On the Combination of Different Observational Classes of Gamma-Ray Bursts into a Single Limit

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Because of the proliferation of instruments for the detection of gamma-ray bursts, it is important to determine which classes of bursts can be combined in the calculation of AMANDA's ν flux limits. We propose a method of calculating a combined limit for bursts detected by BATSE in both real-time (triggered) and off-line (non-triggered) searches, along with bursts from the 3rd InterPlanetary Network (IPN). The potential for incorporating future missions (e.g. Swift, GLAST) into a combined flux limit is also briefly discussed. Finally, this combined limit is placed in the context of AMANDA's ability to test the Waxman-Bahcall GRB model.

1. Introduction

Since the demise of BATSE in May of 2000, the primary source of gamma-ray burst (GRB) timing and localizations has been the satellites Third InterPlanetary Network (IPN) [1]. The number of potentially observable IPN bursts to date significantly exceeds the number of BATSE bursts that have thus far comprised AMANDA-II's search for GRB neutrino emission (see Table 1). If all of these bursts can be combined, our observed sensitivity to neutrinos would increase significantly.

In addition, there are a number of bursts detected by BATSE which have yielded a null result for neutrino emission but have not yet been incorporated into a flux limit determination. Because these bursts were not detected in real-time by BATSE, but were found through off-line scans of archival data [2,3], it was not immediately clear if they were a different class of bursts. The current AMANDA analysis strategy assumes that if current theoretical models do not explicitly take such bursts into account, then they should be excluded from the observationally-derived flux limit. However, inclusion of these bursts could also potentially improve the limit that AMANDA can set on the neutrino flux.

There are three important questions that must be answered definitively before combining these different subsets of GRBs. First, can IPN bursts be considered equivalent to BATSE triggered bursts? Next, despite the differences in detection criteria, are the non-triggered BATSE bursts sufficiently similar to warrant their (at least provisional) inclusion into a combined flux limit? And finally, does AMANDA's (discrete) GRB search strategy permit the testing of specific theories of GRBs, like the Waxman-Bahcall (W-B) model? There has been disagreement within the AMANDA collaboration on this issue for current analyses, and future searches will also face similar issues, so AMANDA's capacity to test the W-B model should be definitively determined. These three topics will be addressed in following sections.

2. Improving the Analysis with IPN Bursts

The primary justification for combining IPN bursts with BATSE bursts into a single limit revolves around the significant overlap between the two observed burst subsets. During the time that both IPN and BATSE were operational (April 21, 1991 to May 26, 2000), the IPN satellites detected 2015 bursts, 1088 of which were triggered BATSE bursts, and 135 of which were non-triggered BATSE bursts. BATSE's detectors were much larger than the detectors of principle satellite of the IPN network (Ulysses), they operated over a larger energy range, and they were significantly more efficient as well (see Table 2).

Table 1
Bursts by Year and Class

Year	BATSE (Triggered)	BATSE (Non-Triggered)	IPN
2000	44	26	44
2001	0	0	65
2002	0	0	80*
Total	44	26	189*

* Projected

Since BATSE had only ∼1/3 sky coverage at any given time, then, the cases where Ulysses detected a burst but BATSE didn't can be traced to sky coverage and occultation issues rather than sensitivity issues [4]. Further evidence that the two burst subsets can be combined is drawn from a comparison of the burst durations. The BATSE data clearly show a bimodal distribution in time, while the IPN data are likewise consistent with this same type of distribution (though with low statistics, see Fig. 1). Of those bursts detected by IPN and BATSE, roughly 90% are BATSE triggered bursts, and the non-detections by BATSE are easily explained, so the assumption of compatibility between BATSE and IPN bursts is warranted.

