GRB Sensitivity Update

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1 Introduction

This memo is a continuation of previous work on GRB sensitivity. Some results from the previous memo have been updated, and I present new results on constraining GRB properties.

2 Distance probed by Milagro

As in the previous memo, I calculate the number of photons expected (N_γ) to be detected by Milagro from a GRB with duration $t90$, redshift z, isotropic energy E_{iso}, occuring at some zenith angle θ, with a power law spectrum extending from E_{min} to E_{max} with index α. I use Milagro's effective area for MC gammas, and account for the interaction with infrared background photons using various models (here I used Stecker's baseline model, see astro-ph/0107103). For a given duration I then estimate the background (N_{bkg}), and compare this to the number of photons. If the poisson probability for observing $N_\gamma + N_{bkg}$ events when expecting N_{bkg} is less than 1e-20 (or whatever threshold one cares to set to claim a detection), then for that set of parameters a burst is observable. The number of photons expected for an E^{-2} spectrum between 100 GeV and 10 TeV is shown in Fig. 1. In the figure, the dotted lines are the number of photons expected in Milagro for the listed burst parameters. The horizontal lines are the minimum number of photons needed for a poisson probability less than 1e-20. Where the lines intersect gives the maximum redshift to which a burst with that set of parameters may be seen. The maximum observable redshift is plotted as a function of isotropic energy in Figs. 2 and 3 for a 1e-20 probabilty and 5 σ probability respectively. The two probability thresholds are shown to see how much of an effect GRB localizations will have on our sensitivity. Included on the plots are the redshifts and implied isotropic energies of measured GRBs. These points are binned in duration ($t_{min} < t90 < t_{max}$) with the color of the point corresponding to the color of the line with duration t_{min}. For example, the dark blue line is for a 40s duration, and the dark blue dots correspond to GRBs with measured z having durations between 40 and 100 seconds. So in order to observe one of the blue points, it must be at least beneath the blue line. When the distance and duration are taken into account, there are two bursts that we would have detected (assuming equal energy and duration of the high and low energy components). GRB030329 would have been observable at either probability threshold, while GRB980425 becomes detectable at 5σ. Both of these GRBs were not in our field of view.

In this plot there are a large number of distant, high energy bursts. This is likely due to a bias, and does not necessarily reflect the true distribution. At large redshifts there is more volume available and so more bursts. But these must be bright in order for them to be detectable. Nearby there are fewer bursts, but the dim ones are detectable. Now that SWIFT is up, hopefully we will get a better idea of the true distribution.

An upper limit may be set from this analysis. For the period over which we searched for GRBs (T years), we there was no significant detection. So at the 90% confidence level there are fewer than 2.3/T GRBs per year that emit photons with energies between 100 GeV and 10 TeV and occuring within the space probed by Milagro.

3 GRB Simulations

In the above, it is the average number of photons that are calculated. To do a proper analysis, I should take into account poission fluctuation of the number of signal and background events. Then I can take models for the distribution of GRB redshifts and isotropic energies, the measured duration distribution from BATSE, and throw a large number of GRBs at random position on the sky (actually on a $cos(\theta)$ distribution) to see how many we would see for that set of models.

3.1 Case 1: Measured Distribution

There are only on the order of 30 GRBs with measured redshifts, so it is hard to get a redshift distribution from the data. In addition to this, the sample is likely to contain biases. However, an attempt may be made to use this data. In Fig. 4 is a plot of the measured redshift distribution. I have fit this to a function of the form:

$$Az^2e^{-(z-z_o/\sigma)^2} \quad (1)$$

One would expect the nearby behavior of the distribution to go like z^2 since the number should be proportional to the surface area of a sphere with radius z and the distribution should go to zero at $z = 0$. In Fig. 5 is shown the implied isotropic energy of these bursts. This distribution doesn't have a very clear shape, but I smoothed it, and fit it to a gaussian. The duration distribution I used is just the measured BATSE distribution, fit to a sum of two gaussians (Fig. 6).

