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Cosmological Gamma-Ray Bursts

Edward Fenimore*, Richard Epstein, Cheng Ho, and Johannes Intzand

Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). Gamma-ray bursts are brief events that dominate the emission from all other gamma-ray objects in the sky, flicker for tens of seconds, and then turn off. Their nature remains uncertain despite years of efforts to understand them. One hypothesis is that the bursts arise within our galaxy albeit in an extended halo of neutron stars. Another hypothesis uses the isotropic distribution of gamma-ray bursts to argue that they come from nearly the edge of the universe. If gamma-ray bursts originate from cosmological distances, then the expansion of the universe should cause the dimmer (and presumably further) bursts to last longer. We have developed methods for measuring this time stretching, related the time stretching to the distance to the bursts, determined how the detailed physics causes temporal variations, and found the amount of total energy and peak luminosity that the events must be producing.

1. Background and Research Objectives

Gamma-ray astrophysics is undergoing rapid expansion since the April 1991 launching of NASA's second "Great Observatories," the Compton Gamma-Ray Observatory (GRO). One of the most intriguing results from GRO concerns gamma-ray bursts (GRBs). Gamma-ray bursts were discovered at Los Alamos [1]. These brief events dominate by a huge factor the emission from all other gamma-ray objects in the sky, flicker for tens of seconds, and then turn off. For a review see [2].

In the past, evidence accumulated favoring the "local" galactic interpretation for GRBs; that GRBs occur on neutron stars within a few kpc. The most compelling evidence has come from the observations by the LANL/ISAS Gamma-Ray Burst Detector on the Ginga satellite.

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This experiment discovered two bursts that exhibited pairs of harmonically spaced absorption lines in the energy range 20-50 keV, the signature of a nearby neutron star [3].

Recent observations with the Burst And Transient Source Experiment (BATSE) on the GRO satellite have shattered the prevailing view that gamma-ray bursters are galactic [4]. The BATSE experiment observed that GRBs are distributed isotropically relative to the Earth, yet there are fewer weak events than one would estimate by extrapolating from the number of strong bursts assuming a homogeneous distribution. The deficiency of weak (presumably more distant) events occurs because BATSE is seeing nearly all the events. The bursts could conceivably still be within our galaxy if they are in an extremely large, extended halo (core radius ~50 kpc) or they are distributed like distant galaxies, that is, they are at cosmological distances.

If GRBs are at cosmological distances, it would be one of the most important astrophysical discoveries in the past fifty years with important impact on many issues. The energy release mechanism must be able to generate the equivalence of nearly the entire energy output of a supernova in gamma rays rather than neutrinos and optical light. Such an effective conversion of energy into gamma rays has not been known before. Cosmological GRBs could provide an unprecedented view of the overall evolution of the universe.

By combining our unique data bases from our experiments on Pioneer Venus Orbiter (PVO) and Ginga with data from GRO, our work sought to put limits on how far away the bursts are. This is crucial since currently it is not clear if they are local (within our galaxy) or extremely far away (further than most galaxies). We addressed both the microscopic physics of how the gamma-rays can be generated as well as the macroscopic physics of the energy source that drives the bursts.

2. Importance to LANL's Science and Technology Base and National R&D Needs

The question of whether gamma-ray bursts are cosmological or galactic has been called the "Great Debate of the 90s" similar to earlier astrophysical debates such as the nature of the expansion of the universe (1930s) or the nature of quasars (1960s). In fact, a public debate was held pitting the cosmological view [5] against the galactic view [6]. Our work has been on the forefront of this topic with important contributions to both sides.

LANL has a multi-pronged experimental effort for both programmatic activities (treaty verification) and basic research (the study of high-energy cosmic sources). The basic research effort is vital for ensuring the health of the programmatic activities in x-ray and gamma-ray instrumentation by providing testbeds for developing instruments (PVO, Ginga, MOXE, and

ALEXIS were started this way). The theoretical efforts provide insight such that the designs of our experiments address the most important issues.

3. Scientific Approach and Results

We have explored the possible radiation mechanism for the soft- gamma repeaters [7], particularly those that can explain how the source can exceed the maximum allowed radiation pressure by 10^3 . We investigated how a super-strong magnetic field could confine the plasma and concluded it would be most likely possible if the radiation was 100% polarized (at least to one part in 10^4). We determined that the statistical approach of Quashnock and Lamb [8], which claimed that the GRB positions contained too many close encounters implying that the bursts repeat, did not properly incorporate the uncertainties in the burst location. We conclude that there is no evidence for bursts repeating on a time scale of months [9].

We developed the technique of using the average auto-correlation of gamma-ray bursts to measure time scales. Heuristically, an auto-correlation measures the average relative intensity between points in the time history that are separated by an amount of time called the lag. The technique can be used to detect changes in time scales that might be associated with the expansion of the universe if GRBs are at cosmological distances. We have derived the relationship between time stretching and the distance to the events. The resulting distance is much larger than expected, placing the dim GRBs beyond where galaxies have formed [10]. We concluded that either a large fraction of the time stretching is intrinsic to the bursts (and therefore cannot be used as evidence that they are cosmological) or that it is only a coincidence that the nearby GRBs appear homogenous. To assist in that analysis, we accurately calculated the efficiency of the ability for BATSE and PVO to measure the homogeneity [11].

The key to relating time stretching to distance is an energy correction that accounts for the tendency for peaks to be narrower at high energies. We have determined that this tendency follows a particular function: the width scales as $E^{-0.4}$ where E is the energy [12]. Extremely high energy photons have been observed from GRBs that require a super relativistic outflow with a bulk Lorentz factor between 10^2 and 10^3 . It has been proposed that merging neutron stars generate a fireball that expands as a shell. We show that the expansion must have much smaller patches on the shell than previously assumed. These patches can have a large effect on the bulk Lorentz factor, a key ingredient for all models. The observed time structure also limits the size of duration of substructure within the shell [13]. This predicts the size of the emitting regions, which we use to calculate the limits on the relativistic bulk Lorentz factor [14].

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