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THE DISCOVERY OF 8.7 SECOND PULSATIONS FROM THE ULTRASOFT X-RAY SOURCE 4U 0142+61

G. L. ISRAEL[1]
International School for Advanced Studies, via Beirut 2–4, I-34014 Trieste, Italy
israel@vxrmg9.icra.it

S. MEREGHETTI
Istituto di Fisica Cosmica del CNR, via Bassini 15, I-20133 Milano, Italy
sandro@ifctr.mi.cnr.it

AND

L. STELLA[1]
Osservatorio Astronomico di Brera, via Brera 28, I-20121 Milano, Italy
stella@astmib.mi.astro.it
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ABSTRACT

We discovered an X-ray periodicity at ~8.7 s from the direction of the two sources 4U 0142+61 and RX J0146.9+6121. The pulsations are visible only in the 1–4 keV range, during an observation obtained with *EXOSAT* in 1984 August. In the same data, periodic oscillations at 25 minutes had been previously found in an additional hard spectral component above 4 keV. The newly discovered periodicity most likely originates from the optically unidentified source 4U 0142+61, previously considered a possible black hole candidate on the basis of its ultrasoft spectrum. Marginal evidence for the ~8.7 s pulsations is found in the two 1985 *EXOSAT* observations and in a 1991 *ROSAT* high-resolution imager pointing; if true, these measurements imply a spin-up timescale of ~530 yr. Although the very high ($>10^4$) X-ray to optical flux ratio of 4U 0142+61 is compatible with models based on an isolated neutron star, the simplest explanation involves a low-mass X-ray binary with a faint companion, similar to 4U 1626−67. A search for delays in the pulse arrival times caused by orbital motion gave negative results. The discovery of periodic pulsations from 4U 0142+61 weakens the phenomenological criterion that an ultrasoft spectral component is a signature of accreting black holes.

Subject headings: stars: individual (4U 0142+61) — stars: neutron — X-rays: sources

1. INTRODUCTION

The persistent X-ray source 4U 0142+61 was discovered by *Uhuru* and was soon observed to possess an ultrasoft spectrum. In the X-ray color-color diagram of White & Marshall (1984) it occupies the same region of black hole candidates in their "high state," such as LMC X-3, LMC X-1, and A0620−00. 4U 0142+61 lies in the Galactic plane ($l = 129^\circ.4$, $b = -0^\circ.4$), and, despite its small error circle (a few arcseconds), no optical or radio counterparts have yet been identified (White et al. 1987). While the X-ray luminosity of 4U 0142+61 [$L_x \sim 10^{36}(d/4\ \mathrm{kpc})^2$ ergs s^{-1}] is one or two orders of magnitude lower than that measured for the sources above, its spectrum (power law with energy index of ~3–4) is reminiscent of high-state black hole candidates.

During one of three *EXOSAT* observations of 4U 0142+61 carried out in 1984–1985, an additional spectral component was detected above 3 keV within the ~90′ collimator response of the medium-energy (ME) experiment. Correspondingly, ~25 minute periodic oscillations were discovered in the 3–10 keV energy range (White et al. 1987). It is still unclear whether this component and the ~25 minute oscillations originated from 4U 0142+61 or from a second source in the field of view. Mereghetti, Stella, & De Nile (1993) pointed out that such a source could be RX J0146.9+6121, an X-ray transient recently discovered with *ROSAT* and identified with the Be star LSI +61°235 (Motch et al. 1991).

Here we present the results of a reanalysis of the *EXOSAT* data, which led to the discovery of 8.7 s coherent pulsations in the 1–4 keV band (Israel, Mereghetti, & Stella 1993).

2. TIMING ANALYSIS

During the ~12 hr observation of 1984 August 27–28, the average 1–10 keV count rate of 4U 0142+61 in the *EXOSAT* ME experiment was ~10.7 counts s^{-1}. Due to the presence of the 3–10 keV spectral component showing the 25 minute oscillations, this rate was ~40% higher than that measured during the 1985 November 11 and December 11 observations, when the additional component was not present. In the 1984 observation, the ME instrument provided light curves with a time resolution of 1 s in different energy bands. The times were corrected to the barycenter of the solar system. The power spectrum of the 1–3 keV light curve over an interval of 32,768 s (Fig. 1) revealed the presence of two highly significant peaks (random occurrence probabilities of 8.9×10^{-8} and 3.6×10^{-9}) at the fundamental and the second harmonic, respectively, of a coherent modulation with a period of 8.6872 s. The power spectrum of the 4–11 keV light curve did not show any evidence for this pulsation. On the contrary, the peaks corresponding to the first three harmonics of the 25 minute modulation were clearly visible in the 4–11 keV power spectrum but not in the 1–3 keV one (Fig. 1).

