# X–ray timing and spectral measurements of the X–ray pulsar 4U 1538–52

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## Abstract

The Medium Energy experiment on-board the EXOSAT satellite observed the X-ray binary system 4U 1538-52 on four occasions during March and August 1984. Observed pulsation periods of $529.97 \pm 0.16$ sec (17 March) and $530.14 \pm 0.03$ sec (10 August) indicate that the neutron star in the 4U 1538–52 system continued to spin down with $\dot{P} = 3.9 \cdot 10^{-9}$ sec/sec ($\dot{P}/P = 2.3 \cdot 10^{-4}$ yr$^{-1}$) in the period 1976–1988. The eclipse transition time of $\sim 0.06$ days gives an height of $\sim 1.5 \cdot 10^{11}$ cm for the atmosphere of the optical counterpart. The phase-average X-ray spectrum, consistent with a power-law of photon spectral index of $\sim 1.5$ (17 March) and $\sim 1.4$ (10 August), shows an Iron line with an E.W. of $\sim 100$ eV. The spectral form shows variations with pulse-phase.

Keywords: Stars: neutron — X-ray: binaries

## 1. Introduction

The X-ray source 4U 1538–52 (Ref. 1) belongs to that particular class of objects which show a pulsed emission when observed in the X-ray energy band. It is a binary system formed by a 14.5 mag B0 supergiant, QV Nor (Refs. 2,3,4), and a neutron star which spins with a period of about 530 sec (Refs. 5,6). The X-ray luminosity of 4U 1538-52, assuming a distance of 6 kpc (Refs. 7,8), is about $2 \cdot 10^{36}$ erg/sec. This system also exhibits a 0.51 day long X-ray eclipse, with a period of about 3.73 days, assumed to be the orbital period, and a projected X-ray source semi-major axis of 55 lt-sec (Refs. 6,8,9,10). From these values it is not possible to distinguish if QV Nor fills or slightly underfills its Roche lobe, and therefore if 4U 1538–52 is a wind-fed or a disk-fed binary system. From the value of the typical mass-loss rate from a supergiant as QV Nor, of the order of $10^{-6}$ $M_\odot$/yr, we can only infer that the wind activity is surely of great importance in the dynamics of this system.

The X-ray spectrum of 4U 1538-52 has been well fitted by the typical model for X-ray pulsars, namely a power-law continuum modified by an high energy cutoff, although the problem of contamination by the galactic ridge emission, as pointed out by Makishima *et al.* (Ref. 10), may still exists. An Iron $K_\alpha$ emission line with an E.W. of about 50 eV has also been detected at 6.3 keV by Makishima *et al.* (Ref. 10) and with an E.W. of about 570 eV by White *et al.* (Ref. 11).

In this paper we report results from a temporal and spectral analysis performed on four EXOSAT observations, part of which were taken from the EXOSAT archival, carried out during March and August 1984.

## 2. Observations and analysis

The X-ray satellite EXOSAT observed 4U 1538–52 on four occasions on 17 March and 7, 10 and 11 August 1984. Details for each observation are given in Table 1. The present analysis is based on data from the Argon cells of the Medium Energy (ME) detector array. The description of the EXOSAT mission and scientific instruments may be found in Taylor *et al.* (Ref. 12), de Korte *et al.* (Ref. 13) and Turner *et al.* (Ref. 14).

The background subtracted X-ray light curves obtained in the four EXOSAT observations in the 1–11 keV energy range versus binary phase (we folded the data with the orbital parameters given by Makishima *et al.* (Ref. 10)) are shown in Fig. 1a and 1b with 530 sec time resolution. The intensity was highly variable; in the first observation we can distinguish an episode of increasing luminosity about 5000 sec long, while an intensity dip about 1000 sec long is present at the beginning of the third observation. A gradual entry into eclipse of the X-ray source, with a transition time of about 5000 sec, is clearly visible in both the second and the fourth observation. This time, consistent with the value reported by Makishima *et al.* (Ref. 10) (although their data did not cover the ingress as the EXOSAT data did, because of the orbit of the Tenma observatory), gives a scale height of $\sim 1.5 \cdot 10^{11}$ cm for the atmosphere of QV Nor using the orbital parameters given by Makishima *et al.* (Ref. 10).

