EXOSAT observations of the ultra–soft X-ray binary 4U1957+11

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Abstract. We present results from the analysis of the two EXOSAT observations of the low mass X-ray binary (LMXRB) 4U1957+11. The 1–20 keV spectrum of the source is best fitted by a power law model with an exponential cutoff, that provides an approximation of a thermal Comptonisation spectrum. The cutoff energy (∼ 2 keV), as well as the X-ray colours, are intermediate between those of ultralow sources containing black hole candidates (BHCs) and those of soft LMXRBs containing an old accreting neutron star. We find no evidence for a black body spectral component. During the 1985 observation the source flux was ∼ 10% higher than in the 1983 observation, and the ME spectra provide evidence for a high energy tail (up to ∼ 16 keV), which strengthens the similarity with the spectra of high state BHCs. However the source luminosity was only ∼ 5 × 1035 erg s−1.

During the 1985 observation the GSPC spectra revealed the presence of a 100 eV EW iron K-line emission feature with a centroid energy of 6.96 ± 0.09 keV; this value is among the highest measured by EXOSAT. The ME light curves showed only a low-amplitude variability on timescales of a few hours. No evidence for a periodic modulation with periods between 0.016 and 13000 s was found.

Key words: X-rays: general – X-rays: binaries – Black holes – Stars: neutron

1. Introduction

4U1957+11 is a relatively poorly studied 20–80 μJy X-ray source close to the galactic plane. Discovered with Uhuru (Giacconi et al. 1974) the source was subsequently associated with a blue star-like optical counterpart (V = 18.7, B−V = 0.3 and U−B = −0.6), thanks to the SAS–3 positioning capabilities (Margon et al. 1978). This is located within 10 arcsec of the position of 4U1957+11 and has colours similar to those of the optical counterpart of Sco X–1 and 4U0614+09. Optical CCD photometry of 4U1957+11 revealed a ∼ 0.2 mag roughly sinusoidal modulation with a period of 9.3 hr, which most likely corresponds to the orbital period of the system (Thorstensen & T. Terrel 1984). These findings clearly indicate that 4U1957+11 is a low mass X-ray binary (LMXRB) with an X-ray luminosity of a few × 1035 erg s−1 for the estimated distance of ∼6 kpc.

X-ray data were also obtained with the Vela 5B and HEAO–1 satellites. No significant long-term periodicity between 20 d and 1 yr was found in the Vela 5B data (Priedhorsky & Terrell 1984). In the HEAO–1 A–2 X-ray colour–colour diagram assembled by White and Marshall (1984) 4U1957+11 lies close to the region occupied by ultralow sources, most of which are BHCs in their high state, such as Cyg X–1, LMC X–3, 4U0620–00 and GX 339–4. A similar conclusion is obtained based on the EXOSAT X-ray colour–colour diagram (Schultz et al. 1989). These results suggest that 4U1957+11 might host a BHC. However, in a recent paper Singh et al. (1994) report that the EXOSAT spectra of 4U1957+11 are similar to those of high luminosity LMXRB containing an accreting weakly magnetic neutron star. Based on a ∼ 33 hr Ginga observation, Yaqoob et al. (1993) conclude that the source spectrum is well represented by the sum of a soft component, which they model with a black body emitting disk, and a hard component (with a power law photon index of ∼ 2) detected up to energies of ∼ 18 keV. The derived values of the inner radius and temperature of the disk are r_in (cos i)^1/2 ∼ 2 km (i is the inclination angle) and kT_in ∼ 1.5 keV, respectively, suggesting a similarity with LMXRBs containing a neutron star.

In this paper we present a detailed analysis of the EXOSAT spectral and timing data. Details of the EXOSAT observations are summarised in Section 2. Section 3 and 4 describe our analysis of the source spectra and light curves, respectively. Our results are discussed in Section 5.

