X-ray Binaries in M101

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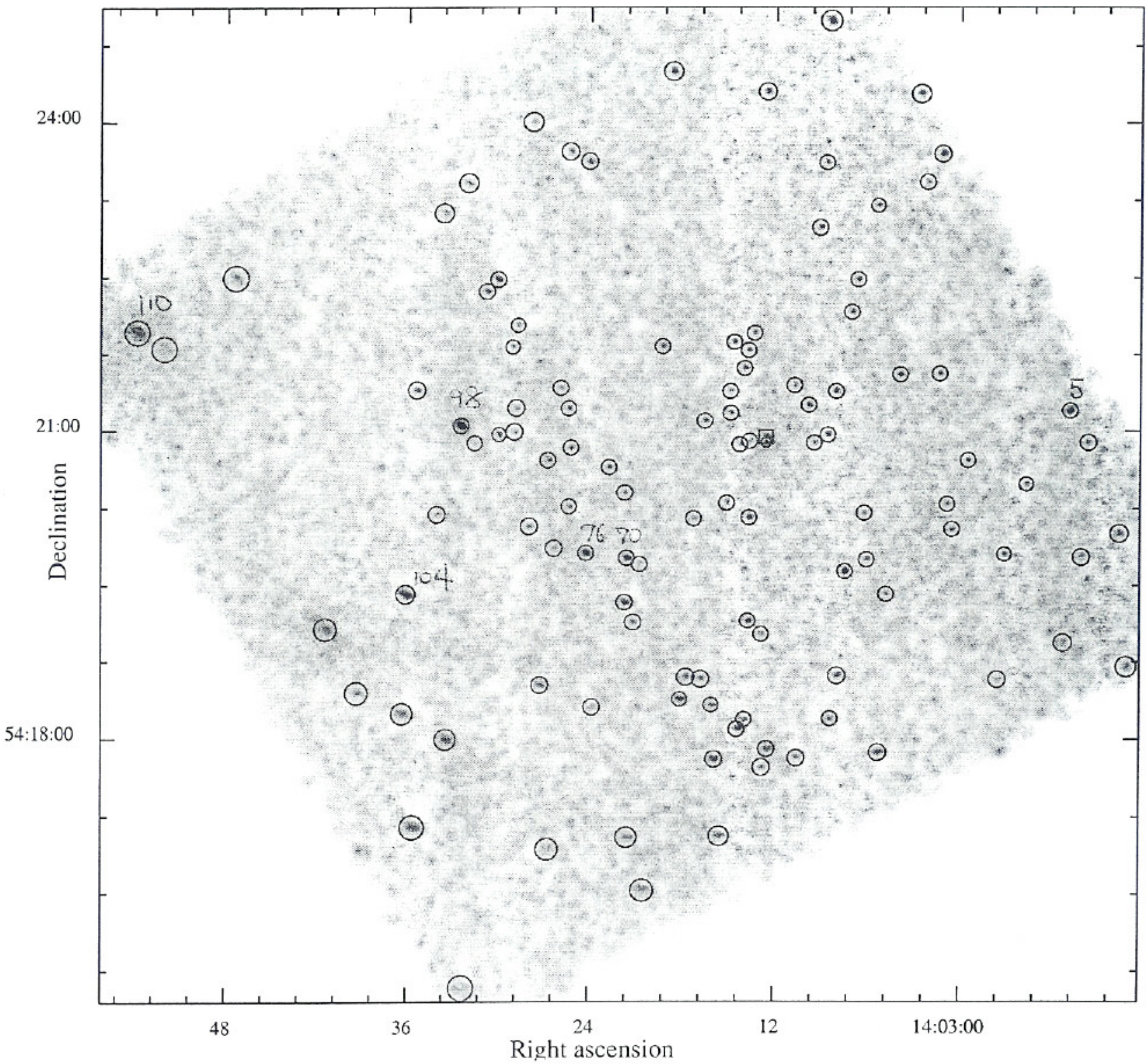
ApJ January 1, 2003, in press

- M101: A face-on spiral galaxy at ~7.2 Mpc.
- Chandra observed M101 for 98.2 ksec with ACIS-S during 26–27 March 2000.
  - Snowden et al 2001, AJ 121, 3001 reconsiders the hypernova remnant candidates.
  - Pence et al 2001, ApJ, 561, 189 catalogs 110 sources detected on the S3 chip.
  - Kuntz et al 2002, ApJ, submitted, studies the diffuse X-ray emission.