### 2.1. Timing analysis

In the first and third observations the single 530 sec X-ray pulses from 4U 1538–52 are well visible and so the arrival times of each individual pulse could be determined, by measuring the times of pulse minima, after smoothing the data to reduce the effect of random fluctuations, and then using the pulse minima as fiducial points. The pulse arrival times so obtained were corrected to solar system barycentre and for the orbital motion of the X-ray source. A least squares analysis was used to determine the best fitting constant pulse period.

In the other two observations the single pulses are not well visible so we divided the part of observation in which the source is not in eclipse into intervals of length 2000 to

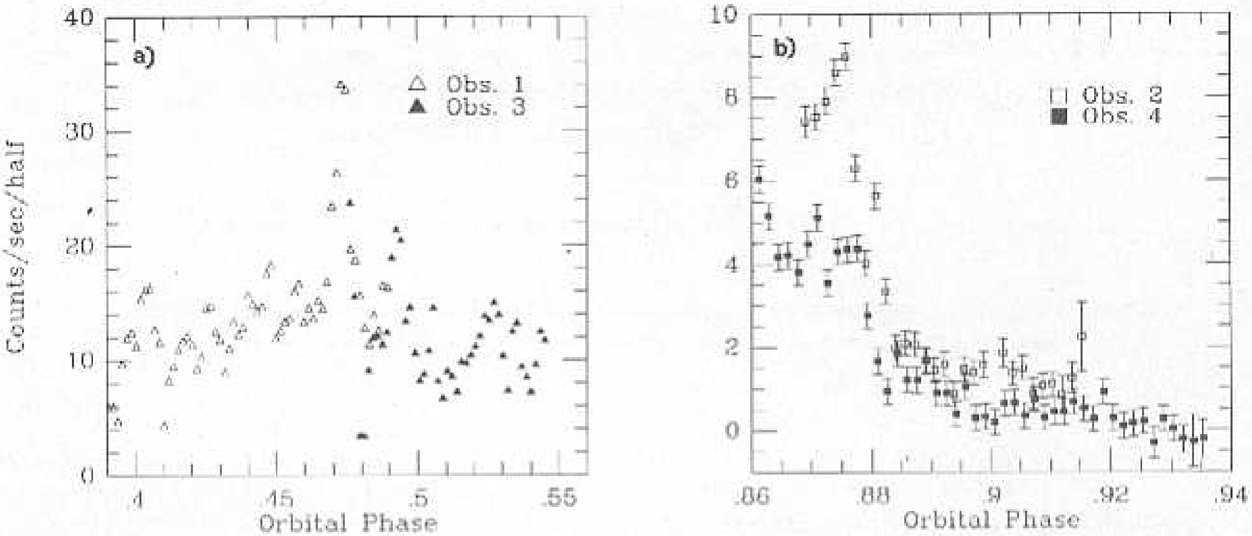


Figure 1: The background-subtracted light curves of 4U 1538–52, in the 1–11 keV energy range versus binary phase, with 530 seconds time resolution. *a)* for the first and the third EXOSAT ME observation; *b)* for the second and the fourth EXOSAT ME observation.

5000 sec, and we folded the data with the previously obtained period. Using the above procedure we determined the arrival times of these pulses. A least squares analysis was then used again.

The timing residuals were minimized for a period of 529.97 ± 0.16 sec and a rms timing residual of 18 sec for the first observation and for a period of 530.14 ± 0.03 sec for the third, plus the available data from the second and fourth observations, with a rms timing residual of 15 sec.

