Chandra Observation of Luminous and Ultraluminous X-ray Binaries in M101

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ABSTRACT

X-ray binaries in the Milky Way are among the brightest objects on the X-ray sky. With the increasing sensitivity of recent missions, it is now possible to study X-ray binaries in nearby galaxies. We present data on six ultraluminous binaries in the nearby spiral galaxy, M101, obtained with *Chandra* ACIS-S. Of these, five appear to be similar to ultraluminous sources in other galaxies, while the brightest source, P098, shows some unique characteristics. We present our interpretation of the data in terms of an optically thick outflow, and discuss implications.

Subject headings: galaxies: X-rays—galaxies:individual (M101)—galaxies: spiral

1. Introduction

X-ray binaries in the Milky Way, with typical intrinsic luminosities in the range 10^{34}–10^{38} ergs s^{-1} at a typical distance of 8 kpc, dominate our 2–10 keV sky. We therefore know a great deal about these Galactic X-ray binaries through many studies over the last several decades (see White et al. 1995 for a review). They are close binaries in which a neutron star or a black hole is accreting from a non-degenerate companion. They can be divided into low-mass X-ray binaries (LMXBs) and high-mass X-ray binaries (HMXBs) depending on the

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spectral type of the mass donor. The HMXBs are young objects that are concentrated in the Galactic plane, preferentially in spiral arms. The LMXBs, on the other hand, appear to belong variously to the old disk, bulge, and globular clusters. Many neutron star LMXBs show thermonuclear flashes (i.e., type I bursts) suggesting a relatively low-magnetic field; many HMXBs are coherent X-ray pulsars, containing highly magnetized neutron stars.

The Eddington limit for a 1.4 $M_\odot$ object is $\sim 2 \times 10^{38}$ $\mathrm{ergs\,s^{-1}}$. Significantly more luminous X-ray binaries can be considered black hole candidates on this argument alone. However, the definitive evidence for a black hole in X-ray binaries comes from radial velocity studies of the mass-donor in the optical. In particular, over a dozen soft X-ray transients (SXTs; a subtype of LMXBs) have a measured mass function which exceeds 3 $M_\odot$, with inferred compact object masses typically in the 5–15 $M_\odot$ range (Bailyn et al. 1998). In the X-ray regime, characteristic spectral shapes have been identified, including a low/hard state, characterized by a power law spectrum, and a high/soft state dominated by a $\sim$1 keV thermal component, usually interpreted as arising from the inner disk (Tanaka & Shibazaki 1995). Although detailed studies have led to suggestions of additional spectral states (see, for example, Życki et al. 2001), these spectral states are different from those of neutron star systems, typically 5–10 keV bremsstrahlung-like (LMXBs) or a power-law with an exponential cut-off (HMXBs).

Although a great deal is known about Galactic X-ray binaries, studies of extragalactic X-ray binaries offer complementary insights. In particular, a complete census of Galactic systems is difficult due to the extinction in the Galactic plane, and the luminosity of Galactic systems are generally subject to large uncertainties.

In recent years, we have gained an additional motivation to study extragalactic X-ray source populations, in the form of off-nuclear point sources with luminosities significantly in excess of 10^{38} $\mathrm{ergs\,s^{-1}}$ (hereafter Ultraluminous X-ray sources, or ULXs[2]) that have been found in many nearby galaxies (Colbert & Mushotzky 1999). One possible interpretation is that they are accreting intermediate mass (10^2–10^4 $M_\odot$) black holes. This would be exciting if confirmed, because previously known black holes could be categorized into stellar ($\lesssim$10 $M_\odot$) or supermassive ($> 10^6$ $M_\odot$) subclasses. However, disk blackbody models of the *ASCA* spectra of ULXs (Makishima et al. 2000) suggest they may have accretion disks as hot as several keV at their inner edges. In the standard model, it is difficult for a disk around an intermediate mass black hole to achieve such high temperatures.

The superb angular resolution of *Chandra* allows the detection of point sources well

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[2]In this paper, we adopt 10^{39} $\mathrm{ergs\,s^{-1}}$ as the luminosity threshold for ULXs. Sources with luminosities in the 10^{38} – 10^{39} $\mathrm{ergs\,s^{-1}}$ range may be closely related to the Galactic BHCs, extragalactic ULXs, or both.

below 10^{38} ergs s^{-1} in nearby (say, closer than 10 Mpc) galaxies, thus sampling LMXBs, HMXBs, and both black hole and neutron star systems. Consequently, many groups are s-tudying X-ray source populations in a considerable number of nearby galaxies as summarized, for example in Prestwitch (2001). Here we present preliminary results of our observation of M101.