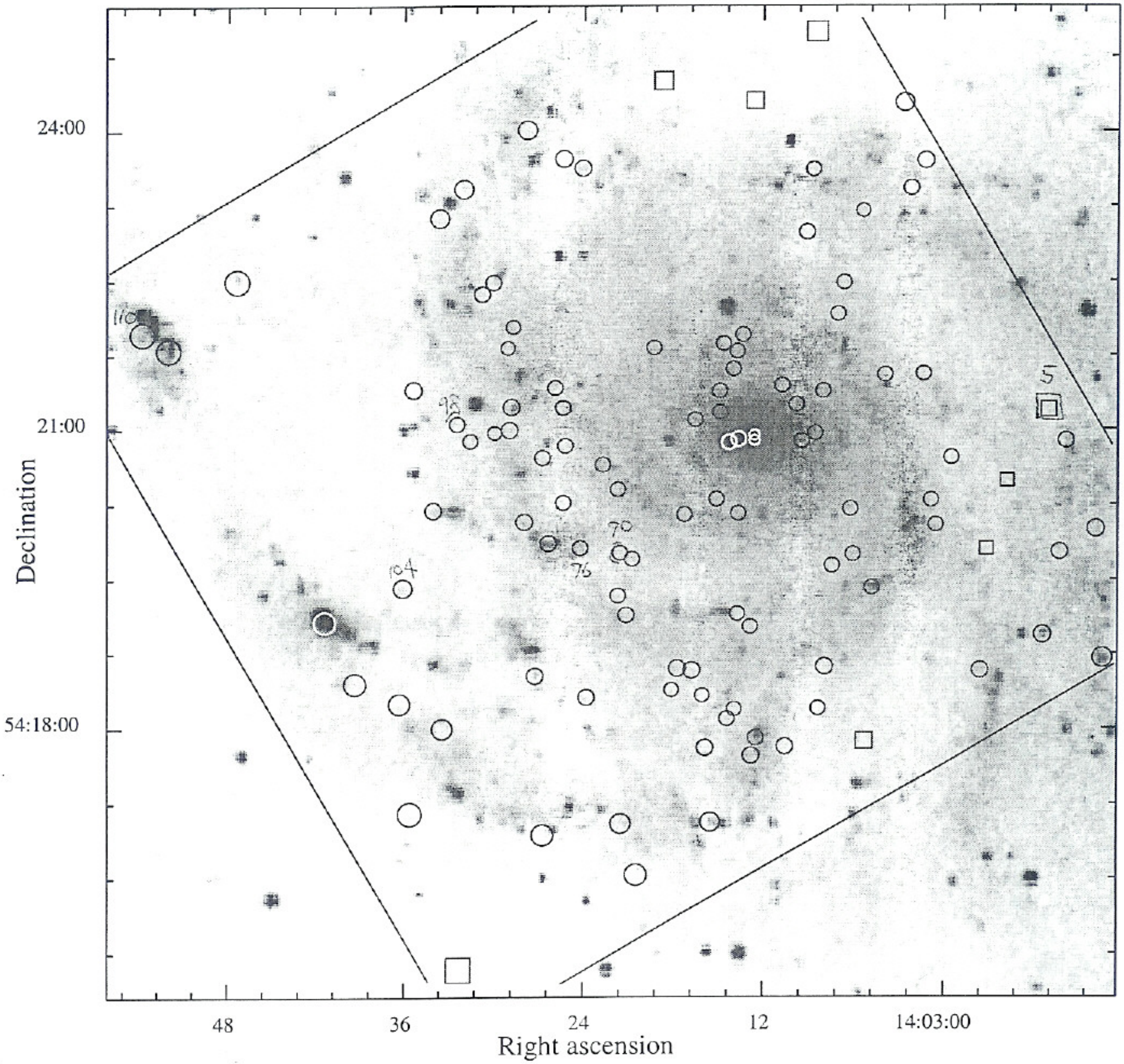
Motivations

- Despite their brightness, our vantage point in the plane of the Milky Way makes it difficult to study the luminosity function and spatial distribution of Galactic X-ray binaries.
  - Both are likely to be a function of other parameters of the galaxy.
- A large number of candidate ultraluminous ($>10^{39}$ ergs s^{-1}) X-ray binaries (ULXs) have been seen with ROSAT HRI (Roberts & Warwick 2000, MNRAS 315, 98; Colbert & Ptak 2002, ApJS 143, 25).
  - Are they accreting Intermediate Mass Black Holes IMBHs?
  - Or are they accreting stellar-mass black hole binaries that are beamed?

