

# What is the redshift of gamma-ray burst 970508?

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## ABSTRACT

A Bayesian likelihood analysis is used to constrain the redshift of the optical transient associated with gamma-ray burst 970508, under the assumption that the absorption at redshift 0.835 is not physically associated with the transient. The maximum-likelihood, expectation value and 95-percent upper limit on the OT redshift are 0.835, 1.3 and 1.9 respectively.

*Subject headings:* methods: statistical — quasars: absorption lines — gamma rays: bursts — X-rays: bursts

Gamma-ray bursts are among the most fascinating mysteries in astrophysics, with their immense fluences, isotropic distribution on the sky, and number-flux relation that is not consistent with homogeneity. The holy grail in the study of gamma-ray bursts is the determination of their distances from the Earth; unfortunately, for lack of solid evidence, distance estimates range from the outskirts of our Solar System to the edge of the Universe. The strongest constraints on models are the intrinsic energies of the bursts, so accurate distance determination is crucial. A breakthrough occurred this year with observations of an optical transient (OT), apparently associated with an X-ray flare apparently associated with gamma-ray burst 970508 (Bond 1997; Djorgovski et al 1997; Metzger et al 1997), which show that the OT, and therefore probably the gamma-ray burst, is at a cosmological distance.

The OT spectrum, taken near maximum light, shows a strong Mg II absorption system at redshift  $z = 0.835$  (Metzger et al 1997). The absorption system could be associated with the OT itself or else the OT is further away and the gas cloud is between us and the OT. If the absorption is associated, the redshift of the OT is  $z_{\text{OT}} = 0.835$ . There are several reasons to believe that the absorption is associated: The absorption is strong (equivalent width roughly  $1.5 \text{ \AA}$ ) and therefore the line-of-sight is not typical (Steidel & Sargent 1992). Furthermore, the relative strengths of the lines in the absorption suggests a line-of-sight through or at least very near the center of a galaxy (Steidel, private communication), which again makes the line-of-sight atypical.

However, if the absorption system is unrelated,  $z_{\text{OT}}$  is not known but can only be constrained. In this *Letter* we make the constraint quantitative with a Bayesian likelihood analysis. The

analysis is based on the known distribution of cosmological absorption systems in high-redshift QSO spectra, which show either Mg II (singly ionized magnesium) or C IV (triply ionized carbon) absorption. The OT is assumed to be at redshift  $0.835 < z_{\text{OT}} < 2.3$  because no Lyman-alpha “forest” lines are observed longward of 400 nm (Metzger et al 1997). The probability of not having an absorption system with  $0.835 < z < z_{\text{OT}}$  is computed and converted into a likelihood function for  $z_{\text{OT}}$  via Bayes’s theorem. This procedure can easily be generalized for future observations by replacing 0.835 with the highest redshift absorption system seen in the spectrum of any cosmological source. Our tacit assumption is that in the OT spectrum there are no Mg II or C IV absorption systems at redshifts  $z > 0.835$  down to the detection limit. This is likely for Mg II systems the doublet is spectroscopically resolved so the systems are easy to identify morphologically. However, the wavelength resolution of the spectrum is not sufficient to make morphological identification of C IV systems easy so it is possible that weak, unidentified absorption lines in the spectrum could in fact be high-redshift C IV (Metzger, private communication).

By Bayes’s theorem, the probability distribution function (pdf)  $p(z_{\text{OT}}|\text{no-abs})$  (probability per unit redshift) for the OT redshift  $z_{\text{OT}}$  given that there are no intervening absorption systems at  $z > 0.835$  is given by

$$p(z_{\text{OT}}|\text{no-abs}) = \frac{p(z_{\text{OT}}) p(\text{no-abs}|z_{\text{OT}})}{p(\text{no-abs})} \quad (1)$$

where  $p(z_{\text{OT}})$  is a pdf summarizing our prior knowledge about  $z_{\text{OT}}$ ,  $p(\text{no-abs}|z_{\text{OT}})$  is the probability of observing no Mg II or C IV absorption systems given a particular value of  $z_{\text{OT}}$ , and  $p(\text{no-abs})$  is a normalization constant. In this case the prior information is that the OT must have  $0.835 < z_{\text{OT}} < 2.3$  and here it is assumed that all redshifts in this range are equally likely. Perhaps a more natural choice is to use a factor related to the comoving volume of the Universe but this requires guessing the world model and the evolutionary behaviour of the OT population, while influencing the final results very little.

