Using STIS to find Gamma-Ray Burst Redshifts

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ABSTRACT

A recent spectrum of the optical afterglow of GRB 970508 suggests that gamma-ray bursts (GRBs) are cosmological in origin and it is of crucial importance to derive an accurate distance to each burst. If GRBs occur near their host galaxies (∼40 kpc) then Lyman limit absorption \( N(\text{HI}) \geq 1.6 \times 10^{17} \text{cm}^{-2} \) should be observable in roughly half the GRB afterglow spectra. Here we outline the methodology to obtain a redshift from the GRB afterglow spectrum using the recently installed Space Telescope Imaging Spectrograph (STIS) instrument onboard the Hubble Space Telescope. A low–resolution spectrum with the Multi-Anode Microchannel Array (MAMA) detector gives complete spectral coverage over the wavelength range 1570–3180 Å (Near UV; NUV) and 1150–1740 Å (Far UV; FUV). Assuming a Target of Opportunity observation is conducted soon (∼3 weeks) after a bright burst, a relatively small integration time (∼3 orbits) would be sufficient to detect the Lyman limit over a wide redshift range (0.3 < z < 2.2). Detection (or non–detection) of the Lyman limit, in concert with ground-based observations of nearby galaxies and Mg II and C IV absorption lines, should provide meaningful constraints on the relationship of GRBs to galaxies.

Key words: Gamma-ray bursts—cosmological redshift—spectroscopy—Lyman limit systems

1 INTRODUCTION

An optical source associated with gamma-ray burst (GRB) 970508 has recently been detected (Bond 1997). Absorption features seen in a spectrum from the Keck 10m telescope indicate that it is at or beyond \( z = 0.835 \) and the lack of a prominent Lyman-\( \alpha \) absorption suggests \( z \lesssim 2.1 \) (Metzger et al. 1997). Presuming that the source is indeed the optical afterglow of the burst, then GRBs have only just been confirmed to be cosmological. As no emission lines have been detected from the transient and it is unclear whether the burst is at the redshift of the absorption system at \( z = 0.835 \) (see §2), an alternative way to get a limit on the redshift is by looking for a Lyman-\( \alpha \) forest or Lyman limit absorption. Lyman limit absorption arises from neutral hydrogen (HI) which is optically thick to Lyman–continuum radiation for wavelengths \( \lambda \leq 912 \) Å in the rest frame of the absorbing system. Since both redshifted Lyman-\( \alpha \) absorption (1216 Å) and the Lyman limit (\( \lambda \lesssim 912 \) Å) remain in the UV passband for \( z \lesssim 2.2 \), currently only the Space Telescope Imaging Spectrograph (STIS) onboard the Hubble Space Telescope (HST) can detect a Lyman limit. As expected from theoretical models, both optical transients detected thus far have started fading soon after discovery, and thus a STIS spectrum must be obtained as soon as possible after the burst so as to maximise signal-to-noise (S/N).

The distance inferred from a Lyman limit in the continuum would provide knowledge of the luminosities and energies involved in the explosion—two vital parameters for constraining GRB models. In section 2 we discuss the possibilities of the GRB afterglow undergoing Lyman limit absorption. Then, in section 3 we discuss the instrumentation and calculate the integration time required to infer the redshift of a GRB.

2 LYMAN LIMIT ABSORPTION EXPECTATIONS

Lyman limit absorption systems, which are generally HI clouds opaque (\( \tau \gtrsim 1 \)) to the Lyman–continuum, are believed to concentrate in the disk and halo of most galaxies. Steidel (1993) has found that the density of Lyman limit systems is high enough to impact parameter of \( \sim 40 \) kpc in the galactic disk that continuum radiation passing through the plane of the disk will always be subjected to Lyman limit absorption. Thus, if GRBs occur at offsets \(< 40 \) kpc from the centres of their host galaxy, it is expected that
roughly 50 percent (half in front of the disk, half behind the disk) of GRB afterglow will have a Lyman limit break in the spectrum; this Lyman limit will correspond to the precise redshift of the burst since the limit system will be local to the GRB.

Intervening galaxies, not associated with the GRB but in the line-of-sight of the afterglow, may also absorb the continuum; thus a redshift inferred from a Lyman limit will not necessarily be the redshift of the GRB. What effect will this have on the determination of GRB redshifts? Storrie-Lombardi et al. (1994) survey QSO absorption spectra and find that for any random line-of-sight, the density of intervening Lyman limit systems is $N(z) \simeq 0.38(1 + z)^{1.04}$ for redshifts $z < 3.0$. Thus at redshifts $z \gtrsim 1.5$ it is expected that most GRB afterglows will be subjected to at least one Lyman limit in their continuum that does not necessarily correspond to the intrinsic redshift of the GRB.

