Mon. Not. R. astr. Soc. (1992) **257**, 471–475

A search for the iron absorption edge in the tail of an X-ray burst from X1636–53

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Accepted 1992 February 11. Received 1992 January 30; in original form 1991 December 18

SUMMARY

Model atmosphere calculations of the spectrum of a neutron star cooling after an X-ray burst show that the photoelectric edge of iron should be prominent. We find no clear evidence for such a redshifted feature in the spectrum of a burst from X1636–53 and conclude that the iron abundance there must be less than 0.3 solar. Unless the iron abundance of the surface matter on the neutron star is highly time-dependent, our result argues against the 4.1-keV absorption line seen in some bursts from X1636–53 by Waki *et al.* being due to iron. We note that the iron edge will be a powerful diagnostic of the surface redshift of the neutron star in burst sources where the iron abundance is more nearly solar.

Key words: line: formation – stars: abundances – stars: atmospheres – stars: individual: X1636 – 53 – stars: neutron – X-rays: stars.

1 INTRODUCTION

Studies of X-ray bursts should enable the radius and other properties of neutron stars to be measured and the equation of state of matter at nuclear densities to be thereby refined (Joss & Rappaport 1984). The continuum spectrum resembles a cooling blackbody from which the radius can be deduced using the Stefan–Boltzmann law. Spectral features reveal the redshift of the surface and so constrain the mass–radius relation of neutron stars.

Unfortunately, the spectrum is not expected to be a simple blackbody, due to the thermalization depth depending on the photon energy and the effects of thermal Comptonization. This has been extensively modelled (London, Taam & Howard 1984, 1986; Foster, Ross & Fabian 1986; Sunyaev & Titarchuk 1986; Ebisuzaki & Nomoto 1986; Titarchuk 1988; Madej 1991) but still requires the surface gravity as an input parameter. Absorption lines have been observed in some burst spectra by Waki *et al.* (1984), at 4.1 and 5.7 keV, the first line of which has also been reported by others (Nikamura, Inoue & Tanaka 1988; Magnier *et al.* 1989). The 4.1-keV line is usually identified as resonance absorption of iron Kα transitions in He-like iron, but this implies a redshift factor $(1+z)^{-1}=0.61$ which is too extreme to be consistent with most mass–radius relations for neutron stars. We (Foster *et al.* 1987) have previously shown that an observable resonance absorption line is most unlikely to occur unless the iron abundance is greatly increased above the solar value; the predicted equivalent width of $W=29\beta^{1/2}$ eV, where β is the fraction of iron (normalized to solar abundance) in the Fe XXV state, is much less than the observed values of >100 eV. Recently, Madej (1990) has suggested that the narrow absorption lines are due to ionized calcium and chromium in turbulent clouds of ionized circumstellar gas. They then provide no information on the surface properties of neutron stars.

A large iron abundance should be detectable in the cooling spectrum of X-ray bursts as a strong photoelectric absorption feature (Foster *et al.* 1987). Indeed the detection of such a feature should by itself enable the surface redshift of the neutron star to be determined. In this paper we use *Ginga* spectra of a burst in the source X1636–53. This was the source from which Waki *et al.* (1984) detected absorption features. It has been well studied from many satellites (e.g. Damen *et al.* 1990 and references therein) and has an iron line present in the spectrum of its persistent emission

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(Breedon *et al.* 1986; Gottwald & White 1991). The iron abundance of the system cannot therefore be negligible, although it cannot yet be deduced from such spectra since there is no satisfactory model for the persistent X-ray emission. The iron absorption edge should be most detectable from burst spectra once the surface has cooled to an effective temperature of $kT < 1.5$ keV, so that there is sufficient recombined iron present in the surface layers (see fig. 1 of Foster *et al.* 1987; the most abundant species is Fe XXV).

