Detecting gamma-ray bursts from M31 with the wide field X-ray cameras on board BeppoSAX

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\textbf{ABSTRACT}
Gamma-ray bursters emit a small fraction of their flux in X rays, and because X-ray detectors are often very sensitive they may probe the gamma-ray burst universe more deeply than the current best gamma-ray instruments. On the reasonable assumptions that spectra of bursts observed by BATSE may be used to predict the X-ray fluxes of gamma-ray bursts, and that any corona of bursts around M31 is similar to the one around the Milky Way, we predict the rate at which the wide field cameras on board BeppoSAX should detect bursts from the Milky Way and M31. These rates are such that a one-month observation of M31 would have to either detect bursts from M31 or exclude most galactic models of gamma-ray bursts. (It is shown how the remainder can be dealt with.) Therefore such an observation would settle the long-standing dispute over their location.

\textbf{Key words:} gamma-ray bursts – X rays – galaxies: M31

\section{INTRODUCTION}

The results of the BATSE mission (see Fishman and Meegan 1995), combined with earlier data sets for bright bursts such as the one collected by PVO (Fenimore et al. 1993) have shown that (1) gamma-ray burst positions are distributed uniformly and randomly on the sky (Briggs et al. 1996a,b) and (2) the cumulative number as a function of peak flux, \(N(\geq P_\gamma)\), is consistent with a constant rate density of bursts within some volume around us, and a decreasing density outside that volume. This implies that we are at the centre of a gamma-ray burst universe of which we can see the edge and which looks the same in all directions. Most distance scales are therefore excluded. The first remaining one is the high-redshift universe, with the edge being caused either by cosmological volume effects near and beyond \(z = 1\) or by evolution of the density at moderate redshift (or both). The second one is an extended corona of our Galaxy, much bigger than the dark-matter halo and invented for the purpose of housing gamma-ray bursts (GRB). We are not strictly in its centre, but the average GRB distance can be made large enough that the anisotropy due to our offset from the centre is below the limit set by the BATSE data on burst positions. At the same time it can still be small enough that we need not see M31 (Briggs et al. 1996b). The aim of this paper is to demonstrate the capability of the Wide Field Cameras (WFC) on board BeppoSAX (launched in April 1996) to distinguish between these options by searching for the hypothetical corona of GRB around M31. We first discuss the X-ray detectability of GRB (Sect. \textsuperscript{2}X) and our implementation of corona models (Sect. \textsuperscript{2}Y). Our results are presented in Sect. \textsuperscript{3}Z and compared to previous results in Sect. \textsuperscript{3}A.

\section{X-RAY DETECTION OF GRB}

Ginga observations and some earlier detections indicate that gamma-ray bursts emit some X rays (for an overview of early X-ray detections, see Preece et al. 1996). It is only a small fraction of the flux (2% or so median; Laros et al. 1984, Yoshida et al. 1989), but since X- and gamma-ray instruments are photon counting devices it is the higher count rate ratio of X rays to gamma rays that matters. In addition, X-ray detectors usually have lower backgrounds because of their imaging capability. In all, they can see some fainter bursts than BATSE, the currently most sensitive gamma-ray detector looking for GRB, at a price of having a much smaller field of view. This was recently used by Hamilton et al. (1996) to constrain galactic-coronal models of GRB using archival Einstein data. They used galaxies typically a few Mpc away, the compromise distance for Einstein’s exquisite sensitivity but very small field of view. The lower sensitivity of the WFC mean we should observe more nearby galaxies to constrain galactic-coronal models with them; the large...
field of view means that we can go as close as M31 without losing too many bursts because they lie outside the field of view.