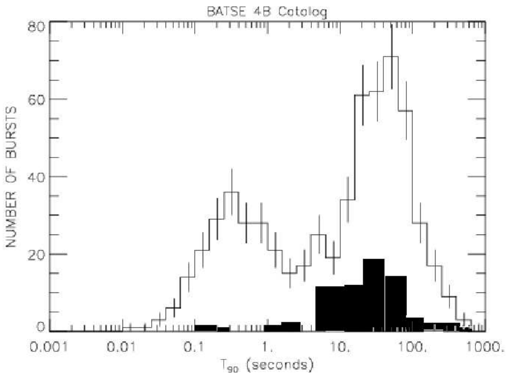

Figure 1. Bimodal t_{90} Duration of All BATSE Bursts (open histogram) and IPN Bursts from 2000-2001 (shaded histogram)

3. Improving the Analysis with Non-Triggered BATSE bursts

Since the theoretical models that offer predictions of neutrino emission draw heavily on the information gleaned from the BATSE triggered bursts, it is not obvious how the non-triggered bursts can be accommodated by these same models. Their significantly lower peak flux could point to different physical processes at work in the bursts, and thus to a radically different expectation regarding neutrino emission (Figure 2). At this point, the best option for combining non-triggered bursts with other burst types is to make the auxiliary assumption that the neutrino flux scales with the photon flux ([5]). If this assumption is made, then each non-triggered burst will receive a "weight" relative to triggered (and IPN) bursts. Of course, this auxiliary assumption ought to be stated explicitly whenever such a combined result is presented, and if any particular model is "eliminated" by such a combined limit, it must be made clear that this auxiliary assumption may have been falsified rather than the model itself. But there is no "in principle" reason why the validity of this assumption cannot be experimentally tested.

However, two complications do arise from the inclusion of the non-triggered bursts into a combined limit. First, since the expected annual neutrino flux is calculated by W-B (and related models) based upon the observed UHECR flux, the addition of another class of bursts must be taken into account when comparing the observed AMANDA limit with that particular model. Since the overall expected flux of UHECRs is fixed, the predicted flux of neutrinos is

Table 2
Burst Detector Characteristics

Parameter	BATSE (LAD)[6]	IPN (Ulysses)[7]	Swift (BAT)[8]	GLAST (GBM)[9]
Collecting Area (cm^2)	2025	1.0 (each)	5240	126 + 126 (each)
Energy Range (keV)	50-300	15-150	15-150	5-2500
Trigger Threshold (ph cm^{-2} s^{-1})	0.2	?	?	0.57
Trigger Threshold (erg cm^{-2} s^{-1})	$\sim 5\times10^{-8}$	10^{-7}	10^{-8}	?

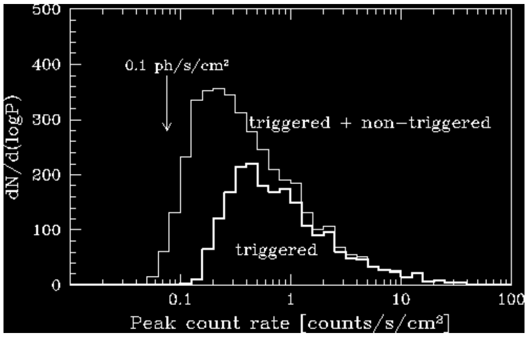

Figure 2. Peak Count Rate for Triggered and Non-Triggered Bursts

also held constant. Therefore, the predicted flux per burst must be reduced when more classes of GRBs are added. The expected flux (and thus, the flux limit) for all bursts together will depend on the total number of weighted bursts, N_{tot}, divided by $(1 + \epsilon_1\times\epsilon_2)$, where ϵ_1 is the photon flux ratio between the two types of bursts (observed to be $\sim$0.2), and ϵ_2 is the relative occurrence of the two types of bursts (observed to be $\sim$0.4). The necessity of this multiplicative factor is seen by comparing the expected flux before and after the non-triggered bursts are taken into account:

$\phi_{\nu,exp} \sim N_{trig} + N_{ipn}$

is modified to

$\phi_{\nu,exp} \sim N_{trig} + N_{ipn} + \epsilon_1\times N_{non}$,

which is just $(N_{trig} + N_{ipn})\times(1 + \epsilon_1\times\epsilon2)$.

As stated before, however, the overall neutrino flux is set by observational constraints to be $\sim N_{trig} + N_{ipn}$, so the contribution from each burst must be reduced by a factor of $(1 + \epsilon_1\times\epsilon2)$ in order for the total flux to remain constant.