2 OBSERVATIONS

The Large Area proportional Counters (LAC) on board *Ginga* observed X1636–53 on 1987 August 18–21 during the initial Performance Verification phase of the mission. A description of *Ginga* is provided by Makino *et al.* (1987); the LAC is described by Turner *et al.* (1989). Altogether, four X-ray bursts were recorded. Here, however, we concentrate on the only burst to be observed with both high temporal and high spectral resolution. This burst occurred at 05:17 UT on August 18, and was observed in MPC-2 mode at high bit-rate, a combination which provides 48-channel spectra summed over all eight units of the LAC every 62.5 ms. Normally, the pass-band extends from 1.1 to 35 keV, but for this observation the gain was increased in order to maximize the signal-to-noise ratio during bursts, the steep spectra of which decline rapidly above 10 keV. Thus the upper bound of the pass-band was reduced to 18.9 keV.

In Fig. 1 we show the X-ray burst in question. A preliminary analysis of the spectral variations during the burst, based on fitting blackbody spectra, indicates that the photosphere of the neutron star expands by a factor of 2 at the peak. Only during the burst tail, however, does the spectrum truly resemble a blackbody, and in this paper we analyse the spectrum during the final phase of the burst tail.

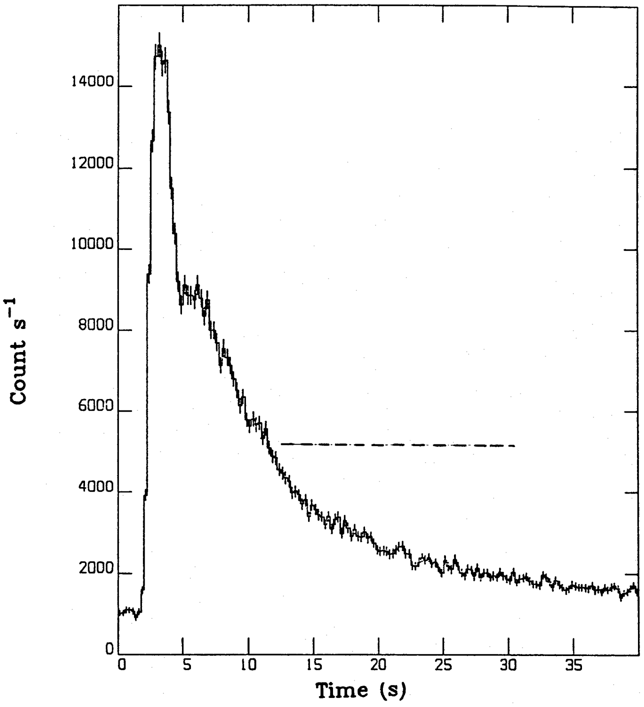

Figure 1. The X-ray light curve, in the range 2–10 keV, of the burst from X1636–53 analysed here. The dashed line indicates the integration period of the spectrum from the burst tail used to search for an absorption edge.

3 THE SPECTRAL MODEL

We have modelled the X-ray spectrum of a burst using the methods discussed in our earlier papers (Foster *et al.* 1986, 1987). The radiation diffusion code of Ross (1979) was used, with the density profile of the matter appropriate for hydrostatic equilibrium in the atmosphere of a 1.4-$M_\odot$ neutron star of radius 10 km (the redshift factor is then 0.76). The inner boundary is taken at a Thomson depth of 20 where local thermodynamic equilibrium is assumed to hold. Solar abundance of iron is defined as a ratio of 3.3×10^{-5} for the number density of iron nuclei to hydrogen nuclei (Morrison & McCammon 1983) and our fractional abundances are measured relative to that value. The spectra which we have used (Fig. 2) range from 0.1 to 1 times solar abundance in iron and have an observed 1–19 keV colour temperature of $kT_{\mathrm{col}} = 1.2$ keV, i.e. the redshifted spectrum is best fitted over the *Ginga* energy range of 1–19 keV by a blackbody of temperature kT_{col}.

In order to fit the data (for which the redshift is unknown) to the model, we have made a simple spectral parametrization of the model spectra and fitted that rather than the complete model. To achieve this parametrization, the model spectra have been fitted with a blackbody spectrum and an absorption feature of various forms over the energy range of 1–19 keV. The model data points have been weighted according to the square root of the photon luminosity, since this roughly parallels the weighting occurring in the observed spectrum. Neither a Gaussian feature nor a 'sawtooth' appropriate to photoelectric absorption provide good fits.