### 2.1 The WFCs on board SAX

There are two WFCs on board SAX, looking at opposite directions on the sky and perpendicular to the on-axis instruments. They are coded-mask imaging instruments with an entry mask of 256×256 mm² pixels placed 700 mm away from the detector plane. This leads to a response that is approximately triangular in both x and y and falls to zero 20” away from the optical axis along the x and y directions. It is sensitive to the energy range 1.6–32 keV. The response function was kindly supplied to us by Dr. J. Heise of SRON Utrecht. The angular resolution is a few arcminutes for bright sources. The 130 cts/s background of the instrument is mainly due to the diffuse extragalactic emission integrated over the field of view. The instrumental backgrounds are small and stable due to the low equatorial orbit which avoids the radiation belts and the South Atlantic Anomaly.

### 2.2 The X-ray fluxes of GRB

Previous workers have used a mean flux ratio of typically 2% between the BATSE flux and the X-ray flux of a gamma-ray burst. Rather than rely on the few X-ray detected gamma-ray bursts, we note that the WFC and BATSE sensitivity ranges overlap in the 10–30 keV range, and that therefore extrapolating the BATSE spectra into the WFC band should give reasonably good estimates of the expected SAX WFC count rates. Band et al. (1993) published detailed spectral fits to a sample of bright GRB from the first-year BATSE catalogue. The model consists of two power laws connected by a smooth transition at a break energy. Almost all break energies are well within the BATSE range. The best-fit model spectra for the GRB sample from Band et al. with their extrapolation into the WFC band. Note that the range over which the model fits were made significantly overlaps with the WFC band.

![Figure 1. The best-fit model spectra for the GRB sample from Band et al. with their extrapolation into the WFC band. Note that the range over which the model fits were made significantly overlaps with the WFC band.](image)

In what follows we shall use the Φ_WFC distribution from the Band et al. sample to estimate the X-ray detectability of GRB. We note that all the known and potential biases discussed would increase the number of detectable bursts from M31 over the calculations presented below.

### 2.3 X-ray detectability given a gamma-ray flux

To decide whether a given GRB will be detected by the WFC, we assume that it is a standard candle in the BATSE band. It has already been shown (Hakkila et al. 1995) that the range of gamma-ray luminosities of GRB must be small for all corona models that are still viable. Ulmer and Wijers (1995) also showed that for most luminosity functions, the luminosity distribution of detected GRB is narrow even if
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The distribution of classical X-ray flux (2–10 keV) to BATSE (50–300 keV) flux ratio (top) and the WFC (1.6–32 keV) to BATSE photon number flux ratio, which is more relevant for burst detection. The large difference is partly due to the energy per photon being much less in X rays, and partly due to the fact that the WFC band is much wider than the classical X-ray band.

The model also specifies the location of the burst, from assumption will yield the lowest estimate of the number of X-ray detectable GRB.

The procedure to decide whether a model GRB will be detected by the WFC is then as follows. First, the 50–300 keV peak flux $P_\gamma$ is given by the model. Then the WFC on-axis count rate is computed by multiplying with $\Phi_{WFC}$. The model also specifies the location of the burst, from which we calculate the position $(x, y)$ of its image in the detector plane (to be precise, the intersection of the line connecting the burst location and the centre of the mask with the detector plane). The count rate due to a burst at $(x, y)$ is less than that due to one on axis by a factor $R(x, y)$, which accounts for the fact that it only illuminates a fraction of the detector and for the usual factor $\cos \theta$ to account for the fact that the detector plane is not perpendicular to the direction to the burst:

$$R(x, y) = (1 - \frac{|x|}{256})(1 - \frac{|y|}{256}) \cos \theta.$$  \hspace{1cm} (1)

(x and y are measured in mm from an origin at the detector centre, and the x and y axes are parallel to the edges of the square mask.) Given an integration time $T$ and background count rate $b$, we get the total number of source counts $S = f P_\gamma \Phi_{WFC} RT$ and background counts $B = b T$. The factor $f$ is required because $P_\gamma$ is the peak flux, which will generally not be sustained for the full time $T$. In terms of the instantaneous number flux $p_\gamma(t)$ from the burst (assumed 0 outside the interval $(0, T)$) we can formally define $f$ as

$$f \equiv \int_0^T p_\gamma(t) \, dt \quad \Rightarrow \quad P_\gamma \frac{T}{RT}.$$  \hspace{1cm} (2)

Obviously, for a fixed value of $T$ we will find a different $f$ for each burst and $f$ will usually be smaller for shorter bursts.