I use these distributions to simulate a large number of GRBs. I throw the bursts on a $cos(\theta)$ distribution to account for our exposure, and draw randomly from the redshift, energy, and duration distributions. Given a θ, redshift, energy, and duration I can calculate the expected number of photons arriving at the earth from:

$$I_0(z, E_{iso}) = \frac{(1+z)}{4\pi D_l^2} \frac{E_{iso}}{\int_{E_{min}}^{E_{max}} E E^{-\beta} dE}, \tag{2}$$

where $I_0(z, E_{iso})$ is the normalization to the spectrum for a fixed total isotropic energy E_{iso}. And then:

$$N_{\gamma,exp}(z, E_{iso}, \theta) = I_o(z, E_{iso}) \int_{E_{min}}^{E_{max}} A_{eff}(E, \theta) E^{-\beta} e^{-\tau(E,z)} dE. \tag{3}$$

See my previous memo for more details.

I then account for the poisson fluctuations of $N_{\gamma,exp}$ by generating a random probabilty (P) and finding what value of $N_{\gamma,obs}$ gives this probability. Where

$$P = \sum \frac{e^{-N_{\gamma,exp}} (N\gamma, exp)^{N\gamma,obs}}{N\gamma, obs!} \tag{4}$$

I can then solve for $N_{\gamma,obs}$ given P and $N\gamma, exp$. The same procedure is carried out for calculating the number of background events (i.e, given an $N_{bkg,exp}$, I calculate a $N_{bkg,obs}$). Finally, I calculate the poisson probability of observing $N_{\gamma,obs} + N_{bkg,obs}$ events when expecting $N_{bkg,exp}$. If this probability is less than our threshold for claiming a detection in the untriggered search, then we would be able to see it.

3.1.1 Results

The results of the simulation are shown in Fig. 7. The top three plots in the figure are the redshift, duration, and energy distributions of the simulated bursts. I only threw out to a redshift of 2 since we don't expect to see much beyond there. The bottom left figure is the redshift distribution of the observed bursts (those with a probability less than 1e-15). The bursts were thrown out to a zenith angle of 90°, with 41858 out of 5000000 (0.84%) being detected. The total rate of GRBs in the universe implied by BATSE is about 700 bursts/year. Since I threw bursts out to 90°, this means 350 GRBs/year. But I only threw out to $z = 2$, which contains about 84.4% of all bursts, given this redshift distribution. This gives 295 bursts, of which we should see 0.84%, or about 2 per year.

Since we have not observed a GRB with Milagro, this analysis may be used to set upper limits on the burst parameters. If we assume that all bursts have a high energy component, and that the total energy in this component is some constant factor times the total energy in the low energy component, a limit may be set on this factor if we assume that it is the same for all

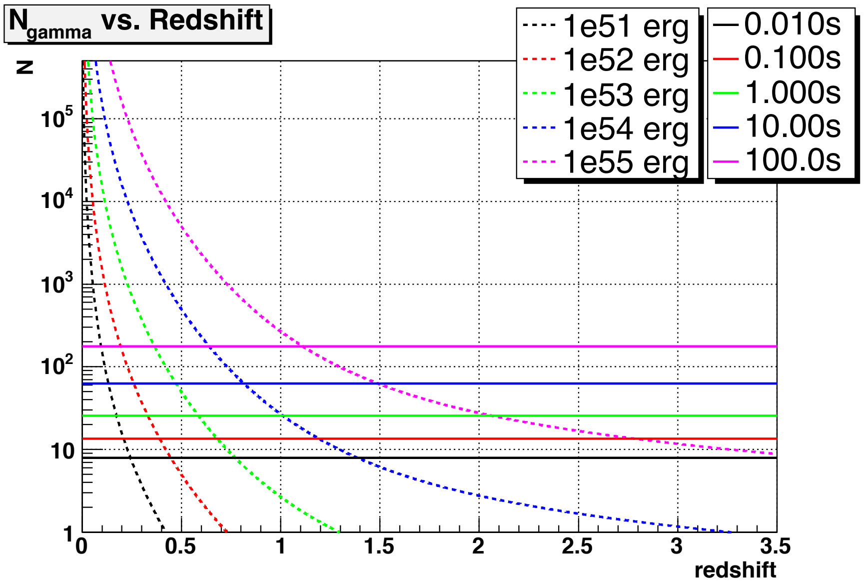

Figure 1: Number of photons detected for an $E^{-2.0}$ spectrum from 100 GeV to 10 TeV vs redshift for different amounts of isotropic energy. The horizontal lines are the minimum number of photons required for a 1e-20 probability for different durations.

bursts. This is shown in the bottom right plot on Fig. 7. This plot was made by simply scaling the number of photons expected by this factor (since N_γ is just proportional to E_{iso}) and calculating the number of GRBs expected per year.