The best simple expression we found was to cause the normalization of the blackbody to drop abruptly at the

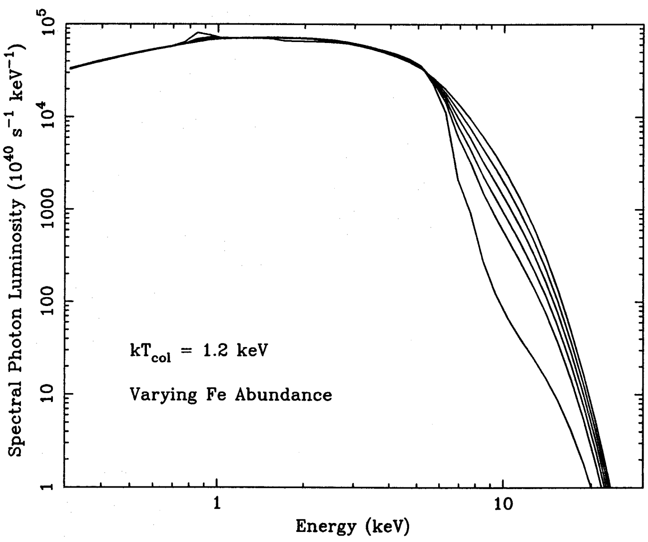

Figure 2. Model spectra computed for a neutron star of mass $1.4 M_\odot$ and radius 10 km with the iron abundance varied from 0.1–0.5 (in steps of 0.1) and 1.0 times solar abundance. The spectra have been appropriately redshifted and the (observed) colour temperature is 1.2 keV.

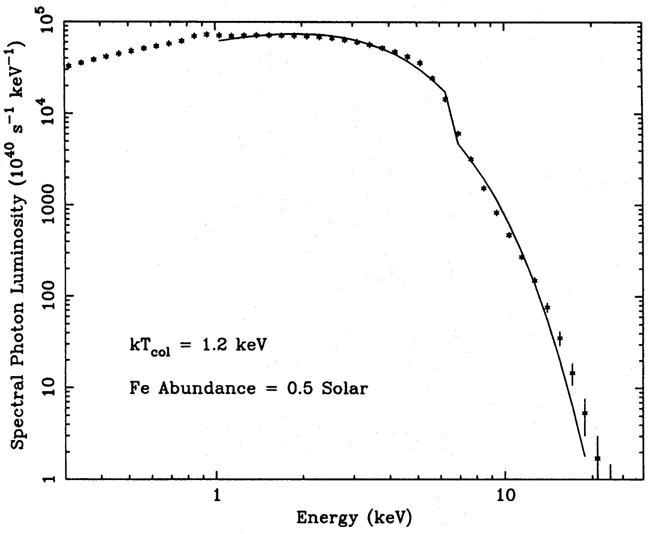

Figure 3. Model spectrum for 0.5-solar iron abundance (solid line) with the best-fitting spectrum over the energy range of 1–19 keV obtained from a blackbody which is abruptly renormalized at the redshifted Fe xxv edge.

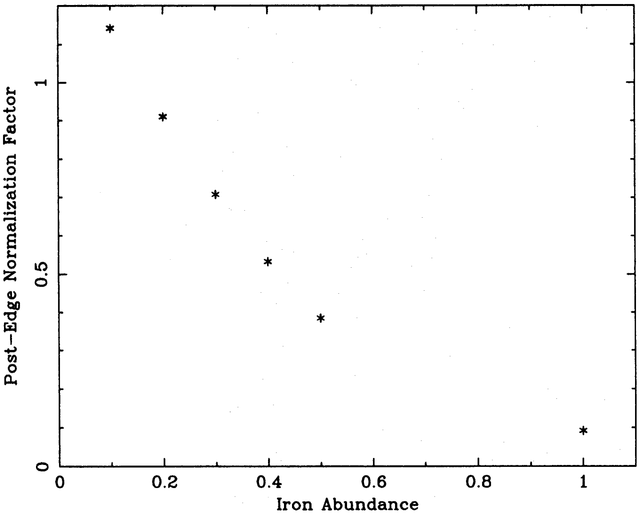

Figure 4. The post-edge normalization factor, obtained by fitting the model spectra over the energy range 1–19 keV, plotted as a function of iron abundance. The factor is the amount by which the 1.2-keV blackbody is renormalized at energies above the Fe xxv edge.

