Luminosity Distribution of GRB Afterglows

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Virtual Afterglows

It is now well established that the general behaviour of gamma-ray burst (GRB) afterglows can be adequately described by the standard fireball model, excluding the early behaviour. Using this model, we create a virtual world of afterglows to study theoretically their luminosity distribution. To create the afterglows, we use the model as described in Jóhannesson et al. (2006). It is a slight modification of the standard fireball jet model, in which the energy is assumed to be released instantaneously into a narrow jet. Interaction with the surrounding medium creates a shock wave and the shock heated material emits synchrotron radiation. Full account is taken of both synchrotron self absorption and inverse Compton scattering.

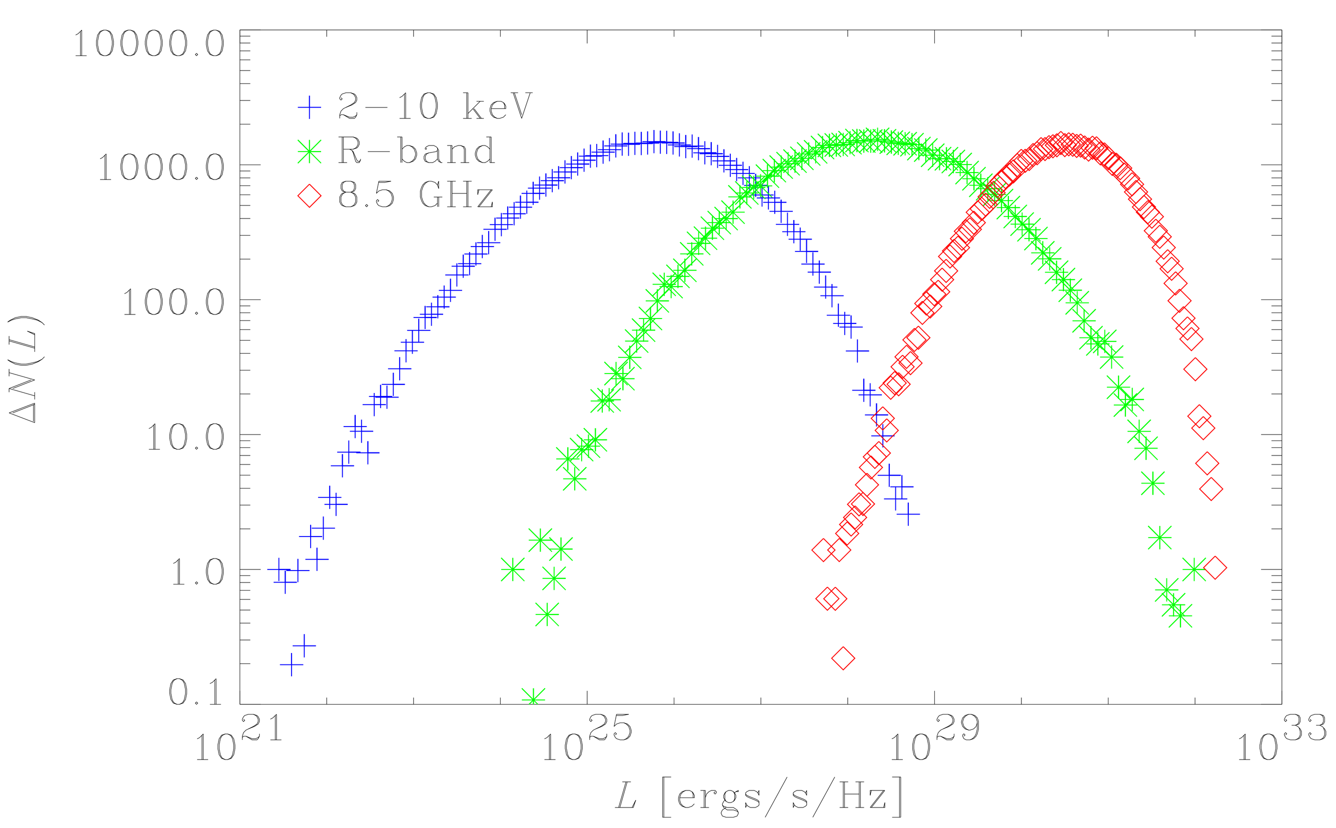
The Method

Using our model, we numerically create a population of 50,000 afterglows by randomly choosing model parameters from Gaussian distributions. The distribution for each parameter is limited to a range which represents values obtained by fitting afterglow observations with the standard fireball model (see table 1 for the default distributions). To eliminate any cosmological effects, we fix the redshift of our model to $z = 1$. Using the luminosity at an observers time of 1 day, we calculate the luminosity distribution for several frequencies, ranging from radio to X-ray (see figures below for example distributions).

