SEARCHING FOR MILLISECOND FLARES IN INTEGRAL GRBS — TOWARDS PROBING QUANTUM GRAVITY WITH INTEGRAL GAMMA-RAY BURSTS

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ABSTRACT

Since the discovery of the cosmological origin of GRBs there has been growing interest in using these transient events to probe the Quantum Gravity energy scale in the range 10^{16}–10^{19} GeV, up to the Planck mass scale. This energy scale can manifest itself through a modification in the electromagnetic radiation dispersion relation, specifically, an energy-dependence of the velocity of light. To impose stringent limits on a possible modification of the dispersion relation, a flare within a GRB must be both short, and significant over a wide energy band to provide a sufficient baseline for determining dt/dE, the difference in the arrival times of photons of different energies. To approach the Planck mass scale, we must measure arrival time differences on the order of 0.5 ms from soft to hard ($\sim$10 MeV) photons within a flare for a GRB at a redshift of a few. We have searched INTEGRAL-observed GRBs for suitable flares, requiring a 5 sigma trigger on a 2 ms, 10 ms, or 100 ms time scale using only photons above 1 MeV. This search has been made more difficult by false triggers from the SPI electronic noise component evident in single-event spectra at 1.4–1.6 MeV. We report on the status of our work.

Key words: quantum gravity energy scale, Lorentz invariance, GRBs, millisecond flares, INTEGRAL.

1. INTRODUCTION

Quantum gravity theories predict a violation of Lorentz Invariance manifesting itself in a slight dependence of the speed of light c on the photon energy [1, 2]. The magnitude of the variation depends on the quantum gravity energy scale E_{QG}.

While for some theories the propagation of electrons is also affected, others predict this energy dependence for photons only, and therefore the effect might not be visible in processes involving electrons and/or positrons. Similarly, while polarization changes are a very sensitive probe of some quantum gravity theories (namely loop quantum gravity) which predict birefringence, this phenomenon is not predicted by all quantum gravity theories.

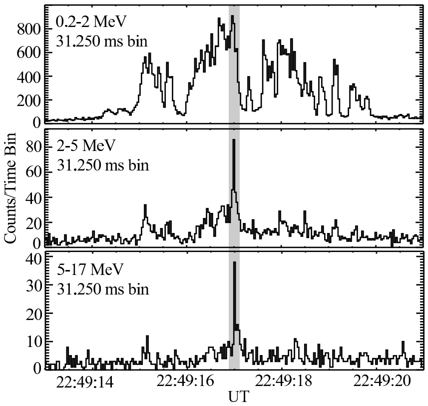

Figure 1. Lightcurves of GRB021206 in different energy bands, as recorded by RHESSI. (from [4])

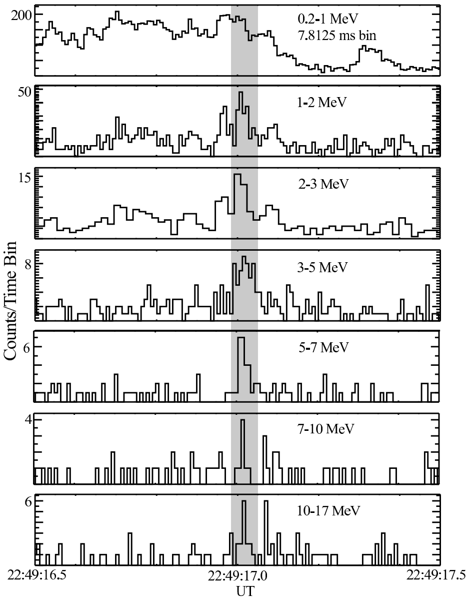

Figure 2. Detail of GRB021206 lightcurve in gamma rays as recorded by RHESSI, revealing the millisecond-timescale flare at MeV energies. (from [4])

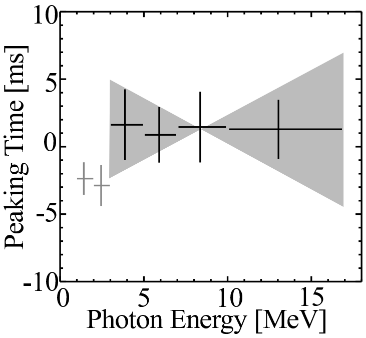

Figure 3. Constraints on photon disperson relation derived from the RHESSI observation of the ms flare in GRB021206. (from [4])

In this study, we aim to find "flares" in GRB lightcurves that both extend to MeV energies and last on the order of a few milliseconds for a GRB at high redshift.

