MERGING OF IRON LINES IN SPECTRA OF X-RAY BURST SOURCES

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ABSTRACT. Model atmospheres and synthetic spectra of neutron star of the effective temperature 10^7 K are presented. All the iron spectral features in the energy range 6 - 10 keV (uncorrected for redshift) are washed out by instrumental or intrinsic broadening, which leaves only a single line of the equivalent width comparable with the observations.

1. INTRODUCTION

Waki et al. (1984) detected prominent 4.1 keV absorption line in spectra of MXB 1636-536 (cf. also Turner and Breedon 1984), and suggested that the line represents resonance K_α transition in highly ionized iron ions in stellar atmosphere with energy around 6.7 keV, if measured on the neutron star surface. The equivalent width (W_E) of this line was very large, and exceeded 200 eV in some bursts. Existence of the 4.1 keV line was also confirmed in few other X-ray bursters.

No other spectral features were credibly detected in X-ray burst spectra. Consequently, identification of the line with $K\alpha$ transition of iron is strictly arbitrary, but - if correct - would be a direct measure of the mass to radius ratio, M/R, of a neutron star. In this paper we examine the appearance of all iron spectral features in model atmosphere of a neutron star, when observed with X-ray detectors of limited spectral resolution.

2. SPECTRAL FEATURES

This paper is based on set of nongrey model atmospheres in radiative and hydrostatic equilibrium, computed for T_e = 10^7 K, log g between 14 and 15, and with various abundance of iron. The most important opacities included in the models are: electron scattering (taken in Thomson approximation), and free-free absorption of fully ionized hydrogen and helium. Contribution of iron opacity to the models (in LTE) included b-f and f-f opacity of iron in the highest four

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stages of ionization, and blanketing by resonance lines of He-like and H-like ions. More extensive description of the models is given elsewhere (Madej 1988a; 1988b).

Careful line profile calculations show, that equivalent widths (W_E) of the resonance lines of iron can approach 400 eV in such conditions, with iron abundance increased only 10 times above the solar value (Madej 1988a; 1988b). However, this result should be revised when the assumption of local thermodynamic equilibrium (LTE) in the equation of state of iron is removed. After correction for gravitational redshift with $g \approx 0.6$, the observed equivalent widths W_E still exceed 200 eV, which is fully compatible with the observations.

One can note, that such values of W_E correspond to two resonance lines of heliumlike and hydrogenic iron, which are formed in neighboring atmospheric layers with different temperatures, and partly overlap each other on the continuum dominated by electron scattering. Additional (instrumental or intrisic) broadening assumed in the above papers causes merging of both lines into a single spectral feature.

If we accept presence of resonance lines in the X-ray spectrum, then one has to explain simultaneously the following questions:

A. Why we do not see lines corresponding to transitions between higher excited levels in both iron ions?
B. Why we do not see two ionization (bound-free) jumps at 8.8 keV and 9.28 keV (times redshift factor), which could eventually merge into a single absorption edge?

3. CALCULATIONS AND RESULTS

Ready for use model atmospheres were subsequently used for determination of the emergent monochromatic flux in many (almost 200) energies in range 5.4 - 9.4 keV. (Gravitational redshift is not included here). Spectrum synthesis included opacity of the 4 lowest lines of the singlet series (1s $^1S_0$ - 1s np $^1P_1^0$) of He-like iron, and 5 doublet lines of H-like iron (1s $^2S_{1/2}$ - np $^2P^0_{1/2,3/2}$). These are the only series of allowed lines arising from the ground levels in both ions. Corresponding wavelengths and oscillator strengths are taken from Mewe et al. (1985).

Line opacity profiles were obtained as careful numerical convolution of natural, thermal and Stark profiles. Thermal and natural broadening profiles were computed in a standard way (Mihalas 1978, cf. also Madej 1987b), and the pressure (Stark) profiles were estimated according to Griem (1974). (cf. Chap. IV.6 of his book.) Final computations of the flux were done with the Feautrier method (Mihalas 1978).

Fig. 1 shows hard energy part of the synthetic spectrum of an X-ray burster with $T_e = 10^7$ K, assuming low gravity log g = 14.0, and iron number abundance 10 times the solar value (DOTTED LINE). Horizontal axis gives decimal logarithm of energy (in keV), and vertical axis gives logarithm of the monochromatic flux (in cgs units). Assumed abundance of iron produces well developed pair of the resonance lines (the leftmost lines in the Figure). The resonance line of He-like iron (6.70 keV) is more prominent than neighboring resonance line of hydrogenic iron (6.97 keV). Huge b-f edges of both ions practically coincide, and decrease flux by more than two orders of magnitude.