Table 1: The center and width of the Gaussian distributions of the model parameters. Each distribution is actually restricted to be within the specified width and is therefore not a complete Gaussian. We choose the standard deviation of each Gaussian distribution to be 1/4th of the width.

Parameter	Center	Width[a]
E_0	10^{50} erg	100
n_0	$1\ \mathrm{cm}^{-3}$	100
θ_0	5 deg	10
p	2.4	0.5
ϵ_e	0.1	10
ϵ_B	10^{-4}	100

[a] All parameters except p are distributed logarithmically, the width in those cases represents the ratio between the upper and lower limits.



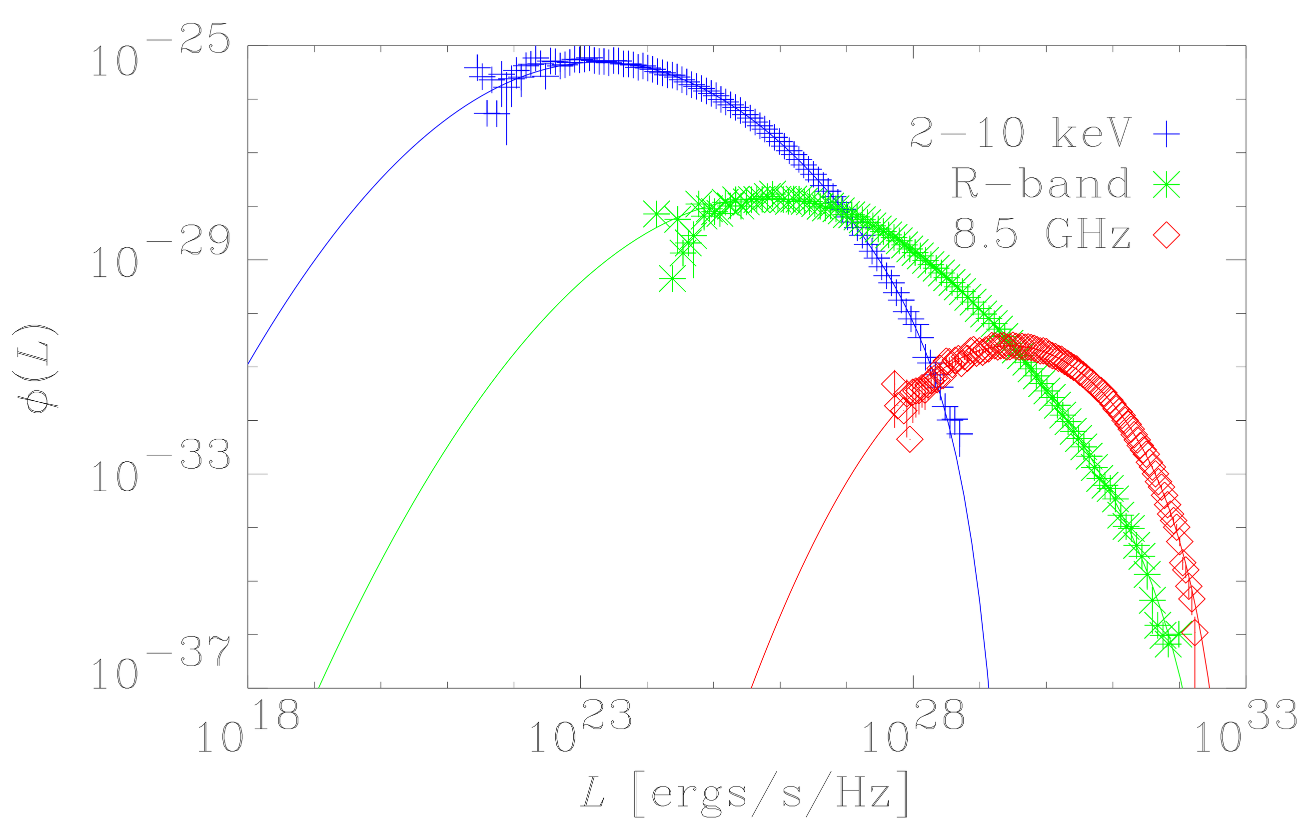
The figure above shows a logarithmic plot of the number of afterglows per luminosity bin. It was the parabolic resemblance of this plot that inspired the use of equation (1) for the fits. The curves are, however, not pure parabolas, hence the exponential cutoff (last factor) in function (1).