The present pulse period result is shown in Table 2 and Fig. 2 together with previous determinations. Our new values, together with values from *OSO 8* (Ref. 6), *Ariel 5* (Refs. 5,9), *Tenma* (Ref. 10) and *Ginga* (Ref. 15), indicate that 4U 1538–52 was spinning-down during 1983–84 with $\dot{P}/P \sim 2.2 \cdot 10^{-11}$ sec$^{-1}$. The general trend in the period 1976–1988 is a spin-down with $\dot{P}/P \sim 7.3 \cdot 10^{-12}$ sec$^{-1}$.

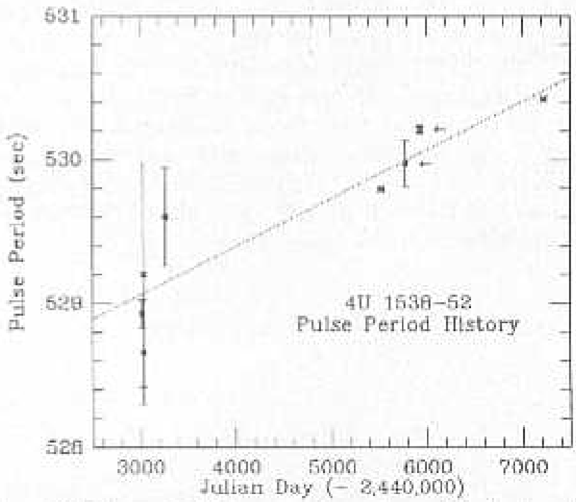


Figure 2: Pulse period history results as observed by Becker *et al.* (1977), Davison (1977), Davison *et al.* (1977), Makishima *et al.* (1987), Nagase (1989), and ourselves (marked by arrows).

TABLE 1: JOURNAL OF OBSERVATIONS

| Nr. Obs. | Date | Start Time (U.T.) | Duration (sec) | Binary Phase[a] | Half ME on Source |
|---|---|---|---|---|---|
| 1 | 17 March 1984 | $09^h\ 36^m$ | 35,400 | 0.40–0.51 | H2 |
| 2 | 7 August 1984 | $20^h\ 03^m$ | 16,400 | 0.87–0.92 | H2 |
| 3 | 10 August 1984 | $02^h\ 48^m$ | 22,500 | 0.48–0.54 | H1 |
| 4 | 11 August 1984 | $12^h\ 53^m$ | 25,000 | 0.86–0.93 | H2 |

[a] Ephemeris were taken from Ref. 10

TABLE 2: PULSE PERIOD HISTORY OF 4U 1538–52

| Date of Observation | Epoch (JD – 2,440,000) | Pulse Period (sec) | Satellite | Ref. |
|---|---|---|---|---|
| 25 August 1976 | 3016.3 | 528.93 ± 0.10 | *OSO 8* | 6 |
| 6 September 1976 | 3029.2 | 528.66 ± 0.36 | *Ariel V* | 5 |
| 9 September 1976 | 3032.3 | 529.20 ± 0.78 | *Ariel V* | 5 |
| 23 April 1976 | 3257.7 | 529.60 ± 0.34 | *Ariel V* | 9 |
| 2 July 1983 | 5518.2 | 529.792 ± 0.009 | *Tenma* | 10 |
| 17 March 1984 | 5777.3 | 529.97 ± 0.16 | *EXOSAT* | this paper |
| 10 August 1984 | 5923.1 | 530.14 ± 0.03 | *EXOSAT* | this paper |
| 2 March 1988 | 7223.0 | 530.420 ± 0.014 | *Ginga* | 15 |

## 2.2. Aperiodic variability

In the study of the temporal behavior of 4U 1538-52 we investigated the intensity variability not associated to the pulsation, the so called aperiodic variability, in order to obtain information about the time scales of the variations, and therefore to extract some hints as to the possible physical processes which may originate them. In doing this, we studied the Power Spectral Density (PSD) function of the intensity of 4U 1538-52 for both the first and third observations. The time resolution of the count data was 10 sec and the 1-8 keV energy band was chosen as it was in this energy range that the best signal-to-noise ratio was obtained.