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We assume the background noise is Poissonian and large enough to be approximated by a normal distribution, so we can express the requirement that the burst be more than $\sigma$ standard deviations above the background as a constraint on $P_\gamma$:

$$P_\gamma \geq P_{\gamma, \min} \equiv \frac{\sigma \sqrt{B}}{f \Phi_{WFC} R(x, y) \sqrt{T}}.$$  \hspace{1cm} (3)

So we have now phrased the X-ray detectability as a constraint on the gamma-ray flux, which is convenient because most of the modelling of GRB populations is done in terms of the latter quantity. To account for the fact that $\Phi_{WFC}$ has a distribution of values rather than a fixed value, we treat a burst at a given $(x, y)$ with a given $P_\gamma$ as being detectable with probability

$$P_{\text{det}} = \frac{1}{54} \sum_{i=1}^{54} S(P_\gamma - P_{\gamma, \min}^i),$$  \hspace{1cm} (4)

where $S(x)$ is the Heavside step function and we have defined $P_{\gamma, \min}^i$ as the minimum detectable flux for the $i$th sample member. In other words, we just add up the fraction of model spectral shapes in the Band set for which its X-ray flux is above threshold. Since we do Monte Carlo simulations to find the rate of GRB detection (Sect. 3) we can then simply add up the $P_{\text{det}}$ values in each sky and flux bin to get the detected rates.

In principle, the signal-to-noise of an off-centre source will be higher once it has been located, because the background need only be taken over the part of the detector that is illuminated by the source. However, we will not be aware of such sources until they are first noted in the full data stream so this does not change the detection rate.

For the preliminary investigation in this paper, we shall use $T = 20$ s and $f = 0.05$. This means we concentrate on the long part of the bimodal duration distribution of the bursts, which contains about 80% of the ones detected by BATSE. More advanced search techniques are clearly possible. For example, one can use a number of trial values of $T$ or even trial sky positions for the bursts to enhance the sensitivity of the search. At the same time, this would increase the number of attempts at detection and therefore require a higher signal-to-noise threshold to avoid spurious signals. It is not meaningful in our view to explore these possibilities here because the optimal strategy will depend on details of the data set we will obtain. There will be real signals from other sources, such as X-ray bursts and flare stars, that may well constitute a higher contaminating rate signals from other sources, such as X-ray bursts and flare stars, that may well constitute a higher contaminating rate.

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In Fig. 3 we show the detection probability for bursts at the centre of the detector field of view as a function of $P_\gamma$. The thick dashed curve is for BATSE, and the thick solid one is for the WFC using the nominal Band spectral set. Comparison of the two shows that above 0.3 phot cm$^{-2}$s$^{-1}$ BATSE is more sensitive, but the curve for the WFC extends to well below the absolute limit for BATSE. This advantage vanishes if we look at bursts far away from the detector centre: 10$^\circ$ away along the detector diagonal the curve shifts up in flux by a factor 2.4, and 20$^\circ$ away that factor has grown to 12. So the effective field of view over which the WFC can probe fainter bursts than BATSE has a radius of about 10$^\circ$.