The distribution of Mg II absorption systems along QSO lines of sight is well fit by a power law  $dN/dz = N_0(1+z)^\gamma$  (number per unit redshift per line of sight) with  $\gamma = 0.78$  (Steidel & Sargent 1990) for absorption systems with rest frame equivalent width  $EW > 0.3 \text{ \AA}$ . The distribution of C IV systems with  $EW > 0.3 \text{ \AA}$  is well-fit with  $\gamma = -0.90$  (Sargent, Boxenberg & Steidel 1988). The amplitudes  $N_0$  of these relations vary with rest-frame EW limit  $W_{\text{lim}}$  as

$$N_0 = N_{(0.3)} \exp\left(\frac{0.3 \text{ \AA} - W_{\text{lim}}}{W^*}\right) \quad (2)$$

where parameters  $(N_{(0.3)}, W^*)$  are  $(0.56, 0.66 \text{ \AA})$  for Mg II (Steidel & Sargent 1990) and  $(10.9, 0.41 \text{ \AA})$  for C IV (Sargent et al 1988). The estimated rest-frame equivalent-width sensitivity of the OT spectrum (Metzger, private communication) is plotted in Fig. 1, along with the differential number  $dN/dz$  of detectable systems per unit redshift, both as a function of redshift.

The mean expected number  $m$  of independent absorption systems along the line of sight from  $z = 0.835$  to  $z = z_{\text{OT}}$  is just the integral of the detectable  $dN/dz$  over this range, where the Mg II

$dN/dz$  is used at  $z < 1.52$  and is replaced by the C IV  $dN/dz$  at  $z > 1.52$  (when C IV enters the spectroscopic window) because essentially all Mg II systems are also detected in C IV (Steidel & Sargent 1990). The probability  $p(\text{no-abs}|z_{\text{OT}})$  of getting no absorption systems is then simply  $e^{-m}$ . This probability is plotted in Fig. 2, along with the expectation value  $z_{\text{OT}} = 1.3$  (integral of  $z$  times  $p(z_{\text{OT}}|\text{no-abs})$  over all redshifts) and the 95 percent confidence upper limit  $z_{\text{OT}} < 1.8$  (point at which the integral of  $p(z_{\text{OT}}|\text{no-abs})$  is 0.95) marked. The roughly 20 percent uncertainties in the normalizations of the absorber distribution  $dN/dz$  lead to smaller than 5 percent uncertainties in the expectation value and upper limit. It is worthy of note that even though the absorption system is not assumed to be associated, the maximum likelihood redshift is very naturally  $z_{\text{OT}} = 0.835$ .

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Fig. 1.— (*Top*) The rest-frame equivalent width detection limit (observed detection limit divided by  $1 + z$ ) of the OT spectrum, as reported by Metzger (private communication), appropriate for Mg II (dashed curve) and C IV (solid). The spike in the Mg II limit at  $z \approx 1.7$  is caused by a sky line, Mg II leaves the spectroscopic window at  $z \approx 1.9$  and C IV enters at  $z \approx 1.5$ . (*Bottom*) The differential number  $dN/dz$  of absorption systems expected per line of sight for Mg II (dashed, Steidel & Sargent 1990) and C IV (solid, Sargent et al 1988), down to the detection limit plotted in the (*Top*) panel.

Fig. 2.— The probability that a source at redshift  $z_{\text{OT}}$  will show no Mg II or C IV absorption systems at  $z > 0.835$  as a function of redshift, times the prior probability that the source is in the range  $0.835 < z_{\text{OT}} < 2.3$ . This is proportional (by Bayes’s theorem) to the pdf (probability per unit redshift) for the redshift  $z_{\text{OT}}$  of the OT given that it shows no intervening absorption systems at redshifts  $z > 0.835$ . The steepening at  $z_{\text{OT}} \approx 1.6$  results from the great increase in the expected number of observable absorbers when C IV enters the spectroscopically observed range. The expectation value for the redshift and the 95 percent confidence level upper limit are marked with vertical bars.