We performed our analysis dividing the first observation into 6 runs and the third observation into 4 runs containing 512 data points each. We then computed by means of a Fast Fourier Transform algorithm the PSD for each run. Then for each observation we obtained the average PSD and we subtracted the variance due to the counting statistics. The results are shown in Fig. 3a and 3b for both the observations.

The PSD function so obtained gives the frequency dependence of the variance of the data due to the aperiodic non-Poissonian flux of the source. The peaks visible in the plots correspond to the fundamental frequency of pulsation and its harmonics and are indicated by arrows in Fig. 3a and 3b. As can be seen from these figures, the source shows aperiodic time variability with time scales down to the Nyquist frequency of 0.05 Hz.

We fitted the power spectra with a power-law of the form $kf^{-\alpha}$, obtaining $\alpha \sim 1.4$ for the first observation and $\alpha \simeq 1.6$ for the third. We performed the same analysis on data with 16 ms time resolution taken from the third observation. The result is shown in Fig. 4: no power is apparent above 0.05 Hz. We can extract a $2\sigma$ upper limit of the order of 25% to the aperiodic variations in counts for time scales less than 20 sec.

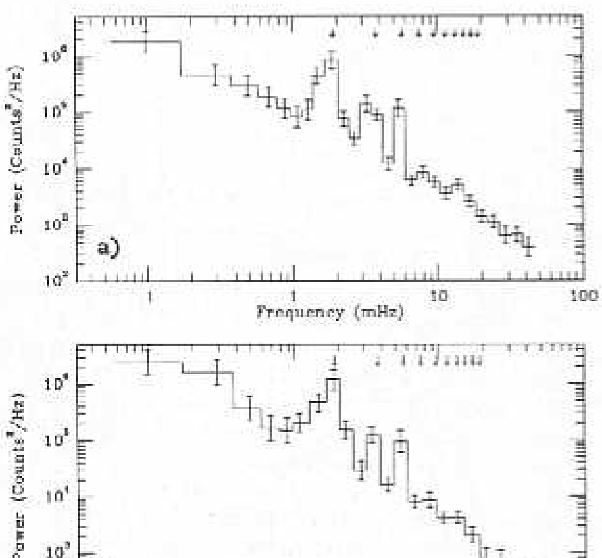


Figure 3: Power Spectral Density function of the intensity of 4U 1538-52 for data with 10 seconds time resolution, performed dividing the observation in runs 512 data long. *a)* PSD relative to the first observation, obtained dividing the observation in 6 runs; *b)* PSD relative to the third observation, obtained dividing the observation in 4 runs. The pulsation frequency (fundamental) and the first nine harmonics are marked by arrows.

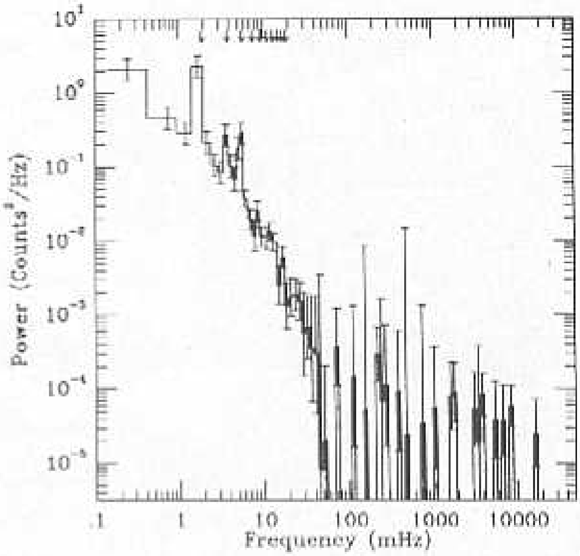


Figure 4: Power Spectral Density function of the intensity of 4U 1538-52 for data with 16 ms time resolution, relative to the third observation. The pulsation frequency (fundamental) and the first nine harmonics are marked by arrows.