There is one more spectral effect, however, that could dramatically increase the detected rate by the WFC: in a recent paper, Preece et al. (1996) find that many GRB have an excess flux above the Band et al. fits at energies between 5 and 10 keV. Inspecting their figure 5, it appears that about half of all GRB have an excess that is a factor 10 at 5 keV and decreases to near zero above 10 keV. To investigate the possible effect of this excess, we model it as a multiplicative factor $C_{\text{Preece}}$ that is constant below 5 keV and decreases smoothly from 10 to 1 between 5 and 12 keV. To be precise, we multiplied the spectrum by

$$C_{\text{Preece}}(E) = \begin{cases} 10 & E < 5 \\ 1 + 4.5(1 + \cos(\frac{\pi(E - 5)}{7})) & 5 < E < 12 \\ 1 & E > 12 \end{cases}$$

(with $E$ in keV.) Adding this excess to each of the 54 spectra and recalculating the detection probabilities, we find that the entire sensitivity curve shifts down in flux by a factor of 7 (thin dashed curve in Fig. 3). Since only about half the bursts may have this excess, a more realistic case would be an even mixture of bursts with and without excess (thin solid curve). We stress that the fraction, $f_{\text{ex}}$, of bursts with excesses and the form of the excess are quite uncertain, so we explore the range $0.1 < f_{\text{ex}} < 0.9$ here. But since we will have spectra of all detected bursts in the eventual observations we can consistently account for it in the data, since even if no excess of GRB from M31 is found, a population of bursts with X-ray excesses would also greatly increase the foreground rate of GRB from our own Galaxy. Therefore we are in no danger of eventually overestimating the constraints on halo models from WFC data.

3 CORONA MODELS

For standard-candle gamma-ray bursts, the rate density of observable bursts as a function of distance from the centre of the corona follows directly from the observed $N(> P)$. It is usually approximated as

$$\rho(R) = \frac{\rho_0}{1 + (R/R_c)^\alpha}$$

and has three parameters, the central rate density $\rho_0$, the core radius $R_c$, and the exponent $\alpha$. Since the best values of $\alpha$ are small enough that the integrated density does not converge at large $R$, we have to add as a fourth parameter a cutoff radius of the corona, $R_o$, beyond which $\rho = 0$. An additional model parameter is the standard-candle gamma-ray photon emission rate $N_\gamma$. It turns out that we only need two of these, $R_c$ and $R_o$, because the others follow from them if we use known observational constraints. Moreover, the results depend only weakly on $R_o$. We briefly indicate how a complete model is defined once the two radii are given: First, we note that the break in the counts slope from $-1.5$ to a smaller value occurs at $P_{\text{break}} = 20$ phot cm$^{-2}$ s$^{-1}$. Since a burst with this flux is at distance $R_o$, this fixes the standard-candle value as $N_\gamma = 4\pi R_o^2 P_{\text{break}}$. Next we use the fact that BATSE observes 300 bursts per year per 4$\pi$ steradians above $P_{\text{comp}} = 1$ phot cm$^{-2}$ s$^{-1}$. Because this flux is 20 times less than the break flux, it corresponds to a distance $R_c\sqrt{20}$, and we fix $\rho_0$ by requiring the integrated rate up to that distance to be 300/yr. $\alpha$ follows from the fact that $N(> P_\gamma) \propto P_\gamma^{-\alpha}$ at the faint end of the BATSE distribution. Because the asymptotic counts slope at low fluxes for Eq. (3) is $(3-\alpha)/2$, this implies $\alpha = 1.6$. This completes the model for given $R_c$ and $R_o$.