2. Observation and source detection

M101 is a nearby face-on spiral galaxy at an estimated distance of ~7.2 Mpc. It is an ideal galaxy for the observation of X-ray binaries, supernova/hypernova remnants (Snowden et al. 2001), and diffuse emission (Kuntz et al. 2002). We have therefore observed M101 with *Chandra* ACIS for 98.2 ksec during 2000 March 26–27. The details of the observation, data reduction, source search, the catalog of 110 sources detected on the S3 chip and their collective properties are described in Pence et al. (2001). Here we concentrate on the 6 brightest sources, listed in Table 1. The source name in this table refers to the source number in Pence et al. (2001).

One of the six sources, P098, is an order of magnitude brighter (as seen with ACIS-S) than the others and has other peculiar properties; this object will be the focus of this paper. However, we will first discuss the other 5 systems listed in Table 1 with observed luminosities in excess of 10^{38} ergs s^{-1}. The inferred bolometric luminosities are higher, almost certainly exceeding the Eddington limit for a 1.4 $M_{\odot}$ object. These 5 systems (three of which have been discussed in Snowden et al. 2001 as likely binaries, rather than hypernova remnants) are therefore black-hole candidates (BHCs), even though they do not qualify as ULXs using the threshold of 10^{39} ergs s^{-1}.

3. The Five Bright Black-Hole Candidates

We have attempted a simple continuum spectral fit to the five BHCs, using power-law, bremsstrahlung, blackbody and disk blackbody (diskBB) models. The spectrum of P104 is best fit with a power-law model, while the diskBB model works best for the others. We have also examined the timing properties of these sources: their light curves in 5000 s bins are shown in Fig. 1. Of the five, P104, the power-law source, is highly variable on a relatively short timescale (e.g., note the factor of ~2 drop in count rate in one 5000 s bin near the end of the observation). This is also one of the hypernova candidates of (Wang 1999), since it is coincident with a radio-detected supernova remnant MF83 (Matonick & Fesen

1997), although the observed variability excludes the hypernova interpretation (Snowden et al. 2001). The power-law index of P104, ~2.6, is unusually steep for a black hole binary in a low/hard state. Although such an index is often seen in the power-law component of high/soft state (e.g., 2.2–2.7 in GS 1124−68: Ebisawa et al. 1994), a soft component is not obvious in the *Chandra* spectrum of P104. Nevertheless, the rapid variability clearly establishes P104 as an X-ray binary in M101.

According to a χ^2 test for constancy of the light curves of these 5 sources, only P104 is found to be significantly variable, in the total *Chandra* band. Of the remaining 4 sources, P76 is a possible exception: when its light curve in the 2–8 keV band is tested for constancy, we obtain χ^2=24.9 for 19 degrees of freedom. The probability of a constant source displaying this level of apparent variability is ~16% (in the total *Chandra* band, we obtain χ^2=16.1, and a chance probability of 65% for P076).

We also detect an apparent emission line in the spectrum of P104 at 1.02 keV, probably the Ne X Lyα line (Fig. 2). This line may be intrinsic to the binary, since it is present in one Galactic X-ray binary, 4U 1626−67 (Angelini et al. 1995). However, another likely origin of the line is the hot plasma in MF83. The total luminosity in this line is of order 10^{37} $\mathrm{ergs\,s^{-1}}$ at the distance of 7.3 Mpc. Other lines are not required or excluded by the data. Similarly, in the spectrum of P005 there is an apparent line at 1.34 keV with an inferred line luminosity of $\sim 4 \times 10^{37}$ $\mathrm{ergs\,s^{-1}}$, and another possible line at 1.85 keV. It is interesting to note that P005 is one of the eight "interarm" sources detected in the S3 chip Pence et al. (2001), which coincides with the ROSAT HRI source H18 of Wang et al. (1999). The latter authors suggested a blue optical counterpart, interpreted as AGN; however, the *Chandra* and optical positions are about 5 arcsec apart (Wang et al. 1999, and Wang, private communication), and therefore this source may turn out to be in M101 after all. The analogy with P104 suggests a combination of a luminous X-ray binary, responsible for the optically thick continuum, and a supernova remnant, responsible for the line emission.