The Template Function

The figure below shows typical luminosity distributions ($\phi(L)dL = \Delta N(L)$) from our numerical calculations (symbols). Also shown overlaid are fits to the results using the function

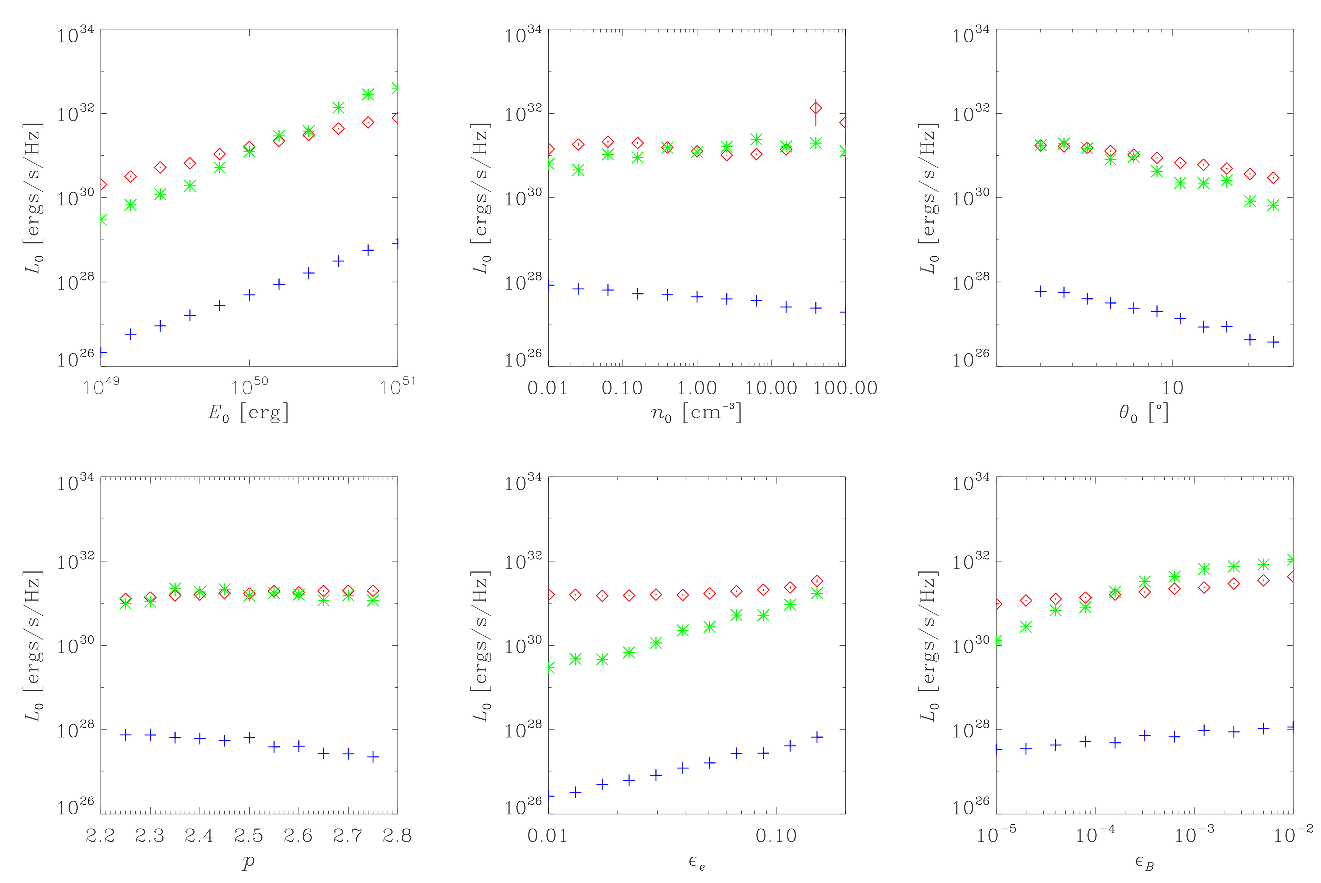
$$\phi(L) = C\left(\frac{L_0}{L}\right)^{\lambda} \exp\left(-\frac{\log\left(\frac{L}{L_0}\right)^2}{2\sigma^2}\right) \exp\left(-\frac{L}{L_0}\right). \tag{1}$$

