Primordial black holes (PBHs) are hypothetical objects that could have formed during the early universe. Those with masses below $10^{-19}M_\odot$ are predicted to have evaporated by now through Hawking radiation. PBHs above this limit may contribute a significant fraction of the dark matter in our universe. However, there are theories that predict even lower mass black holes to have survived to the present day. These low mass BHs can be detected through the gravitational lensing of a gamma-ray burst. Keeton and Petters (2006) show how this lensing can cause interference in the energy spectrum of the GRB. We create energy spectra of 7 GRBs using data from the Fermi Gamma-ray Space Telescope. Our analysis is similar to those done using Fermi/GBM data, but we want to look for lower masses and thus use higher energy photons from the Large Area Telescope (Fermi/LAT). The spectra are fit well by the Band model for GRBs, but show interesting deviations from the power law tail at high energies. We will need to fit the interference model due to PBH lensing to our data before making any statements regarding the features in our spectra.

1. Introduction

In addition to the stellar-mass and supermassive black holes that we observe, scientists have hypothesized the existence of objects called primordial black holes (PBHs; Hawking 1971; Hawking and Carr 1974; Carr 1975). These black holes could have formed during the early universe when it was extremely dense. The Schwarzschild radius of a black hole is $2GM/c^2$. The Sun, for example, would have a Schwarzschild radius of 3 km. Since the Schwarzschild radius scales linearly with mass, a PBH with $M = 10^{-18}M_\odot$ would have a radius on the scale of an atomic nucleus! Because of their extremely small size, these objects would have little effect on their surroundings and thus could contribute a fraction of the dark matter mass in our universe. If these PBHs exist, there are alternative gravity models that could push their possible masses even lower. Finding PBHs at any low mass would provide important information on how our universe works.

Braneworld gravity is one model that has been proposed as an alternative to General Relativity. The type II Randall-Sundrum model includes a 5-dimensional spacetime in which our 4-dimensional “brane” lies (Randall and Sundrum 1999). This model also allows the existence of primordial black holes that are forbidden by General Relativity. GR predicts these objects of masses lower than $10^{-19}M_\odot$ to have evaporated by now through Hawking radiation (Page 1976). But the existence
of an extra dimension in braneworld gravity affects the spacetime geometry around black holes in such a way that they evaporate more slowly (Guedens et al. 2002). Finding black holes with masses less than $10^{-19} M_\odot$ would help confirm alternate gravity theories. In fact, black holes as small as 1 kg ($10^{-30} M_\odot$) may exist under the type II Randall-Sundrum model (Majumdar 2003; Majumdar and Mukherjee 2005).

The motivation of this project is to put constraints on the abundance of these primordial black holes. Gravitational lensing is a one potential probe of these objects. Their small masses and radii require a high energy source to produce visible lensing effects. Gamma ray bursts are such a source and are the subject of this project. Because the Schwarzschild radius of the black hole is on the order of photon wavelengths, interference patterns are produced in the energy spectra of the lensed burst due to time delays between lensed images. The model of this interference pattern is shown in Fig. 1. This is dubbed ‘attolensing’ (Keeton and Petters 2006). The energy scale where this pattern occurs scales inversely with the black hole mass. Although similar to femtolensing by low mass black holes in GR (Gould 2002), attolensing patterns differ slightly and are visible at different energy scales. Our analysis is similar to others who looked for the effects of femtolensing in Fermi/GBM spectra (Barnacka et al. 2012). For our analysis, it is important to look not only at gamma ray burst spectra, but specifically at the highest end of their emission so as to probe lower mass scales for PBHs.

Gamma ray bursts are events of high energy that last time spans on the order of seconds to minutes. To investigate their properties we look at data from the Fermi Gamma-ray Space Telescope. There are two instruments onboard Fermi that together gather photons with energy from 10keV to 300 GeV. The Gamma-ray Burst Monitor (GBM) contains 12 Sodium Iodide (NaI) scintillators and 2 Bismuth germanate (BGO) scintillators that cover from 8keV to 40MeV (Meegan et al. 2009). The GBM is triggered by a change in count rate in two or more of the NaI detectors. The triggered event is recorded in the form of counts in 128 energy bins. The other instrument aboard Fermi is the Large-area Telescope (LAT). The LAT is a pair conversion telescope that is sensitive to energies of 20 MeV to 300 GeV (Atwood et al. 2009). LAT data consist of photons with energy and position information that may be binned at a later time. Since we are looking for high energy events on the range of 10s to 100s of MeV, GRBs with significant LAT data are our main focus.