The spectra of the three remaining BHCs (P076, P070, and P110) can be characterised as a disk blackbody with inferred temperatures at the inner edge of the disk in the 0.6–1.6 keV range, with no obvious emission lines. Their luminosities in the *Chandra* band are inferred to be 1.7–4.0 $\times 10^{38}$ $\mathrm{ergs\,s^{-1}}$. Together with P104, these 4 sources appear to be accreting black holes in high/soft states, similar to the ULXs and other bright BHCs observed with *ASCA* Makishima et al. (2000). For the interpretation of the diskBB model parameters as disk inner radius and temperature to be viable, P076 and P005 need to be relatively low-mass ($\lesssim$3 $M_\odot$) black holes accreting at the Eddington limit.

4. The Peculiar ULX P098

The brightest source we have discovered in M101, P098, stands out from others in luminosity, variability, and spectral shape. We have already noted the clear variability in P098 (Pence et al. 2001). Furthermore, the variability is far more pronounced in the 0.8–2.0 keV range than in the lower energy ranges (Fig. 3). We have extracted spectra of P098 at three time intervals (indicated in Fig. 3) and fitted them with simple models. Either diskBB or blackbody models work reasonably well, although an excess is seen above 2.0 keV which can be fit, e.g., using an additional power-law component. Using the blackbody model, the inferred temperature ranged from 0.09–0.17 keV, the radius changed from ∼5,000 km to ∼20,000 km, while the bolometric luminosity stayed near $\sim 3 \times 10^{39}$ $\mathrm{ergs\,s^{-1}}$ (see Table 2). With the diskBB model, the temperature range was 0.1–0.2 keV, the inner radius of the disk changed from ∼4,000 km to ∼20,000 km, while the bolometric luminosity stayed at $\sim 5 \times 10^{39}$ $\mathrm{ergs\,s^{-1}}$. The differences between parameters derived using these two different models are better indicators of true uncertainties in derived parameters. Using either model, the inferred radii are anti-correlated with the temperatures, and are far larger than the typical inner disk radius (Table 1). The apparent variability in the *Chandra* band is caused in large part by the bulk of the flux moving in and out of the *Chandra* band.

In many other ULXs, we have a puzzle in that the black hole mass inferred from the Eddington limit argument is high, while that inferred from using the disk blackbody model is low. In P098, however, the situation is very different. The low temperature and the large luminosity can both be accommodated in the framework of an intermediate mass black hole accreting at much less than the Eddington rate. The problem with this picture is the large disk radius changes inferred by the fit (roughly by a factor of 4) while the inferred bolometric luminosity changes little. It is difficult to understand how a slight change in the mass accretion rate (as suggested by the near-constant luminosity) can trigger such a drastic change in inner radius of the accretion disk in such a short timescale.

This behavior of P098 is reminiscent of the slow evolution of classical novae in the constant bolometric luminosity phase (Balman et al. 1998) and of the X-ray variability of super-soft sources (Southwell et al. 1996). In these systems, nuclear burning on the surface of an accreting white dwarf keeps the luminosity at or near the Eddington limit. The nuclear energy also drives a strong outflow; this wind is optically thick, hence the observed spectrum is determined by the radius of last scattering. When the outflow rate is higher, the effective photospheric radius is large, hence the observed temperature is low. When the outflow rate is lower, the photosphere is smaller, hence a higher temperature is seen.

Based on this analogy, we can construct the following model for M101 P098. It is an HMXB with a 20–30 $M_\odot$ black hole (the mass is constrained by equating the inferred bolometric luminosity during our *Chandra* observation with the Eddington limit). Its X-ray emission is embedded in a strong wind whose mass loss rate varies on a short timescale. We observe X-rays scattered at a typical radius of ~5,000 km, or more than 100 gravitational radii. The surface of last scattering changes, as the wind outflow rate fluctuates. The changing radius of the effective photosphere drives the correlated change in the temperature and model normalization, while the total luminosity is roughly constant at the Eddington luminosity. For this interpretation, the nature of the scattering medium (a wind, a jet, or a corona) is not important, as long as the amount of material along the line of sight is allowed to fluctuate rapidly. It is possible that such a mechanism is responsible for most of the variability of P098 down to the fastest timescale detected (Fig. 3), not just the spectral changes between intervals *a*, *b*, and *c*, though we cannot prove this with the available data.

