tag{3}$$

Similar results have been derived for related cases before.[5–7] Note that this distribution is a function only of the combination of neutrino parameters $m_\nu\tau$ and B_γ; to break this degeneracy between m_ν and τ, we must relax our assumption of short decay times.

We will also assume that the initial neutrino luminosity is given by a zero-chemical-potential Fermi-Dirac distribution. Normalized to the known temperature and total energy of the suprenova, this gives

$$L_\#(E) = \frac{120}{7\pi^4} \frac{E_T}{T_\nu^4} \frac{E^2}{1 + e^{E/T_\nu}}. \tag{4}$$

Finally integrating over this distribution, this gives the photon spectrum as a function of time,

$$\frac{dN}{dk\, dt} = \frac{240}{7\pi^4} \frac{B_\gamma}{4\pi D^2} \frac{E_T}{T_\nu^2} \frac{2k}{m_\nu\tau} e^{-2kt/m_\nu\tau} h_i(k/T_\nu). \tag{5}$$

where h_i is a separate function for each of the helicity possibilities that is of order unity for the energies and temperatures of interest.

3. PVO Instrumentation

The Pioneer Venus Orbiter Gamma Burst Detector (OGBD)[8] was designed to detect gamma ray bursts—transient, high energy events that last from milliseconds to tens of seconds. It has four separate bands, 0.1–0.2 MeV, 0.2–0.5 MeV, 0.5–1 MeV, and 1–2 MeV. In the background mode that we will be using, it has a timing resolution of 12 or 16 seconds with full spectral information (*i.e.*, counts in each of the four bands).

Because gamma-ray bursts are singular events, the OGBD was designed to have full-sky coverage, although it is incapable of independently providing directional information about the photons it receives. However, the OBGD detectors do, in fact, face the South Ecliptic Pole, and thus are ideally suited for measurements of gamma-rays from the LMC. Thus, even though it was not "pointing" at the LMC at the time, it can still be used to analyze data associated with the supernova. Although the response of the instrument changes for is a function of the gamma-ray direction, the bulk of the decay photons come from the direction of the supernova itself on the sky (the exceptions are the rare photons which reach us after decaying at a very large angle from the outgoing neutrino).

4. Analysis

After a brief look at the data from the four OGBD channels in Fig. 1, it is clear that there is no obvious signal of gamma rays over the background (the variation in the signal is in fact consisitent with pure $\sqrt{N}$ noise). Thus, we will be putting limits on our free parameters: $m_\nu \tau$ and B_γ.