If we assume that all flare photons were emitted at the same time, a difference in the photon arrival times between lower and higher energy photons — with lower-energy photons arriving earlier — would allow us to place lower limits on E_{QG} based on a single GRB. Given the "right" GRB ($z \approx 2$, ΔE baseline 10 MeV, flare peak time shift of ~0.5 ms over ΔE), our constraints on E_{QG} could potentially reach the Planck mass scale.

However, if flare photons are indeed emitted at the same time, or if there are source-intrinsic spectral lags, has not been established at MeV energies and on the timescales of interest. Assuming simultaneous emission at the source might be viable at least for short GRBs [6]. A systematic study of flare time-lag properties on ms timescales and at MeV energies of several GRBs is needed to disentangle source-intrinsic lags from z-dependent lags induced by QG effects.

2. THE SCIENTIFIC POTENTIAL: RHESSI OBSERVATION OF GRB021206

On December 2, 2002, the Ge detectors on the Reuven Ramaty Solar Spectroscopic Imager (RHESSI, [5]) observed an intense, hard GRB. Analysis of the emission from this burst revealed a flare on millisecond timescales, visible up to several MeV (see Figs. 1 and 2). We used the MeV photons from this millisecond flare to derive a lower limit on the Quantum Gravity energy scale. The upper limit on the photon dispersion that can be derived from the RHESSI data (see Fig. 3) corresponds to a lower limit on E_{QG} of $1.8 \cdot 10^{17}$ GeV [4], assuming a GRB redshift of $z \simeq 0.3$ (pseudoredshift, derived according to [3]).

A similar GRB flare, observed from a redshift of z≈2 with high enough significance to discern a peak time lag on the order of 0.5 ms, would enable placing a lower limit on the quantum gravity energy scale that would be on the order of the Planck mass. INTEGRAL, especially with its well-shielded Ge spectrometer, has the potential of detecting a suitable GRB flare at MeV energies with high significance.

Of course, with only one measurement of a time lag dt/dE, the derivation of an upper limit on E_{QG} has to be based on the assumption that all flare photons — regardless of their energy — were emitted at the source at the same time. Only a systematic study of the properties of such millisecond flares will allow us to relax this assumption and replace it by a realistic assessment of systematic errors due to GRB flare properties.

3. INTEGRAL GRB OBSERVATIONS

Sufficiently accurate gamma-ray timing and energy information is available from INTEGRAL instruments for the SPI events and for IBIS Compton-mode data.

Available to this study are GRBs in the public INTEGRAL archive (cutoff date June 2005), and the GRBs occuring in INTEGRAL's FoV in the AO3 period fulfilling a set of "trigger" conditions, described in more detail below.

3.1. Approach to Millisecond Flare Search

The GRB's lightcurve above 1 MeV is analyzed to determine if a significant flare on timescales 100 ms or less is present. This is done by creating INTEGRAL (SPI + IBIS Compton) lightcurves of the GRB above 1 MeV with 2 ms, 10 ms, and 100 ms binning. If the number of counts in any one bin exceeds a 40-bin running average by more than 5σ on one or more of the binning timescales, and this excess is not confined to one SPI time bin of 102.4 μs duration and consists predominantly of photons in the energy range 1.4–1.6 MeV, we consider this GRB to contain a significant flare on short enough timescales to warrant in-depth analysis.

This trigger criterion was chosen for two reasons: For one, requiring a significant flare in the >1 MeV data alone ensures a significant number of high-energy counts — a large energy baseline in *linear* (not logarithmic) scale is required for sensitive lower limits on E_{QG}. Secondly, it must be ensured that the available MeV photons would yield significant flares even if subdivided into at least two energy bands — necessary to allow the measurement of ΔE/E without having to rely on sub-MeV photons. The latter is highly desirable because in the example case of GRB021206 the flare structure appeared less pronounced at sub-MeV energies.

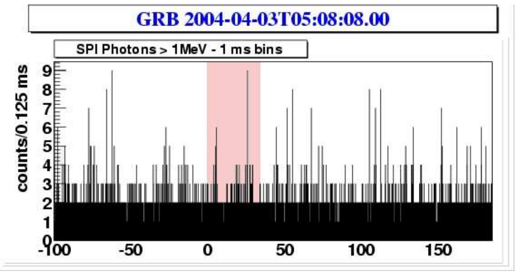

Figure 4. SPI >1 MeV lightcurve of GRB040403, in 1 ms time bins. The shaded area marks the GRB. Note "flares" on 1 ms time scale appear frequently outside as well as inside the GRB time window.