For a total exposure of 3 years, our 90% confidence level upper limit is $2.3/3 = 0.77$ events per year. On the plot a line is drawn to show this value. Therefore, from this analysis we can say that, at the 90% confidence level, the emission between 100 GeV and 10 TeV is less than 12% of the low energy emission.

The next step in this analysis is to take any model that makes a prediction for the simulated parmeters, and obtain limits. I can then take a large number of different models, and see how we can constrain them.

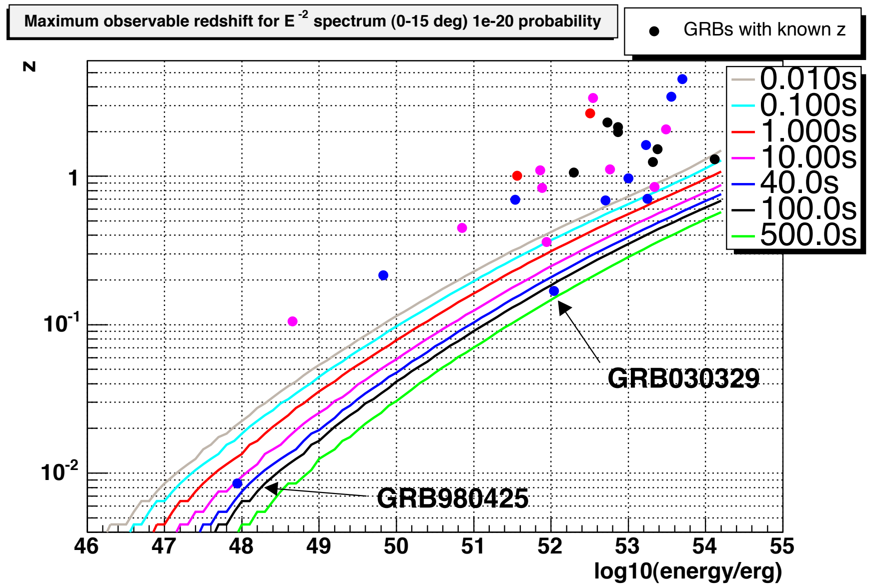

Figure 2: Maximum observable redshift for an E^{-2} spectrum from 100 GeV to 10 TeV vs isotropic energy for different durations. A 1e-20 probability was required to claim a detection. This is only for zenith angles less than 15°, and therefore represents the best case scenario. GRBs with measured redshifts are included for reference. To be observable, the dot must be below the line of the same color. GRB030329 is the only one that meets this requirement.

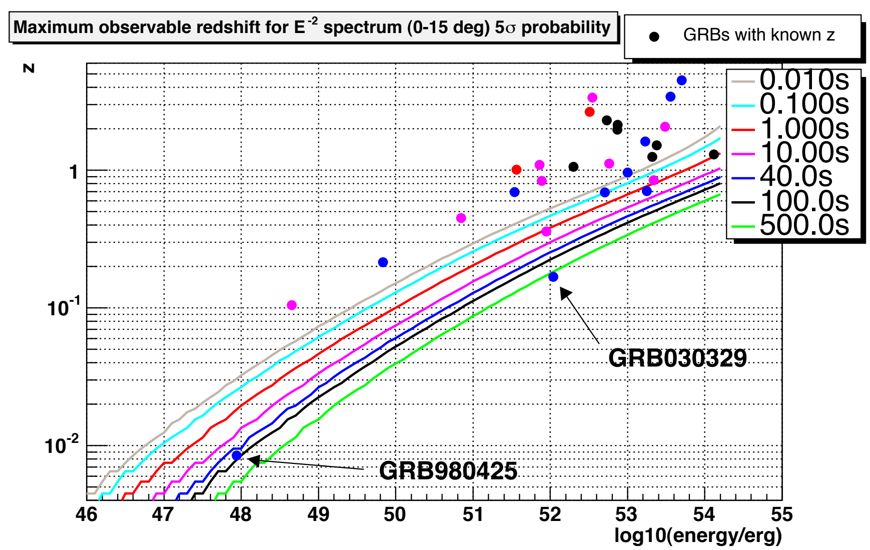

Figure 3: Same as above, but with a 5σ probability required to claim a detection. Now GRB980425 would be detectable also.

