# Evidence for an anomalous state in the black-hole candidate 4U 1630-47

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# EVIDENCE FOR AN ANOMALOUS STATE IN THE BLACK HOLE CANDIDATE 4U 1630−47

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## ABSTRACT

We have reanalyzed two *EXOSAT* medium-energy observations during part of the 1984 X-ray outburst of the black hole candidate transient system 4U 1630−47. One observation (May 10) shows fast-timing properties (on timescales shorter than ∼250 s) typical of those of other black hole candidates in their high states. The power spectrum shows a power law with index ∼0.7 and a fractional rms amplitude (0.001–1 Hz) of ∼2%. Another observation, obtained 1 month earlier (April 11), shows different fast-timing behavior. The power spectrum of this observation can be described by a power law with index ∼1.5 and a fractional rms amplitude (0.001–1 Hz) of ∼7%. This is inconsistent with the behavior during low, high, or very high states known to occur in most of the black hole candidates. Instead, the timing properties resemble those recently reported from the *Advanced Satellite for Cosmology and Astrophysics* observations of the superluminal black hole candidates GRS 1915+105 and GRO J1655−40 (X-ray Nova Sco 1994). This timing behavior may represent a new state of black hole candidates.

In addition, the X-ray spectra of the three sources show similar properties. Since GRS 1915+105 and GRO J1655−40 exhibit superluminal jets, we propose that 4U 1630−47 is also a relativistic jet source.

*Subject headings:* accretion, accretion disks — binaries: close — black hole physics — stars: individual (4U 1630−47) — X-rays: stars

## 1. INTRODUCTION

The star 4U 1630−47 is an ultrasoft X-ray transient, which has shown multiple outbursts. It was discovered by Jones, Forman, & Tananbaum (1976) and has the shortest known outburst recurrence interval of ∼600 days (e.g., Parmar, Angelini, & White 1995; Parmar et al. 1996). In general, the outbursts rise within a few weeks and decay on an *e*-folding timescale of ∼50 days. The outburst duration is variable, with some outbursts having durations of up to ∼2.4 yr (Kaluzienski & Holt 1977; Share et al. 1978; Kaluzienski et al. 1978; Sims & Watson 1978; Kitamoto 1996).

Based on its observed properties, Parmar, Stella, & White (1986) proposed that 4U 1630−47 should be regarded as a black hole candidate. The X-ray spectrum has two components, an (ultra) soft component and a (ultra) hard power-law tail. As an outburst proceeds, the soft component fades, and the hard component becomes relatively more intense. Close to outburst maximum, strong variability is observed with a characteristic timescale of ∼20 s. No pulsations or bursts have been detected. These properties are similar to those of other black hole candidates (see, e.g., Tanaka & Lewin 1995).

Recent studies have revealed that the black hole candidates show three different states, mainly based on the characteristics in the X-ray spectral and power spectral behavior (see Tanaka & Lewin 1995; van der Klis 1995, and references therein). These are the so-called low, high, and very high states. The three states are thought to be governed by the mass accretion rate. During the low state, the power spectra are characterized by a power law with index $\alpha \sim 1$–1.7. Below ∼0.1 Hz, the power spectrum flattens, and above ∼10 Hz, it steepens. This shape is called band-limited noise. The fractional rms amplitude of the noise is large, typically between 30% and 50%. Quasi-periodic oscillations (QPOs) in this state have been reported with centroid frequencies in the range 0.04–0.8 Hz. During this state, the X-ray spectrum is dominated by the hard power-law component. The high state is characterized by weak power-law noise with $\alpha \sim 1$ and fractional rms variability of a few percent. QPOs at ∼0.08 Hz with a harmonic, and fractional rms up to ∼3%, were seen in LMC X-1 (Ebisawa, Mitsuda, & Inoue 1989). During this state, the X-ray spectrum is dominated by the soft component. In the very high state, the power spectra show 3–10 Hz QPO and rapidly variable broadband noise. The X-ray spectrum is similar to the high-state spectrum scaled to higher intensities, although the hard power law is slightly steeper (index ∼2.5 in the very high state vs. ∼2 in the high state; see, e.g., Ebisawa et al. 1994).