[1] Affiliated with the International Center for Relativistic Astrophysics.

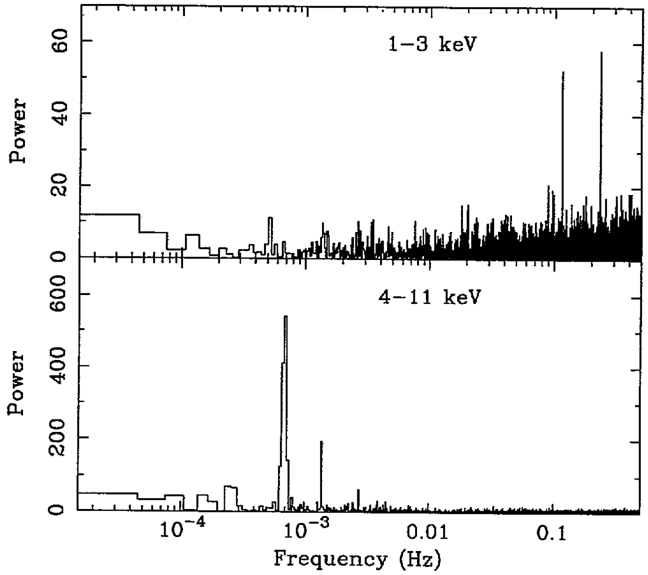

FIG. 1.—Power spectra of the 1984 *EXOSAT* observation of 4U 0142+61 in two different energy ranges. The peaks corresponding to the first two harmonics of the ~8.7 s pulsations are clearly visible in the 1–3 keV power spectrum (*upper panel*). The three peaks in the 4–11 keV power spectrum testify to the presence of the ~25 minute modulation in that energy range.

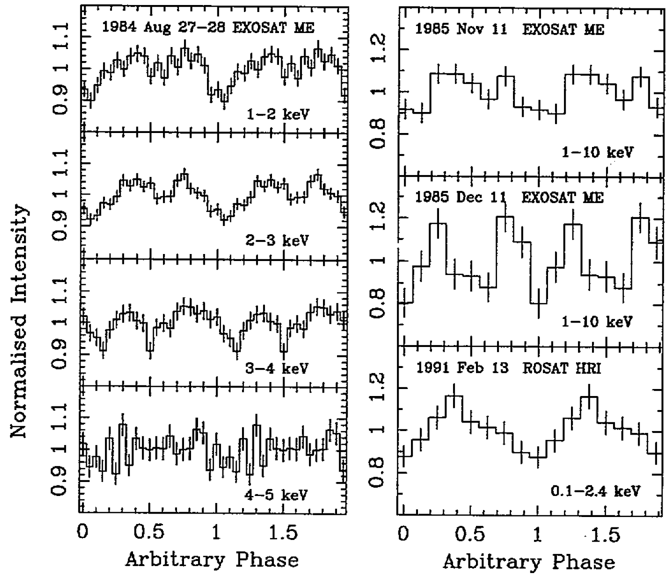

FIG. 2*a* FIG. 2*b*

FIG. 2.—(*a*) Folded light curves of the ~8.7 s pulsations in four different energy bands during the 1984 *EXOSAT* observation. (*b*) Light curves folded at the most significant period of the two 1985 *EXOSAT* observations and the 1991 *ROSAT* observation.

To measure the pulse period precisely, the observation was divided into intervals of $\sim 10^3$ s, and for each interval we determined the relative phase of the 8.7 s pulsations. This was done by fitting with a Gaussian the central peak of the cross-correlation function obtained from the folded light curve of each interval and that of the entire observation. These phases were then fitted to a linear function giving a best-fit period of 8.68723 ± 0.00004 s. Introducing a quadratic term did not significantly improve the fit and allowed us to derive a 90% confidence upper limit to the period derivative of $\dot{P} < 6.2 \times 10^{-9}$. Between 1 and 4 keV the light curve (Fig. 2*a*) consists of two peaks separated in phase by ~0.4–0.5, with a peak-to-peak amplitude of ~15%. We note that, being heavily absorbed ($N_{\rm H} \sim 4 \times 10^{23}$ cm^{-2}; White et al. 1987), the high-energy spectral component does not significantly contribute below 4 keV.