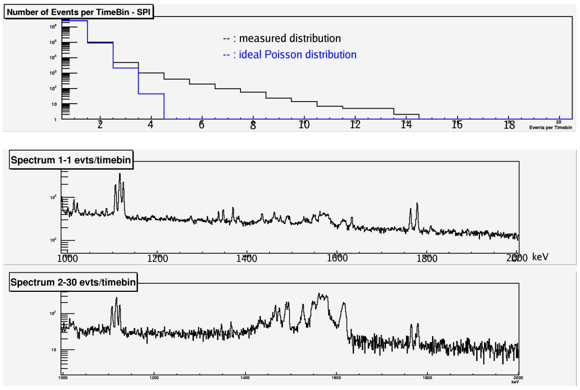

Figure 5. Timing of SPI events (top; plotted is the frequency with which a given number of SPI events (x-axis) share a SPI time bin of 102.4 µs) and correlation with SPI electronic noise feature (spectra from one-event-per timebin photons (middle) and multiple-events-per-timebin photons (bottom)). Significantly more SPI events share a 102.4 µs time bin than Poisson statistics would predict, and the electronic noise feature is significantly more pronounced in a spectrum of SPI events restricted to those sharing a time bin.

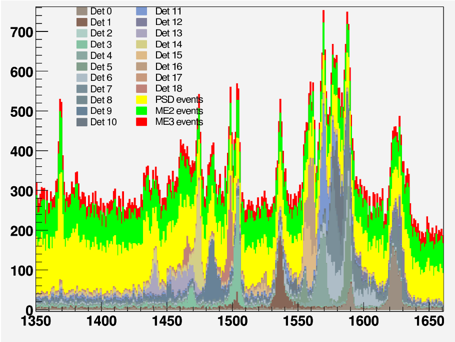

Figure 6. SPI electronic noise. SPI spectra subdivided by detector (shown in a cumulative plot) illustrate that each single event detector contributes noise peak(s) at different energies.

3.2. SPI electronic noise features — resembling 2ms flares

An earlier version of the trigger criterion, which did not look at timescales shorter than 2 ms and did not discriminate according to recorded energies beyond the >1 MeV criterion, did result in a multitude of 2 ms-timescale triggers from "flares" extending over no more than one SPI time bin (102.4 µs). Binned on a ms time scale, such "flares" are evident both within and outside of the GRB time window in >1 MeV data (see Fig. 4).

Significantly more SPI events share a SPI time bin (102.4 µs) than would be expected from poisson statistics (see Fig. 5), and events sharing a time bin are much more likely to be contributing to the well-known SPI electronic noise feature around 1.4–1.6 MeV than events without coincident photon signals within the same 102.4 µs time window (see Fig. 5).

For many purposes, a simple rejection of e.g. (>1 MeV) photons sharing their instrument time bin would reject a significant fraction of the SPI electronic noise without significant adverse effects on the scientific investigation. This approach is of course not feasible for a search for millisecond-timescale flare events. Instead, electronic noise events must be discriminated based purely on their energy: the SPI noise features have characteristic energies that differ by detector (see Fig. 6). For the GRB flare search, we have compiled GRB lightcurves >1 MeV that neglect events from the electronic noise energy bands for each of the detectors.

This approach has reduced the fraction of GRBs with apparent MeV flares from ∼80% to ∼30%.

4. GRBS WITH TRIGGERED FLARES

Table 1 lists the GRBs to which we have applied our trigger algorithm, and for the AO2 GRBs also gives the results of the old trigger algorithm which did not account for the SPI electronic noise properties. In this section, we show a few of the triggering events — some of which are likely due to instrumental effects, while others might be of GRB origin.

Fig. 7 shows the per-SPI-timebin lightcurve associated with the 2 ms-timescale "flare" trigger in GRB030501. Before noise removal, the "flare" had almost double the events; in addition, it consists mostly of single events (SEs), which is atypical for good photons at >1 MeV.

Fig. 8 shows a 2 ms-timescale trigger event from GRB040223. This event is mainly composed of multiple (MEs) and PSD events — i.e. there is no resemblance to the electronic-noise "flares". The energy distribution of all events recorded during the 2 ms time window is somewhat unexpected (all but one event around 1 MeV or above), and the event consists of only a few photons. While there is no indication that this is a noise-induced event, we also cannot claim it as a millisecond flare of GRB origin. More such events, and a better understanding of their collective properties, are required.