Interest in black hole transients has been heightened by the discovery of superluminal jets in the two Galactic transient sources GRS 1915+105 and GRO J1655−40/X-ray Nova Sco 1994 (see, e.g., Mirabel & Rodríguez 1996 for a recent review). It was argued by Mirabel & Rodríguez (1994), after their discovery of the jets in GRS 1915+105, that other black hole candidate transients might also exhibit relativistic jets (see also Hjellming & Rupen 1995). Bailyn et al. (1995) presented dynamical evidence that the compact object in GRO J1655−40 has a mass appropriate to a black hole.

Recently, Ebisawa (1996) presented the timing behavior of GRO J1655−40 as observed on two occasions (see also Zhang et al. 1996) and of GRS 1915+105 as observed on one occasion, using the *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*). The power spectra were characterized by a featureless power law with power spectral indices between 1.2 and 1.7, and fractional rms amplitudes of 6%–8% in the 0.001–1 Hz frequency range. As we will show, such a shape does not fit in with the typical black hole candidate behavior described above.

We report on *EXOSAT* observations made on two occasions during the 1984 outburst of 4U 1630−47. This outburst was discovered by *Tenma* (Tanaka et al. 1984). Energy spectra and

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TABLE 1

*EXOSAT* ME ARGON OBSERVATION LOG OF 4U 1630−47

| Year | Date | Day[a] | UT Start (hr: minutes) | UT End (hr: minutes) | Mode[b] | Time Resolution | Configuration[c] |
|---|---|---|---|---|---|---|---|
| 1984 ............. | April 11 | 102 | 08:08 | 15:10 | E4/E5/T3[d] | 10 s/0.1 s/8 ms | WA |
| | May 10 | 131 | 02:00 | 06:45 | E5/E6/T3[e] | 0.6 s/20 ms/8 ms | WA |

[a] January 1 = day 1.
[b] E = High Energy Resolution (HER) mode, T = High Time Resolution (HTR) mode.
[c] Array configuration on source: WA = whole array.
[d] From 08:08 to 13:16 HER4/HTR3, from 13:39 to 15:10 HER5/HTR3.
[e] From 02:00 to 02:32 HER5/HER6, from 02:38 to 06:45 HER5/HTR3.

autocorrelation functions of the *EXOSAT* data were reported in Parmar et al. (1986). We demonstrate that during one of the observations, 4U 1630−47 exhibited temporal variability that is different from the variability in the three black hole candidate states described above. We discuss this behavior in the light of the recent *ASCA* timing results of the two newly discovered X-ray transients GRS 1915+105 and GRO J1655−40. Our analysis provides evidence that 4U 1630−47 belongs to the class of black hole candidates.

## 2. OBSERVATIONS AND ANALYSIS

We analyzed the *EXOSAT* medium-energy (ME) experiment argon data (Turner, Smith, & Zimmerman 1981; White & Peacock 1988) of two observations made on 1984 April 11 and May 10 (see also Parmar et al. 1986). In Table 1, we present an observation log, together with the instrument setup. For details concerning the data modes, we refer to, e.g., White & Peacock (1988). During the two further *EXOSAT* observations reported in Parmar et al. (1986), the source was too faint to perform a significant temporal analysis.

The fast-timing behavior of 4U 1630−47 was studied by performing fast Fourier transforms (FFTs) on successive 256 s blocks of the HTR3 data. This resulted in 81 and 54 FFTs for the April and May observations, respectively. The white noise level, or Poisson level, was subtracted from the data. We estimated the Poisson level, modified by instrument dead time, using the results obtained from the study of dead-time effects on High Time Resolution (HTR) data (Berger & van der Klis 1994). The study of the HTR data also revealed the presence of an instrumental band-limited noise component, with a cutoff frequency of ~100 Hz and a fractional rms amplitude of ~3% of the total observed count rate (Berger & van der Klis 1994, 1996). This component was also subtracted from the power spectra.

In this Letter, we describe the X-ray power density spectrum as a sum of two noise components: (1) a power-law–shaped, very low frequency noise (VLFN) [$P_{\rm VLFN}(\nu) = A_V \nu^{-\alpha_V}$, where $\nu$ is the frequency, $\alpha_V$ the power-law index, and $A_V$ the normalization constant], and (2) a Lorentzian-shaped QPO ($P_{\rm QPO}(\nu) = A_Q[(\nu-\nu_Q)^2 + (\Delta\nu_Q/2)^2]^{-1}$, where $\Delta\nu_Q$ is the FWHM of the QPO, and $A_Q$ a normalization constant). The strengths of these noise components are expressed in terms of the fractional rms amplitudes of the corresponding fluctuations in the time series. They are calculated by integrating their contributions to the power spectra over certain frequency ranges, as determined from fits of the functional shapes to the power spectra. The VLFN integration range was 0.001–1 Hz. All errors on the quoted power spectral parameters were determined from an error scan through the $\chi^2$ space using $\Delta\chi^2 = 1$.

