

X-ray Spectral Diagnostics of Gamma-Ray Burst Environments

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ABSTRACT

Recently, the detection of discrete features in the X-ray afterglow spectra of GRB970508 and GRB970828 was reported. The most natural interpretation of these features is that they are redshifted Fe K emission complexes. The identification of the line emission mechanism has drastic implications for the inferred mass of radiating material, and hence the nature of the burst site. X-ray spectroscopy provides a direct observational constraint on these properties of gamma-ray bursters. We briefly discuss how these constraints arise, in the context of an application to the spectrum of GRB970508.

Subject headings: gamma rays: bursts — X-rays: general — techniques: spectroscopic — line: formation

1. Introduction

The detection of a discrete spectral feature in the X-ray afterglow spectrum of GRB970508 was recently reported by Piro *et al.* (1999a,b). A similar feature in the afterglow of GRB970828 was reported by Yoshida *et al.* (1999). The redshift of the host galaxy of GRB970508 was determined to be $z = 0.835$ (Metzger *et al.* 1997; Bloom *et al.* 1998). The apparent energy of the discrete feature in the X-ray spectrum is consistent with the redshifted energies of the $n = 2 - 1$ transitions in all possible charge states of Fe, *i.e.*, from Fe K α at 6.4 keV, to H-like Fe Ly α at 6.95 keV. Therefore, none of the possible line excitation mechanisms (fluorescence, collisional excitation in hot gas, or

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recombination in photoionized gas or a transient collisional plasma) is currently ruled out on the basis of the measured line energy alone.

The conditions required for each of these emission mechanisms (*i.e.* the presence of a given charge state of Fe) are all still compatible with the constraints on ionization parameter and gas temperature that can be derived from the fact that the line source must be located no more than about 1 light day from the ionizing source, and from the shape of the ionizing spectrum. All three mechanisms require high gas density ($n_e \gtrsim 10^{11} \text{ cm}^{-3}$) for bound Fe to exist at all this close to the burst site. The presence of a large mass of dense gas close to the burst has led to the suggestion that a merging neutron star-neutron star binary is an unlikely site for this burst, and that a scenario involving some sort of stellar collapse is more likely (Piro *et al.* 1999b). In that case, the line source may be associated with debris from the stellar collapse.

Resolved X-ray spectroscopy can of course distinguish between the various line emission mechanisms, and lead to the correct characterization of the conditions in the source and the implied mass of radiating Fe. In the following, we will briefly recapitulate the constraints imposed by proximity and the energy budget, and then draw attention to an example of direct spectroscopic analysis of the X-ray spectrum: the fact that the measured centroid position, and to some extent even the shape, of the X-ray emission feature in the afterglow of GRB970508 already imply that recombination in afterglow-photoionized gas is unlikely to be the emission mechanism for this burst.

Our analysis applies to an optically thin, homogeneous medium. Complications arising from radiative transfer effects or external heat input by a relativistic shock may conspire to alter the shape of the spectrum, perhaps to the point that no definitive conclusions can be drawn from an instantaneous, low sensitivity spectrum. Such effects have been calculated by Weth *et al.* (1999) for the case of photoionization in the context of two specific geometries for the burst site, and by Vietri (1999) for a scenario in which the relativistic shock heats the medium shortly after the onset of the afterglow. With better data, it may hopefully be possible to reverse the argument, and infer the geometry, thermal history, and abundances from spectroscopy.

2. Ionization and Thermal Conditions in the GRB970508 X-ray Line Source

The discrete feature appears in the *BeppoSAX* Medium Energy Concentrator Spectrometer (MECS) spectrum immediately before a sudden rise in the afterglow flux, beginning at $\sim 6 \times 10^4$ sec after the burst, and disappears thereafter (Piro *et al.* 1999b). If one attributes the feature to emission by Fe, one requires bound Fe to be present close to the source, which emits a very large flux of ionizing photons in the afterglow ($L_{1 \text{ Ryd}-10 \text{ keV}} \sim 10^{51} (t/1 \text{ sec})^{-1.1} \text{ erg s}^{-1}$; here, t is the time since the burst [Piro *et al.* 1999b]).