absorption energy of Fe xxv, i.e. 8.83 keV appropriately redshifted, and to maintain the same decrement at all higher energies (see Fig. 3). This leads to a conservative estimate of the abundance of iron in the surface matter, since the fit gives a slightly smaller edge decrement than is actually present at the edge energy. Comptonization leads to the iron photoelectric edge and the associated K emission line appearing as a very broad absorption feature with a slight plateau at energies just below the line energy (see Fig. 2). This, together with the energy dependence of the thermalization depth, causes the post-edge normalization factor to exceed unity at abundances of 0.1 solar and less, since the model spectrum is harder than a true blackbody spectrum. We show in Fig. 4 the variation in post-edge normalization factor with iron abundance, for a 1–19 keV colour temperature of 1.2 keV.

The colour blackbody temperature is slightly sensitive to the energy range over which the model spectrum is fitted, but remains within 0.1 keV of the required value of 1.2 keV if the range is reduced from 1–19 to 2–10 keV. The best-fitting edge energy is consistent with that of redshifted Fe xxv to within the resolution of the photon energy grid used in the spectral models (~ 0.7 keV around 7 keV). If the surface gravity is higher than we have assumed, as required if the 4.1-keV feature is due to iron, then the normalization factor at a given abundance will be less than that shown in Fig. 4, since the surface will be denser and the gas more recombined (see fig. 5 of Foster *et al.* 1986). It only leads to an underestimate of the iron abundance if the surface gravity is less, which implies a hard equation of state for the neutron star.

The simple and robust parametrization summarized in Fig. 4 is adequate for preliminary work of the kind reported here. More detailed modelling will be required when an iron edge is detected. In future work we intend to fit the complete model spectra to such data from a variety of bursts in order to obtain accurate measurements and limits of abundances and gravitational redshifts.

4 DATA ANALYSIS

4.1 Background subtraction

Before discussing the selection of our data, we describe the subtraction of background. In burst analysis, the persistent emission is often used as background. Despite the obvious advantage of removing the non X-ray background in a straightforward way, this procedure has a potentially serious drawback, especially during the burst tail where the net flux is low. For if, as noted by Van Paradijs & Lewin (1986), the persistent emission also contains a blackbody component from the surface of the neutron star, systematic errors will arise when the persistent emission is subtracted from the burst emission, itself that of a neutron star blackbody. On the other hand, a different, more damaging source of systematic error arises when the persistent emission is not subtracted. The LAC has a large field of view which, when directed at the Galactic plane, observes enough of the Galactic X-ray background for this component to contribute significantly to the spectrum. The Galactic X-ray background contains a strong thermal iron line (Koyama 1989), the energy of which coincides with the Fe xxv absorption edge redshifted by a 1.4-$M_\odot$ neutron star of radius 10 km, which would impair our search for absorption features if not completely removed. We therefore choose to use the persistent emission as background, making sure that the net burst flux is not too low.