## 3. RESULTS

The average count rates (1–20 keV) during the April and May observations of 4U 1630−47 were ~0.8 and ~0.3 counts s$^{-1}$ cm$^{-2}$, corresponding to ~$1 \times 10^{-8}$ and ~$4 \times 10^{-9}$ ergs s$^{-1}$ cm$^{-2}$, respectively. During the April observations, the intensity was extremely variable, while during the May observation, there was almost no intensity variability (see Fig. 3 in Parmar et al. 1986).

The average power spectra of these two observations are shown in Figure 1*a*. It is clear that the two power spectra are different. We fitted the power spectra to the functional forms described in § 2. These fit results are shown in Figures 1*b* and 1*c*. The April power spectrum showed strong VLFN up to ~5 Hz, with a fractional rms of 6.7% ± 0.2% and a power-law index of 1.50 ± 0.02 ($\chi^2$ = 69.1 for 35 degrees of freedom). The May power spectrum could be represented by a power law with an index of 0.65 ± 0.05 and a fractional rms amplitude of 1.8% ± 0.1% ($\chi^2$ = 32.8 for 35 degrees of freedom).

There is evidence for excess variability around ~1 Hz in the May power spectrum. Although a power law described the

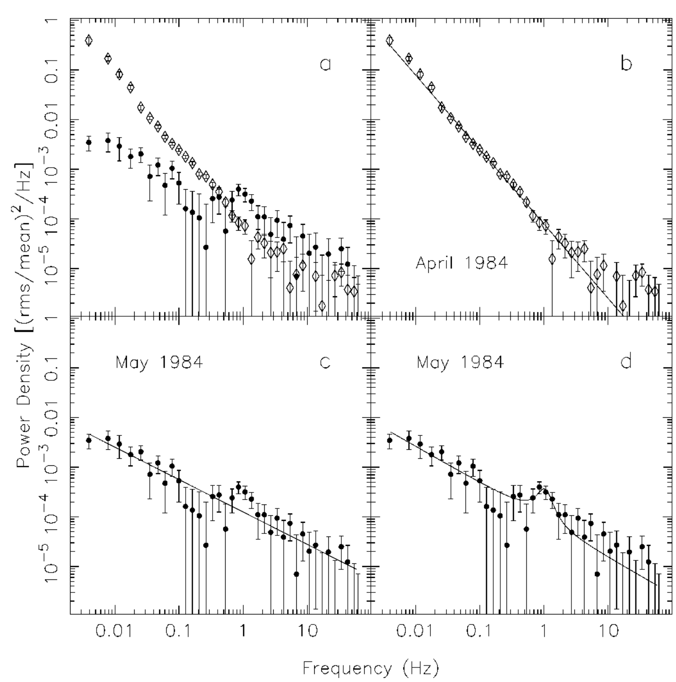


FIG. 1.—(*a*) Average power spectra for the 1984 April (*diamonds*) and 1984 May (*filled circles*) observations. (*b*) The 1984 April power spectrum with the best-fit power-law component. (*c*) The 1984 May power spectrum with the best-fit power-law component. (*d*) Same as (*c*), but with the inclusion of the QPO component.

data satisfactorily (see above), we also included a QPO in our fits (Fig. 1*d*). We find that if there is QPO present, it has a fractional rms of 1.6% ± 0.4%, a FWHM of 0.6 ± 0.5 Hz, and centroid frequency of 1.02 ± 0.13 Hz ($\chi^2 = 20.2$ for 32 degrees of freedom). In this case, the VLFN has a power-law index of 0.74 ± 0.12 and fractional rms of 1.7% ± 0.1%. From an *F*-test for the additional QPO term and a 90% confidence error scan of the integrated power in $\chi^2$ space ($\Delta\chi^2 = 1$), we conclude that this QPO is significant at a level of ∼2.5 $\sigma$.

## 4. DISCUSSION

We have demonstrated that on two occasions during the 1984 outburst, 4U 1630−47 showed different fast-timing behavior.

