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DISCOVERY OF THE X-RAY COUNTERPART TO THE ROTATING RADIO TRANSIENT J1819–1458

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ABSTRACT

We present the discovery of the first X-ray counterpart to a Rotating RAdio Transient (RRAT) source. RRAT J1819–1458 is a relatively highly magnetized (B $\sim 5\times10^{13}$ G) member of a new class of unusual pulsar-like objects discovered by their bursting activity at radio wavelengths. The position of RRAT J1819–1458 was serendipitously observed by the *Chandra* ACIS-I camera in 2005 May. At that position we have discovered a pointlike source, CXOU J181934.1–145804, with a soft spectrum well fit by an absorbed blackbody with $N_H = 7^{+7}_{-4}\times10^{21}$ cm^{-2} and temperature $kT = 0.12\pm0.04$ keV, having an unabsorbed flux of $\sim 2\times10^{-12}$ ergs cm^{-2} s^{-1} between 0.5 and 8 keV. No optical or infrared (IR) counterparts are visible within 1″ of our X-ray position. The positional coincidence, spectral properties, and lack of an optical/IR counterpart make it highly likely that CXOU J181934.1–145804 is a neutron star and is the same object as RRAT J1819–1458. The source showed no variability on any timescale from the pulse period of 4.26 s up to the five-day window covered by the observations, although our limits (especially for pulsations) are not particularly constraining. The X-ray properties of CXOU J181934.1–145804, while not yet measured to high precision, are similar to those of comparably-aged radio pulsars and are consistent with thermal emission from a cooling neutron star.

Subject headings: pulsars: individual (J1819–1458) — radio continuum: stars — stars: flare, neutron — X-rays: stars

1. INTRODUCTION

The discovery of a new class of "Rotating RAdio Transients" (RRATs) has recently been reported by McLaughlin et al. (2005). These objects, 11 so far identified, are characterized by repeated radio bursts with durations between 2 and 30 ms and average intervals between bursts ranging from 4 minutes to 3 hours. Their dispersion measures (DMs) place them within the Galactic plane at distances from 2 to 7 kpc. If bursts are periodic, periods can be found from the greatest common divisor of the differences between burst arrival times. For ten of the sources, this calculation results in periods between 0.4 and 7 seconds, suggesting that the objects are rotating neutron stars. The periods measured for the RRATs are longer than those of most normal radio pulsars and more similar to those of the populations of X-ray dim isolated neutron stars (XDINSs; Haberl 2004) and magnetars (Woods & Thompson 2006). For the three sources with the highest bursting rates, period derivatives, $\dot{P}$, have been measured. No binary motion is detected. If the $\dot{P}$ values are interpreted as due to magnetic dipole spin-down, they imply characteristic ages and magnetic field strengths in the general range of pulsars.

In this paper we report the X-ray detection of RRAT J1819–1458, the first detection at other wavelengths of any of the RRATs. This source has a 4.26-s period, a relatively high inferred characteristic surface dipole magnetic field strength of 5×10^{13} G, a characteristic age $P/2\dot{P} = 117$ kyr, and a spin-down luminosity of 3×10^{32} ergs s^{-1}. The distance of this source inferred from its DM using the electron-density model of Cordes & Lazio (2002) is 3.6 kpc, with considerable uncertainty. RRAT J1819–1458 is characterized by radio bursts of average duration 3 ms, with one burst detected every $\sim$ 3 minutes. This object was fortuitously in the ACIS-I field of a 30 ks *Chandra* observation toward the Galactic supernova remnant G15.9+0.2 (Reynolds et al., in preparation). The brightest source on any of the 6 CCD chips of the *Chandra* field, besides G15.9+0.2 itself, is coincident to within 2″ with the radio position of RRAT J1819–1458 (whose error ellipse has semimajor axes 5″ × 32″). The positional coincidence, as well as properties we describe below, make us confident that this new source, which we designate CXOU J181934.1–145804, is the X-ray counterpart to the radio-bursting source RRAT J1819–1458.