A further consideration depends upon the exact weighting given to each non-triggered burst. As stated above, non-triggered bursts were given a weight of 0.2, since their mean photon flux is $\sim$1/5 of the mean triggered burst photon flux. Since each burst is expected to contribute roughly equally to the mean background rate, it must be determined if bursts with only a fraction of the expected signal would improve the sensitivity of the combined burst search, or whether they would render the search less sensitive. This should depend on the overall number of bursts in any given search, along with the expected MRF for both the triggered and non-triggered subsets. Note, however, that the flux limit will be modified by a factor of $(1{+}\epsilon_1\times\epsilon_2)$ even if the non-triggered bursts are ultimately excluded from the combined limit due to sensitivity considerations, since the expected flux from triggered (and IPN) bursts will still be reduced relative to previous expectations. And finally, entirely different values for ϵ_1 are predicted for models where F_ν is not proportional to F_γ. Table 3 shows N_{tot} and $N_{tot}/(1{+}\epsilon_1\times\epsilon_2)$ for several different values of $\epsilon1$.

4. Incorporating Swift and GLAST Bursts

Swift's Burst Alert Telescope (BAT) has a larger collecting area, a broader energy range, and is more efficient than BATSE, thus the Swift/BATSE datasets will have some overlap, but they may not be completely compatible ([10]; see again Table 2). Though GLAST is specifically designed to be analogous to BATSE, it has a smaller collecting area but a larger energy range, so its bursts may likewise not be completely compatible with BATSE bursts. Thus we *could* assume (to a first approximation) that Swift and

Table 3
Effects of Variation in ϵ_1 for ϵ_2=0.4

ϵ_1	N_{tot}	$N_{tot}/(1+\epsilon_1\times\epsilon_2)$	Flux Limit (Relative to ϵ_1=0.2)
0.2	93	86	1.00
0.5	101	84	1.02
1.0	114	81	1.06
2.0	140	78	1.10
5.0	218	73	1.18
10.0	344	69	1.25

GLAST bursts are of the same class as BATSE bursts, but additional work must be done once these instruments are on-orbit to rigorously deteremine (perhaps even on a burst-by-burst basis) whether the burst sets are fully compatible. For this reason, a theory of GRBs that incorporates all BATSE, Swift, and GLAST bursts bursts is highly desirable.

5. Testing the Waxman-Bahcall Model

It has thus far been argued that the BATSE triggered bursts can be combined with the IPN bursts and the BATSE non-triggered bursts to determine a neutrino sensitivity for the aggregate of all bursts. But given widespread variation in GRB theories, can we test these models with this (or any other) specific set of bursts?

In general, the Waxman-Bahcall model of GRBs [11] is based upon the expected neutrinos from bursts which may or may not be resolved (and thus do not contstitute a purely discrete flux); further, the AMANDA GRB search can only test models that posit discrete sources of neutrinos. Fortunately, even though the W-B model is explicitly formulated from the averaged properties of all bursts (resolved and unresolved) throughout cosmic time, the model is also described in terms of the observed *discrete* bursts detected by BATSE [12] (and both of these are distinct from the diffuse neutrino upper bound discussed in [13–15]). The formulation in terms of observed (discrete) bursts is reinforced in Waxman and Bahcall's published work [11]; for example, they acknowledge that the observed (diffuse) UHECR flux is consistent with the energy released from GRBs, but they also state that GRB neutrinos "would be correlated, both in time and angle, with the GRB gamma rays," which is precisely the definition of a *point* source search! Similar statements are also made in a more recent paper by Waxman [16], who had shown previously that discrete GRBs can produce diffuse UHECRs due to the influence of magnetic fields in the IGM and the energy dispersion of the particles [17,18]. Therefore, the W-B model can be construed as a (time-averaged) flux from unresolved GRBs, but it can also be formulated in a manner that is directly testable by AMANDA observations of discrete GRBs. However, the discrete flux predictions, while in principle testable, are not as rigorously defined as the more general (diffuse) predictions; thus care must be exercised to be certain that one is actually testing the proper form of the predictions.