2. The EXOSAT observations of 4U1957+11

The European Space Agency’s X-ray observatory EXOSAT was operational from May 1983 to April 1986. Its low energy imaging telescopes (LE1 and LE2), used in conjunction with the channel multiplier array (CMA), covered the 0.05–2 keV band and provided broad band filter spectroscopy. The Argon chambers of the medium energy (ME) proportional counter array operated over the 1–20 keV band and produced spectra (with a resolution of ΔE/E ∼ 0.2 (E/7 keV)^−1/2 and
light curves with high throughput. The ME was often operated with one half of the detector array offset from the source in order to provide a simultaneous monitor of the particle background; the pointing directions of the two halves were usually swapped every 3–4 hours in order to minimize the systematic uncertainties in the background subtraction. The gas scintillation proportional counter (GSPC) provided a factor of ~2 improved spectral resolution in the 2-20 keV band, with a factor of ~5 lower effective area than the ME.

*EXOSAT* observed 4U1957+11 on 1983 August 27 for about 6 hours and on 1985 May 28–29 for about 11 hours. The data were obtained from the *EXOSAT* database available within High Energy Astrophysics Database Service at the Astronomical Observatory of Brera (Tagliaferri & Stella 1993) except for the high time resolution light curves presented in Section 4, which were accumulated by using ESA’s on-line interactive analysis system. Table 1 gives a summary of the source count rate and exposure times in each instrument during the two observations. In all cases the instrumental background was stable.

### Table 1. *EXOSAT* observations and count rates

| Date       | Instrument | Filter or Energy Range | Exposure (s) | Counts s⁻¹ |
|------------|------------|------------------------|--------------|------------|
| 1983       | CMA-LE2    | 3000 Å Lexan           | 6203         | 0.48±0.02  |
| August 27  | CMA-LE2    | Aluminium/Parylene     | 5814         | 0.24±0.01  |
| CMA-LE2    | Boron      | 6430                   |              | 0.21±0.01  |
| CMA-LE2    | Polypropylene | 536                   |              | 0.46±0.04  |
| ME         | 1–20 keV   | 20382                  |              | 66.9±0.2   |
| GSPC       | 3–10 keV   | 26654                  |              | 4.69±0.02  |
| 1985       | CMA-LE1    | 3000 Å Lexan           | 15228        | 0.42±0.01  |
| May 28–29  | CMA-LE1    | Aluminium/Parylene     | 10201        | 0.21±0.01  |
| CMA-LE1    | Boron      | 11954                  |              | 0.18±0.007 |
| ME         | 1–20 keV   | 37265                  |              | 80.18±0.19 |
| GSPC       | 3–10 keV   | 36897                  |              | 5.19±0.02  |

#### 3. Energy Spectra

##### 3.1. ME and LE Data

The 1–20 keV pulse height source spectra from the ME Argon chambers were analysed together with the source count rates derived from the LE-CMA and each of the filters used. The data from the ME Xenon chambers were excluded due to systematic uncertainties in the background subtraction. Several trial spectral models were convolved through the instrumental response and fitted to the data. Neither a single power law, a thermal bremsstrahlung, nor a black body model produced an acceptable representation of the spectrum of 4U1957+11.

A power-law model with an exponential high-energy cutoff ("cut-offpl") provided instead a good fit to the 1983 data, for a power-law photon index of $\Gamma_S \sim 0.2$ and a cutoff energy of $E_{\text{cut}} \sim 2.1$ keV (Table 2 and Fig. 1). The column density was constrained to a value of $(5.2 \pm 0.8) \times 10^{20}$ H cm⁻² mainly through the LE rates measurements.

The thermal Comptonisation model of Sunyaev & Titarchuck (1980) ("CompST"), of which the power law with exponential cutoff model provides an approximation, gave instead a substantially worse fit. In this case an electron temperature of $kT_e \sim 1.4$ keV and a Thomson optical depth of $\tau_\infty \sim 22.1$ were estimated. For both models the 1-20 keV luminosity of the source was derived to be $L_X \approx 4.6 \times 10^{38}$ ergs s⁻¹.