A search for an orbital modulation of the arrival times of the 8.7 s pulses was carried out for 199 orbital periods ranging from 430 to 43,000 s, with a spacing equal to half the Fourier resolution. The data were folded at the best period for seven different phase intervals of each trial orbital period. The resulting light curves were cross-correlated with the average one, and the peak of the cross-correlation function was fitted with a Gaussian. The centroid of the Gaussian provides an estimate of the delay of the 8.7 s pulses in each of the seven phase intervals of a trial orbital period. A circular orbit would be revealed by a sinusoidal modulation of the delays. To search for such a modulation, we calculated the squared Fourier amplitudes of the delays, without finding any significant deviation from the expected χ^2_2-like distribution. The 99% confidence upper limit to $a_x \sin i$ was derived to be 0.37 light-s (this limit reduces to 0.25 light-s under the single-trial hypothesis that the 25 minute modulation corresponds to the orbital period). Therefore, we conclude that the *EXOSAT* data do not provide any evidence for an orbital motion.

Unfortunately, during the two 1985 observations, energy-resolved ME data were obtained only with an integration time of 10 s. Only the summed rates from the ME argon and xenon chambers were available with a time resolution of 0.25 s. Based on these data, we accumulated 1 s resolved light curves, which, however, were characterized by a very high level of counting statistics noise due to the high background from the xenon chambers (~250 counts s^{-1}). The periodicity was searched in these light curves using the folding technique. To increase the sensitivity, we considered only trial periods in the 8.55–8.80 s range, as expected for a rate of spin change of $|P/\dot{P}| < 100$ yr (comparable to the highest value observed from X-ray pulsars) from the 1984 observation. We used eight phase bins and a period spacing which oversampled by a factor of ~20 times the Fourier resolution. Maximum χ^2 values of 30.0 and 29.6 were obtained for the 1985 November 11 and December 11 observations, corresponding to periods of 8.6658 ± 0.0005 and 8.6663 ± 0.0005 s, respectively. The chance probability of these maxima is difficult to estimate, because the trial periods are not independent. A lower and an upper limit can be obtained by considering a number of independent trials equal to the number of Fourier periods and the total number of trial periods, respectively. This gives a probability between 6×10^{-3} and 0.12 for the November observation, and between 4×10^{-3} and 0.08 for the December one. For the latter observation the probability reduces to between 2×10^{-4} and 4×10^{-3} if the range of possible periods is restricted by assuming that the November detection is statistically significant. In both cases the folded light curves (1–10 keV; Fig. 2*b*) show a double-peaked shape similar to that of the 1984 data, although the peak-to-peak amplitudes are larger (30%–40%; we note, however, that these values might be affected by systematic uncertainties in the background subtraction of the xenon chambers).

During the three *EXOSAT* ME observations, simultaneous imaging in the 0.05–2 keV band was obtained with the low-energy (LE) telescope. For each observation, we folded the LE light curve of 4U 0142+61 at the corresponding period determined from the ME data, without finding any evidence of modulation. However, because of the small counting statistics in the LE instrument, the derived upper limits on the peak-to-peak amplitudes are not very constraining (25%, 32%, and 35%, respectively, for the 1984, 1985 November, and 1985 December observations, at the 99% confidence level).

A 2180 s long *ROSAT* observation of 4U 0142+61 was carried out on 1991 February 13 with the high-resolution imager (HRI) instrument (0.1–2.4 keV). After correction to the solar system barycenter, the arrival times of the 2846 counts within a radius of 20″ from the position of 4U 0142+61 were searched for periodicities using the Rayleigh test (Leahy, Elsner, & Weisskopf 1983). We considered 87 independent periods between 8.0 and 9.4 s, finding a maximum value of the Rayleigh test statistics of 17.23 for $P = 8.600 \pm 0.017$ s (chance probability $\sim 1.6\%$). The folded light curve shows a broad, almost sinusoidal modulation, with a peak-to-peak amplitude of $\sim 30\%$ (see Fig. 2*b*).

In view of the relatively high probabilities of chance occurrence, the detection of the periodicity in the 1985 and 1991 data cannot be considered certain. It is, nevertheless, intriguing that the four period values are consistent with a line of constant spin-up, on a timescale of $\simeq 530$ yr.