Chandra ACIS-S (S3) Image of M101

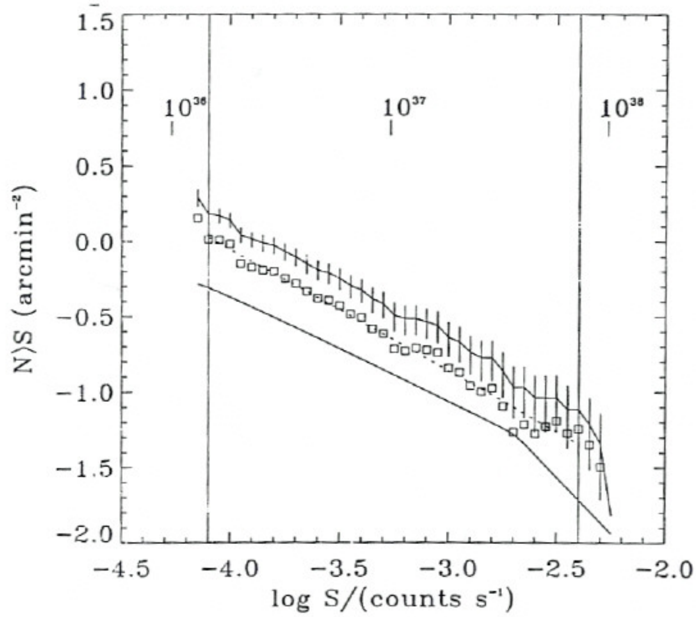


POSS (E) Image of M101
with Chandra Source locations



6 brightest sources in M101

The $\log N - \log S$ relation for M101.