The reasonable range of $R_c$ and $R_o$ to explore is also limited by data. First, for $R_c \lesssim 30 - 40$ kpc BATSE would have detected an anisotropy due to our offset from the Galactic centre (Briggs et al. 1996b), and for $R_o \gtrsim 70$ kpc it would have seen M31. A minimum value for the outer radius follows from the fact that BATSE sees no sign of a truncation down to its 50% completeness limit of 0.28 phot cm$^{-2}$ s$^{-1}$. The distance to bursts of this flux is $8.5 R_o$, i.e. at least 250 kpc, so we conclude that $R_o \gtrsim 250$ kpc. Due to the low sensitivity of our results to $R_o$ we fix it at half the distance to M31 in our calculations, noting that this is by no means required by all models. (For neutron-star ejection models with beaming, we use $R_o = 2$ Mpc; see below.)
As stated, all standard-candle galactic-corona models have to satisfy this model for the effective rate density. Since non-standard-candle models have greater difficulty satisfying the BATSE constraints and also lead to easier detection of M31 we shall not consider them here. However, the net rate density is obtained in very different ways by different models, and this has some effect on detecting M31. It does not matter whether a static halo is used or one in which the bursters fly out of the Galaxy at high velocity, because all models of the latter type contain a provision of gradual or delayed turn-on of the bursting mechanism to ensure that the net rate density becomes the same again. However, some models (e.g. Duncan et al. 1993) invoke beaming of emission from fast neutron stars along their velocity direction to avoid anisotropy. The opening angle of the beams required in such models is of order the distance $R_{\text{GC}}$ from us to the Galactic centre divided by $R_c$. This does matter, because it means that only bursters in M31 that move roughly towards or away from us will be seen. While this reduces the number of visible bursts, it also limits region of the sky where they are seen to a circle of angular radius about $R_c \sin \theta / D$ around the centre of M31, where $\theta$ is the opening angle of the beaming cone and $D$ is the distance to M31. Since $\theta \simeq R_{\text{GC}} / R_c$, the angular radius is $R_{\text{GC}} / D$, independent of core radius. This area is quite small (typically a few square degrees) and therefore the background in it is very small, which may compensate for the lower expected rate to still give a detectable excess.

In our practical implementation, we used a Monte Carlo algorithm to create maps of the detectable rate of GRB per square degree per year from M31 and the Galactic foreground given a WFC pointing direction. The algorithm picks a burst in the Galaxy or M31 from the integrated density distribution between $R = 0$ and $R = R_c$ and random angular coordinates. Then we compute the detection probability for the WFC. This probability is then added to the total in the appropriate sky location and/or flux bin and the procedure is repeated until the rate maps have sufficiently low Monte Carlo errors. In the case of beamed models, we also check whether the burst is shining in our direction before counting it as detectable. For this we make the approximation that GRB are ejected from a galaxy at such high velocities that they move at constant velocity in straight lines. We also assume that they are all born at the centre of the galaxy and that their emitted flux is constant for all directions close enough to the direction of motion, and zero outside some critical angle. This simplification allows us to check the detectability of the burst using only the angle between our line of sight to the burst and the direction from the burst to the centre of M31. (This approximation is quite good, because the neutron star formation rate drops exponentially from the centre with a small scale length of only about 4 kpc, leading to an extra ‘smearing’ of the maps with an angular width of only $\theta_{\text{smear}} \sim 0.3^\circ$.)
where GRB can be seen, the total rate in the field of view will be much less for beamed bursts. This is very apparent in Fig. 5, in which we show the expected number of bursts as a function of position on the sky. The contour values are 1 (thick-dotted), 2 (thick-dashed), 4 (thick-solid), 8 (thick-dotted), 16 (thick-dashed), and 32 (thick-solid). Left is the number from M31, right that from the Galactic foreground.

4 RESULTS

There are three main variables on which the detectability of an excess of GRB to M31 depends most: the core radius, the fraction of bursts, $f_{ex}$, with an X-ray excess, and beaming. To illustrate the dependence on $R_c$ and beaming, we show in Fig. 4 maps of the detectable rate of GRB as a function of position on the sky (in number per square degree per year). The top panels are for unbeamed bursts, the bottom ones for beamed bursts. The influence of $R_c$ is reflected by the differences between the left (30 kpc) and right (60 kpc) panels. As noted above, the image becomes much smaller for beamed bursts and the size is independent of $R_c$, whereas for unbeamed bursts the increase of the image size with $R_c$ is clear. Also note the increased peak rate (labelled ‘max’ in each panel) for smaller core radii. This is because the central density scales as $R_c^{-3}$, and we do see a fair fraction of the bursts at the centre of M31. For comparison, the detectable rate from our own Milky Way is about 0.03/deg$^2$/yr without beaming to 0.1/deg$^2$/yr with beaming (the latter is greater due to the larger assumed outer radius for beamed models).