## 2.3. The pulse phase averaged spectrum

The spectral energy analysis has been performed using only the data obtained from Argon ME detectors in the energy range 1.5–12 keV. In previous observations, the X-ray spectrum of 4U 1538-52 was fitted by a power-law plus a low energy absorption and a high energy cutoff, as summarized in Table 3. Given the limited energy range of our spectral analysis, we used as spectral laws a thermal bremsstrahlung model and a power-law, both of them with low energy photoelectric absorption. Both a power-law and a thin thermal bremsstrahlung law fit the data well. In Table 4 we show the results of power-law fits for the first and the third observations. An Iron line with an E.W. $\approx$ 100 eV is present. This value is in agreement with Tenma measurement (Ref. 10), but a factor 5 smaller than HEAO 1-A2 measurement (Ref. 11).

## 2.4. Pulse profiles with energy

The average background subtracted pulse profiles obtained for the first and third observations by folding the data at the pulse period, are shown in Fig. 5 and Fig. 6 for different energy ranges. They show a double peak structure with the first brighter than the second, separated by two minima of about the same intensity. The profiles show a dependence with energy and, for the third one, a sharp dip (about 10 sec long) is present in the low energy light curves at the maximum of intensity. At high energies the main pulse is sharper, while the interpulse becomes broader.