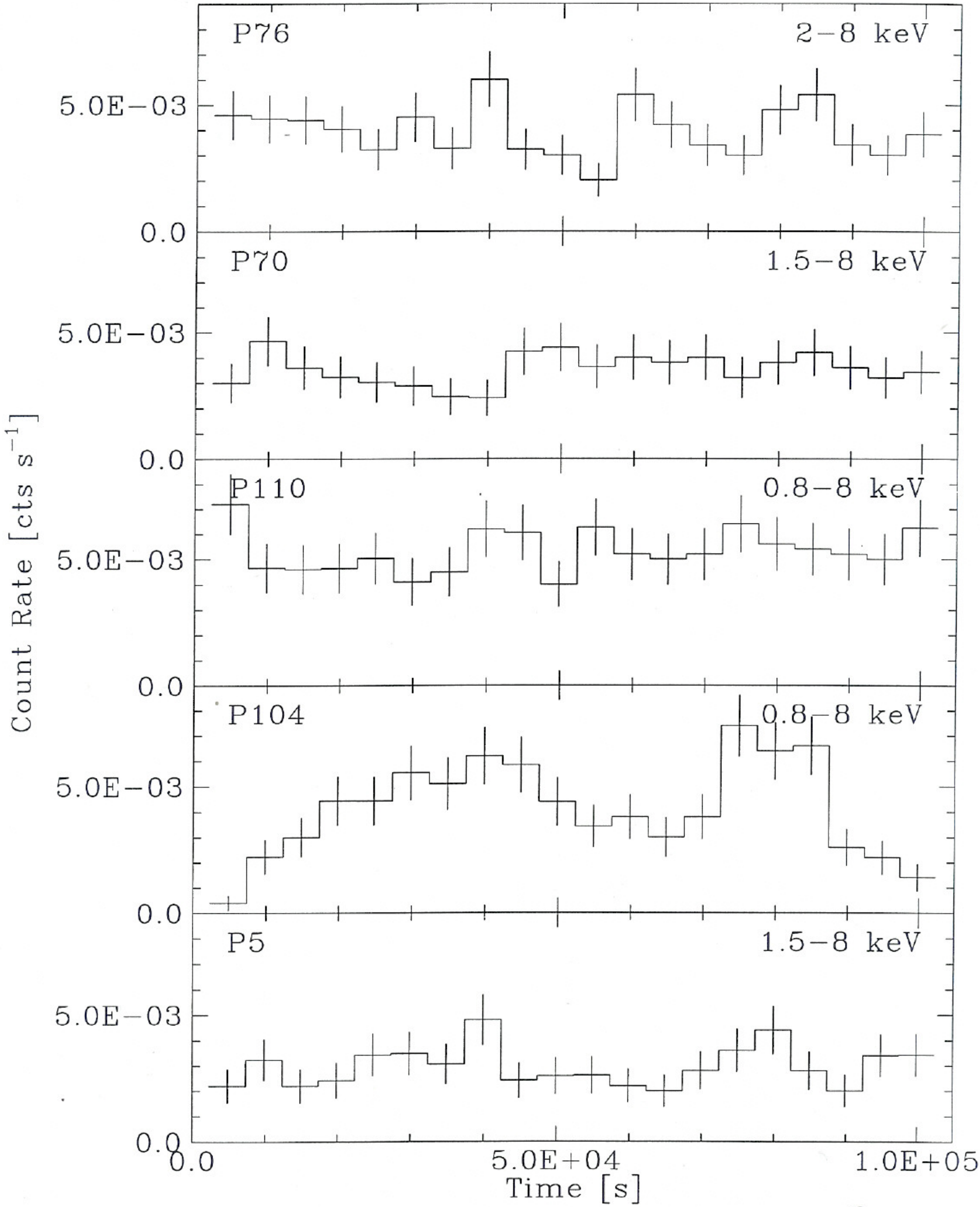


The lower smooth line represents the background AGN.

We have attempted simple continuum spectral fits to the six brightest sources detected. Five out of the six can be best fitted with the disk blackbody model. Power Law works best for the sixth.

Spectral Parameters of the 6 Brighest Sources

Name	Net cts	Model	T_{in}/α	R_{in}	Obs. L.
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}



P76
2–8 keV
P70
1.5–8 keV
P110
0.8–8 keV
P104
0.8–8 keV
P5
1.5–8 keV
5.0E−03
0.0
Count Rate [cts s^{-1}]
0.0
5.0E+04
1.0E+05
Time [s]

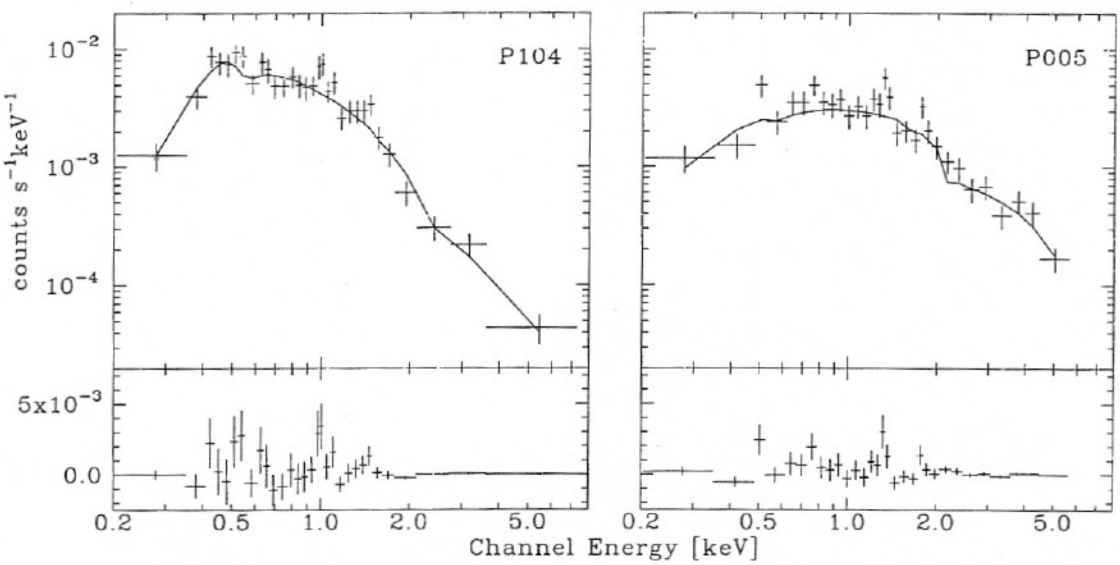
- The Chandra observed luminosities of all six sources exceed the Eddington limit for a $1M_\odot$ object. Since the inferred bolometric luminosities are higher, these can be considered black hole candidates.

- P104 is highly variable. Fitting the time-averaged spectrum may not be reliable. An emission line is detected at 1.01 keV: since this source coincides with a radio detected SNR (MF83), this may be a contribution from the hot SNR plasma.

