

A BeppoSAX observation of the massive X-ray binary 4U 1700-37

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Abstract. A 0.5–200 keV BeppoSAX spectrum of the non-pulsating high-mass X-ray binary 4U 1700-37 is presented. The spectrum is well characterized by the standard accreting pulsar model of an absorbed power-law with a photon index of $1.07 \pm_{0.03}^{0.02}$, sharply modified by an exponential cutoff above 5.9 ± 0.2 keV. The e-folding energy of the cutoff is 23.9 ± 0.5 keV. A soft bremsstrahlung component with a temperature of 0.2 ± 0.1 keV is also required, together with a narrow iron line at 6.5 keV. Both continuum components are absorbed by a column of $(5.1 \pm 0.2) \times 10^{22}$ atom cm^{-2} . There is some evidence for the presence of a broad cyclotron absorption feature at ~ 37 keV, although we cannot exclude the possibility that this is due to an incorrect modeling of the continuum, or instrumental effects. The hypothesis that the compact object is a neutron star rather than a black hole seems most likely.

Key words: stars: individual: 4U 1700-37 = HD 153919 – stars: neutron – X-rays: stars

1. Introduction

4U 1700-37 is a massive eclipsing X-ray binary consisting of a compact accreting object embedded in the wind of HD153919, a supergiant O star (Jones et al. 1973). Orbiting every 3.4 days, the compact object has an X-ray spectrum reminiscent of an accreting highly magnetized neutron star system (Haberl et al. 1989), although no X-ray pulsations have ever been confirmed. The X-ray flux is significantly less than expected on the basis of standard wind accretion theory.

The most recent estimates of the mass of HD 153919 and its companion are from Heap & Corcoran (1992), and Rubin et al. (1996). Heap & Corcoran (1992) propose a mass for HD 153919 of $50 \pm 2 M_{\odot}$, with a companion mass of $1.8 \pm 0.4 M_{\odot}$. Rubin et al. (1996) reanalyzed the system parameters using Monte Carlo methods, finding masses of $30_{-7}^{+11} M_{\odot}$ and $2.6_{-1.4}^{+2.3} M_{\odot}$ for HD 153919 and its companion, respectively. Both estimates are, at their lower ranges, consistent with the compact object being a neutron star, but a black hole cannot be excluded.

Since pulsations have never been detected, further evidence for the object’s nature must be sought from its X-ray spectrum.

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In general, X-ray pulsar spectra require an exponential cutoff to the continuum between ~ 10 –20 keV, unlike black hole spectra, which require either a single power-law or an ultra-soft component plus hard power-law tail (e.g., Tanaka & Lewin 1995). Additionally, about half of the sample of 23 X-ray pulsars observed by *Ginga* show cyclotron features in their spectra, usually at energies between 10–60 keV (Makishima & Mihara 1992; Mihara 1995), indicating the presence of strong magnetic fields.

2. Previous X-ray spectroscopy of 4U 1700-37

The X-ray spectrum of 4U 1700-37 has been studied using many different satellites, including HEAO-1 and *Einstein* (White et al. 1983a), and EXOSAT (Haberl et al. 1989). The spectral shape is highly reminiscent of other X-ray pulsars (White et al. 1983b), being well described by a power-law with photon index, α , of ~ 0.15 , modified by a high-energy cutoff above 6–7 keV. Haberl & Day (1992) confirmed the above results with *Ginga* observations, also finding that α varies between -0.5 and 1.0 . Haberl et al. (1994) show that the 0.1–2.4 keV ROSAT Position Sensitive Proportional Counter (PSPC) spectrum is consistent with a thermal bremsstrahlung model with a temperature, kT, fixed at 0.74 keV, as originally found by *Ginga* (Haberl & Day 1992), plus a hydrogen column density of 3.6×10^{22} atom cm^{-2} . Haberl & Day (1992) also found that the best-fit values of α varied depending on the photoelectric column density. Since this is physically unrealistic, the authors show that the spectral variations could also be modeled using a two-component scattering model, consisting of two power-laws with the same slopes but variable absorption, one of which represents a less absorbed scattered component.

The spectrum above 20 keV was examined using BATSE data by Rubin et al. (1996, and references therein) who confirmed earlier findings that it can be represented by a thermal bremsstrahlung model with kT ~ 25 keV, out to 120 keV. There have been no reported changes in the shape of the high energy spectrum due to orbital phase or source intensity.

While the above observations are individually useful, the launch of BeppoSAX, with its very wide spectral bandpass, offers the first opportunity to study the entire X-ray spectrum of 4U 1700-37 simultaneously. BeppoSAX is proving to be a highly capable mission for discovering and studying cyclotron

lines (e.g., Dal Fiume et al. 1998). For the first time, therefore, we present a single analysis of the entire spectrum, obtained at one epoch, spanning 0.5–200 keV.