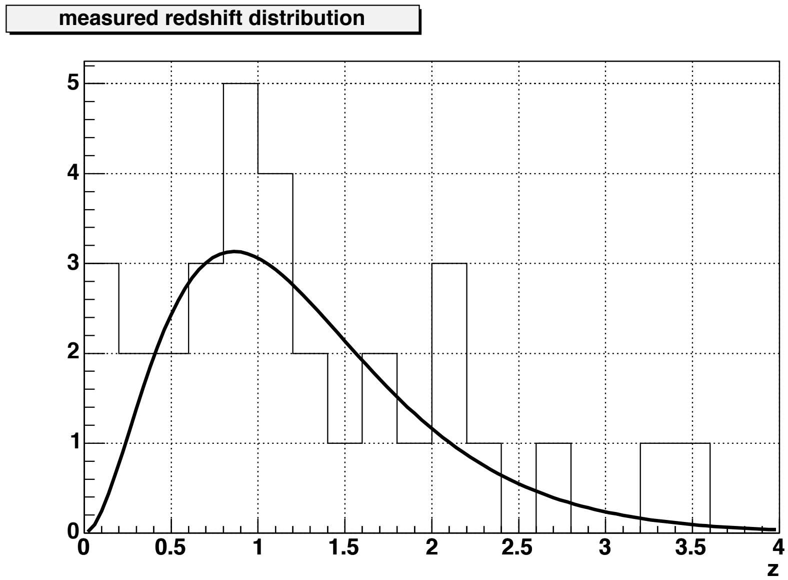

Figure 4: Fit to the measured redshift distribution.

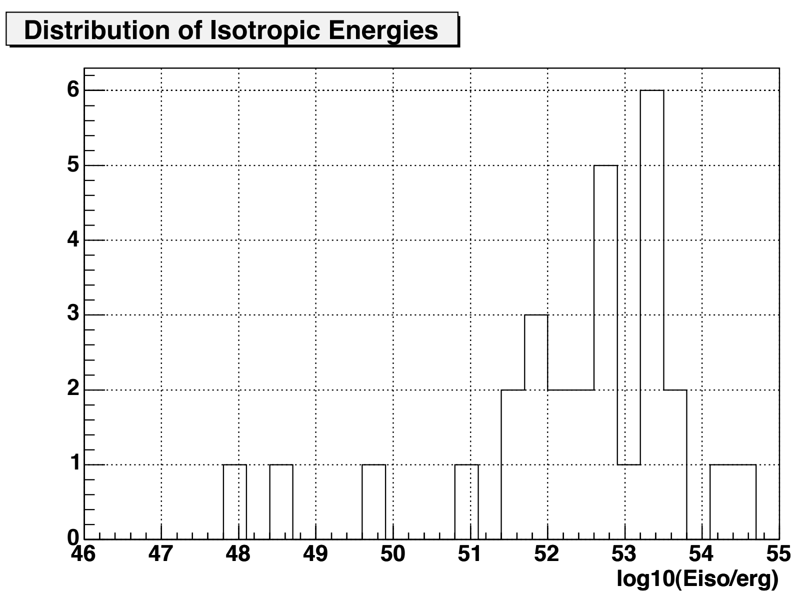

Figure 5: Distribution of implied isotropic energies.