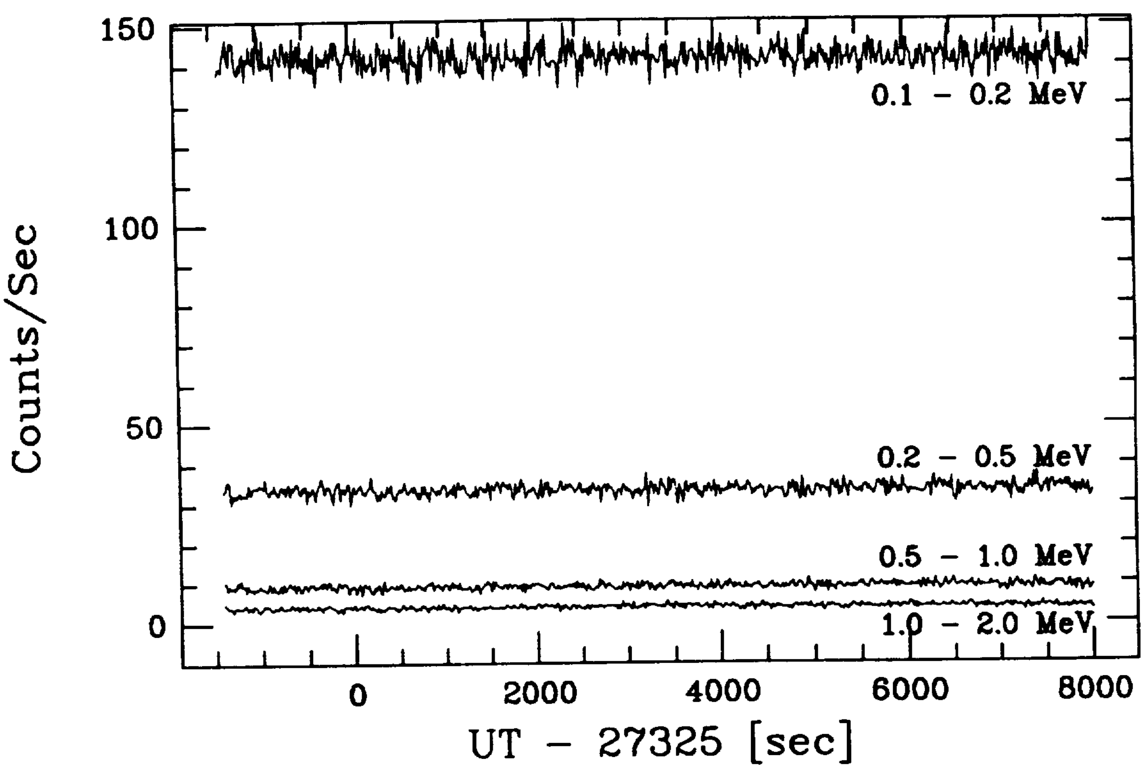

Fig. 1. Raw counts/sec in each of the four OGBD channels for the time surrounding the arrival at Venus of the supernova's optical burst, at time $UT - 27325 = 0$ sec.

To do this, we utilize the SPANAL code which was developed for analyzing the instantaneous spectra of gamma-ray bursts. Given the spectrum averaged over 12- or 16-second bins, SPANAL calculates the best fit set of parameters, $m_\nu \tau$ and B_γ, for the data (thus far, we simulataneously fit the data for up to six time bins, or about 90 seconds after the supernova). In Fig. 2, we show the results for a small area of parameter space, only analyzing the first time bin after the expected arrival of the supernova gamma-rays. The points are χ^2 minima, with $\chi^2 \approx 22$ (with 2 degrees of freedom) for all of the points. For the point $m_\nu \tau = 10^3$ keV sec, we show in addition the 1-σ upper limit on B_γ; it is not very far from the χ^2 minimum, so we expect that the actual upper limits are not far from these points throughout. The area below the line is roughly excluded; the area above is allowed by the OBGD data. To compare with previous analyses, Kolb and Turner[2] found a limit in a similar area of parameter space of $B_\gamma \lesssim 2.8 \times 10^{-10}$ without taking into account the angular distribution of decay photons (by simply assuming $k = E/2$).

In order to more fully map the limits of parameter space, we must keep the full information of the arrival ellipsoid in the delta function of Eq. 1, and compare to longer signals from the spacecraft. For such long arrival times that this effect matters, however, the expected number of gamma rays is much lower (since fewer neutrinos would have decayed before reaching earth), so the limits will be somewhat weaker. Nonetheless, because of the quality and amount of the PVO data, we expect to strengthen the current limits on the radiative-decay properties of neutrinos. We are currently pursuing the analysis in this realm.[9]