2. OBSERVATIONS

The *Chandra* observations were performed with the ACIS instrument in full-frame mode on 2005 May 23 (10 ks), May 25 (5 ks), and May 28 (15 ks). CXOU J181934.1–145804 lies on the I3 chip of the ACIS-I camera. We checked aspect correction, created a new level–1 event file appropriate for VFAINT mode (without applying pixel randomization in energy), and applied light-curve filtering to reject flares. CTI correction was applied and calibration was performed using

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CALDB version 3.1.0.

CXOU J181934.1–145804 is by far the brightest compact source on the I3 chip or on any of the others. We find a net count rate after background subtraction of 0.018 ct s^{-1} (0.5–8 keV), for a total of 524 ± 24 counts. Radial profiles were created for the source and for the 1 keV point-spread function (PSF) at that location on the I3 chip, and are shown in Figure 1. There is no evidence for any extended emission. The source position (fit with WAVDETECT) is $18^{\mathrm{h}}19^{\mathrm{m}}34\overset{\mathrm{s}}{.}17 \pm 0\overset{\mathrm{s}}{.}02$, $-14^\circ58'04''\!.6 \pm 0''\!.2$ (J2000). The errors are statistical only. We measured the position of a bright star visible in X-rays to be within $0''\!.1$ of its USNO UCAC2 position, but position errors for sources $10'$ off-axis may be $\lesssim 0''\!.4$ (Getman et al. 2005). We adopt $0''\!.5$ as a conservative total error estimate.

We searched various catalogs for optical or IR counterparts within $1''$ of our best-fit position. No counterparts were detected in the 2MASS catalog or any of the others searched by VizieR[11], with magnitude upper limits of $19\overset{\mathrm{m}}{.}9$ (B2), $18\overset{\mathrm{m}}{.}0$ (R1), $17\overset{\mathrm{m}}{.}5$ (I), $15\overset{\mathrm{m}}{.}6$ (J), $15\overset{\mathrm{m}}{.}0$ (H), and $14\overset{\mathrm{m}}{.}0$ (K). Nothing was seen in the GLIMPSE survey of *Spitzer*'s IRAC camera (Benjamin et al. 2003), but the limits are comparable or less stringent. We expect a surface density of Galactic-plane X-ray sources of at least the flux of CXOU J181934.1–145804 of about 2 deg^{-2}, based on the *ASCA* Galactic Plane survey (Sugizaki et al. 2001). Within the radio error ellipse of RRAT J1819–1458, the likelihood of finding such a source by chance is $\lesssim 10^{-4}$, supporting its identification with RRAT J1819–1458.

The K-magnitude limit from 2MASS, combined with our X-ray detection, implies an X-ray to IR flux ratio for CXOU J181934.1–145804 of $f_x/f_K \gtrsim 0.7$. Comparing this to the known X-ray and IR properties of stars, galaxies and neutron stars (see, e.g., Fig. 20 of Kaplan et al. 2004), we find that CXOU J181934.1–145804 has a considerably higher X-ray flux than the bulk of the extragalactic population, and a much higher X-ray to IR flux ratio than most stars. On the other hand, its flux and colors are entirely consistent with all classes of isolated neutron star. Deeper IR and optical observations are needed to provide better constraints.

There is no X-ray evidence for a supernova remnant (SNR), pulsar wind nebula or any other extended emission anywhere within about $7'$ of CXOU J181934.1–145804.

3. SPECTRAL ANALYSIS

We extracted the source spectrum from a circular region $15''$ in radius centered at the X-ray source position. Individual response files were created for the source and for a large ($\sim 3' \times 3'$) adjacent background region. Data from all three observations were merged by adding spectra and combining the response files weighted by observation times (for both source and background), and then grouped into bins of at least 20 counts to allow the use of χ^2 statistics.