3. DISCUSSION

Since the 8.7 s periodicity has been detected at a high confidence level only in nonimaging data, we cannot exclude the possibility that it originates in a source different from 4U 0142+61. The only other X-ray source presently known in this region is the Be star LSI +61°235, probably a binary system containing an accreting compact object (Motch et al. 1991; Mereghetti et al. 1993). If the latter spins at 8.7 s, a reasonable value for a neutron star accreting from a Be companion, the 25 minute periodicity remains to be explained. It could result from an orbital modulation in a low-mass X-ray binary (4U 0142+61), or from (quasi)-periodic flares in LSI +61°235, similar to those observed in other Be systems (Parmar et al. 1989; Finley, Belloni, & Cassinelli 1992), but both possibilities present some difficulties (see White et al. 1987; Mereghetti et al. 1993). Although a third, as yet unknown, source in the field of view could help in solving the puzzle, we regard this as an unlikely ad hoc explanation, and therefore assume in the following that the 8.7 s pulsations are due to 4U 0142+61. The lack of an optical counterpart down to limits of $V \sim 24$ and $R \sim 22.5$ (Steinle et al. 1987; White et al. 1987) implies an X-ray/optical flux ratio $F_x/F_{opt} > 10^4$. The only known classes of Galactic sources which can yield such a high F_x/F_{opt} value are low-mass X-ray binaries (LMXRBs) and isolated neutron stars.

3.1. *A Low-Mass X-Ray Binary?*

A neutron star accreting from a low-mass companion is the most likely explanation for 4U 0142+61, especially if the spin-up evidence is confirmed by further observations. Coherent pulsations are rarely seen in LMXRBs: the only known examples among optically identified systems, 4U 1626−67, Her X-1 and GX 1+4, have very different X-ray properties, companion stars, and evolutionary origins (see, e.g., White, Nagase, & Parmar 1993). The spin period of 4U 0142+61 is very similar to that of 4U 1626−67 (7.7 s; Rappaport et al. 1977), and it is interesting to note that two other optically unidentified pulsars, which are likely accreting from low-mass companions, 1E 2259+586 and 1E 1048.1−5937 (Coe & Jones 1992; Mereghetti, Caraveo, & Bignami 1992), have periods of the same order, 6.98 and 6.44 s, respectively (Davies et al. 1990; Corbet & Day 1990).

The position of 4U 0142+61 is close (<0°.5) to that of two open clusters with well-determined distances and reddening: NGC 654 at 2.5 kpc ($A_V = 2.67$ mag), and NGC 663 at 2.1 kpc ($A_V = 2.43$ mag) (see Leisawitz, Bash, & Thaddeus 1989 and references therein). The column density $N_H \sim 1.5 \times 10^{22}$ cm^{-2} derived from the power-law spectral fits of 4U 0142+61 (White et al. 1987) corresponds to a higher absorption, $A_V \sim 7$ mag (Gorenstein 1975), hinting at a greater distance. However, 4U 0142+61 is not necessarily much farther than these clusters, since a part of its absorption could be intrinsic or due to a local ($d < 1$ kpc) molecular cloud which is present in this region, as clearly visible on the POSS prints. 4U 0142+61 lies near to the edge of this cloud, which does not significantly affect NGC 654 and NGC 663 (Leisawitz et al. 1989). A distance of 4 kpc would yield a 1–10 keV luminosity of $\sim 10^{36}$ ergs s^{-1}, similar to that of 4U 1626−67. At this distance and reddening the faint optical counterpart of the latter source would be fainter than the present limits for 4U 0142+61. On the other hand, an evolved companion similar to that of GX 1+4 or Cyg X-2 ($M_V \sim -1$; van Paradijs 1991) would have been detected even at ~ 10 kpc (which for this direction is well outside the Galaxy). A companion star similar to that of 4U 1626−67, i.e., either a main-sequence star with $M \approx 0.08\ M_\odot$ or a white dwarf of mass 0.02 $M_\odot$ (Verbunt, Wijers, & Burm 1990), is also compatible with the limits on $a_x \sin i$ derived in the previous section, which, however, also allow for more massive companions. For instance, a hydrogen main-sequence star of $\sim 0.3\ M_\odot$ would fill the Roche lobe for an orbital period of ~ 3 hr, requiring $i < 46°$.