![Fig. 1. ME and LE spectrum from the 1983 observation; the "cut-offpl" model has been used.](image-url)
Table 2. Spectral fits of the 1983 data. Errors in the spectral parameters are at 68% confidence level.

| Date       | Model      | $\chi^2$/dof | Best fit parameters |
|------------|------------|--------------|---------------------|
| 1983       | cutoffpl   | 21.6/28      | $\Gamma_S = 0.18 \pm 0.04$, $E_{\text{cut}} = 2.67 \pm 0.04$ keV |
| Aug. 27    | compST     | 65.2/28      | $kT = 1.37 \pm 0.01$ keV, $\tau_{\text{es}} = 22.1 \pm 0.4$ |
| disk       | 30.9/28    |              | $M = 3.83 M_\odot$, $M = 9.9 M_{\text{edd}}$, norm$^a = 1.3 \times 10^{-3}$ |
| diskbb     | 36.2/29    |              | $T_{\text{in}} = 1.63 \pm 0.01$ keV, norm$^b = 8.02$ |

* norm$^a = \cos(i)/d_0^2$, where $i$ is the inclination of the disk and $d_0$ is the distance in units of 10 kpc.  
* norm$^b = (R_{\text{in}}/d_0)^2 \cdot \cos(i)$, where $R_{\text{in}}$ in km, is the inner disk radius.

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Fig. 2. ME and LE spectrum from the 1985 observation. In panel A the single component "cutoffpl" model has been used. In panel B a second power-law component with a slope of 2 has been added in order to fit the high energy excess.

spectra. In turn a very high inclination ($i > 87.7^\circ$) would be required if the derived inner disk radius were to be compatible with the neutron star radius or the marginally stable orbit of a few solar masses black hole.

The source count rate increased by ~ 20% during the 1985 observation. The values obtained from the spectral fitting of the 1985 data are similar to those discussed above (Table 2), except for a rather noticeable high energy-excess in the ME rates above 10 keV. This excess was not adequately modelled by any of the single component models adopted for the 1983 observation. The cutoff power law provided the best single component model with a $\chi^2$ of 54.8 for 57 degrees of freedom (dof) (see Fig. 2 A). To model the high-energy excess an additional spectral component consisting of a power law was added. Owing to poor statistics, the photon index of this high energy power law could not be obtained with an acceptable accuracy (range between -1.2 and 2.5). Therefore we fixed its value to 2, compatible with the measurement by Ginga (Yaqoob et al. 1993). A $\chi^2$/dof of 48.8/56 was obtained in this case. The statistical significance of the additional power law component was evaluated through an F-test to be ~ $10^{-2}$ (Fig. 2 B). Therefore we conclude that the 1985 EXOSAT data confirm the Ginga result of an additional spectral component above ~ 10 keV.

The 1-20 keV source luminosity during the 1985 observation was $L_X \approx 5.1 \times 10^{38}$ ergs s$^{-1}$, with the high energy component contributing up to ~ 10% of the total.

3.2. GSPC observations

The 3-10 keV GSPC spectra from both observations were fitted with the same continuum model that provided the best fit
Table 1: Spectral fits of the 1985 data.

Best fit parameters

\begin{tabular}{|c|c|c|}
\hline
Parameter & Value & Uncertainty \\
\hline
\hline
\end{tabular}

The table shows the best fit parameters obtained from the spectral fits of the 1985 data.
4.2. Power Spectra

The lightcurves described above were used to carry out a detailed search for coherent pulsations. Since the 1985 observation is longer and has a higher average count rate than the 1983, it allows for a more sensitive search. In order to maximize the Fourier resolution, and therefore the sensitivity, a single power spectrum was calculated for the 0.3125, 0.625 and 30 s resolved lightcurves of each observation and energy range. Missing data points were replaced with the average count rate. In Fig. 5 the power spectra are marked with a "a" and normalised such that the white noise arising from counting statistics corresponds to a power of 2.