The prompt burst and afterglow are intense enough that the photoionization timescale, t_{ion} , is extremely short compared to the burst duration and the time during which the emission feature is visible. Specifically, the (inverse of the) ionization timescale for Fe in the afterglow radiation field

is

$$\begin{aligned} t_{\text{ion}}^{-1} &= \int_{\chi}^{\infty} dE F(E) \cdot E^{-1} \sigma(E) = \\ &= 1.4 \times 10^4 (t/1 \text{ sec})^{-1.1} r_{16}^{-2} \text{ sec}^{-1}, \end{aligned} \quad (1)$$

with $F(E)$ the ionizing flux at the line source, $\sigma(E) \approx 6 \times 10^{-18} Z^{-2} (\chi/E)^3 \text{ cm}^2$ the K-shell photoionization cross section for neutral atoms of nuclear charge Z , χ the ionization potential, and r_{16} the distance to the burst site in units 10^{16} cm . We have assumed a E^{-2} photon number spectrum to calculate $F(E)$ from the 2 – 10 keV afterglow flux quoted by Piro *et al.* (1998), converted to luminosity assuming $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 1/2$, and we extrapolate the luminosity to 1 MeV. Ionization is essentially instantaneous.

The recombination timescale is given by $t_{\text{rec}} \sim (n_e \alpha(T_e))^{-1}$, where $\alpha(T_e)$ is the recombination coefficient, n_e the electron density, and T_e the electron temperature. Since α depends on the temperature, we first need to consider the thermal evolution of the source subject to irradiation by the prompt burst and afterglow radiation fields.

Given sufficient interaction time, the gas will relax to the Compton temperature, T_C , at which the Compton heating and cooling rates equal each other, and which is therefore determined only by the shape of the ionizing spectrum. In the non-relativistic limit (both the photon energies E and the electron energies $kT_e \ll m_e c^2$), the Compton temperature is given by

$$kT_C = \frac{1}{4} \frac{\int dE E F(E)}{\int dE F(E)} \quad (2)$$

(Ross 1979). As either the photon energies or the gas temperature approach the electron rest energy, the correct relativistic scattering cross section should be used, and the energy exchange between photons and electrons should be calculated to higher order than linear in $E/m_e c^2$ and $kT_e/m_e c^2$. In order to obtain a very rough estimate, we will assume here that we can mimic the effects of these modifications by simply cutting off the integrals at photon energies of order 1 MeV. If we assume a prompt burst spectrum of the form $F(E) \propto E^{1/2}$ at low energies, and $F(E) \propto E^{-3/2}$ above a break energy of order 1 MeV (Connors *et al.* 1998), the Compton temperature becomes approximately $kT_C \text{ (MeV)} \sim (3/16)(E_{\text{max}}/1 \text{ MeV})^{1/2}$, with E_{max} the cutoff energy. For E_{max} in the few MeV range, the Compton temperature is therefore in the several hundred keV range. The timescale for the Compton interactions to equilibrate should be of order (Rybicki & Lightman 1979)

$$t_{\text{Compton}} = \frac{1}{n_e \sigma_T c} \frac{m_e c^2}{4kT_e} \sim 7 \times 10^4 n_{10}^{-1} T_8^{-1} \text{ sec} \quad (3)$$

with σ_T the Thomson cross section. Unless the density is much higher than 10^{10} cm^{-3} , this timescale is much longer than the burst timescale, which implies that the Compton temperature will not be reached. Moreover, the average photon energy in the burst spectrum is of order 1 MeV, which produces mildly relativistic electrons. The stopping timescale of these fast particles on stationary

electrons is (*e.g.* Longair 1992)

$$t_{e-e} \sim \frac{\gamma m_e^2 c^3}{2\pi e^4 n_e \ln \Lambda} = 1.3 \times 10^3 n_{10}^{-1} (\gamma/2) ((\ln \Lambda)/10)^{-1} \text{ sec}, \quad (4)$$

(with γ the electron Lorentz factor, and $\ln \Lambda$ the Coulomb logarithm) which leads to the interesting conclusion that the plasma may not be in equilibrium at the end of the burst.