We have also computed the modulation index, defined as

$$\Phi(E) = 1 - \frac{I_{\min}(E)}{I_{\max}(E)}$$

where $I_{\max}$ is the maximum intensity in the background sub-

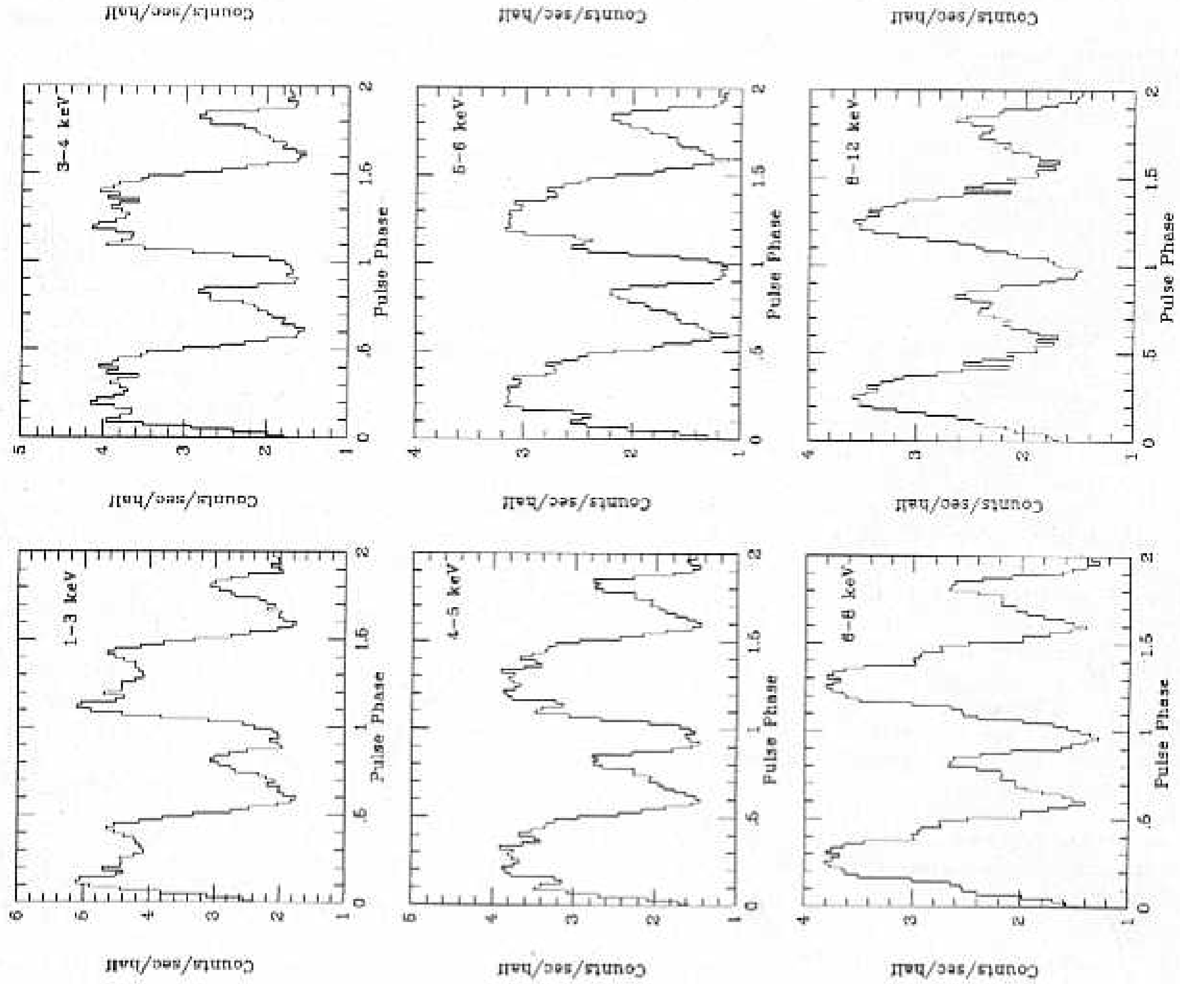


Figure 5: Time-average background-subtracted pulse profiles of 4U 1538–52 in six energy bands, for the first EXOSAT observation.