An absorbed blackbody fit (XSPEC models `phabs` plus `bbodyrad`) was statistically acceptable ($\chi^2 = 10.8$ for 18 degrees of freedom); it is shown in Figure 2. An absorbing column density $N_H = 7^{+7}_{-4} \times 10^{21}$ cm^{-2} was required (all errors are 90% confidence limits unless otherwise specified). The fitted temperature is $kT = 0.12 \pm 0.04$ keV and the observed flux (0.5–8 keV) is $(1.1 \pm 0.1) \times 10^{-13}$ ergs cm^{-2} s^{-1}. The absorption-corrected flux is much less certain due to uncertainties in N_H: we find a flux (0.5–8 keV) of $\sim 2 \times 10^{-12}$ ergs cm^{-2} s^{-1}, with uncertainty of an order of magnitude in either direction.

A blackbody with the best-fit flux would have a radius of 10 km at a distance of 1.8 kpc; at the DM distance of 3.6 kpc, the implied blackbody radius is 20 km. However, the unabsorbed flux uncertainties are large. Note that, given the uncertainties in DM-derived distances (Cordes & Lazio 2002), a distance of 1.8 kpc is still consistent with the observed DM. The X-ray luminosity is $3.6 \times 10^{33} (D/3.6\ \mathrm{kpc})^2$ ergs s^{-1} (0.5–8 keV) (uncertain by an order of magnitude), though of course most of the bolometric luminosity is at lower photon energies (a spherical blackbody with $kT = 0.12$ keV and $R = 10$ km has a total luminosity $L_{\mathrm{bol}} = 2.7 \times 10^{33}$ ergs s^{-1}). We also fit the data with a neutron-star atmosphere model (XSPEC model `nsa`; Pavlov, Shibanov, Zavlin 1991; Zavlin, Pavlov & Shibanov 1996), obtaining a slightly worse but acceptable ($\chi^2_\nu = 0.66$) fit with $N_H = (0.4 - 1.3) \times 10^{22}$ cm^{-2}, $kT_{\mathrm{eff}} = 0.02 - 0.2$ keV, and a flux corresponding to roughly full-surface emission from a 10-km neutron star. These values are completely consistent with those of the simple blackbody fit.

An absorbed power-law fit (XSPEC models `phabs` plus `power`) was significantly worse ($\Delta\chi^2 = 3.9$, or worse at the 95% level). In addition, the power-law fit required a photon index Γ of at least 9.5, far steeper than any observed magnetospheric or other nonthermal X-ray emission from any known source. However, a nonthermal component at higher energies might be present in addition to the thermal emission. To search for such a component, we fitted only the data above 1 keV, and obtained a best-fit power-law index of 5.5, still unreasonably steep. There appears to be no evidence for a nonthermal component in the X-ray spectrum of CXOU J181934.1–145804, at our current level of sensitivity. We note that even with the large uncertainties, $L_x > \dot{E}$ independent of distance, making a nonthermal explanation for most of the emission highly unlikely.

4. TIMING ANALYSIS

The time resolution of *Chandra*'s CCDs in imaging mode is 3.2 s, the read-out time. We binned the lightcurve on a variety of time scales to look for evidence of bursts or other time variability on scales longer than this.

We have examined all $\sim 10^4$ of the 3.2-s CCD frames of the source extraction region to look for any bursts resembling the radio bursts (McLaughlin et al. 2005). Pileup is not a concern because of the substantially broadened off-axis PSF. All frames contained either zero or one events, except for 17 frames which contained two events from the source, and one frame which contained a cluster of three events. For the time-averaged count rate of ~ 0.05 counts per frame, these clusters are entirely consistent with Poisson statistics. Given this rate, the number of events in a single frame which would deviate from a steady flux at the 3-σ level is 4 photons. We thus adopt this as the upper limit on the X-ray flux of any burst of duration of 3.2 sec or less. Assuming a spectrum of the same shape as that fitted for the overall source in §3 above, this limits the observed fluence of any burst to $\lesssim 3 \times 10^{-11}$ ergs cm^{-2} (0.5–8 keV), corresponding to an absorbed flux limit of $\lesssim 1 \times 10^{-8}$ ergs cm^{-2} s^{-1} (0.5–8 keV) if we assume that any X-ray burst lasts for 3 ms. At a distance of 3.6 kpc, these limits correspond to 1×10^{36} ergs and 1×10^{38} ergs s^{-1}, respectively. A burst might, of course, have a very different spectrum from that seen in Figure 2.