In any case, as the (much softer) afterglow begins, the plasma will rapidly cool by inverse Compton scattering, bremsstrahlung, and, at low temperatures, atomic emission. For an initial gas temperature of order 10^8 K or hotter, the Comptonization timescale is of the order of, or shorter than the duration of the afterglow, and equilibrium is established at the afterglow Compton temperature, which for an E^{-2} photon spectrum is equal to $kT_C = (1/4)E_{\max}/\ln(E_{\max}/E_{\min})$, with E_{\min} the lowest photon energy in the afterglow spectrum; E_{\max} is the upper end of the integration range, $E_{\max} \sim 1$ MeV. Assuming the afterglow spectrum flattens below $E_{\min} \lesssim 1$ Ryd (Wijers & Galama 1999), we find $T_C \lesssim 2 \times 10^8$ K. Kallman and McCray (1979) in their numerical models for X-ray photoionized nebulae, actually find that the electron temperature saturates at a lower temperature of approximately $T_C \sim 10^7$ K, due to bremsstrahlung cooling, so most likely the gas is cooler than 10^8 K in the afterglow.

The recombination coefficient as a function of temperature for recombination onto a bare nucleus is given by Seaton (1959); a powerlaw fit to the coefficient is $\alpha \approx 1.26 \times 10^{-6} T_e^{-0.75} \text{ cm}^3 \text{ s}^{-1}$ (for $Z = 26$), accurate to $\lesssim 20\%$ in the range $T_e = 10^5 - 2 \times 10^8$ K. Thus, the recombination timescale is

$$t_{\text{rec}} = 1.4 n_{11}^{-1} T_7^{0.75} \text{ sec}. \quad (5)$$

We conclude that at sufficiently high densities ($n_{11} \gtrsim 1$), the line source will be relatively cool, and close to ionization equilibrium at all times during the afterglow.

Assuming ionization equilibrium, we can derive a constraint on the density from the requirement that bound Fe be present in the line source. For Fe to recombine to the H-like charge state requires an ionization parameter in equilibrium of $\xi \equiv L/nr^2 \lesssim 10^4$, with L the ionizing luminosity, n the particle density, and r the distance to the ionizing source. This value of the ionization parameter applies to an E^{-2} ionizing photon spectrum (Kallman & McCray 1982, their model 7). Inserting numbers and extrapolating the ionizing luminosity to 1 MeV, one infers a lower limit to the density at a distance of 6×10^4 lt sec from the source, of

$$n \gtrsim 1.7 \times 10^{11} (t/6 \times 10^4 \text{ sec})^{-1.1} (r/6 \times 10^4 \text{ lt sec})^{-2} \text{ cm}^{-3} \quad (6)$$

Similarly, for Fe to be recombined to Li-like or less ionized, necessary for fluorescence to operate, $\xi \lesssim 1000$ in equilibrium, yielding a ten times higher density than the above estimate.

3. X-ray Spectroscopy

From the previous we conclude that if the interaction with the afterglow radiation is the only source of heating in the line emitting gas, then, later in the afterglow, the source is likely to be dense ($\gtrsim 10^{11} \text{ cm}^{-3}$) and relatively cool. Line emission can be excited both by fluorescence and cascading following recombination. Only if there is an additional source of heat, sufficient to heat the gas to $T \gtrsim 10^8 \text{ K}$, will collisional excitation play a role in driving Fe $n = 2 - 1$ lines.

Obviously, X-ray spectroscopy of the discrete emission strongly distinguishes between these various possible emission mechanisms. If one is confident of the redshift of the emission complex, fluorescence can be distinguished from emission by highly ionized Fe, simply from the apparent energy of the emission. Unfortunately, the resolution of the MECS, and the statistical quality of the spectra under discussion are not sufficient to allow this distinction to be made.