The above example demonstrates spectrum of X-ray burster atmosphere in perfect hydrostatic equilibrium, seen on the neutron star surface with perfect spectral resolution. Spectrum at infinity can be immediately obtained rescaling horizontal scale by gravitational redshift factor. However, comparison with the existing observational data should be done taking into account limited spectral resolution of X-ray detectors, which is still rather poor.

Theoretical spectrum from Fig. 1 (dotted line) has been numerically folded with the normalized gaussian profile of the full width at half maximum (FWHM) equal 0.7 keV (about 10% of the energies in Fig. 1). Such a FWHM very roughly corresponds to spectral resolution of TENMA proportional counters (Koyama et al 1984). Smoothed spectrum (SOLID LINE) drastically changes: all the higher lines merge practically perfectly into continuum and only pair of resonance lines remains visible as a single, broad spectral feature. At the same time huge bound-free opacity jump gets invisible. Smoothing procedure changes it into steep continuum, which is very similar to high energy branch of a blackbody.

5. CONCLUSIONS

Detailed model atmosphere and line profile computations in LTE show, that broad, single absorption features observed in some X-ray burst spectra can be interpreted as merging resonance lines of both heliumlike and hydrogenic iron ions, at least in favourable effective temperatures. Iron lines arising from transitions to higher excited levels, as well as b-f ionization edges, are efficiently washed out due to limited spectral resolution of satellite X-ray detectors and are not visible. (Existence of strong turbulences in surface layers of a burster can cause the same smoothing effect).

This conclusion supports identification of the strongest 4.1 keV line with redshifted lines of iron, i.e. this means that the assumption of atomic origin of the single X-ray

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line is not in contradiction with observations. Results of this paper do not imply, however, that iron is the necessary source of the 4.1 keV line.

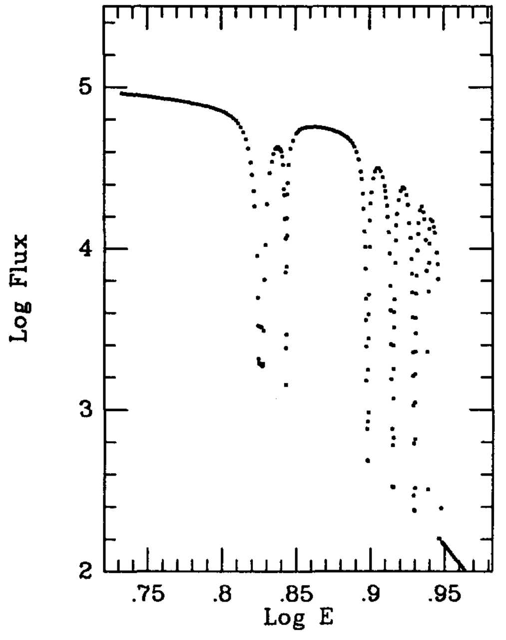

Fig. 1. Synthetic iron features in spectrum of X-ray burster with $T_e = 10^7$ K, log g = 14.0, and iron abundance = 10 x solar value (dotted line). Solid line represents spectrum seen by X-ray detectors.

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DISCUSSION-J. Madej

T. Kallman: The degree of gravitation redshift needed to explain the observed line energy must constrain the neutron star equation of state. Have you thought about this?

J. Madej: No, I did not go so far, because results of my research do not prove strictly that 6.7 - 7.0 keV lines of iron are seen as the redshifted 4.1 keV line in bursters. There exists only indication for that. Moreover, additional effects can perhaps contribute to the atomic line shift (e.g. magnetic fields, even less than 10^{12} g), making determination of the redshift inaccurate.

A. Fabian: The enormous photoelectric edges you predicted would mean few photons observed $\sim>$ 7 keV. This is not the case, (see also Foster et al, *M.N.R.A.S.*, 1987, **228**, 259).

J. Madej: Bound-free iron edges predicted in synthetic spectrum of a burster (cf. dotted line in Fig. 1) cannot be detected observationaly. After folding with some schematic detector response function such edges vanish and an observer can see very smooth continuum spectrum (solid line in the Figure). As a result of such broadening, number of photons predicted above 7 keV gets significant.