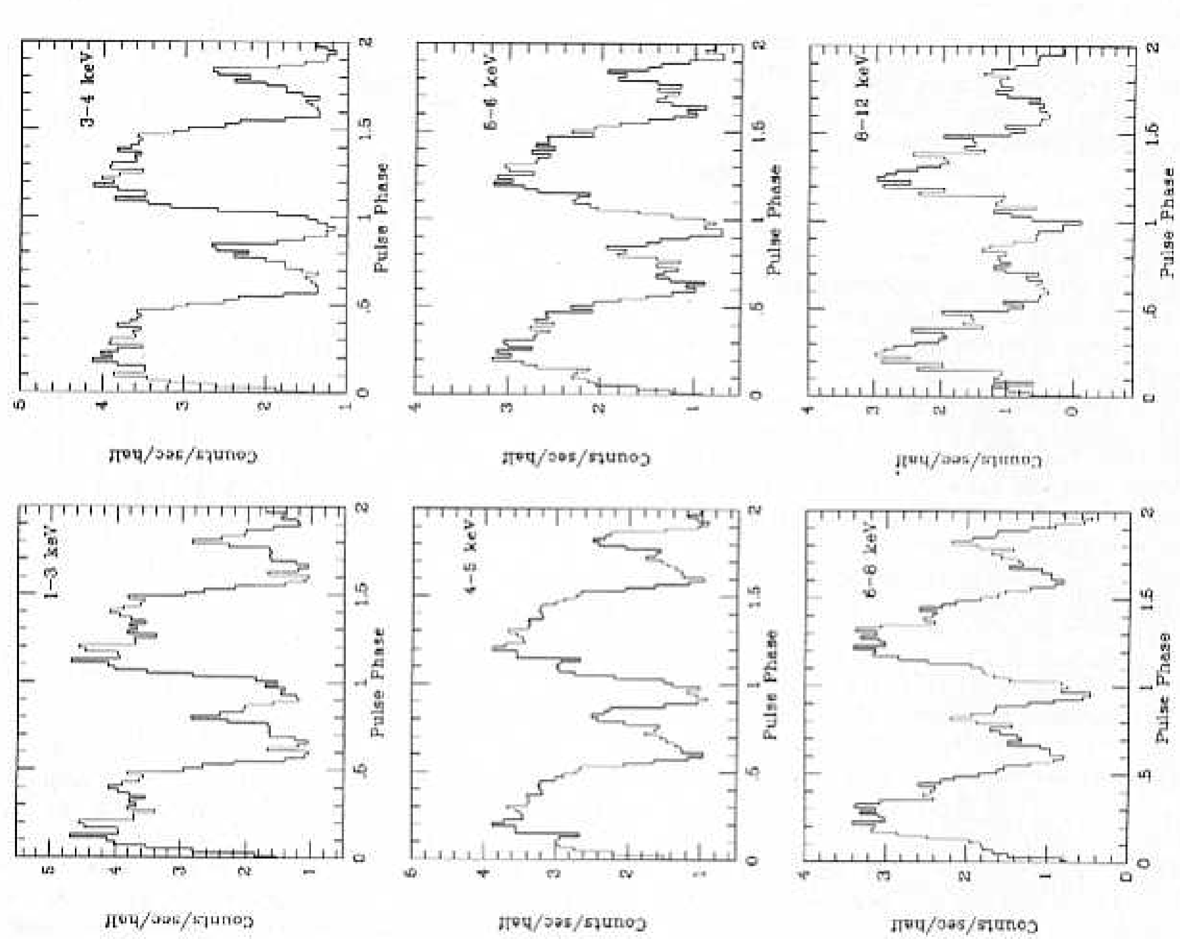


Figure 6: Time-average background-subtracted pulse profiles of 4U 1538–52 in six energy bands, for the third EXOSAT observation.

TABLE 3: OTHER SPECTRAL MEASUREMENTS OF 4U 1538−52

| Satellite | Energy (keV) | Photon Index | $E_c$ (keV) | $E_f$ (keV) | $N_H$ ($10^{22}$ H/cm$^2$) | Iron Line Energy (keV) | Iron Line E.W. (eV) | Ref. |
|---|---|---|---|---|---|---|---|---|
| *OSO-8* | 2–20 | $1.2 \pm 0.2$ | | | $3.2 \pm 1.0$ | | | 6 |
| *Ariel V* | 2–15 | $1.1 \pm 0.1$ | | | $2.6 \pm 1.0$ | | | 5 |
| *HEAO 1-A2* | 2–30 | 1.42 | $17 \pm 2$ | $11 \pm 3$ | | | $572 \pm 140$ | 11 |
| *Tenma* | 2–12 | $1.12 \pm 0.04$ | $14.8 \pm 0.5$ | $5.9 \pm 1.2$ | $3.7 \pm 0.4$ | $6.3 \pm 0.2$ | $52 \pm 30$ | 10 |

TABLE 4: EXOSAT SPECTRAL MEASUREMENTS OF 4U 1538−52[a]

| Nr. Obs. | Photon Index | $N_H$ ($10^{22}$ H/cm$^2$) | Iron Line Energy (keV) | Iron Line E.W. (eV) | Flux[b] (2–12 keV) | $\chi^2$/dof |
|---|---|---|---|---|---|---|
| 1 | $1.49 \pm 0.04$ | $2.7 \pm 0.2$ | $6.7 \pm 0.15$ | $100 \pm 30$ | 3.20 | 38/34 |
| 3 | $1.40 \pm 0.07$ | $2.6 \pm 0.3$ | $6.2 \pm 0.10$ | $100 \pm 40$ | 2.19 | 44/34 |

[a] $1\sigma$ error.
[b] Units of $10^{-10}$ erg sec$^{-1}$ cm$^{-2}$.

tracted light curve and $I_{min}$ is the minimum, at the given energy $E$. This index gives information on the dependence on energy of the process which determines the modulation.