Recombination and collisional excitation, however, can readily be distinguished in the following way. For a given degree of ionization, a photoionized medium in equilibrium is much cooler than the corresponding collisional plasma, in which the electron temperature has to be of order the ionization potential in order to support a given charge state. The low electron temperature in photoionization equilibrium has a dramatic spectroscopic signature. Since most of the free electrons have small kinetic energies compared to the ionization potential, photons resulting from radiative recombination will have a narrow energy distribution, bunched up just above the ionization potential, with a typical width of order $\Delta E \sim kT_e \ll \chi$. In a collisional plasma on the other hand ($kT_e \sim \chi$), the recombination rate is much reduced, and in addition, the recombination photons are spread out over a wide energy range above the ionization potential. The narrow radiative recombination continuum (RRC) in a photoionized source is easy to detect, because it contains an integrated photon flux comparable to that in the $n = 2 - 1$ discrete transition; in fact, for H-like Fe, the ratio between the fluxes in the RRC to that in the Ly α line is approximately equal to $0.93 (kT_e/1 \text{ keV})^{0.21}$. So far, narrow RRC's have only been seen in the spectrum of the massive binary Cyg X-3 (Liedahl & Paerels 1996; Kawashima & Kitamoto 1996).

4. Application to the Spectrum of GRB980508

We use the dataset shown by Piro *et al.* (1999b; their dataset 1a). At the resolution of the MECS ($\Delta E \sim 340 \text{ eV}$ at 3 keV), the RRC is barely resolvable if the electron temperature is of order or less than 1 keV. For simplicity we use a model for the emission spectrum of cool, photoionized gas consisting of a narrow line plus exponentially decaying RRC, to represent the Ly α emission line and RRC at 6.95 and 9.28 keV, respectively, with equal photon fluxes. The He-like recombination spectrum would look much the same at the MECS resolution. To this, we added a simple power law with absorption by neutral gas, to represent the continuum. We let the redshift float, as well as the continuum parameters.

By fixing the electron temperature (*i.e.*, the width of the RRC) and fitting for the remaining free parameters we obtain the minimum χ^2 values displayed in Figure 1. At either very low T_e ($kT_e \lesssim 0.2$ keV) or very high T_e ($kT_e \gtrsim 4$ keV) we obtain χ^2 values of order $\chi_{\min}^2 \approx 7$ for 5 degrees of freedom. In themselves these values are acceptable (given the small number of degrees of freedom). However, at low temperatures the model has a best fitting redshift of $z > 1.6$ (for Hydrogenic Fe; 68% confidence for one parameter of interest only). At high temperatures, the RRC becomes essentially undetectable and the model consists effectively of a single narrow line. This model will of course fit the data, but at these temperatures the plasma would be closer to collisional equilibrium, which is not consistent with the assumption we set out to test. Finally, at $kT_e \sim 1$ keV (which is about the temperature for a source in photoionization equilibrium with the afterglow), we find $\chi_{\min}^2 \approx 12$, which indicates a poor fit (χ_{\min}^2 about two standard deviations away from the expected $\chi_{\min}^2 = 5$). By itself, this is probably not enough to confidently reject the model, and the fit can be improved by changing the temperature somewhat. But the implied redshift is still $z \sim 1.20$, higher than for a single line because we have an additional emission component at 4/3 times the line energy. Unless we are willing to entertain the possibility that the line source is actually behind the galaxy at $z = 0.835$, we conclude that the emission spectrum from a cool photoionized source is incompatible with the measured spectrum. In Figure 1, we have indicated the (68% confidence) limits on the redshift as a function of the assumed temperature of the gas, assuming H-like emission. At high temperature, the contrast in the RRC becomes very small, and the spectrum is dominated by a single line. In this limiting case, the implied redshift approaches $\sim 1.05 \pm 0.05$ (68% confidence), appropriate for H-like Fe Ly α . Widening the confidence interval to 90% confidence will produce agreement with the optical redshift of $z = 0.835$ (Piro *et al.* 1999b).