3. Observations

The X-ray astronomy satellite BeppoSAX (Boella et al. 1997a) contains four coaligned Narrow Field Instruments, or NFI. Results from the Low-Energy Concentrator Spectrometer (LECS; 0.1–10 keV; Parmar et al. 1997), Medium-Energy Concentrator Spectrometer (MECS; 1.3–10 keV; Boella et al. 1997b), High Pressure Gas Scintillation Proportional Counter (HPGSPC; 5–120 keV; Manzo et al. 1997) and the Phoswich Detection System (PDS; 15–300 keV; Frontera et al. 1997) are presented here. The MECS consisted of three identical grazing incidence telescopes with imaging gas scintillation proportional counters in their focal planes. The LECS uses an identical concentrator system as the MECS, but utilizes an ultra-thin entrance window and a driftless configuration to extend the low-energy response to 0.1 keV. The non-imaging HPGSPC consists of a single unit with a collimator that is alternatively rocked on- and off-source. The non-imaging PDS consists of four independent units arranged in pairs each having a separate collimator. Each collimator can be alternatively rocked on- and off-source.

4U 1700-37 was observed by BeppoSAX between 1997 April 1 11:21 and 22:15 UTC. This interval corresponds to orbital phases 0.44–0.58, where mid-eclipse of the X-ray source occurs at phase 0.0, using the ephemeris of Rubin et al. (1996). Good data were selected from intervals when the elevation angle above the Earth’s limb was $>4^\circ$ and when the instrument configurations were nominal, using the SAXDAS 1.3.0 data analysis package. The standard collimator dwell time of 96 s for each on- and off-source position was used, together with rocking angles of $180'$ and $210'$ for the HPGSPC and PDS, respectively. The exposures in the LECS, MECS, HPGSPC, and PDS instruments are 12.2 ks, 23.7 ks, 11.2 ks, and 10.7 ks, respectively. LECS and MECS data were extracted centered on the position of 4U 1700-37 using radii of $8'$ and $4'$, respectively. Background subtraction in the imaging instruments was performed using standard files, but is not critical for such a bright source. Background subtraction in the non-imaging instruments was carried out using data from the offset intervals. The background subtracted count rates in the LECS, MECS, HPGSPC and PDS were 5.3, 18.5, 40.5, and 27.0 s^{-1} , respectively.

3.1. Spectral fits

The 4U 1700-37 spectrum was investigated by simultaneously fitting data from all the NFI. The LECS and MECS spectra were rebinned to oversample the full width half maximum of the energy resolution by a factor 3 and to have additionally a minimum of 20 counts per bin to allow use of the χ^2 statistic. Data was selected in the energy ranges 0.5–5.0 keV (LECS) and 1.8–10.0 keV (MECS) where the instrument responses are well determined. The HPGSPC and PDS data were rebinned using standard procedures in the energy ranges 7–40 keV and

15–200 keV, respectively. The photoelectric absorption cross sections of Morrison & McCammon (1983) and the solar abundances of Anders & Grevesse (1989) are used throughout.

The spectrum was first fit with an absorbed power-law model, including an iron line, but with no cutoff or soft component. The iron line energy, E_{Fe} , was fixed at 6.5 keV, but the width, σ_{Fe} , and normalization (and all other parameters) were allowed to vary. Unsurprisingly, given the simplicity of the model, only a very poor fit with a reduced χ^2 of 47.0 for 280 degrees of freedom (dof) was obtained. Matters are significantly improved if a high energy cutoff and a low energy thermal bremsstrahlung component are included, resulting in a reduced χ^2 of 2.00 for 276 dof. The best-fit thermal bremsstrahlung component (see Haberl et al. 1994) has a kT of 0.2 ± 0.1 keV. Both continuum components suffer low-energy absorption, N_{H} , of $(5.1 \pm 0.2) \times 10^{20} \text{ atom cm}^{-2}$. The line width was consistent with a narrow line and so was fixed at a value (0.1 keV) much smaller than the instrumental resolution. This gives an equivalent width, EW, of 120 ± 20 eV for the iron line. The functional form of the cutoff above energy E_{cut} is $\exp[(E_{\text{cut}} - E)/E_{\text{fold}}]$, where E_{cut} and E_{fold} are the cutoff and folding energies, respectively. The count rate spectrum for this model is shown in the left panels of Fig. 1, together with the contributions to χ^2 .