We have also binned the data on longer time scales to look for any more gradual variability. At the 3-σ level, we find no

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[11] http://vizier.u-strasbg.fr/viz-bin/VizieR

evidence for X-ray flux variations on any time scale ranging from 3.2 s up to the overall time span covered of ~ 5 days. We note however that data were only being recorded during 7% of this window, so within the range of variability considered, we are not sensitive to variations on time scales falling between ~ 4 hours and ~ 2 days.

While we cannot detect pulsations at the 4.26 s period directly, we searched for a possible alias of this period at a predicted frequency of 0.073975824(1) Hz (correcting for spin-down and barycentered to the midpoint of the three observations). We folded the arrival times at this frequency and found no significant power. Including attenuation of sensitivity at frequencies high compared to the binning rate, our 3-σ upper limit on the pulsed fraction f is $\sim 0.5A^{-1/2}$, where A is a constant which depends on the pulse shape (Leahy, Elsner & Weisskopf 1983; Ransom, Eikenberry & Middleditch 2002). For a narrow pulse ($A = 2$) as observed in the radio bursts, we estimate $f \lesssim 0.35$, while for a sinusoid ($A = 0.5$) we find $f \lesssim 0.7$.

5. DISCUSSION

The spatial coincidence of RRAT J1819–1458 and CXOU J181934.1–145804 and the lack of any obvious optical or infrared counterpart makes it extremely likely that these sources are associated, and that the emitting source is a neutron star. We now compare the X-ray and other properties of RRAT J1819–1458 to those seen from the other known categories of isolated neutron star: radio pulsars, magnetars, XDINSs, and central compact objects (CCOs).

We first note that the pulsed fraction upper limits that we obtained in §4 are generally unconstraining. Pulsed thermal emission from a "hot spot" on a neutron-star surface is expected to be broad and quasi-sinusoidal, with a low level of modulation (Psaltis, Özel & DeDeo 2000). Thus the pulsed fraction upper limit of $\sim 70\%$ which we have determined for a broad profile is insufficient to have detected pulsations from almost all the sources which we consider below.

Over much of their lives, ordinary radio pulsars emit quasi-blackbody emission from their surfaces, the temperature dropping with time as they cool through first neutrino, then photon emission (see Yakovlev & Pethick 2004 for a recent review). A 1.4 $M_\odot$ neutron star at an age of 10^4 years is predicted by typical models to have a surface temperature (as viewed by an observer at infinity) ~ 100 eV, while by 10^5 years this has dropped to ~ 70 eV (Page et al. 2004; Yakovlev & Pethick 2004). We note that the X-ray emission from neutron star surfaces is expected to be significantly modified by propagation through the stellar atmosphere, which shifts the emission into a harder component (Zavlin & Pavlov 2002; Lloyd, Hernquist, & Heyl 2003). Applied to such spectra, blackbody fits overestimate the surface temperature by a factor of $\gtrsim 2$, and also underestimate the radius.