Figure 2 displays the data and the lowest- χ^2 recombination model with $kT_e = 1$ keV; the values for the other spectral parameters are: power law photon index -3.1 , column density $N_H = 7.1 \times 10^{21}$ cm $^{-2}$. This continuum spectral shape appears to be quite a bit steeper than the best fit given by Piro & al. 1999b, but in fact, the uncertainty on the index is large (≈ 1.1 for one parameter of interest, at 1σ), and so the continuum shapes are in fact consistent.

5. Conclusion

We find that Fe emission from a cool photoionized source in equilibrium with the afterglow cannot account for the X-ray spectrum of GRB970508. Fitting a spectral model for such a source either implies a large redshift, or indicates such high electron temperatures that the source would be closer to collisional ionization equilibrium.

This would imply that the discrete feature in the spectrum of GRB970508 arises from either Fe fluorescence or from collisional excitation, each of which implies a very different estimate for the total mass of radiating Fe ($M_{\text{Fe}} \sim 2.6 \times 10^{-4} M_{\odot}$ for fluorescence, $M_{\text{Fe}} \sim 7 \times 10^{-2} M_{\odot}$ for collisional excitation, which corresponds to $M_{\text{total}} \sim 8 \times 10^{-2} M_{\odot} (A_{\text{Fe}}/A_{\text{Fe},\odot})^{-1}$ and $M_{\text{total}} \sim 28 M_{\odot} (A_{\text{Fe}}/A_{\text{Fe},\odot})^{-1}$, respectively (see, for instance, Meszaros & Rees [1998], Piro *et al.* [1999b],

Lazzati et al. [1999]); here, A_{Fe} is the abundance of Fe).

With higher spectral resolution and sensitivity, we may be able to distinguish spectroscopically between a fluorescent and a collisional spectrum (a recombination spectrum is readily identified from the presence of the RRC). Working from the K-shell spectrum of a single ionization stage of Fe alone, one might use the $n = 2 - 1$ and $n = 3 - 1$ transitions, which are resolved at $E/\Delta E \sim 10$. Intensity ratios do not effectively discriminate between collisional excitation and fluorescence: $I(\text{Ly}\beta)/I(\text{Ly}\alpha) = 0.10 - 0.15$ (Hydrogenic Fe) for electron temperatures between 3×10^7 and 10^9 K (Mewe, Gronenschild, & van den Oord 1985), while for neutral Fe $I(\text{K}\beta)/I(\text{K}\alpha) = 0.13$ (Kaastra & Mewe 1993). Instead, with somewhat higher resolution, one might use the fact that the ratio of the transition energies depends on the charge state: $E(\text{Ly}\beta)/E(\text{Ly}\alpha) = 1.18$, while $E(\text{K}\beta)/E(\text{K}\alpha) = 1.10$.

At higher resolution, one would resolve the $1s - 2p_{1/2}$ and $1s - 2p_{3/2}$ transitions ($E/\Delta E > 500$). The ratios of the energies are $E(\text{Ly}\alpha_2)/E(\text{Ly}\alpha_1) = 1.0030$ and $E(\text{K}\alpha_2)/E(\text{K}\alpha_1) = 1.0020$, and a resolving power of 1000 is required to distinguish between these two.

A collisional source at $kT < 15$ keV will also show emission from He-like Fe, and the simultaneous appearance of both the H- and the He-like charge states readily indicates a high degree of ionization of the source. For temperatures in the range $3 < kT < 15$ keV, the He-like emission dominates, which could still be identified as such if the characteristic "triplet" structure of the $n = 2 - 1$ lines is resolved ($E/\Delta E > 300$). The highest resolution available at energies above 2 keV is provided by the High Energy Transmission Grating Spectrometer on *Chandra* (Canizares et al. 2000). The Fe K spectrum will be resolved at $E/\Delta E \approx 150 (1 + z)$, which would at least enable charge-state spectroscopy at moderately large redshift.