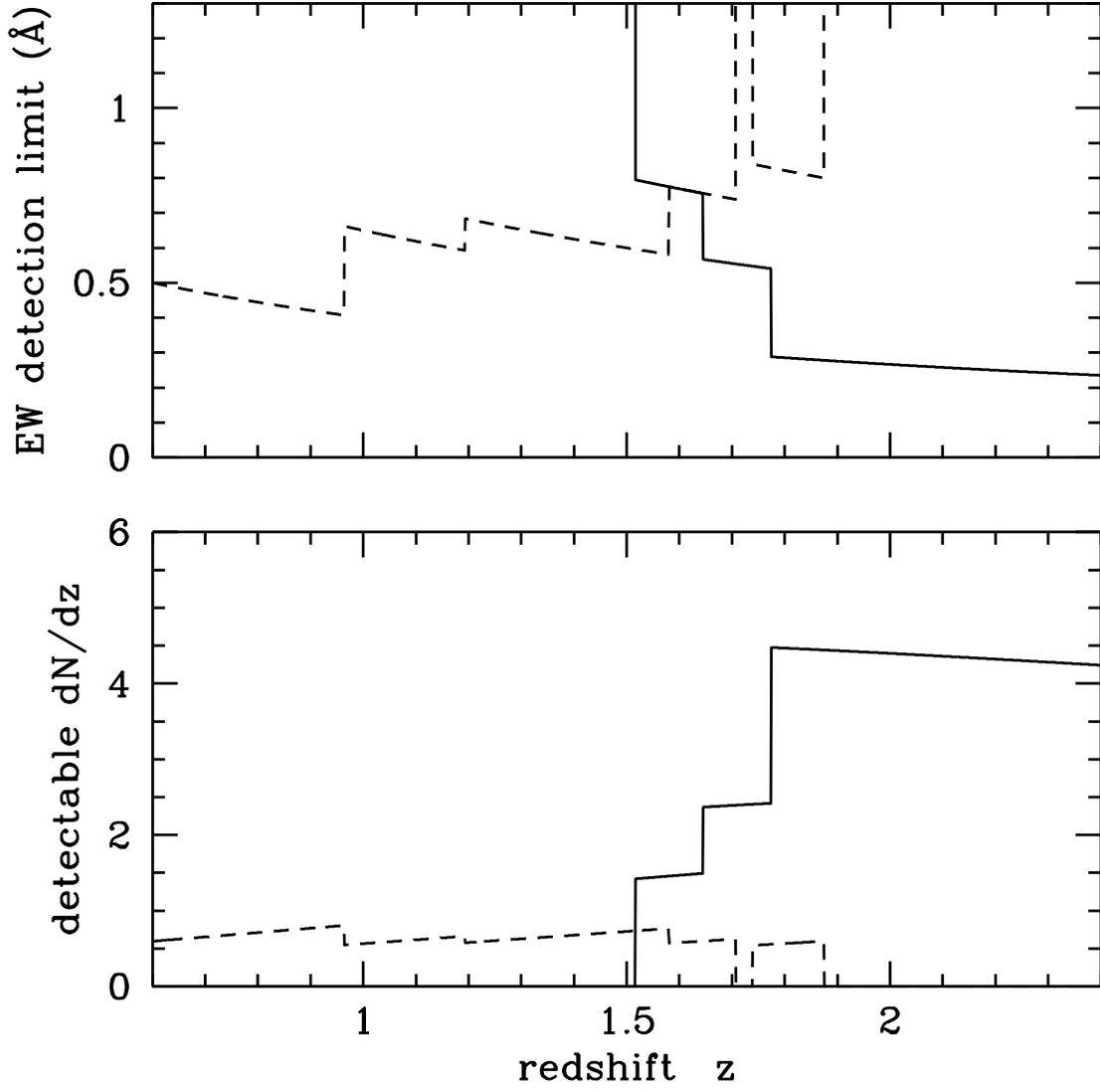


Fig. 1.—