During the first observation in April, near the peak of the outburst, the intensity showed a strong variability down to seconds, whereas during the May observations, the variability was less strong, as already pointed out by Parmar et al. (1986). We investigated these intensity changes by computing FFTs of the data. The power spectra during the April observation showed a VLFN power law with index $\alpha \sim 1.5$ and fractional rms amplitude of ∼7%. The strength is comparable to the rms excess variability in the 1–7 keV band reported by Parmar et al. (1986). The power spectra of the May observation, however, showed a VLFN power-law component with a fractional rms of only ∼2% and a flatter slope, $\alpha \sim 0.7$. Although, formally, the May power spectrum can be satisfactorily fitted by a power law, we find evidence (at a ∼2.5 $\sigma$ level) for the presence of QPO at ∼1 Hz, with fractional rms of ∼1.6% and FWHM of ∼0.6 Hz. During both the April and the May observations, the soft spectral component dominated the X-ray spectra (Parmar et al. 1986).

The timing properties of the May observation are reminiscent of those of other black hole candidates in their high states, where power-law VLFN with indices $\alpha \sim 1$ and small fractional rms amplitudes (a few percent) are commonly observed. In this state, the X-ray spectra are normally dominated by the soft component in the 2–10 keV band. We note that QPOs in the high state have also been reported by Ebisawa et al. (1989) in LMC X-1 at a frequency of ∼0.08 Hz.

Parmar et al. (1986) classified the spectral evolution of 4U 1630−47 from 1984 April to July as consistent with a transition from high to low state. This suggests that the source was also in the high state during the April observation. However, as we have shown above, the April power spectra are different from the May (high-state) power spectra and different from power spectra generally seen for black hole candidates in their high state, and we therefore conclude that during the April observations, 4U 1630−47 was not in a high state.[4] Black hole candidates in their low state show very strong band-limited noise (up to ∼50%) and hard power-law X-ray spectra. Since the April power spectrum shows only moderately strong (∼7%) power-law noise, together with an (ultra) soft X-ray spectrum, the source was also unlikely to be in a low state.

Up to now, only two sources have been seen in the very high state, i.e., GX 339−4 and GS 1124−68 (Miyamoto et al. 1993; van der Klis 1995, and references therein). In the very high state, the power spectra show rapidly variable broadband noise with amplitudes between 1% and 15%, flat tops below 0.05–10 Hz, and power-law shapes with index ∼1 above these frequencies. The broadband noise becomes stronger at higher energies. Most of the time, 3–10 Hz QPOs are present during the very high state. The April power spectrum differs from these very high state variability characteristics: it has a featureless, steeper ($\alpha \sim 1.5$) power-law shape, with no indication of a flat top. Moreover, Parmar et al. (1986) found that the variability at high energies (14–30 keV) is weaker than that at lower energies (1–7 keV), i.e., ∼4% versus 7%, respectively, which is different from the very high state broadband noise energy dependence. So we conclude that the observed timing behavior does not fit in with the characteristic timing behavior of either the low state, the high state, or the very high state.

GRS 1915+105 (Castro-Tirado et al. 1994) and GRO J1655−40 (Harmon et al. 1995) are recently discovered X-ray transients, of which the latter has been established dynamically to contain a black hole (Bailyn et al. 1995). Ebisawa (1996) presented the power spectral behavior of these two X-ray transients from data observed with *ASCA*. The power spectral shapes during the observations of GRO J1655−40 (see also Zhang et al. 1996) on two occasions (end of 1994 September and mid-1995 October) and of GRS 1915+105 (end of 1994 September) were consistent with a single power law with indices 1.2–1.7 and fractional rms amplitudes of 6%–8% in the 0.001–1 Hz frequency range. Moreover, during the recent (soft) X-ray outburst of GRO J1655−40 (Remillard et al. 1996), similar strong variations on timescales of 2 s–10 minutes (0.002–0.5 Hz) were found (5%–10%) in data obtained with the *X-Ray Timing Explorer* (Horne et al. 1996). These *ASCA* power spectra are very similar in shape and strength to the power spectra of the April *EXOSAT* observation of 4U 1630−47. Since they are all inconsistent with the low, high, and very high state behavior usually observed (see above), we suggest that this behavior represents an anomalous state in black hole candidates. We note, however, that recent *Rossi X-Ray Timing Explorer* (*RXTE*) observations of GRS 1915+105 (Greiner, Morgan, & Remillard 1996) revealed that this source also shows several other power spectral shapes. Close monitoring and a detailed intercomparison of the outbursts of GRS 1915+105, GRO J1655−40, and 4U 1630−47 with, e.g., *RXTE* are therefore needed in order to make sure that the anomalous timing behavior represents a completely new state in (black hole) X-ray binaries.