5. Implications for other ULXs

We have studied the six brightest sources detected in our *Chandra* ACIS-S observation of M101. We briefly consider the possible implications of our findings on the nature of ULXs in general.

Of the 5 non-ULX BHCs that we have studied, one (P104) is spatially coincident with a supernova remnant (MF83). Another source, P005, although located in the interarm region and originally suspected of being a background AGN, may also be a combination X-ray binary/supernova remnant in M101. In our own Galaxy, the jet source SS 443 is in the supernova remnant W 50 (Seward et al. 1976), while the super-Eddington neutron-star binary Cir X-1 has tentatively been linked to the nearby supernova remnant G 321.9−0.3 (Stewart et al. 1993). The case of P104 may point towards an interesting link between bright extragalactic BHCs and some of the unique and extreme X-ray binaries in our Galaxy.

The ULX P098 is highly variable, particularly above 0.8 keV, and has a soft blackbody-like spectrum. Fitting of spectra from P098 extracted from three time intervals shows that the bolometric luminosity may have been relatively constant. The apparent violent variability appears to reflect anti-correlated changes in the source temperature and size. We have therefore presented an interpretation based on optically thick wind, because we find it unlikely that the inner radius of the accretion disk can change by a factor of 4 on such a short timescale.

Yet the spectrum of P098 can be fit with a disk blackbody model and a power law excess, a traditional model for black hole candidates which is also applied to ULXs. Interpretation of diskBB model fits, or fits using more sophisticated spectral models of optically thick disk (e.g., Ebisawa 1991; Merloni et al. 2000; Ebisawa et al. 2001), have resulted in a puzzle for many ULXs: the inferred disk temperatures are too high, and the radii are too low, for the inferred mass of the central black hole. We therefore caution, based on our experiences with P098, that the optically thick disk interpretation of ULX spectra Makishima et al. (2000) is almost certainly not unique. An additional argument for caution is provided by Życki et al. (2001), who show that the soft component in Galactic BHCs are often too broad to be fit by models of an optically thick disk. They argue that an intermediate temperature material is likely present, providing either additional blackbody contributions or additional Comptonization. Unfortunately, existing X-ray spectra of extragalactic ULXs are not sufficiently constraining to allow discrimination between pure disk models and Comptonized disk models.

Abandoning the "pure disk" assumption for the ULX spectra solves the problem of disks that appear to be too small and too hot for the black hole mass. However, it leaves the question of the black hole mass unresolved: ULXs are either unbeamed objects containing intermediate mass black holes, or they are beamed objects containing stellar-mass black holes. Our contributions to this debate are twofold. First is that no object we have detected in M101 requires a intermediate mass black hole. Even the most luminous object, P098, can be an Eddington limited, unbeamed X-ray source with a $\sim$20 $M_{\odot}$ black hole. This is somewhat larger than the typical mass of stellar black holes, but not so large as to require a new class of black holes.

Our second contribution to this debate comes from the strong variability seen in P098 and P104. The very fact that variability can be detected with less than a thousand photons suggests an impressive degree of variability in P104, perhaps favoring a beamed model for ULXs such as suggested by King et al. (2001). In addition, the energy dependent light curves of P098 suggest the possibility that the true variability of other ULXs may have been underestimated; similar analysis of light curves of P076 proved suggestive, but not conclusive. It would be very important to search for similar energy-dependent variability characteristics in other ULXs, whenever counting statistics permit: existing studies may have severely underestimated the true variability of ULXs if they often are variable predominantly at higher energies, because observed counts are generally weighted heavily towards lower energies.