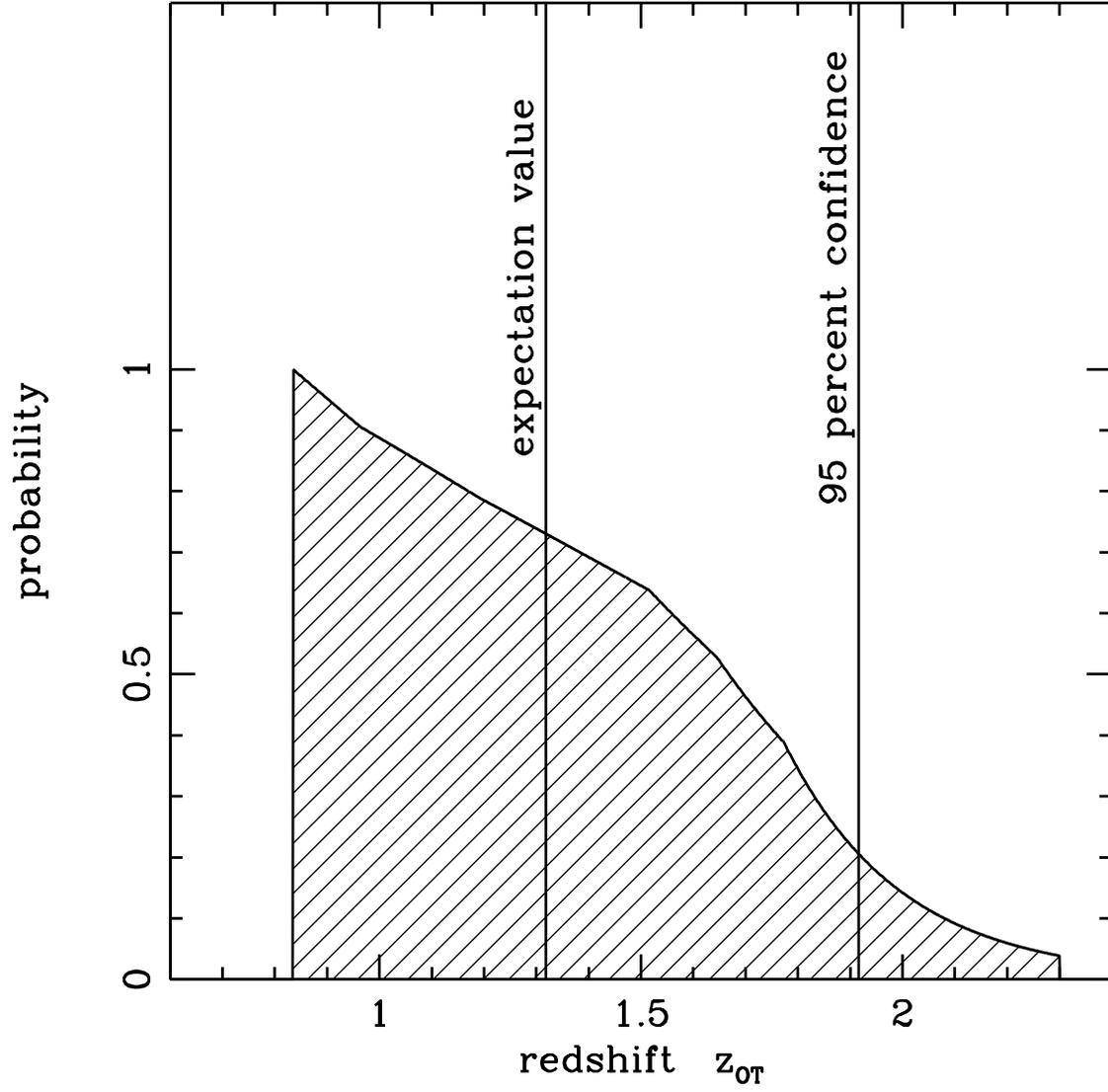


Fig. 2.—