While our data are insufficient for fitting to more detailed neutron-star atmosphere models, the considerations above suggest that the emission from RRAT J1819–1458 is consistent with a cooling neutron star of age[12] $\sim 10^4 - 10^5$ yr, at a distance $\lesssim 2$ kpc. For comparison, the radio pulsars B0833–45, B1706–44, J2021+3651, J0538+2817 and B0656+14 have fitted blackbody temperatures of 130, 170, 150, 160 and 70 eV for approximate ages of 11, 17, 17, 30 and 110 kyr, respectively (Romani et al. 2005; Hessels et al. 2004; Romani & Ng 2003; Kramer et al. 2003; Brisken et al. 2003), again consistent with an interpretation for RRAT J1819–1458 as a cooling neutron star of age $10^4 - 10^5$ yr. While the temperature we find for CXOU J181934.1–145804 is a bit higher than that of the comparably-aged B0656+14, our errors are large. Better data will be required to determine whether CXOU J181934.1–145804 is in fact hotter than the range of predictions from standard cooling curves. The high magnetic-field strength might support such a possibility (Shibanov & Yakovlev 1996).

These crude estimates are in satisfactory agreement with the characteristic age, $\tau_c = 117$ kyr, inferred for RRAT J1819–1458 from its spin-down (McLaughlin et al. 2005). If RRAT J1819–1458 was born spinning much faster than its present period of 4.26 s, then for standard magnetic dipole spin-down the characteristic age should be a good match to the true age. If it was born a slow rotator, then τ_c could be a considerable overestimate (e.g., Kramer et al. 2003).

Since the surface magnetic field of RRAT J1819–1458 is about 10 times greater than those of the pulsars listed above, another interesting comparison may be performed with high-B-field pulsars (Camilo et al. 2000; McLaughlin et al. 2003). The two of these sources detected in X-rays, PSRs J1718–3718 and J1119–6127 (Kaspi & McLaughlin 2005; Gonzalez et al. 2005), also show temperatures ($kT \sim 150 - 200$ eV) and luminosities ($\sim 10^{32} - 10^{33}$ ergs s^{-1}) compatible with that of RRAT J1819–1458, although both sources are probably much younger (35 kyr and 1.7 kyr, respectively), and have $L_x < \dot{E}$.

The high inferred surface magnetic field strength, long spin period, and lack of persistent radio emission also suggest a comparison of RRAT J1819–1458 with the population of magnetars. These objects (which include both the anomalous X-ray pulsars and soft gamma repeaters) are characterized by quiescent, bursting, and flaring X-ray emission all powered in different ways by ultra-strong magnetic fields (Woods & Thompson 2006, and references therein). However, magnetars are typically hotter ($kT \sim 0.3 - 0.6$ keV), show a non-thermal spectral component with $\Gamma \sim 2 - 4$, and are brighter by one to three orders of magnitude ($L_X \sim 10^{34} - 10^{36}$ ergs s^{-1}; Woods & Thompson 2006). Moreover, the characteristics of the radio bursts seen from RRAT J1819–1458 and from the other RRATs are completely different in their energetics and recurrence times from the much rarer X-ray bursts seen from the magnetars. The soft X-ray spectrum of RRAT J1819–1458 does have a comparable temperature to the quiescent state of the transient magnetar XTE J1810–197 ($kT \sim 0.15 - 0.18$ keV; Ibrahim et al. 2004; Gotthelf et al. 2004). However, the X-ray luminosity of the latter is ~ 10 times larger. XTE J1810–197 also has a possible transient radio counterpart (Halpern et al. 2005), though with quite different properties from the RRATs. Further observations are required for a detailed comparison with RRAT J1819–1458.

The lack of persistent radio emission and the long spin period of RRAT J1819–1458 also raise the possibility of a link with the XDINSs (Haberl 2004). The XDINSs are slightly cooler ($kT \sim 0.04 - 0.1$ keV) and less luminous ($L_X \sim 10^{31} - 10^{32}$ ergs s^{-1}) than RRAT J1819–1458. However, the measured period derivatives of two XDINSs (RBS 1223 and RX J0720.4–3125; Kaplan & van Kerkwijk 2005a, 2005b), and the detection of possible proton cyclotron lines in their spectra (van Kerkwijk 2004), imply magnetic field strengths similar to those of RRAT J1819–1458. No radio emission

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[12] Our result that $L_x \gtrsim \dot{E}$ for this source is not consistent with polar-cap reheating models for the thermal X-rays seen for much older sources (e.g. Cheng & Zhang 1999; Harding & Muslimov 2001).

of any kind has been reported from XDINSs; recent observations (Bradley 2006) show no RRAT-like radio bursts toward RX J0720.4–3125 (or toward magnetars).