4.2 Data selection

In order to achieve our aim of detecting absorption features in the burst spectrum, we need the highest signal-to-noise ratio possible, that is, the longest possible integration time. As pointed out in the Introduction, we also need to select data from a part of the burst where the surface effective temperature is less than 1.5 keV (and with a reasonable redshift

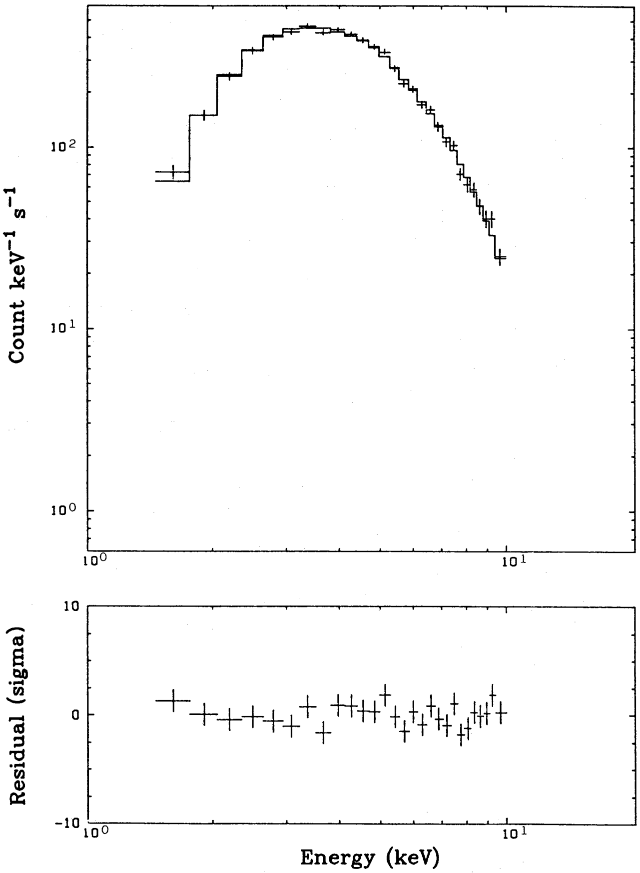

Figure 5. The count spectrum from the burst tail shown with the best-fitting blackbody and its residuals.

this means an observed effective temperature less than about 1.3 keV). Two further constraints limit the length of integration. First, the start-time cannot occur too close to the burst peak lest the integration sum over too wide a range of temperature. To satisfy this constraint we require that the spectral continuum be fitted adequately with a single-temperature blackbody. Secondly, we require that the net burst flux in the highest energy channel of interest be significantly large to avoid the sort of systematic errors in background subtraction described by Van Paradijs & Lewin (1986). Since we do not expect iron absorption features above 9 keV, we stop the integration at the point where the flux at 10 keV is 5σ above the persistent level. Enforcing these constraints results in the integration period of 17.94 s, shown by the dashed line in Fig. 1, and in the count spectrum shown in Fig. 5.

4.3 Model fitting

A simple blackbody with low-energy, interstellar absorption fits the spectrum well. For the 25 degrees of freedom, the reduced chi-squared is 1.03. The best-fitting temperature is 1.19 ± 0.02 keV; the hydrogen column is $10^{21.8 \pm 0.14}$ cm^{-2}, consistent with previous observations (Breedon *et al.* 1986, and references therein). Clearly, there is no compelling evidence of absorption features in the data.

To quantify this, we fitted the model discussed in Section 3. Covering the range 4–9 keV in steps of 0.25 keV, the edge energy was held constant and the post-edge normalization factor was varied. The results are shown in Fig. 6 where the error bars are those for a single parameter and correspond to the 95 per cent confidence level. We find that there is no strong evidence for an iron absorption feature. The lower limit of ~0.8 for the post-edge normalization factor implies an upper limit to the iron abundance of ~0.3 solar using Fig. 4.

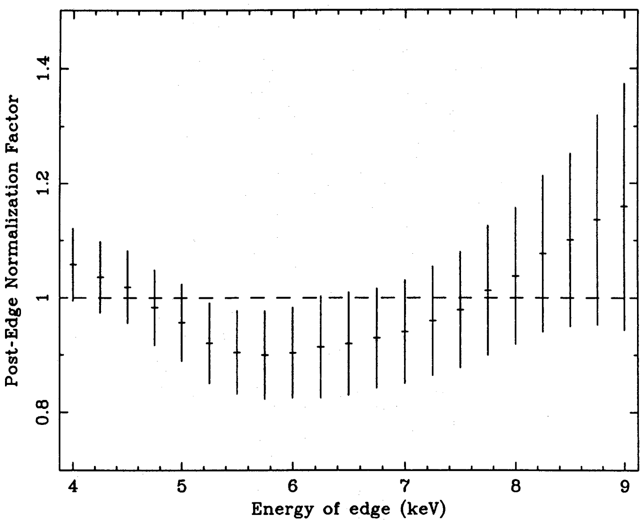

Figure 6. The allowed range of post-edge renormalization factor shown as a function of edge energy. The error bars are for a single parameter with 95 per cent confidence.