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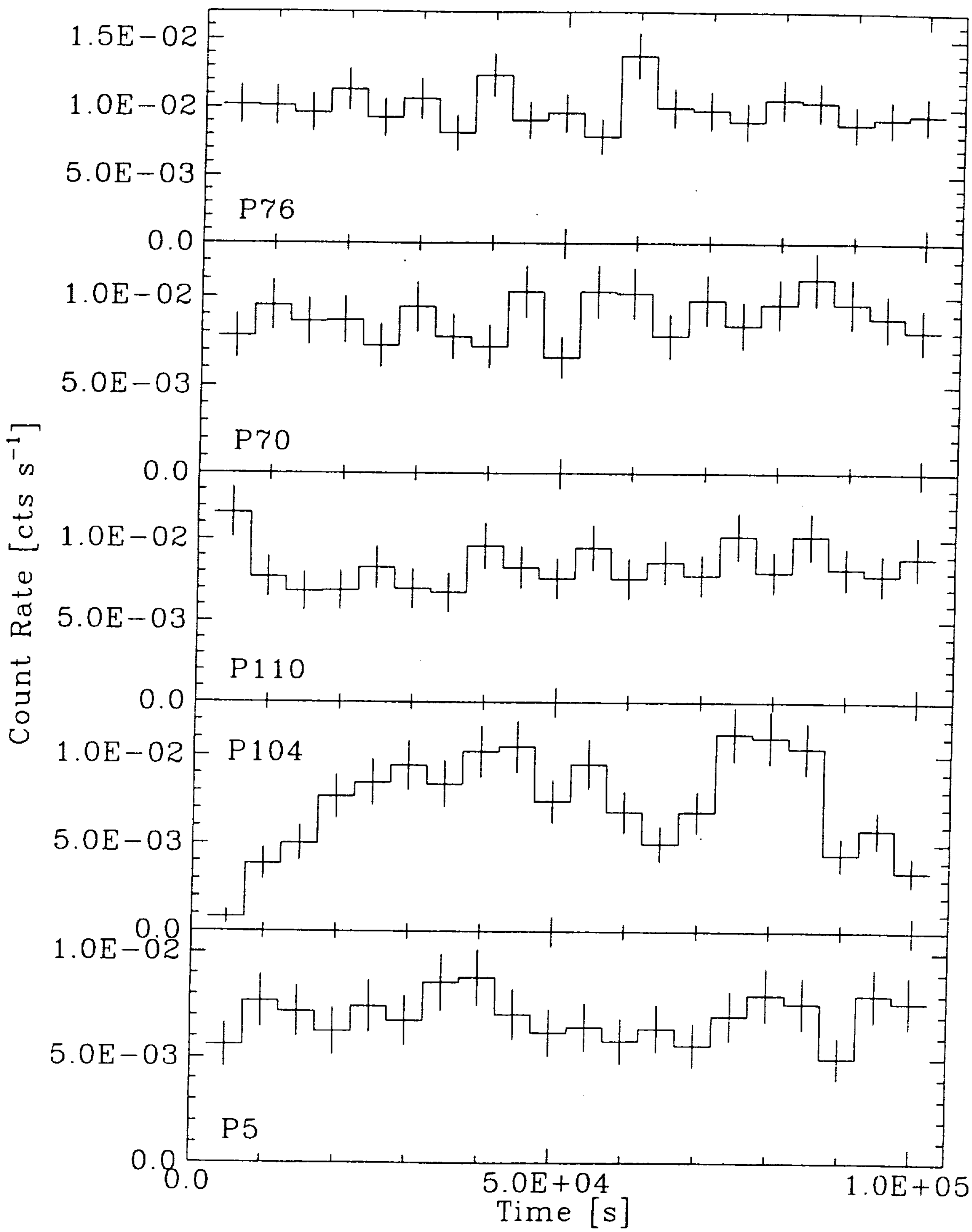

Fig. 1.— *Chandra* ACIS-S light curves of the 5 bright normal ULXs.