RRAT J1819–1458 does not appear to have an associated SNR. It has no apparent connection to the nearby SNR G15.9+0.2 (see below), and shows no extended radio or X-ray emission around its position. Nevertheless, for completeness we compare its X-ray emission to that seen from the so-called CCOs, a small and heterogeneous sample of X-ray point sources seen in young SNRs, corresponding to a population of young neutron stars whose connection to pulsars, magnetars and XDINSs is as yet unclear (see Pavlov, Sanwal & Teter 2004 for a review). The CCOs have spectra which can generally be fitted by a blackbody plus a power-law tail, the former component having a temperature $kT \approx 0.3-0.5$ keV with a typical bolometric luminosity $L_{\rm bol} \gtrsim 10^{33}$ ergs s^{-1}. Periodicities have been reported for four of the CCOs, but with periods much faster (100–400 ms) or much slower ($\sim$ 6 hr) than seen for RRAT J1819–1458. The properties of RRAT J1819–1458 thus seem to have little in common with those seen from the CCOs, although RRAT J1819–1458 is likely much older than these objects and the evolutionary paths followed by the CCOs are unclear in any case.

The shell SNR G15.9+0.2 has a much higher absorbing column density ($\sim 4 \times 10^{22}$ cm^{-2}) than CXOU J181934.1–145804, suggesting that it is at considerably greater distance. In any case, G15.9+0.2 appears to be younger than 1000 yr (Reynolds et al., in preparation), so disregarding the much older spin-down age of RRAT J1819–1458 and hypothesizing an association, the $10'.3$ offset between RRAT J1819–1458 and the center of G15.9+0.2 requires a tranverse velocity for the former of $> 10\,000$ km s^{-1} at a distance of 3.6 kpc. This makes any physical association of G15.9+0.2 with RRAT J1819–1458 highly improbable.

6. CONCLUSIONS

We have discovered the first X-ray counterpart to a Rotating RAdio Transient source, CXOU J181934.1–145804. The X-ray source is well described by a thermal spectrum consistent with emission from a cooling neutron star of age 10^4-10^5 years, broadly consistent with the characteristic age of RRAT J1819–1458. The X-ray properties also suggest possible connections to the population of X-ray dim isolated neutron stars and to the transient magnetar XTE J1810–197. A search for an X-ray modulation at the aliased radio pulse frequency was unsuccessful. No variations were seen in the X-ray flux on longer time scales either, and no optical and infrared counterparts to the source have been found. Deeper X-ray observations are required to search for pulsations, bursts, and in general to clarify the nature of the RRATs.