When seeking to test the W-B model, one also should note that there are significant unknowns in the physical processes and the environment of GRBs, and thus the parameters of the W-B model are based on several assumptions [19]. As with the assumption made in the context of the BATSE non-triggered bursts, any falsification of the W-B model can only be said to falsify (at least) one auxiliary assumption of their model. For example, the model assumes a particular break energy in the neutrino spectrum, along with a particular range of relativistic acceleration factors for the matter entrained in the burst. If the current calculated W-B limit is "excluded" by AMANDA or IceCube, then the underlying mechanism can still be valid if these additional hypotheses can be altered to accommodate a lower expected flux. So caution is warranted when making claims regarding the comparison of AMANDA limits and W-B predictions. Initially, the most that can be said is that AMANDA has performe observational tests of a *specific set of parameters* for the W-B model, though at some point a continued null result would exhaust the possible set of realistic parameters, and falsify the model itself.

This limitation on testability holds whether we use averaged burst properties and assume that we are adequately sampling from among the observed distribution of bursts, or whether we derive specific neutrino flux expectations for each burst based on its redshift, observed photon fluence, and so on. The uncertainties are inherent to the proposed burst mechanism, *not* just to the specific characteristics of any given burst. Thus there remains some limitations to AMANDA's ability to truly "test" the W-B model, but these limitations do not stem solely from the distinction between diffuse and discrete GRB sources, because both the model and the observations are based upon discrete sources.

6. Conclusions

We have argued that AMANDA is able to set limits on the neutrino flux from a combination of several different types of bursts, including BATSE triggered bursts, IPN bursts, and BATSE non-triggered bursts. Following Waxman and Bahcall, we have further argued that a discrete set of sources can be used to test GRB models, within certain limits dictated by the uncertainties in the models itself. Thus, we propose that neutrino flux limits include several different burst subsets, specifically:

1) BATSE Triggered Bursts ($N_{tot} = 44$)

2) BATSE Non-Triggered Bursts ($N_{tot} = 26$)

3) BATSE Triggered Bursts + IPN Bursts ($N_{tot} = (44 + 44) = 88$), with the flux weighted by the factor of $(1/(1 + \epsilon_1\epsilon_2))$

4) BATSE Triggered Bursts + IPN Bursts + BATSE Non-Triggered Bursts ($N_{tot} = (44 + 44 + \epsilon_1{\times}26) = 93$), with the flux weighted by the factor of $(1/(1 + \epsilon_1\epsilon_2))$

The expected background, expected signal (given a broken power-law spectrum), event upper limit, and MRF [20] for these subsets are shown in in Table 4. The calculation of Green's Function fluence limits for these burst subsets will be presented in future work.

REFERENCES

1. Hurley, K. et al., ATel 19 (1998).
2. Stern, B. et al., A&AS 138, (1999) 413S.
3. Kommers, J, et al., PhD thesis available from http://space.mit.edu/BATSE/intro.html
4. Hurley, K., private communication.
5. Waxman, E., private communication
6. see http://www.batse.msfc.nasa.gov
7. see http://ulysses.jpl.nasa.gov
8. see http://swift.gsfc.nasa.gov
9. see http://www-glast.stanford.edu
10. Hurley, K., private communication.
11. Waxman, E. and J. Bahcall, Phys Rev Lett 78 (1997) 2292.
12. Bahcall, J., private communication.
13. Waxman, E. and J. Bahcall, hep-ph/9807282.
14. Waxman, E., and J. Bahcall, hep-ph/9902383.
15. Waxman, E., and J. Bahcall, astro-ph/0210638.
16. Waxman, E., Nuc. Phys. B (Proc. Supp.) 118 (2002) 353.
17. Waxman, E., astro-ph/9505082.
18. Waxman, E., astro-ph/9508037.
19. Bahcall, J., "private" communication to IceCube.
20. Hill, G. and K. Rawlins, AstroPart. Phys 19 (2003) 393-402.

Table 4

Results from Year 2000 Observations

Burst Subset	N_{bursts}	Expected BG	Expected Signal	Event U.L.	MRF
BT	44	0.41	0.078	2.05	26.3
BNT	26	0.24	0.0085	2.19	258.
BT + IPN	88	1.01	0.144	1.61	11.2
All	114	1.25	0.152	1.47	9.67

BT = BATSE Triggered, BNT = BATSE Non-Triggered, IPN = InterPlanetary Network