If GRBs are ejected to distances comparable to the scale length of the Lyman limit absorption systems in the disk, then the probability that the host galaxy will absorb the spectrum shortward of the Lyman limit is reduced. The top portion of figure 1 shows the expected probability of the existence of a Lyman limit ($\tau \geq 1$) in the spectrum of a GRB afterglow as a function of redshift and the offset scale length of GRBs from their host galaxy. The relationship between the frequency of absorption from the host galaxy and the offset scale is computed by assuming that absorption only occurs if the GRB is seen through the 40 kpc absorbing disk and that the disk has random viewing inclination. As seen, the frequency of Lyman limit absorption in the spectrum of GRBs at low redshifts ($z \lesssim 1$) may be used to determine the intrinsic offset of GRBs from their host galaxies since most Lyman limit absorption at low redshifts is expected to come the host galaxy. The bottom half of figure 1 shows, as a function of offset scale and redshift, the probability that the inferred redshift is within 20 percent of the redshift of the GRB afterglow. If GRBs occur with about 60 kpc of their host galaxy (solid line), then more than 60 percent of the redshifts inferred from the Lyman limit in the spectrum will be a moderately accurate (<20 percent) measure of the redshift of the GRB.

Absorption from Mg II, with a galactic impact parameter of $\sim 50$ kpc (Bergeron et al. 1994), and C IV is expected, but not required, to accompany a Lyman limit system (Storrie-Lombardi et al. 1994). Thus, figure 1 could also be seen as a prediction of the frequency of absorption lines in GRB afterglows. Indeed for GRB 970508, both Mg II and Fe II absorption was detected using Keck (Metzger et al. 1997); Arav & Hogg (1997) have found that the absence of detectable C IV in the spectrum of the afterglow limits the redshift of the GRB to $z \lesssim 1.8$ (95 percent confidence).

3 OBSERVING DETAILS

The STIS CCD instrument onboard HST with a G230LB low–resolution grating gives complete spectral coverage over the wavelength range 1685–3065 Å. This would be sufficient to determine the Lyman limit over the redshift range ($0.85 \lesssim z \lesssim 2.4$). The preferred instrument for obtaining redshifts from UV spectra, however, are the Near UV (NUV) and Far UV (FUV) Multi-Anode Microchannel Ar-

![Figure 1. Top plot: The expected probability of the existence a Lyman limit in the spectrum of a GRB afterglow as a function of redshift and the offset scale length of GRBs from their host galaxy. The contribution to the total probability of a Lyman limit system (LLS) from the host galaxy (0.5 solid; 0.3 dashed; 0.1 dot dashed) is computed by assuming the GRBs occur randomly around the galaxy and the impact parameter of the LLSs in the disk is $\sim 40$ kpc (Steidel 1993). The contribution from intervening LLS (not associated with the GRB itself) is calculated assuming the number density of LLS systems evolve as $N(z) = 0.38(1 + z)^{1.04}$ (Storrie-Lombardi et al. 1994). Bottom plot: The probability, if a Lyman limit is present in the spectrum of the afterglow, that the inferred redshift is accurate to within 20 percent of the true redshift of the GRB afterglow itself. Not surprisingly at low redshift, a distance inferred from the Lyman limit is probably the true distance to the GRB since the expected number of LLSs from intervening galaxies is small. See Appendix A for details.](image-url)
find that the afterglow adequately fits the early light curve with $\delta = 0.8$ and $\beta = -1.2$ for GRB 970228. Our preliminary fits to the data from GRB 970508 indicate that $\delta \approx 0.8$ and $\beta \approx -1.0$. If the afterglow is observed as a Target of Opportunity $t_{\text{obs}} \lesssim 3$ weeks after the burst (e.g., $U(t_{\text{obs}}) \approx 22.7$ for GRB 970508), a redshift could be obtained in less than 10 HST orbits (see fig. [2]) using the either FUV or NUV MAMA detectors.

Unless HST is able to observe the afterglow of a GRB while it is still bright ($U \lesssim 21$), detection of damped Lyman-\(\alpha\) absorption at low redshift ($z \lesssim 1.5$) will require a very large integration time on STIS. However, a significant detection of a Lyman limit requires far less S/N per unit wavelength and thus improves the chance of determining a redshift of GRBs from fewer orbits. Although the Lyman break occurs at shorter wavelengths ($\lambda \lesssim 912(1+z)$ Å) than the Lyman-\(\alpha\) forest ($\lambda \approx 1216(1+z)$ Å) where the detectors are less sensitive, the distinct cut-off of this spectral feature is unambiguous and does not require good spectral resolution, making this the most effective and clearcut way to limit the redshift of faint sources.

Figure 2 shows the expected integration time required to achieve a $S/N=3$ in a 100 Å bin as a function of $U$ magnitude of the afterglow and redshift of the Lyman limit source for both the CCD and MAMA detector on STIS$^\star$. As seen in the figure, if the afterglow is observed while it is still reasonably bright ($U \lesssim 21$), detection of a redshift $z \gtrsim 0.3$ would require less than 1 HST orbit. Figure 3 shows a simulated spectrum of an afterglow obtained with MAMA with $\sim 1.5$ HST orbits (5400 sec) where the source is a magnitude $U = 21.0$ and the spectral shape is $\delta = 1$ (eq. 1). We have removed from the spectrum the narrow OII line (2470 Å) expected from geocoronal emission. The Lyman limit is clearly detected at $\lambda \approx 2100$ Å corresponding to a redshift $z \approx 1.3$. The clear break in the spectrum implies that a fairly accurate redshift is obtainable.