Despite the above similarities to 4U 1626−67, there are also important differences. First, the X-ray spectrum is much softer than that of 4U 1626−67, a flat power law (energy index ~ 0.4) with a cutoff at ~ 20 keV, similar to that of most accreting X-ray pulsars (White, Swank, & Holt 1983). In this respect 4U 0142+61 is more similar to 1E 2259+586, whose spectrum can be described by a power law with energy index ~ 3, plus some possible cyclotron features suggesting a magnetic field strength $B \sim 5 \times 10^{11}$ G (Iwasawa, Koyama, & Halpern 1992). Second, the flux in the ultrasoft spectrum of 4U 0142+61 is rather stable, unlike most accreting X-ray pulsars, and 4U 1626−67 in particular, which shows quasi-periodic flares on a timescale of 1000 s (Li et al. 1980). Finally, the spin-up timescale of ~ 530 yr, if confirmed, would be about a factor of 10 shorter than that observed in 4U 1626−67. In the standard framework of accretion disk torques on magnetized neutron stars (see, e.g., Henrichs 1983) this would require a mass accretion rate of $\sim 3 \times 10^{17}(B/10^{12}\ \mathrm{G})^{-1/3}$ g s^{-1}. Such a high accretion rate is not incompatible with the flux measured from 4U 0142+61, since the accretion luminosity can easily be two orders of magnitude higher than that observed in the 1–10 keV range, if the steep spectrum extends down to ~ 0.1 keV.

3.2. *An Isolated Neutron Star?*

The possibility that 4U 0142+61 is an isolated neutron star is suggested by its very high F_x/F_{opt}, its ultrasoft spectrum, and the absence of significant variability on long timescales (of course this possibility requires that the evidence for secular spin-up is the result of chance detections in the 1985 and 1991 data). In principle the X-ray emission could be due to non-thermal magnetospheric processes powered by the rotational energy, to thermal emission from the neutron star surface, or to accretion from the interstellar medium. While examples of the first two mechanisms are well known (see, e.g., Mereghetti, Caraveo, & Bignami 1994), no compelling evidence for a compact object accreting from the interstellar medium has yet been found, despite the fact that several studies show that such sources could be relatively common (Treves & Colpi 1991; Blaes & Madau 1993).

For a spin period of 8.7 s and any reasonable magnetic field ($\lesssim 10^{14}$ G), the available rotational energy loss is too small, unless 4U 0142+61 is at a distance of a few parsecs. To investigate the possibility of thermal emission, we fitted blackbody spectra to the 1985 ME + LE data, obtaining $kT \sim 0.5$ keV, $N_H \sim (2\text{–}4) \times 10^{21}$ cm^{-2}, and a bolometric luminosity $\sim 10^{32}(d/100 \text{ pc})^2$ ergs s^{-1} (however, these fits were substantially worse than those with a power law: reduced χ^2 of $\sim$3–6). This implies an emission region of $\sim 0.1(d/100 \text{ pc})^2$ km^2, compatible with a hot spot on the surface of a neutron star, possibly the magnetic polar cap heated by accretion from the interstellar medium. In this case the accretion-induced luminosity would be $\sim 10^{32}(v/50 \text{ km s}^{-1})^{-3}(n/100 \text{ cm}^{-3})$ ergs s^{-1}, where v is the neutron star velocity relative to the interstellar medium of density n (Blaes & Madau 1993). The already mentioned molecular cloud (Leisawitz et al. 1989) could be at a distance of only a few hundred parsecs and easily provide the density required to power the observed luminosity. For accretion onto the neutron star to take place, the magnetospheric centrifugal barrier must be open, and the low rates implied by the above luminosity therefore require a magnetic field strength $B \leq 10^{10}(d/100 \text{ pc})$ G (see, e.g., Stella et al. 1994).

4. CONCLUSIONS

The discovery of 8.7 s pulsations further complicates the puzzle of the X-ray emission from the region of sky containing 4U 0142+61 and LSI +61°235/RX J0146.9+6121. The most likely origin for the newly discovered periodicity is the ultrasoft source 4U 0142+61, which is probably a LMXRB with a very faint companion, similar to 4U 1626−67. In the absence of an optical identification for 4U 0142+61, this would be supported if the evidence for the secular spin-up reported in this *Letter* were confirmed. Independent of the nature of 4U 0142+61, we note that the detection of coherent pulsations weakens the phenomenological criterion that the presence of an ultrasoft X-ray spectral component is a characteristic of accreting black holes (White & Marshall 1984).

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Note added in proof.—A recent *ROSAT* PSPC observation performed in 1993 February (C. Hellier 1994, IAU Circ., No. 5994) has definitely established the origin of the two periodicities: pulsations at 8.6878 ± 0.0001 s and 1413 ± 8 s were clearly detected from 4U 0142+61 and RX J0146.9+6121, respectively. This confirms the interpretations given in Mereghetti et al. (1993) and in the present *Letter*.