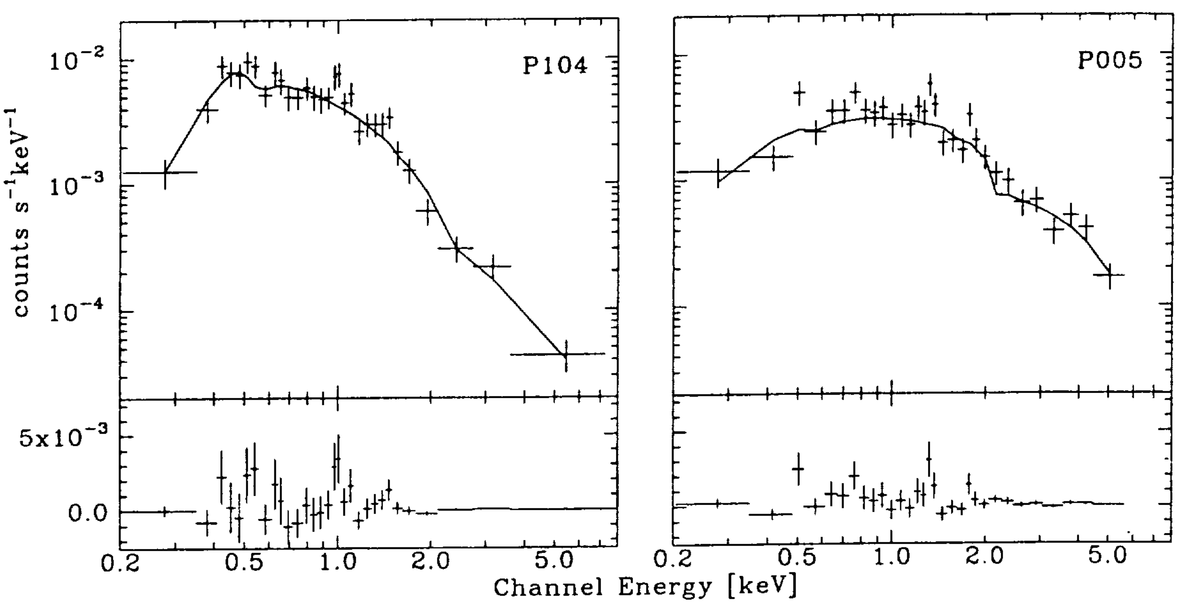

Fig. 2.— *Chandra* ACIS-S spectra of P104 and P005. Observed spectra with the best-fit continuum (power-law for P104 and disk blackbody for P005) are plotted in the upper panels, while the residuals are shown in the lower panels. There are apparent emission line-like features at 1.02 keV (P104) and 1.34 keV (P005).