2. GRB Selection

The NASA Fermi website lists 32 confirmed LAT GRBs. GRB Selection

The NASA Fermi website lists 32 confirmed LAT GRBs. GBM and LAT data can be downloaded using trigger time, right ascension, and declination in the query. This information is garnered through the Gamma-ray Coordinate Network (GCN) Circulars. We examine the GRB using the

\[1\] http://fermi.gsfc.nasa.gov/ssc/observations/types/grbs/grb_table/
Fig. 1.— Sample energy spectrum from Keeton and Petters (2006) of a gamma-ray burst attolensed by a black hole with $M = 10^{-18} M_\odot$. (a) The intrinsic energy spectrum overlaid with the attolensed spectrum. Plotted is the logarithm of the number of photons per logarithmic energy interval. (b) Here, the ideal spectra are plotted with histograms of a sample ‘observation’ as it would be seen by Fermi.

Fermi Science Tools suite of commands.\(^2\) The command `gtselect` allows cuts to be made that filter out Earth limb emission and non-burst photons from the LAT data. The position reported by the GBM and GCN circulars are fairly accurate but do not give the exact position of the center of the burst. This is due to the GBM’s use of only the initial moments of the burst’s lightcurve to compute its position. The LAT also has intrinsic uncertainties in position due to the way it recreates the path of the incident high energy photons. To better localize the burst we use the command `gtfindsrc`, which outputs the best point source location using a likelihood test-statistic (TS). We create a TS map centered around both the reported location and the suggested location given by `gtfindsrc`, as seen in Figure 2, to confirm we are looking at the correct GRB. We also create lightcurves of the triggered GBM detector and the LAT using `gtbin` to confirm the elapsed time of the burst. A GBM lightcurve is shown in Figure 3. We chose 7 GRBs with well defined positions and significant LAT counts. This also excludes any GBM GRBs that triggered mid-burst and thus are missing full photon data.

\(^2\)http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
3. Energy Spectra

To create a joint spectrum, we treat GBM and LAT data in different ways. Each GBM detector carries its own count information and thus is analyzed separately. We only use one triggered detector in our analysis, which is usually one of 2-3 NaI detectors that triggered. The lightcurve in Fig. 3 has a fairly constant level of background radiation. We take advantage of this fact and use 20s of data from before the trigger time for background subtraction. The `gtbin` tool creates a file containing an energy spectrum for the selected background and duration of the burst itself. GBM photons are already binned in 128 energy channels. The LAT data do not require a background spectrum because of the rejection of cosmic rays by the instrument itself and the short time interval over which the GRB data was taken, since the rate of high energy non-burst photons is very low. We use XSPEC\(^3\) for the analysis of the GBM and LAT spectral files created using `gtbin` in which we selected 30 energy bins for the LAT data. XSPEC specifies the background of the GBM and the response matrices for each instrument which is included in the downloaded data from Fermi. We fit our data using a GRB model within XSPEC. This model is the Band function. The Band

\(^3\)http://heasarc.gsfc.nasa.gov/xanadu/xspec/
Fig. 3.— Lightcurve of GRB 110721A from a triggered GBM detector. This GRB has a duration of 25s.

function features a power law with an exponential cutoff at low energies and a steeper power law at higher energies (Band et al. 1993). We create plots joining GBM and LAT spectra using XSPEC. These plots are shown in Figures 4 and 5.

4. Discussion

As seen in Figures 4 and 5, our data seem to be fit relatively well by the Band model. However, at higher energies, there are some interesting deviations (greater than $3\sigma$), from the power law tail. Such large deviations point to this being a real feature of the data and not just statistical noise. It is not possible to know the cause of these features until we have fit the interference model from Figure 1 to our data. Even then, our task would be to rule out any other possible causes for the deviations. It is also noted that our power law indices for the fit LAT data were similar across all 7 GRBs, ranging from -2 to -2.2. While not directly relevant to this project, this information could be useful to those studying the mechanisms of GRB creation, as the power law tail is thought to be indicative of inverse compton scattering (Wei and Lu 1998).
5. Summary

The goal of this project was to search for evidence of primordial black holes in the energy spectra of gamma-ray bursts. We faced some challenges in localizing the GRBs due to inaccurate positions provided by the GBM data and reports by GRB scientists. Another issue was finding GRBs with more than a few LAT counts. We wanted to ensure correct and significant spectra. We chose 7 GRBs that fit this criteria and created plots of their energy spectra using XSPEC. These spectra were well fit using the Band model for GRBs, but there were some deviations from the power law tail at high energies. Our future work includes fitting the interference model due to primordial black hole lensing to our data.

REFERENCES

Hawking, S. W., 1971 MNRAS, 152, 75
Majumdar, A. S., 2003, Phys. Rev. Lett. 90, 031303
Page, D. N., 1976, Phys. Rev. D 13, 198; 14, 3260

This preprint was prepared with the AAS \LaTeX\ macros v5.2.
Fig. 5.— Energy spectra of GRBs 081024B, 090323, 090510, 091031, 100325A, and 110328B.