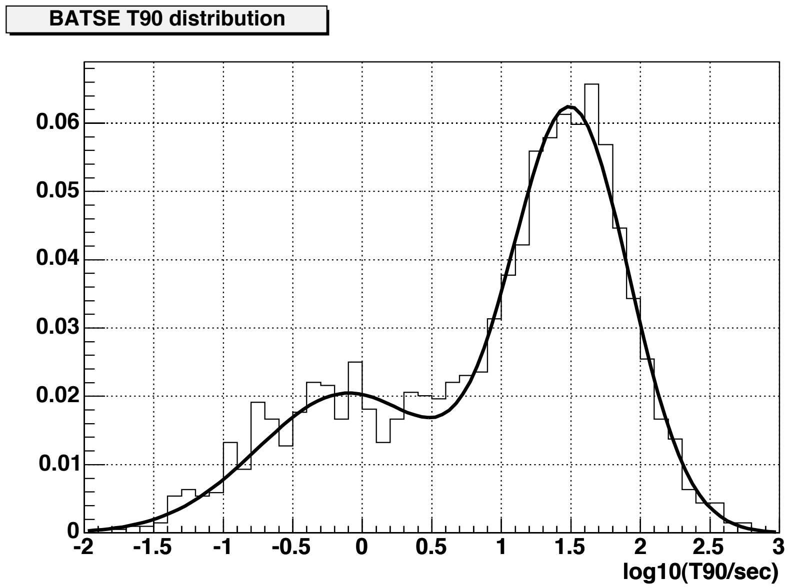

Figure 6: BATSE T90 distribution fit to 2 gaussians.

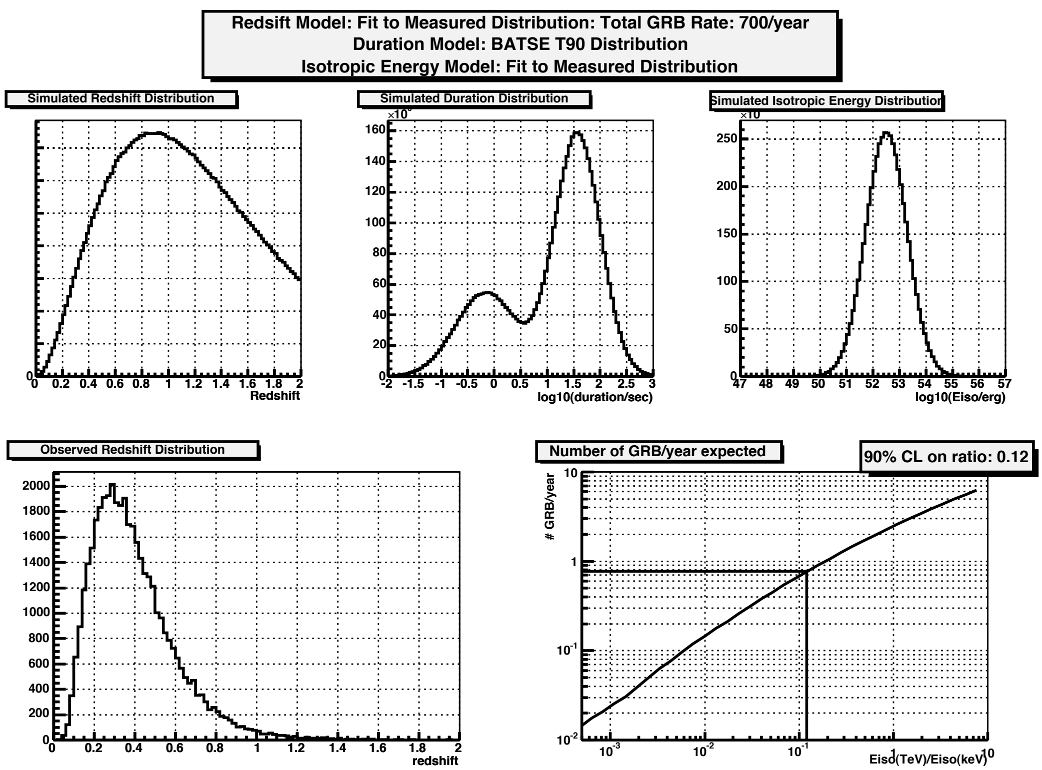

Figure 7: Results of the simulations with a simple model. It is assumed that all GRBs have a high energy component that is a constant factor times the low energy component, and which is the same for all bursts. Varying this factor until the number of GRBs that would have been observed agrees with the non-detection, allows a limit to be set on this factor.