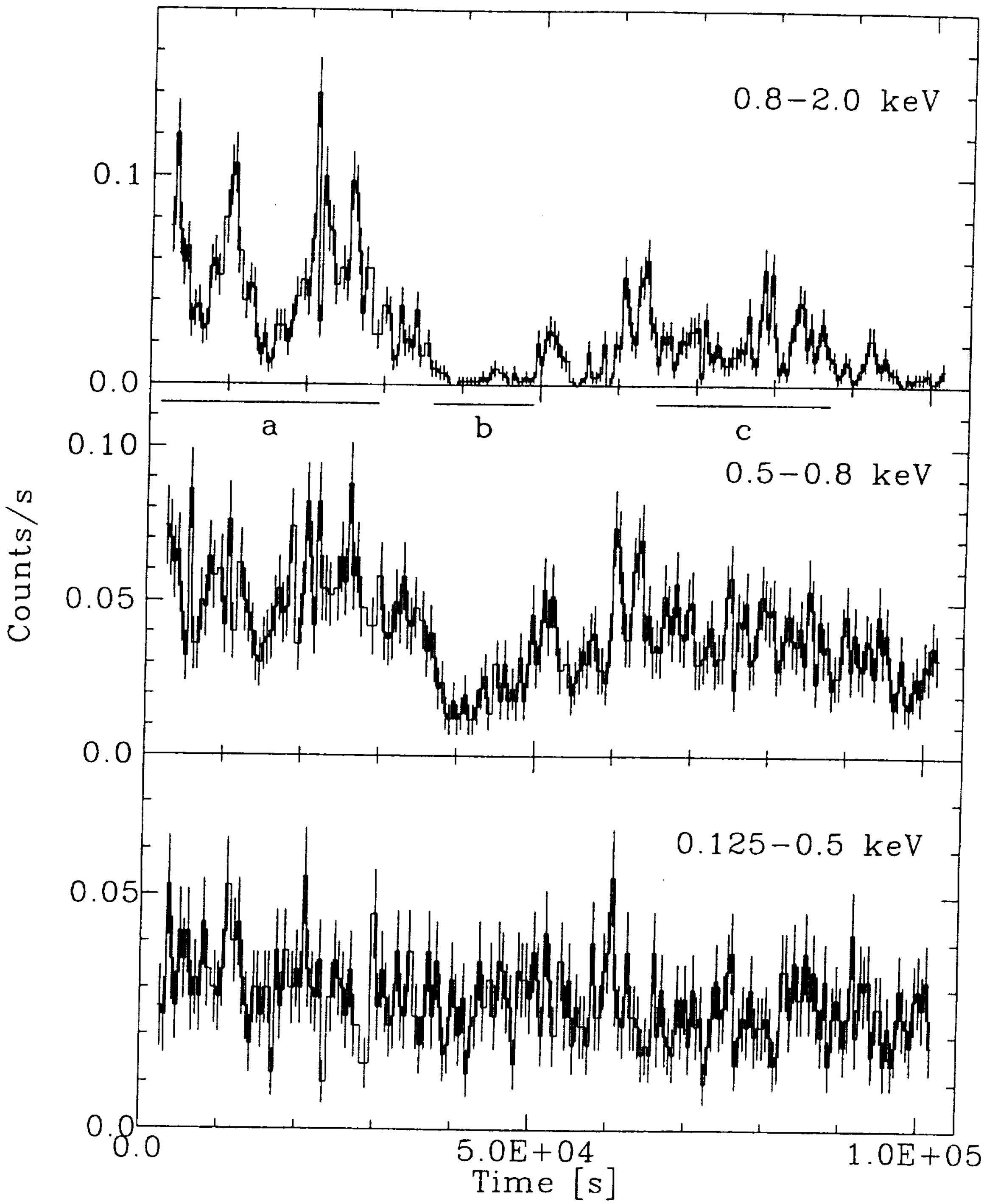

Fig. 3.— *Chandra* ACIS-S light curves of P098 in 3 energy bands. Horizontal bars in the second panel indicate the time intervals selected for spectral analysis.

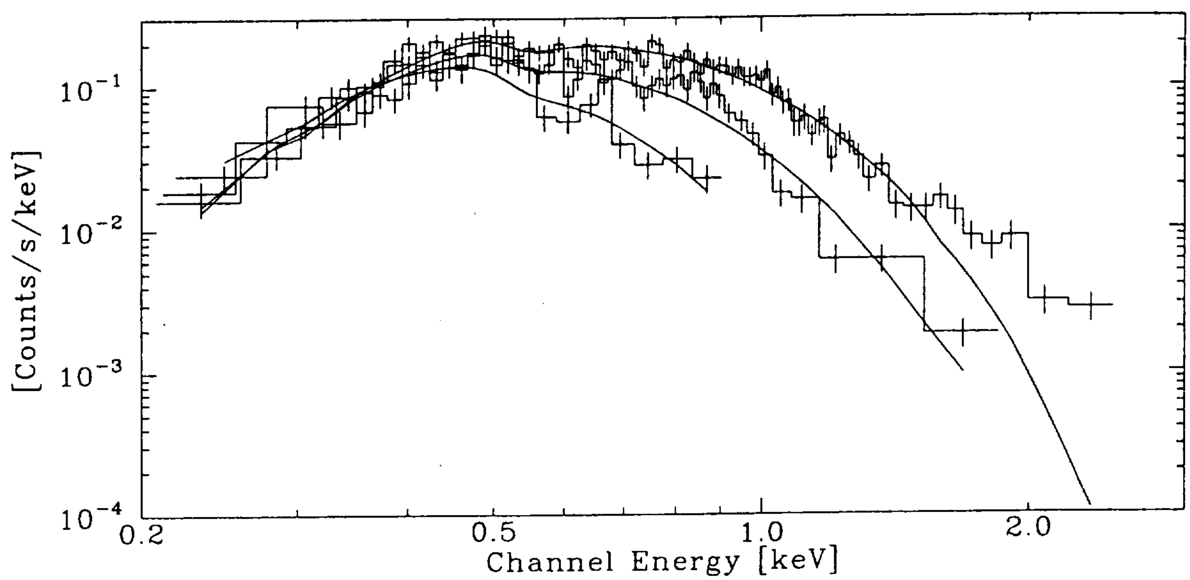

Fig. 4.— *Chandra* ACIS-S spectra of P098 during 3 time intervals indicated in Fig. 3.

Table 1. Candidate ULXs in M101

Name	Net counts	Spectral Model	T_{in} (keV)/α	R_{in} (km)	L (ergs s^{-1})
P098	9308	diskBB	0.18	4400.0	1.4×10^{39}
P076	942	diskBB	1.61	20.2	4.0×10^{38}
P070	872	diskBB	1.07	32.0	2.5×10^{38}
P110	777	diskBB	0.58	89.6	1.7×10^{38}
P104	704	PL	2.61		1.6×10^{38}
P005	679	diskBB	1.64	12.9	2.2×10^{38}

Table 2. Spectral Change in P098

Interval	kT	R (km)	L_{bol} (10^{39} ergs s^{-1})
a	0.173±0.004	5200±100	3.2±0.2
b	0.090±0.007	19600±2000	3.3±0.9
c	0.123±0.006	9600±800	2.7±0.5