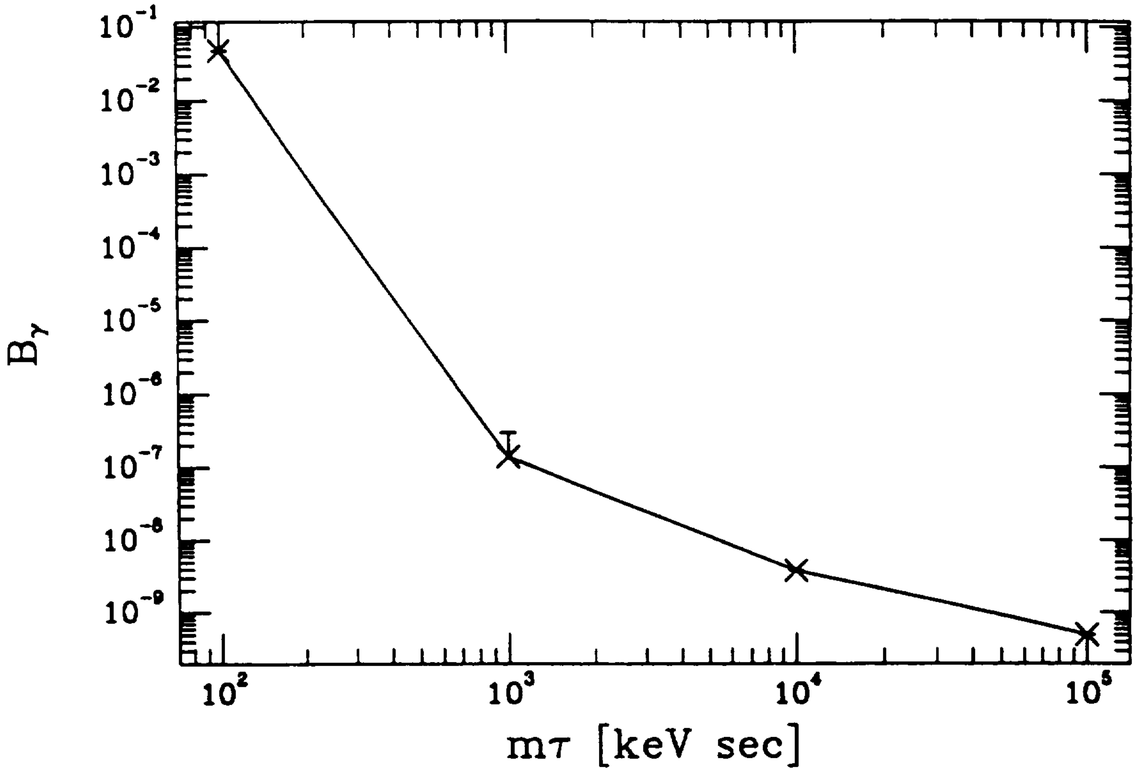

Fig. 2. χ^2 minima for the fit of the theoretical spectrum of photons (Eq. 5) to the OGBD data after the supernova. For $m_\nu \tau = 10^3$ keV sec, we also show the 1-σ upper limit.

References

1. E.L. Chupp, W.T. Vestrand and C. Reppin, *Phys. Rev. Lett.* **62** (1989) 505.

2. E.W. Kolb and M.S. Turner, *Phys. Rev. Lett.* **62** (1989) 509.
3. F. von Feilitzsch and L. Oberauer, *Phys. Lett.* **B200** (1988) 580.
4. J.M. Soares and L. Wolfenstein, *Phys. Rev. Lett.* **64** (1990) 1310(C).
5. S. Dodleson, J.A. Frieman and M.S. Turner, *Phys. Rev. Lett.* **68** (1992) 2572.
6. J.M. Soares and L. Wolfenstein, *Phys. Rev.* **D40** (1989) 3666.
7. A. Burrows, D. Klein and R. Gandhi, *Phys. Rev.* **D45** (1992) 3361.
8. R.W. Klebsadel, W.D. Evans, J.P. Glore, R.E. Spalding and F.J. Wymer, *IEEE Trans. Geosci. Rem. Sens.* **GE-18** (1980) 76.
9. Earlier versions of this document have previously appeared as Jaffe, A., Fenimore, E. and Turner, M., in *Beyond the Standard Model III*, Ottawa, Ontario, Canada, June, 1992; Jaffe, A., in *The Fermilab Meeting*, C. Albright *et al.*, eds. (1993) 1456.