Fig. 9 shows one of the triggering events from GRB041219 with its spectral distribution. This 10 ms-

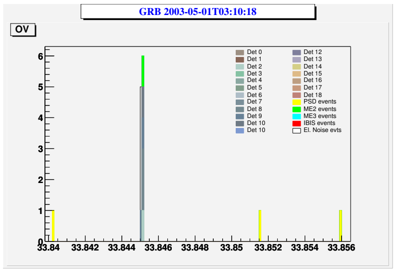

Figure 7. GRB030501 light curve detail around the triggering "flare" event.

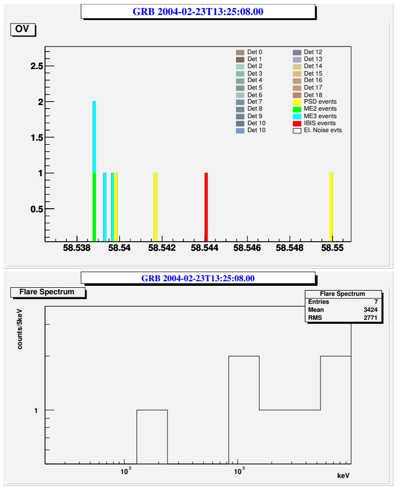

Figure 8. GRB040223 light curve detail around the triggering flare event (top) and event spectrum (bottom).

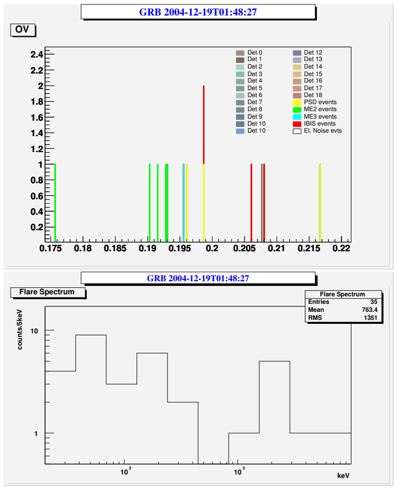

Figure 9. GRB01219 light curve detail around one flare event (top) and corresponding flare spectrum (bottom).

Table 1. INTEGRAL FoV GRBs and flare search results.

GRB	Old AO2 trigger	Revised trigger
GRB021219		no trigger
GRB030131		no trigger
GRB030227		no trigger
GRB030320		no trigger
GRB030501		1 trigger, 2 ms scale
GRB031203		no trigger
GRB040106	3 triggers, 2 ms scale	no trigger
GRB040223	5 triggers, one on 10 ms scale	1 trigger, 2 ms scale
GRB040323	1 trigger, 2 ms scale	no trigger
GRB040403	1 trigger, 2 ms scale	no trigger
GRB040422	no trigger	no trigger
GRB040624	no trigger (IBIS only)	no trigger (IBIS only)
GRB040730	3 triggers, 2 ms scale	1 trigger, 2 ms scale
GRB040812	no trigger	no trigger
GRB040827		no trigger
GRB041015		1 trigger, 2 ms scale
GRB041218		no trigger
GRB041219	multiple triggers	multiple triggers
GRB050223		no trigger
GRB050502		1 trigger, 10 ms scale
GRB050504		no trigger
GRB050520		1 trigger, 2 ms scale
GRB050522		no trigger
GRB050525		no trigger
GRB050714		no trigger
GRB051105		no trigger
GRB051211		1 trigger, 2 ms scale

timescale event could also be a real flare. However, one must keep in mind that GRB041219 is a high-countrate event with significantly increased dead times in both SPI and IBIS, complicating the validation of such events.

5. SUMMARY

SPI event rates above 1 MeV are much higher than IBIS Compton event rates (the only IBIS events with sufficiently accurate time information). Therefore, SPI and its properties dominate in this search for MeV millisecond flares. The search for GRB millisecond flares in INTEGRAL MeV photon data is severely hampered by the MeV electronic noise in SPI due to the noise's sub-millisecond flare-resembling timing properties.

A rejection of the SPI noise based on time coincidences within a single SPI time bin is not feasible in the context of a search for millisecond-timescale flares. Rejecting SPI single event data in the energy bands corresponding to each detector's electronic noise peak(s) significantly improves the situation.

However, given the low number of photons especially for the most frequent 2 ms-timescale triggers, it is very hard to prove one way or another if the flare is a not-completely-cleaned-up "SPI noise" event, explainable e.g. by gaps in "accurate timing" data or variations in dead time (see GRB041219), or truly of GRB origin.

This work is ongoing. We continue to search INTEGRAL GRBs for millisecond flares suitable for obtaining meaningful limits on the quantum gravity energy scale.

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