This function fits the numerical calculations quite well as seen in the figure. Note that the general shape of the luminosity function is frequency independent, although the function parameters need not be.

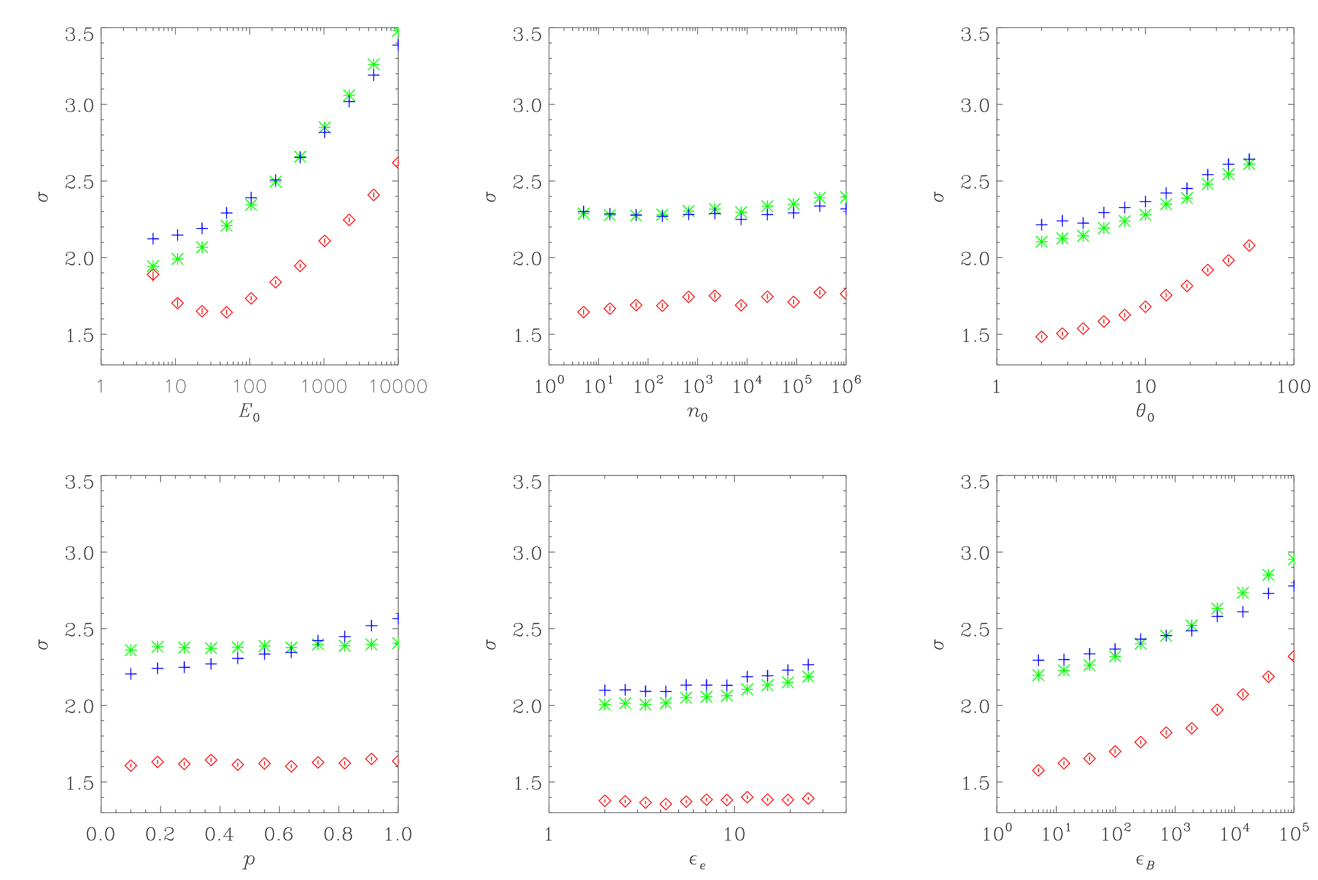


Varying the input

To test the robustness of our results, we repeated the calculations, changing the shape, width and center of the model parameter distributions. We find that none of these affect the general shape of the luminosity distributions. Fits using function (1) usually result in a χ^2 between 50 and 200 for 96 degrees of freedom. The values of the free parameters in function (1) are quite robust, where $\lambda \approx 2$ in most cases although it is frequency dependent, varying from 1.5 to 2.5. The width of the function, σ, is correlated with the width of the model parameter distributions, but its value is again clustered around 2 and frequency dependent. The cutoff, L_0, is the most sensitive function parameter to changes in the input distributions. As expected, the initial energy of the afterglow, E_0, is the parameter that most strongly affects L_0, while the fraction of energy contained in the electron population, ϵ_e, and in the magnetic field, ϵ_B, as well as the initial opening angle, θ_0, have a clear but more subtle effect. Like the other function parameters, L_0 is also frequency dependent.