- P005 is one of the eight "interarm" sources detected in the S3 chip, which coincides with the ROSAT HRI source H18 of Wang et al. They suggested a blue optical counterpart, interpreted as AGN; however, the Chandra and optical positions are about 5 arcsec apart. This source also has lines at 1.34 and 1.85 keV.

P076, P070, P110, and P005 can be described as accreting stellar mass black holes in a soft state. P104 can be a similar system in a hard state.

Chandra ACIS-S spectra of P104 and P005.



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$$\cos i)^{-1/2} . \quad (13)$$

reaching 70–80

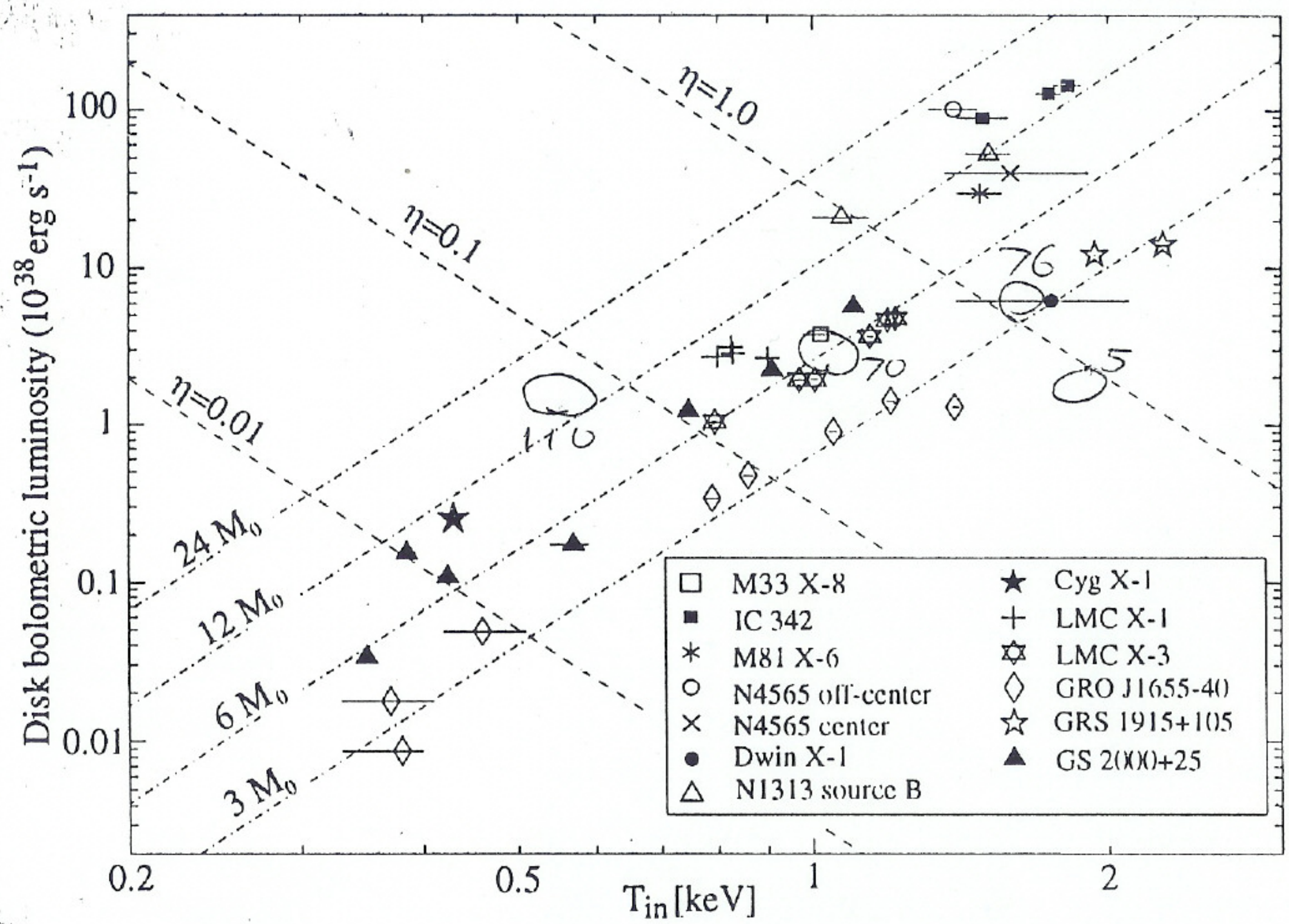
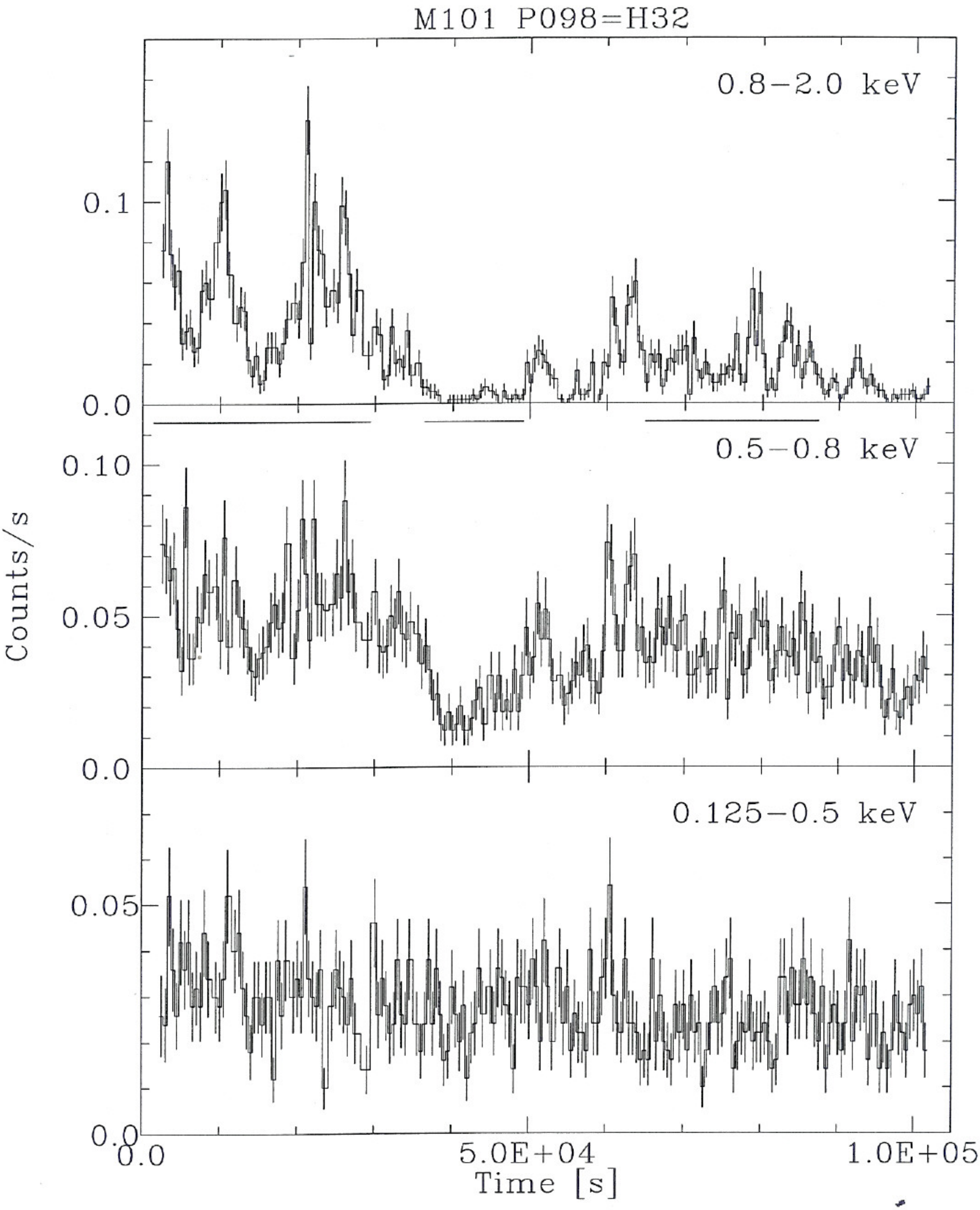
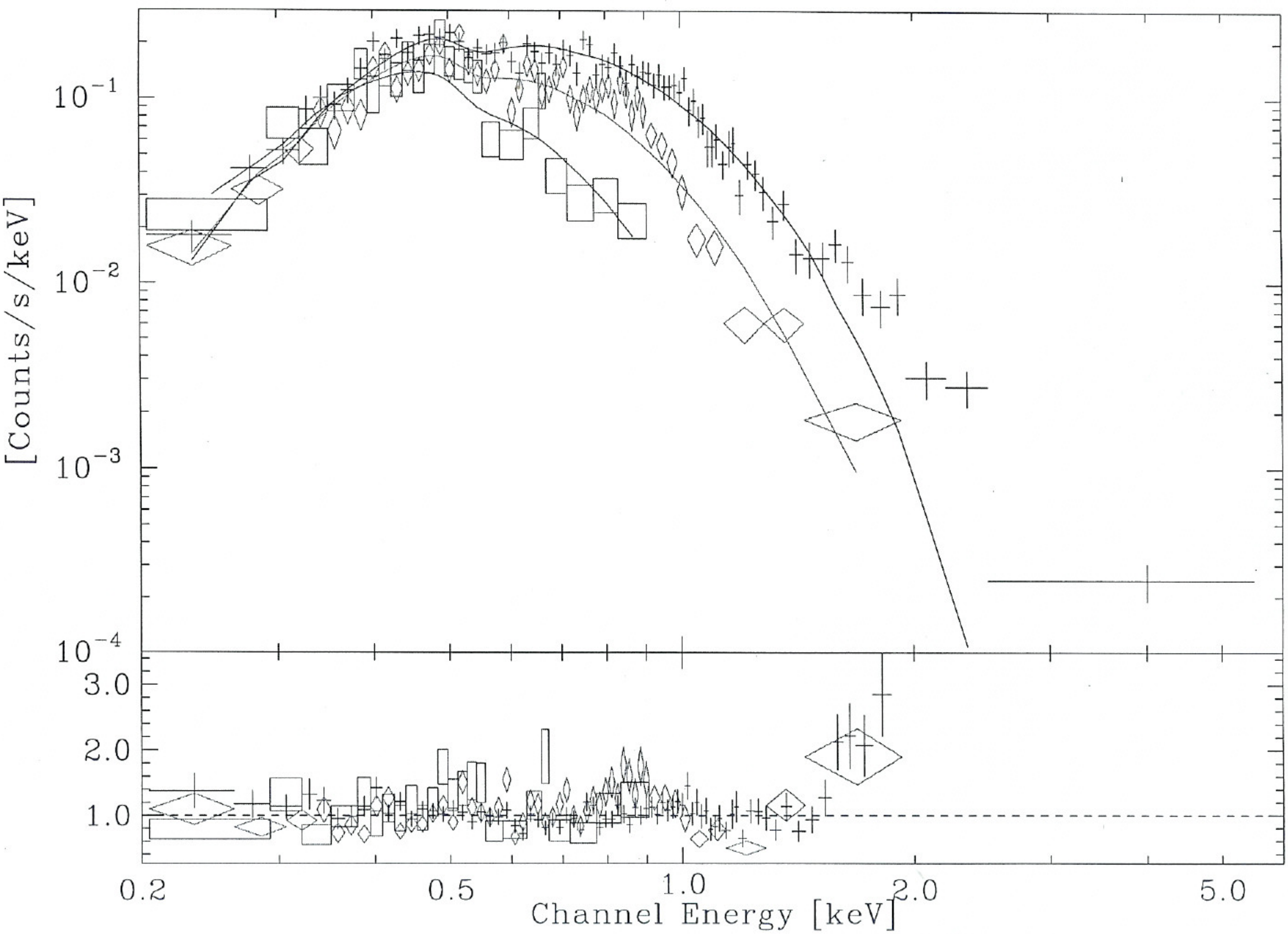