Because beaming so much reduces the area of sky over which GRB can be seen, the total rate in the field of view will be much less for beamed bursts. This is very apparent in Fig. 5, in which we show the expected number of bursts as a function of position on the sky. The contour values are 1 (thick-dotted), 2 (thick-dashed), 4 (thick-solid), 8 (thick-dotted), 16 (thick-dashed), and 32 (thick-solid). Left is the number from M31, right that from the Galactic foreground.

Now we must create a practical test of whether seeing a certain number of GRB towards M31 constitutes evidence for or against a halo of GRB around it. Since the foreground bursts are more spread out on the sky than those of M31, this entails finding the optimum area of the detector to use as the region within which we look for bursts. A good choice of boundary turns out to be a contour on which the summed rate of M31 and Milky Way bursts is a fixed fraction of the summed peak rate. For a given set of halo model parameters, we then fix an observing time and a boundary. This completely specifies the expected number of bursts, $E_{MW}$, if there is no halo around M31, and the expected total number if there is, $E_{MW+M31}$. The actual numbers we would get in an observation, $N_{MW}$ or $N_{MW+M31}$, have a Poisson distribution around the expected values. Let us choose a threshold value $N_{th}$, which defines the boundary between the accepting the null hypothesis $H_0$ ‘there is no halo with these pa-
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5 DISCUSSION AND CONCLUSION

Previous work on constraining coronal models of GRB has many similarities with our own calculations. Liang (1991) found that ROSAT might detect some GRB in X rays assuming a now abandoned disc model for the distribution of GRB. Li, Fenimore, & Liang (1996) used a similar method to our own both for beamed and unbeamed models. Their calculations differ from ours mostly in that they use neither the spread in X-ray luminosity nor the X-ray excesses. Their hypothetical instrument had \( S_{\text{min}} = 0.1\, \text{phot cm}^{-2}\text{s}^{-1} \). As we can see from Fig. 6, 30–90% of the bursts that the WFC can see on-axis are below this limit, so it is no surprise that we find more optimistic prospects for detecting GRB in M31.

Harrison and Thorsett (1996) considered a variety of real instruments, calculating the detectable rate in much the same way as we did (including the spectral variability using the same set of spectra from Band et al. 1993). They conclude that only a novel instrument sensitive to photons in the 10–200 keV range and with a field of view of 18° would be capable of detecting M31 in one year. While they did not include the possibility of X-ray excesses, they would without doubt have realised the potential of the SAX WFC if they had included them in their work.

In summary, we have shown that the hitherto neglected spread in X-ray to gamma-ray luminosity ratios of gamma-ray bursts substantially increases the prospects for deciding the gamma-ray burst distance scale. The case is further improved greatly by the recent discovery that a substantial fraction of gamma-ray bursts have X-ray excesses (Preece et al. 1996). A one-month observation of M31 with an existing instrument, the SAX WFC, will be decisive for establishing whether or not the Andromeda Nebula harbours a population of bursters, unless bursters only emit radiation in fairly narrow cones along their direction of motion. In that case, a dedicated, cheap mission similar to the SAX WFC should resolve the issue in about one year of observing time. Observing proposals to do the experiment in WFC sec-

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Figure 6. Contours of the probability of making the wrong decision based on a 1-month observation of unbeamed GRB (top) and a 6-month one of beamed GRB. The horizontal axis gives \( R_c \), the vertical one the percentage of GRB with an X-ray excess, \( f_{\text{EX}} \). The contour values range from 0.001 (thin-dashed) to 0.1 (thick-solid) in steps of \( \sqrt{10} \).
undy (i.e. unguaranteed) time have been accepted, so the gamma-ray burst distance scale may not remain uncertain much longer.

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