Finally, given sufficient sensitivity at low energies (and sufficiently low absorption in the source), we may of course detect emission from lower- Z elements, either collisional or fluorescent, which would greatly facilitate the spectroscopic diagnosis of the excitation mechanism. With the grating spectrometers on *Chandra* and *XMM*, standard detailed plasma diagnostics can be invoked, at resolving powers of $E/\Delta E \sim 100 - 1500$ at $E \lesssim 2$ keV, depending on photon energy (Canizares et al. 2000, Brinkman et al. 2000, Brinkman et al. 1998). Clearly, it would be very interesting to pursue more sensitive X-ray spectroscopy of gamma ray burst afterglows.

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REFERENCES

- Bloom, J. S., Djorgovski, S. G., Kulkarni, S. R., & Frail, D. A. 1998, *ApJ*, 507, L25.
 Brinkman, A. C., et al. 1998, in *Proceedings of the First XMM Workshop*, M. Dahlem, Ed. ,

http://xmm.vilspa.esa.es/news/ws1/ws1_papers.html.

- Brinkman, A. C., et al. 2000, ApJ, 530, L111.
- Canizares, C. R., et al. 2000, ApJ, submitted.
- Conners, A. & al. 1998, in *Gamma Ray Bursts*, Proc. 4th Huntsville Symposium, Meegan, C. A., Preece, R. D., & Koshut, T. M. (Eds.), p. 344 (AIP: New York).
- Kaastra, J. S., and Mewe, R. 1993, A&AS, 97, 443.
- Kallman, T. R., & McCray, R. 1982, ApJS, 50, 263.
- Kawashima, K., & Kitamoto, S. 1996, PASJ, 48, L113.
- Lazzati, D., Campana, S., & Ghisellini, G. 1999, MNRAS, 304, L31.
- Liedahl, D. A., & Paerels, F. 1996, ApJ, 468, L33.
- Longair, M. S. 1992, *High Energy Astrophysics*, 2nd Ed., (Cambridge UP:Cambridge).
- Meszáros, P., & Rees, M. J. 1998, MNRAS, 299, L10.
- Metzger, M. R., Djorgovski, S. G., Kulkarni, S. R., Steidel, C. C., Adelberger, K. L., Frail, D. A., Costa, E., & Frontera, F. 1997, Nature, 387, 878.
- Mewe, R., Gronenschild, E. H. B. M., & van den Oord, G.H.J. 1985, A&AS, 62, 197.
- Piro, L. *et al.* 1998, A&A, 331, L41.
- Piro, L., *et al.* 1999a, A&AS, 138, 431.
- Piro, L. *et al.* 1999b, ApJ, 514, L73.
- Ross, R. 1979, ApJ, 233, 334.
- Rybicki, G. B., & Lightman, A. P. 1979, *Radiative Processes in Astrophysics*, (Wiley:New York).
- Seaton, M. J. 1959, MNRAS, 119, 81.
- Vietri, M., Perola, C., Piro, L., & Stella, L. 1999, MNRAS, 308, L29.
- Weth, C., Mészáros, P., Kallman, T., & Rees, M. J. 1999, ApJ, submitted (astro-ph/9908243).
- Wijers, R. A. M. J., & Galama, T. J. 1999, ApJ, 523, 177.
- Yoshida, A., *et al.* 1999, A&AS, 138, 433.

Figure Captions:

Fig. 1.— Minimum χ^2 and best fitting redshift for fitting a spectral model appropriate for emission from afterglow-photoionized gas to the *BeppoSAX* MECS+LECS spectrum of GRB970508, as a function of electron temperature kT_e . The grey band represents the 1σ confidence volume for the X-ray redshift; the dotted lines indicate the 1σ contours for the best-fitting X-ray redshift assuming H-like Ly α line emission only (no RRC).

Fig. 2.— Best fitting photoionization equilibrium emission model, for an assumed electron temperature of $kT_e = 1$ keV. Solid triangular datapoints are LECS fluxes, solid circles are MECS fluxes. This model implies a source redshift of $z = 1.20$ for H-like Fe emission. Lower panel displays the post-fit residuals.