Both GRS 1915+105 and GRO J1655−40 were bright during the 1994 September *ASCA* soft X-ray observations, with indications of spectral softening at high energies (Nagase et al. 1994), while the BATSE hard X-ray (20–100 keV) flux was at near quiescent values (Harmon et al. 1995; Paciesas et al. 1995). Similar spectral behavior was reported a few days before these *ASCA* observations from TTM and HEXE data by Alexandrovich et al. (1994). During the 1995 August *ASCA* observations, GRO J1655−40 was a factor ∼3 brighter in the *ASCA* band (Inoue, Nagase, & Ueda 1995), and the BATSE observations showed a steep hard X-ray spectrum with a spectral index near 2.5 (Zhang et al. 1995). This shows that, apart from the power spectral behavior, the X-ray spectral behavior was also similar in the three sources.

We note that these X-ray spectral properties are consistent with the general X-ray spectral behavior in the very high state in black hole candidates (see Miyamoto et al. 1991, 1993, 1994; Ebisawa et al. 1994): the X-ray intensity in the very high state

[4] It was already noted by Parmar et al. 1986 that the rapid variability during the April observations was stronger than that seen during the high state of Cyg X-1.

is 2–3 times higher compared with the high state, and the X-ray spectra are dominated by the (ultra) soft component; the high-energy part of the X-ray spectra ($\gtrsim$10 keV) is described by a power law with index $\alpha \sim 2.5$, i.e., slightly steeper than the high-energy spectrum in the high state ($\alpha \sim 2$). As suggested by Zhang et al. (1996), this may imply that the observed anomalous timing properties are not related to X-ray spectral components, but to the nature of these sources. Since GRS 1915+105 and 4U 1630−47 have not (yet) been shown dynamically to contain a black hole, we do not rule out the possibility that the observed timing behavior may be unconnected to whether the compact object is a neutron star or a black hole.

Since the fast-timing ($\lesssim$250 s) properties of 4U 1630−47 during the April observations (power-law–shaped power spectra with index ~1.5 and fractional rms of ~7%) and the X-ray spectra (ultrasoft component and hard power-law component with index ~2.5) are very similar to that observed from the sources GRS 1915+105 and GRO J1655−40, we propose that these sources have something in common with 4U 1630−47, which is not present in other black hole candidates.

Episodic ejections of relativistic, apparently superluminal jets have been observed from GRS 1915+105 and GRO J1655−40 during radio outbursts (Mirabel & Rodríguez 1994; Tingay et al. 1995; Hjellming & Rupen 1995). Observations in hard X-rays with BATSE (Hjellming & Rupen 1995; Harmon et al. 1995; Paciesas et al. 1995) suggest that the radio ejections may occur in conjunction with the hard X-ray outbursts (see also Meier 1996), although no simple one-to-one relationship does exist (see, e.g., Zhang et al. 1996). We note that during the 1994 September *ASCA* observation of GRO J1655−40, the radio flux was declining after a second radio peak with ejections ~10 days earlier (see, e.g., Hjellming & Rupen 1995), and that recently the radio flux from GRO J1655−40 has increased again (Hunstead & Campbell-Wilson 1996) during the current (soft) X-ray outburst (see above).

If our proposal that 4U 1630−47 is similar to the superluminal sources GRS 1915+105 and GRO J1655−40 is true, we speculate that during the 1984 outburst of 4U 1630−47, relativistic radio jets might have been present during or near the outburst. It is interesting to note that changes in the low-energy absorption observed by Parmar et al. (1986) as the 1984 outburst evolved could indicate the presence of outflowing material (Levinson & Blandford 1996). Whether relativistic radio jets are present or not during other outbursts of 4U 1630−47 can be tested during its current outburst (Marshall 1996; Levine et al. 1996), or at the time of the next outburst, which is expected to occur around 1997 October using the ephemeris of Parmar et al. (1996).

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*Note added in proof.*—We note that the 1996 outburst of 4U 1630−47, which started in March (Marshall 1996; Levine et al. 1996), ended near the beginning of August, when the intensity dropped below the *RXTE* ASM detection limits.