A significant contribution to the existing poor fit quality is residual structure in the PDS spectrum at ~ 37 keV (see the left hand panels of Fig. 1). Note that the same structure is not evident in the HPGSPC spectrum. Since this feature is reminiscent of a cyclotron resonance line, we added a single cyclotron component (the CYCLABS model in XSPEC) to the model and re-fitted the data. The fit quality improves sharply, with a reduced χ^2 of 1.42 for 273 dof. This improved fit is shown in the right hand panels of Fig. 1. The best-fit values of E_{cut} and E_{fold} are 5.9 ± 0.2 keV and 23.9 ± 0.5 keV, respectively. These values are consistent with those of 6.6 ± 0.7 keV and $21.1_{-3.3}^{+4.3}$ keV found by Haberl et al. (1989) using EXOSAT data. Haberl & Day (1992) determined a slightly higher cutoff energy using *Ginga*, measuring $E_{\text{cut}} = 7.6$ keV, and $E_{\text{fold}} = 19.5$ keV, with no uncertainties quoted. Nonetheless, given that these observations were made with different missions at different epochs, the broad agreement is gratifying and shows that the cutoff is a necessary component in the spectrum.

The best-fit energy, E_{cyc} , and width, σ_{cyc} , of the feature are 36.6 ± 1.0 keV and 11_{-3}^{+5} keV, respectively. This width is a factor ~ 2.5 broader than expected from the correlation between these parameters observed by Dal Fiume et al. (1998) for five other massive X-ray binaries. This suggests that the feature may arise through incorrect modeling of the continuum. This is supported by the lack of detection in the HPGSPC. Variations in PDS performance, which could produce a similar spectral feature if the background and source spectra had slightly different gains, are however excluded. The feature is still present if the continuum is modeled with a broken power-law together with a high-energy cutoff, as suggested by Dal Fiume et al. (1998). Following Mihara (1995) and Dal Fiume et al. (1998), we also generated a Crab ratio spectrum, by dividing the PDS data by those obtained from a PDS observation of the Crab Nebula, which is

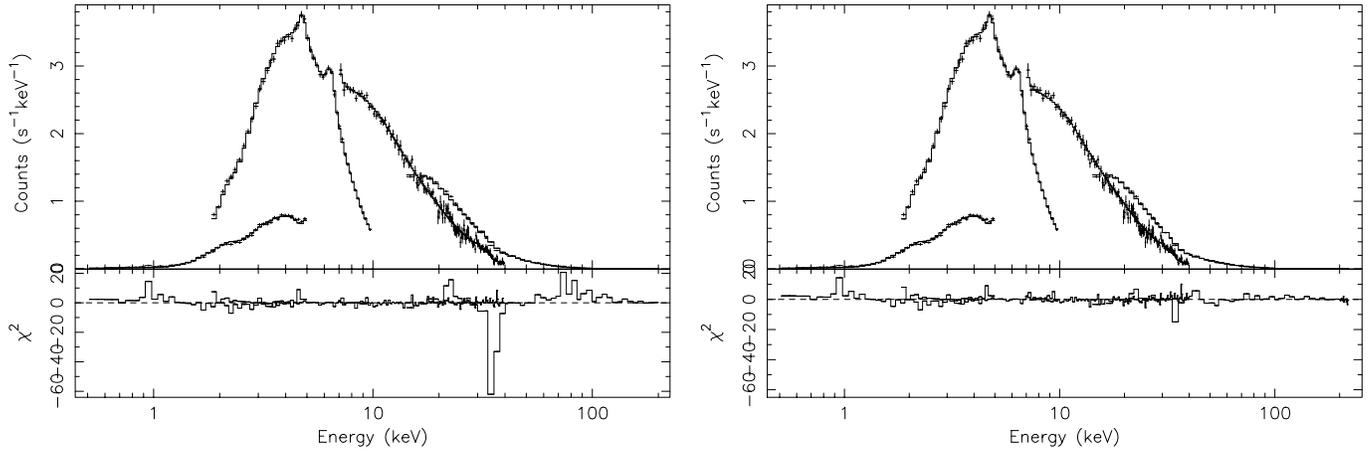


Fig. 1. The NFI 0.5–200 keV spectrum of 4U 1700-37. The left panels show the fit to an absorbed power-law and low-energy thermal bremsstrahlung model together with an iron emission line at 6.5 keV and an exponential cutoff beginning near 6 keV. In the right panels a broad cyclotron absorption 1 feature at ~ 37 keV is included in the model. The contributions to χ^2 are plotted in the lower panels