The modulation index for the first observation is consistent with a constant value of $\sim 0.65$, independent of energy while for the third observation it shows an increase with energy from a value of 0.78 (1–3 keV) to 0.96 (8–13 keV).

## 3. Discussion

The spectral energy analysis has confirmed the form of the spectrum, which is typical of this class of objects, while the presence of an Iron line in the case of a power-law spectrum confirms the previous observation by Tenma (Ref. 10).

From the spectral density analysis performed on the light curve of 4U 1538–52 we were not able to extract any characteristic time scale down to $\sim 20$ sec; this means that the process (or the processes) which occurs at the magnetospheric limit and might be responsible of the fluctuations in the X-ray intensity does not show a unique time scale for frequencies less than 0.05 Hz. No evident feature that could be associated to quasi-periodic oscillation is apparent in the PSD spectra.

The EXOSAT observations of the X-ray binary pulsar 4U 1538–52 confirm the general spin-down trend of the pulse period. Indeed the main theoretical problem about the X-ray binary pulsar 4U 1538–52 consists in the lack of the secular spin-up: theories of both disk and wind accretion predict some occasional spin-down episode but a net spin-up trend over long time scales (Ref. 16).

The time scale due to the accretion torque is computed from the relation

$$I\,\dot{\Omega}_p = \dot{M}_x\,\ell \qquad (1)$$

where $I$ is the moment of inertia of the neutron star, $\dot{M}_x$ is the accretion rate of matter onto the neutron star and $\ell$ is the specific angular momentum carried by the accreted matter. In this expression the variation of the moment of inertia is not taken into account, because the time scale due to this variation, $\dot{I}/I$, is much longer than $\dot{P}_p/P_p$.

From the physical parameters of the 4U 1538–52 system as reported by Joss and Rappaport (the neutron star mass and radius, the supergiant mass; Ref. 17), Parkes *et al.* (the mass loss rate from the supergiant and the terminal velocity of the wind; Ref. 7) and Clark *et al.* (the magnetic field strength of the neutron star; Ref. 18) the characteristic lengths of accretion (see for example Ref. 16) are:

- Magnetospheric Radius $R_m \simeq 1 \cdot 10^9$ cm;
- Accretion Radius $R_a \simeq 3 \cdot 10^{10}$ cm;
- Corotation Radius $R_c \simeq 1 \cdot 10^{10}$ cm.

The fact that $R_a > R_m$ means that this source is accreting matter. Furthermore $R_c > R_m$, so, according to Stella *et al.* (Ref. 19), 4U 1538–52 is in the regime of direct wind accretion. The observed X-ray luminosity of $2 \cdot 10^{36}$ erg/sec (Ref. 10) is in agreement, within the uncertainty in the observed values, with that predicted by Stella *et al.* (Ref. 19). By means of Eq. 1 a value of $\dot{P}_p/P_p \sim -7.0 \cdot 10^{-12}$ sec$^{-1}$ is expected in the case of wind accretion with a radial gradient in density and velocity (Ref. 20) and a value of $\sim -1.3 \cdot 10^{-10}$ sec$^{-1}$ is expected in the case of disk accretion with magnetic coupling (Refs. 21,22). These values must be compared to the observed value of $\dot{P}_p/P_p = +7.3 \cdot 10^{-12}$ sec$^{-1}$.

The modulo of the expected values of $\dot{P}_p/P_p$ agrees well with the observed one, but the general trend of spin-up is not predicted. It has been proposed that the variations in the pulse period of wind-fed X-ray pulsars are the result of small fluctuations of both signs that occur randomly on time scales which are comparable to the orbital period (Ref. 23). Makishima *et al.* (Ref. 10) have shown that the observed period change of 4U 1538–52 in 1976–1983 is really in agreement with this interpretation. The nature of these fluctuations is to date unknown. It can be pointed out that no clear episode of spin-up was observed from this source, therefore a careful monitoring of 4U 1538–52 is necessary in order to clarify its temporal behaviour.

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