5 DISCUSSION

We have found that the iron abundance in the surface atmosphere of the neutron star in X1636−53 is less than 0.3 solar. Under the straightforward assumption that the composition of the atmosphere is unchanged during a burst, and from burst to burst, this means that the 4.1-keV absorption line observed by Waki *et al.* (1984) cannot be due to resonance absorption by Fe XXV or Fe XXVI. It also means that we have a powerful method for determining the iron abundance of the accretion flows in those low-mass X-ray binaries which are burst sources.

Alternatively, it is possible that the composition of the atmosphere varies with time during the burst. Radiation pressure acting on iron ions in the accreted matter could drive them to the surface and/or violent mixing during the burst might bring freshly synthesized matter to the surface. Later in the burst (such as when we have made our spectra), the strong gravitational field of the neutron star may cause iron to undergo sedimentation to the extent that the apparent abundance is much reduced. A persistent accretion rate of 10^{16} g s^{-1} corresponds to a surface accumulation of 800 g cm^{-2} s^{-1} or several thousand Thomson depths per second. It is unlikely that the matter spreads across the surface at speeds of more than 10 per cent of the velocity of light, but this still allows much of the surface layers relevant to our observation to consist of freshly accreted matter not present when the thermonuclear flash took place. Consequently it is possible, but not obvious, that the iron abundance may have been supersolar during the occasions when Waki *et al.* (1984) and others observed absorption lines, although inspection of their spectra shows no obvious photoelectric edge as expected if the iron is mostly Fe xxv or Fe xxvi.

Violent, but subsonic, mixing (turbulence or convection) during the phases of the bursts when the lines were observed (just after maximum luminosity) could therefore have increased both the surface iron abundance and the equivalent width of the resonance absorption line. The equivalent width increases, due to the abundance change and (by a small factor) to the velocity spread of the line (turbulent velocities which are just subsonic for hydrogen greatly exceed the iron thermal velocity). Such a solution to the absorption-line problem requires that the dissipation of the kinetic energy does not further ionize the iron (Foster *et al.* 1987). Quantifying this possibility is not reasonable at the present time. It is unlikely to allow the predicted equivalent width to attain 100 eV (see also the discussion by Magnier *et al.* 1989). Further observations, particularly with higher spectral resolution (e.g. with *ASTRO-D*), should indicate whether it is a viable possibility or if the alternative suggestion of Madej (1990) of circumstellar absorption is correct. In this case, however, the signatures of circumstellar iron and other elements should have been detected, both through resonance line absorption and very strong photoelectric edges (the column density required is $\sim 10^{24}$ cm^{-2}).

Our results do not allow progress to be made directly on the issue of the mass–radius relation of neutron stars. We have only a weak indication of an absorption edge from redshifted iron, at a level where (unquantifiable) systematic effects in the subtraction of the persistent emission and of our approximation of the cooling spectrum as an equilibrium spectrum (see fig. 4 in Foster *et al.* 1987 for a simulation of this effect) may be relevant. What our work has shown, however, is that the photoelectric absorption edge due to iron should be detectable in the cooling spectra of bursts in which its abundance is greater than about 0.3 solar. The detection of such an edge will be an unambiguous diagnostic of the surface gravitational redshift of the neutron star.

ACKNOWLEDGMENTS

CSRD is grateful to the Japan Society for the Promotion of Science for financial support during the first stage of this work. ACF thanks the Royal Society for support. This work was performed while RRR was on a Faculty Fellowship from the College of the Holy Cross.

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