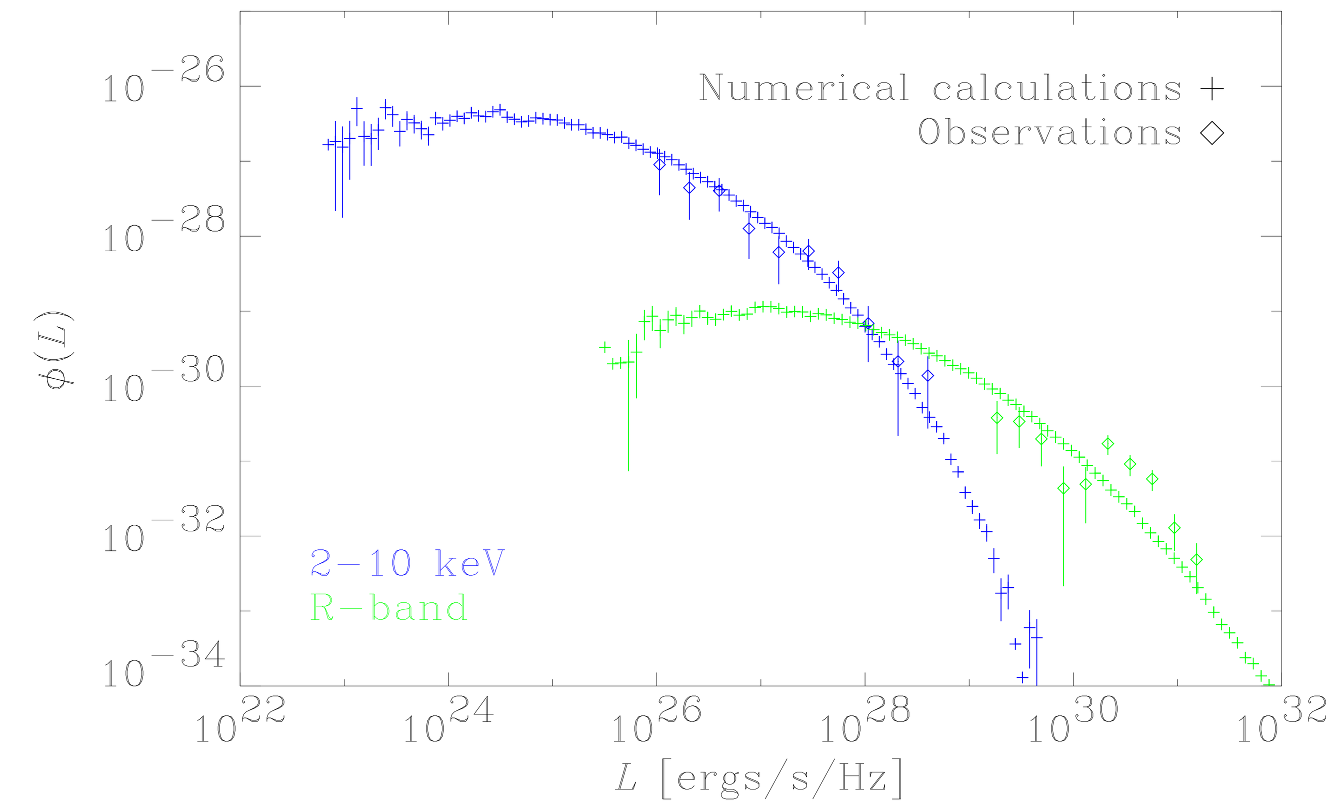


The figures above and below show how some of the parameters of function (1) vary while we change the center and the width of the model parameter distributions. Above, we change the center of the distributions while below we change the width. Only one model parameter distribution is changed at a time. Table 1 shows the default parameter ranges. All model parameters except p, the electron energy distribution index, are varied on a logarithmic scale.



Comparison with observations

Using data from Nardini et al. (2006), we have constructed a luminosity distribution for afterglows at 12 hours rest frame time, $t_{\mathrm{RF}} = t_{\mathrm{obs}}/(1+z)$, comparable to 24 hours observers time at $z = 1$. Our numerical calculations are overlaid in the figure below for the case when the center of the E_0 distribution is at 10^{51} erg. Note that this is not a fit to the data.



It has been suggested that the afterglow luminosity distribution (e.g. Nardini et al., 2006) shows signs of two populations as can be seen in the dip in the R-band luminosity distribution around $L \approx 10^{30}$ ergs/s/Hz. This cannot be explained with our model unless the parameter distribution is very narrow (much narrower than indicated by fits to afterglow data) or that some of the model parameters are correlated rather than randomly distributed.

References

Jóhannesson, G., Björnsson, G., & Gudmundsson, E. H. 2006, ApJ, 647, 1238

Nardini, M., Ghisellini, G., Ghirlanda, G., Tavecchio, F., Firmani, C., & Lazzati, D. 2006, A&A, 451, 821