A red noise component is dominant in the frequency range from \( \sim 5 \times 10^{-5} \) Hz to \( \sim 3 \times 10^{-4} \) Hz. This component results from the long-timescale variability visible in the lightcurves. The presence of this continuum power spectrum component affects the statistical distribution of the power estimates for long periods. This means that techniques which assign probabilities to power spectrum peaks assuming the simple \( \chi^2 \) distribution of power expected from counting statistics noise (see e.g. Leahy et al. 1983) may significantly overestimate their significance. Israel & Stella (1985) developed a technique for reliably searching for power spectrum peaks, corresponding to a periodic modulation, in the presence of "coloured" continuum power spectrum components. A search for coherent pulsations is carried out by looking for significant peaks above the estimated continuum spectrum. If no peaks with a probability of chance occurrence lower than a given threshold are found, then an upper limit to the semi-amplitude of a sinusoidal modulation is worked out for each Fourier frequency of the power spectrum through a generalisation of the method outlined by Leahy et al. (1983). By using this technique, each of the power spectra of 4U1957+11 was searched for peaks with a probability of \( \leq 0.3\% \) (3\( \sigma \) confidence level) of exceeding by chance the level of the continuum power spectrum components.

For the 11 hr 1985 May 28–29 observation, power spectra were calculated from the 0.625 and 30 s time resolved lightcurves in the 1–10, 1–4 and 4–10 keV bands. No significant peaks were found in any of the power spectra. The 99.7% confidence upper limits to the modulation semi-amplitude are given in Table 4 for selected periods.

\[
\begin{array}{cccccc}
\text{Period (s)} & \text{Upper limits} \\
& \text{1983 August 27} & \text{1985 May 28–29} \\
\text{(1–10)} & \text{(1–4)} & \text{(4–10)} & \text{(1–10)} & \text{(1–4)} & \text{(4–10)} \\
13650 & 11.8 & 6.69 & 16.8 \\
10240 & 7.71 & 11.2 \\
8192 & 8.41 & 8.02 \\
4096 & 3.27 & 1.52 \\
512 & 0.83 & 0.52 & 0.59 \\
16^a & 0.67 & - & - \\
8–0.03^a & - & \leq 0.88 & - & - \\
0.02^a & 0.09 & - & - \\
0.016^a & 1.17 & - & - \\
\end{array}
\]

\( ^a \)From the high time resolution ME data (1–20 keV).

For short periods, up to \( \sim 4000 \) s, the sensitivity of the search is mainly limited by counting statistics noise and upper limits of \( \leq 1\% \) are obtained for any sinusoidal modulation. For longer periods, the source red noise component plays an increasingly important role in reducing the sensitivity of the search. The corresponding upper limits have values of \( \sim 3–17\% \) for periods between 8000 and 14000 s. The EXOSAT observations were not long enough to search for a low amplitude X-ray modulation at the 9.3 hr orbital period.

We analysed also the power spectra of the 0.3125 and 30 s resolved 1–10, 1–4 and 4–10 keV ME light curves from the \( \sim 6 \) hr 1983 August 27 observation. All the points in the power spectra are well below the detection threshold and thus no significant periodicities are found. Upper limits for selected frequencies are given in Table 4 and shown in Fig. 6 (for the 1–10 keV energy range).

ME count rates from the entire energy range of the AR chambers (1–20 keV) were also available with a resolution of...
\[ \sim 8 \text{ ms for the 1985 May 28–29 observation.} \]

We divided the lightcurve in 301 intervals, in order to prevent the Doppler frequency variations associated to the orbital motion from smearing the power of a sinusoidal signal over more than one Fourier frequency. These intervals were used to calculate 301 power spectra of 8192 independent Fourier frequencies.

The power spectrum resulting from the average of these power spectra was then analysed with the same technique discussed above. No significant periodicities were detected. The upper limits are reported in Table 4 and plotted in Fig. 5.

5. Discussion

The main component of the EXOSAT spectra is consistent with a power law model with exponential cutoff characterised by a spectral index of \( \sim 0.2 \) and a cutoff energy of \( \sim 2 \text{ keV} \) for both the 1983 and 1985 observations. This spectral form provides a simple analytical approximation to the thermal Comptonisation spectrum of Sunyaev & Titarchuk (1980) and, besides simplicity, it involves no conceptual difference. Indeed thermal Comptonisation models (and their approximations) are found to provide very good fits to the main spectral component of a number of high state BHs and LMXRBs containing old weakly magnetic neutron stars (White et al. 1988).