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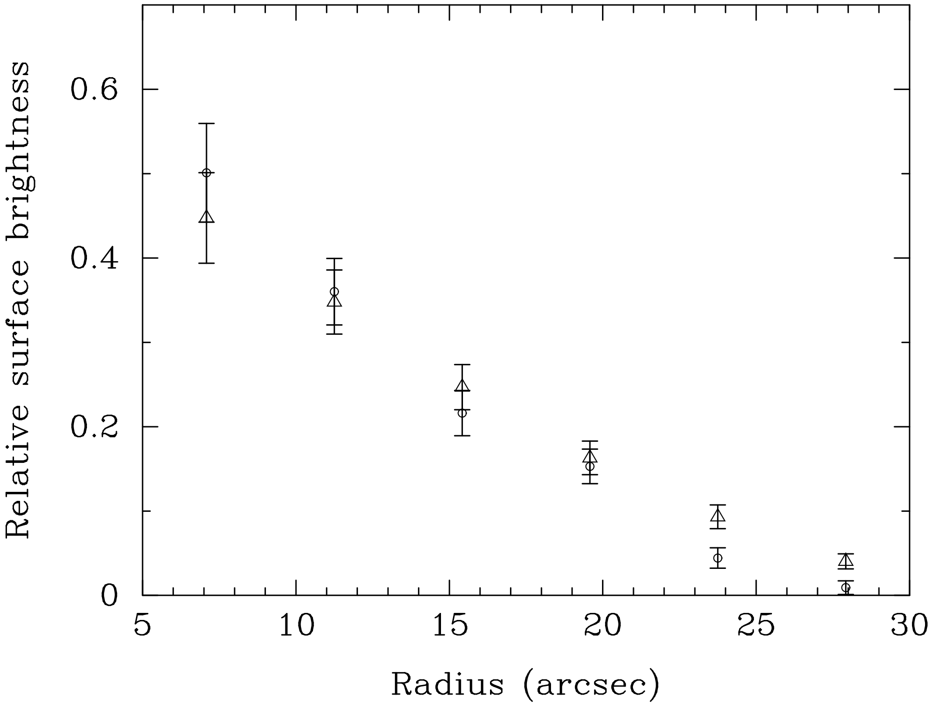

FIG. 1.— The radial profile of CXOU J181934.1–145804 at 1 keV (circles) and the corresponding predicted PSF at that location (triangles). There is no evidence for source extension. Errors are statistical only (90% limits).

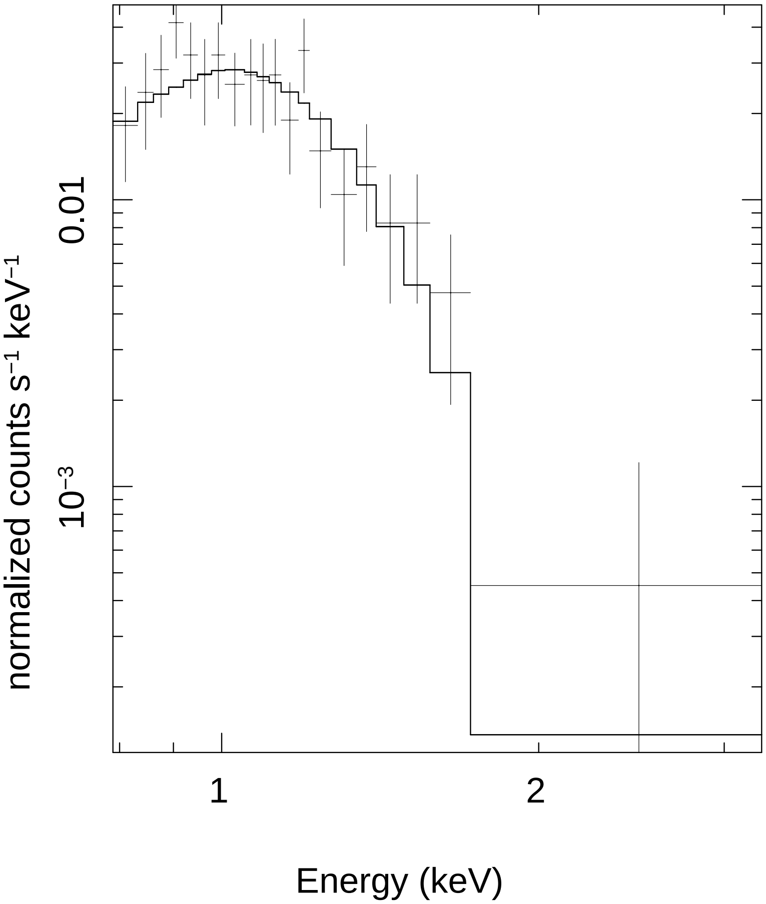

FIG. 2.— Spectrum of CXOU J181934.1–145804, fitted with an absorbed blackbody model.