FIG. 3.—Relation between the bolometric luminosity (L_{bol}) and the highest color temperature (T_{in}) of optically thick accretion disks around black holes. Various symbols indicate measurements with *ASCA* and other missions. Dash-dotted lines show constant-mass grids, calculated via eq. (9), assuming the standard accretion disk. Dashed lines are those for normalized accretion rates, calculated similarly via eq. (11). In addition to the data described in the text, plotted are two intensity-sorted data points for IC 342 source 1 (Mizuno 2000), three *Ginga* data points for LMC X-1



M101 P098=H32
0.8–2.0 keV
0.5–0.8 keV
0.125–0.5 keV
Counts/s
0.1
0.0
0.10
0.05
0.0
0.05
0.0
0.0
5.0E+04
1.0E+05
Time [s]



[Counts/s/keV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
3.0
2.0
1.0
0.2
0.5
1.0
2.0
5.0
Channel Energy [keV]

What is this highly variable source, P098?

- Highly variable — unusual among ULXs?.
  - Variability confined to the highest energies. Needs to check for similar energy-dependent variability characteristics of other ULXs.
- Either diskBB or blackbody models work reasonably well to fit changing spectra, although an additional power-law component is required to fit the high energy end..
  - Temperature changes in the 0.10–0.2 keV range with the diskBB model, or 0.09–0.17 keV with the blackbody model.
  - Inferred radii are anti-correlated with the temperature, and are too large to be the inner disk radius.
  - Inferred bolometric luminosity remains relatively constant at $\sim 5 \times 10^{39}$ $\mathrm{ergs\,s^{-1}}$ (diskBB) or $\sim 3 \times 10^{39}$ $\mathrm{ergs\,s^{-1}}$ (blackbody).
  - It seems unlikely for a slight change in the accretion rate (for example) to trigger such large and sudden changes in the inner disk radius, without changing the luminosity.

The relative lack of variability in bolometric luminosity suggest a limiting mechanism: Eddington limit a likely candidate.

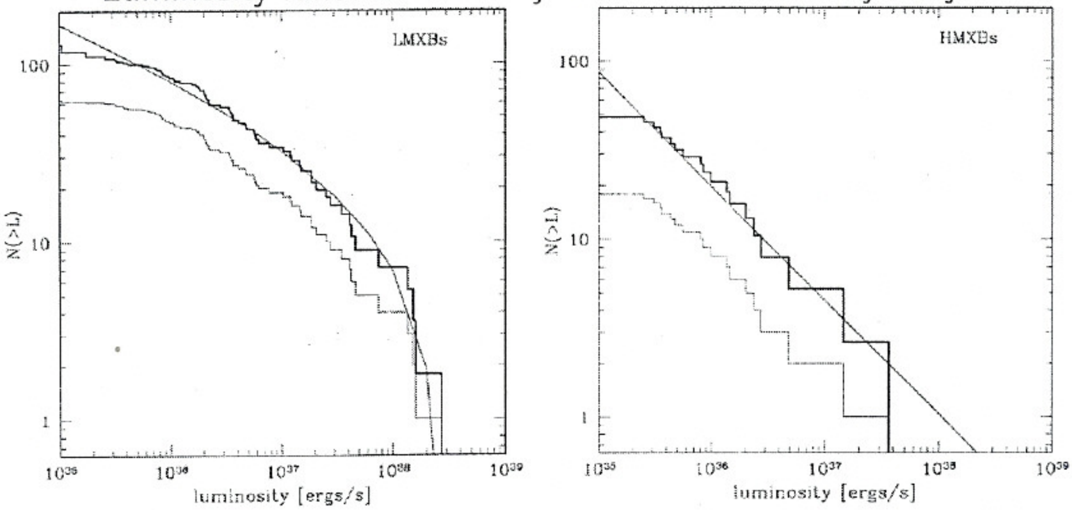
- Black hole mass 15–25 $M_{\odot}$.
- Radiatively driven outflow is a distinct possibility near $L_{emitted} \sim L_{Edd}$.
- A mass loss rate of a few $\times 10^{19}$ $\mathrm{g\,s^{-1}}$ (comparable to the Eddington accretion rate) can become optically thick at R=10000 km for an outflow velocity of 10000 $\mathrm{km\,s^{-1}}$.
- The observed X-rays may be scattered in such an optical thick outflow; variable mass loss rate or velocity can cause the observed variability by changing the effective photospheric radius while keeping the radiative luminosity constant.

Lessons Learned?

- Optically thick X-ray spectra do not necessarily imply a geometrically thin, optically thick accretion disk. Other entities around a black hole can mimic diskBB, to first approximation. We don't have the statistics to distinguish between subtly different models
- Using a conservative assumption — allowing $20 M_\odot$ "stellar mass" black holes and mildly super-Eddington X-ray emission as well as potential source confusion — there is no need to invoke an IMBH in M101 (or for any sources under $\sim 5 \times 10^{39}$ ergs s^{-1}).

A Young Population?

Luminosity function of X-ray sources in the Milky Way.



From Grimm, Gilfanov & Sunyaev 2002, A&A 391, 923.

The luminosity function of M101 extends to higher luminosities. Brightest sources in M101 are preferentially located in the spiral arms, and some are apparently associated with known supernova remnants — these clues point to these sources being HMXBs.

We do not see a similar population of sources in the Milky Way (persistent black hole candidates with $L_x > 10^{38}$ ergs s^{-1}).