Table 1. Best-Fit BeppoSAX spectral parameters. Norm_{PL} and $\text{Norm}_{\text{brem}}$ are the power-law and thermal bremsstrahlung normalizations in units of Photon $\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$. A_{FE} is the total number of iron line photons in units of $\text{cm}^{-2} \text{s}^{-1}$. All uncertainties are quoted at 90% confidence. The values without uncertainties were held fixed in the fits

Parameter	Value
N_{H} ($10^{22} \text{ atom cm}^{-2}$)	5.1 ± 0.2
α	$1.07^{+0.02}_{-0.03}$
Norm_{PL}	0.17 ± 0.08
E_{FE} (keV)	6.5
σ_{FE} (keV)	0.1
A_{FE}	$(2.7 \pm 0.2) \times 10^{-3}$
EW_{FE} (keV)	0.120 ± 0.020
kT (keV)	0.2 ± 0.1
$\text{Norm}_{\text{brem}}$	180^{+480}_{-120}
E_{cut} (keV)	5.9 ± 0.2
E_{fold} (keV)	23.9 ± 0.5
E_{cyc} (keV)	36.6 ± 1.0
σ_{cyc} (keV)	11^{+5}_{-3}

time-invariant and has a smoothly varying $E^{-2.1}$ continuum in this energy range. This technique is useful in minimizing instrumental and model dependent effects. While the Crab ratio spectrum indicates some structure at ~ 37 keV, it does not show the pronounced deficit which is the signature of the cyclotron features discussed in Dal Fiume et al. (1998). We conclude that while the suggestion of a cyclotron line is intriguing, and results in a significantly lower value of χ^2 , we cannot exclude the possibility that the feature is an artefact of the fitting process.

Further improvements in fit quality require a better description of the spectral region covered by the LECS, since the main remaining contribution to χ^2 is a feature at ~ 1 keV (see Fig. 1). This feature has not been seen in broad-band spectra of 4U 1700-37 before, since the *Ginga* observations did not cover the energy region below 1.5 keV, but it may also be evident in the resid-

uals of the ROSAT PSPC spectrum presented in Haberl et al. (1994). Since Rubin et al. (1996) show that the BATSE spectrum above 20 keV is consistent with a thermal bremsstrahlung model, we examined the PDS data separately to check for consistency with this earlier study. The result of Rubin et al. (1996) is confirmed, with the PDS spectrum being described by a thermal bremsstrahlung with $kT = 25.9 \pm 0.3$ keV, in agreement with the temperature of 25 keV derived from the BATSE data, for a reduced χ^2 of 2.16 for 46 dof. The addition of a broad cyclotron line at ~ 40 keV improves the fit significantly giving a reduced χ^2 of 1.03 for 43 dof.

3.2. The nature of the compact object in 4U 1700-37

The broadband BeppoSAX spectrum presented here is very similar to the X-ray spectrum of an accreting pulsar. The underlying shape is an absorbed power-law sharply modified $\gtrsim 6.0$ keV by a cutoff. Although the photon index of ~ 1.0 is rather higher than the average reported by previous authors, it lies within the range of observed variation exhibited by 4U 1700-37, and is at the upper range of the values for various pulsars summarized in White et al. (1983).

In what respects does the 4U 1700-37 spectrum differ from, or resemble that, of a black hole? Four diagnostics of black hole candidates (none of them individually conclusive) are listed in Tanaka & Lewin (1995). These are: (1) ultrasoft spectra when luminous, (2) high-energy power-law tails, (3) bimodal spectral states, and (4) millisecond variability and flickering in the hard state. 4U 1700-37 possesses none of these attributes. In particular, steep, cutoff spectra ($E_{\text{cut}} \lesssim 20$ keV) are a feature of neutron stars rather than black holes (White et al. 1988), while black holes (at least in outburst) generally possess hard tails, emitting significant flux $\gtrsim 100$ keV (see e.g., Ballet et al. 1994). 4U 1700-37 resembles neither the ultrasoft “high-state”, nor the hard power-law “low-state” spectrum of the canonical black hole candidate Cyg X-1.

4. Discussion

We have demonstrated that the broadband X-ray spectrum of 4U 1700-37 is qualitatively similar to that of other accreting neutron star X-ray pulsars. A feature at ~ 37 keV may be modeled as a broad cyclotron absorption line, but its presence is uncertain due to uncertainties in continuum modeling and instrument performance. Such features have only been reported in about half of the known X-ray pulsars – and in some cases only at marginal significance. The lack of pulsations remains puzzling, and may suggest (as has been argued by previous authors) that the magnetic field is intrinsically weak or aligned with the rotation axis. The neutron star's progenitor may have been very massive, suggesting that there may be a range of masses over which progenitors form both black holes and neutron stars, or that black holes are formed only through a limited range of progenitor masses, above which the remnants are again neutron stars.

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