In high state BHs this spectral component is somewhat softer than that of 4U1957+11 \( (E_{\text{cut}} \sim 1.4 \text{ keV in LMC X–3 and LMC X–1}; \text{Ricci} 1998) \). In LMXRBs containing an old neutron star the component is instead harder \( (E_{\text{cut}} \sim 7 \text{ keV in 4U1705–44 and } E_{\text{cut}} \sim 5 \text{ keV in 4U1636–53}; \text{Ricci} 1998) \). A classification of the compact object in 4U1957+11 based on the characteristic of its Comptonised spectral component is therefore premature.

On the other hand the 1985 EXOSAT spectra and, especially, the Ginga spectra show the presence of a high energy power-law component above energies of 10 keV. This kind of two-component spectra has been observed from several BHs in their high state, the luminosity of which, however, is a factor of \( >10 \) higher than that of 4U1957+11.

Our decomposition of the 1983 EXOSAT spectrum of 4U1957+11 is similar to that of Singh et al. (1994), who in their analysis used also the ME Xenon chambers data and excluded the LE-CMA rates. However, according to these authors, the 1985 EXOSAT spectrum of 4U1957+11 consists of the sum of a \( \sim 1 \text{ keV} \) temperature black body, accounting for about 40% of the total luminosity, plus a Comptonised spectrum extending up to \( \sim 20 \text{ keV} \). In this case 4U1957+11 would possess an X-ray spectrum similar to that of the high luminosity LMXRBs \( (>10^{37} \text{ ergs s}^{-1}) \) containing an old neutron star (the so-called "Z-sources") (White et al. 1988, Hasinger & van der Klis 1989). Such a spectral decomposition of the 1985 EXOSAT data appears however unlikely, for the following reasons: (a) despite the moderate \( (\sim 20\%) \) increase of source luminosity, the parameters of the Comptonised spectral component would change drastically from the 1983 to the 1985 observation \( (a \text{ factor of } >10 \text{ and } \sim 0.1 \text{ variation in electron temperature and Thomson depth, respectively}) \), when it would be virtually indistinguishable from a power law; (b) neutron star LMXRBs of luminosity comparable to that of 4U1957+11 do not show evidence for an additional black body component, with upper
limits usually in 10–20% range.

Black body emission disk models can be fit to the data in place of the cutoff power law model (or the Comptonisation model), but they require an unrealistic inclination of $i > 87.7^\circ$ that cannot be reconciled with the absence of X-ray eclipses. This is also unlike other high state BHCs and a number of high luminosity LMXRBs (White et al. 1988).

A Fe K-shell emission feature is detected at an energy of 7.06 ± 0.09 keV in the 1985 data. The centroid energy of such a line is consistent only with $\text{K}\alpha$ transitions from H-like ions ($E_0 = 6.06$ keV) and is among the highest revealed with the EXOSAT GSPC (Gottwald & White 1991). $\text{K}\alpha$ transitions from any of the lower ionisation stages of iron require a substantial blueshift. Similar to the modelling of the Fe K-lines from other X-ray binaries and AGNs, such a blueshift could result from (relativistic) Doppler effects due to bulk plasma motions in the vicinity of the collapsed object. In particular, the observed feature might correspond to the blue horn of the characteristic profile produced in the innermost region of a relativistic accretion disk (Fabian et al. 1989). The line equivalent width ($\sim 100$ eV) is in the range measured from a number of LMXRBs (White et al. 1986). We note that the different line centroid energy derived by Singh et al. (1994) likely results from their drastically different modelling of the continuum.

The EXOSAT light curves of 4U1957+11 show only a moderate variability on timescales of a few hours, similar to BHCs in their high state (e.g. LMC X-3; Treves et al. 1988, Ebisawa 1991). A search for periodicities revealed no coherent modulation.

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Note added in proof. In the recently distributed preprint "EX-OSAT GSPC iron line catalog" by Gottwald et al. (1994, A&A, in press), no iron line detection is reported for the 1985 GSPC spectra of 4U1957+11, despite the fact that the continuum model is the same as that used in our paper. This is surprising since we have verified that the detection condition of Gottwald et al. (a $\chi^2$ improvement of $\geq 13$) is met also for the energy range used in their paper. We can speculate that perhaps their automatic fitting procedure failed to reach the minimum $\chi^2$ in the case of 4U1957+11.