4 DISCUSSION

In general, given the efficiency of STIS and the spectral shape of the afterglow, the S/N increases with higher redshift (see fig. 2) for the NUV MAMA detector. If the burst occurs at a redshift $z \gtrsim 1.5$ then, with only a few orbits, one could determine the position of the Lyman break well enough to determine its redshift to an accuracy of better than 5 percent; it may even be possible to detect a Lyman-\(\alpha\) forest at high $z$ with only a few orbits. As it is easier to

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* Calculated using the STIS Spectroscopic Exposure Time Calculator located at [http://www.stsci.edu/](http://www.stsci.edu/)
detect a redshift for bursts that originate from a higher z
with the NUV MAMA detector, the absence of a Lyman
limit in the spectrum would, in general, always provide an
upper limit to the redshift. From figure (3), it is clear that
use of the MAMA detectors onboard the HST, given their
very low internal countrates, are preferable to the CCD.

The disadvantage of using HST to infer a redshift is the
difficulty of altering its scheduled observations even on the
timescale of weeks. Certainly the advantage is that there are
very few available ground-based telescopes that can resolve
Mg II and C IV absorption lines from faint objects; even then,
such telescopes may not have the proper viewing conditions
to the source and detected lines may place different
limits in the redshift. In addition, there may be important
emission (e.g. lines) in the UV spectrum of GRBs that would
not be observable from the ground.

As the ensemble of optical counterparts begins to grow in
size, it will be possible to infer both their redshift distribution
and the distribution of GRBs with respect to observable
galaxies by noting the frequency of absorption lines and
detected Lyman limit (see fig. 3). If no Lyman limit is detected
in the spectra of the optical transients (especially at
low-redshifts), the conclusion would be that either GRBs do
not originate near galaxies (\(\lesssim 300\)) kpc or they are Galactic
in origin.

5 CONCLUSIONS

A precise redshift of a gamma-ray burst would greatly fur-ther the field by providing an accurate understanding of the
energies involved in the burst. Assuming the extrapolation
of the spectral index (\(\delta\)) from the optical to UV passband is
correct, we find that a MAMA detector observation of the
bright afterglow of a GRB by STIS over \(\sim 1\) orbit could re-
vail a Lyman limit in the spectrum and hence, if the GRB
occurs behind a region of neutral hydrogen of its host galaxy,
provide a direct redshift to a gamma-ray burst. Given that
Lyman limit absorption may come from galaxies along the
line-of-sight, we predict the expected frequency of Lyman
limits in the spectrum as a function of GRB redshift and the distance from their host galaxy.

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APPENDIX A: LLS PROBABILITY

A Lyman limit system (LLS) is defined as the region of space
for which the optical depth (\(\tau\)) to the Lyman-continuum is
greater than one. Most Lyman limit systems are believed to be
clouds of HI with a column density \(N(H) \geq 1.6 \times 10^{17}\)
cm\(^2\). As depicted in the top half of figure 1, the probability
as a function of redshift that a spectrum of a GRB will
contain at least one such LLS is

\[
P(\geq 1 \text{ LLS}) = 1 - \text{Poisson}[0 \text{ LLS} | m(z_{\text{min}},z)]
\times P(\text{No LLS from host Galaxy})
\]

where Poisson \([0 \text{ LLS} | m(z_{\text{min}},z)]\) is the Poisson probability
of no intervening LLS between the GRB source (at redshift
\(z\)) and the observer given the expected number of LLSs:

\[
m(z_{\text{min}},z) = \int_{z_{\text{min}}}^{z} N(z')dz'.
\]

The minimum redshift in which a LLS could be detected is
\(z_{\text{min}}\) and \(N(z)\) is the number density of LLSs per unit
redshift.

The probability that the redshift inferred from an ob-
served Lyman limit in a GRB afterglow spectrum is at least \(x\) times the redshift of the GRB itself is given as

\[
P(z_{\text{LLS}} \geq x \times z | \geq 1 \text{ LLS}) = \frac{P(A | B) \cdot P(B)}{P(A)}
\]

where,

\[
P(A | B) = P(\geq 1 \text{ LLS} | \text{LLS redshift} \geq x \times z) = 1,
\]

\[
P(A) = P(\geq 1 \text{ LLS}),
\]

\[
P(B) = P(z_{\text{LLS}} \geq x \times z)
\]

\[
= 1 - \text{Poisson}[0 \text{ LLS} | m(x \times z, z)]
\times P(\text{No LLS from host Galaxy}).
\]

This probability is depicted in fig. 1 for \(x = 0.8\).