X-ray Binaries in the 21st Century

Phil Charles
University of Southampton

Outline

- quick (potted!) history – 40 years since Sco X-1 discovery
- multi-λ, TOO, all-sky monitoring crucial
- selection of current problems on XRBs where CXO/XMM/TOO/multi-λ important:
- *X-ray transients/unpredictable activity*
- *Latest outburst of GX339-4!*
- *X-ray spectroscopy of XRBs*
- *ULXs in nearby galaxies*
- *L_X population in globular clusters*
- *Evidence for warped discs*

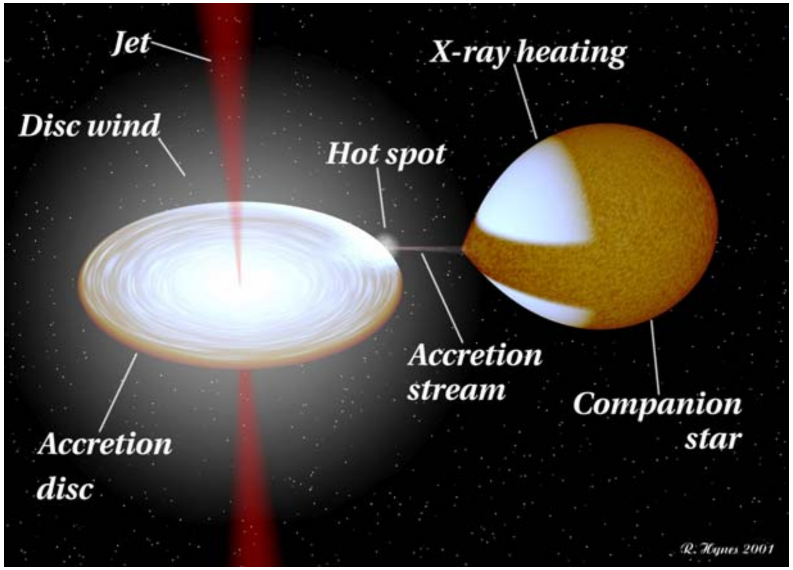
Quick history:

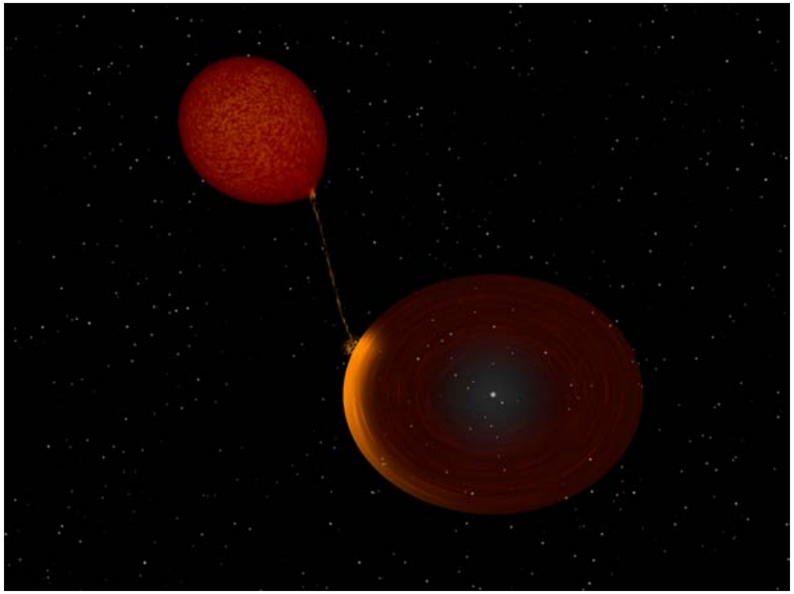
- 1962 Sco X-1, but not ID'd until 1966
- fundamental XRB model: Uhuru discovery of Cen X-3 (eclipsing) in 1971
- 1970s: Uhuru, OSO-8, ANS, SAS-3, OAO-C, HEAO-1 + multi-λ campaigns e.g.
- X-ray/optical bursters (MXB1636-536/MXB1735-444)
- X-ray/optical pulsars (4U1626-67)
- Be X-ray transients (long periods, X-ray pulsars)
- EXOSAT: high orbit, observatory-style operation e.g. 1984 turn-on of Her X-1 (following extended "off")
- EXO0748-676 NS "transient" (bursts, dips, eclipses)
- first grating spectrum of XRBs

Black Hole X-ray Transients

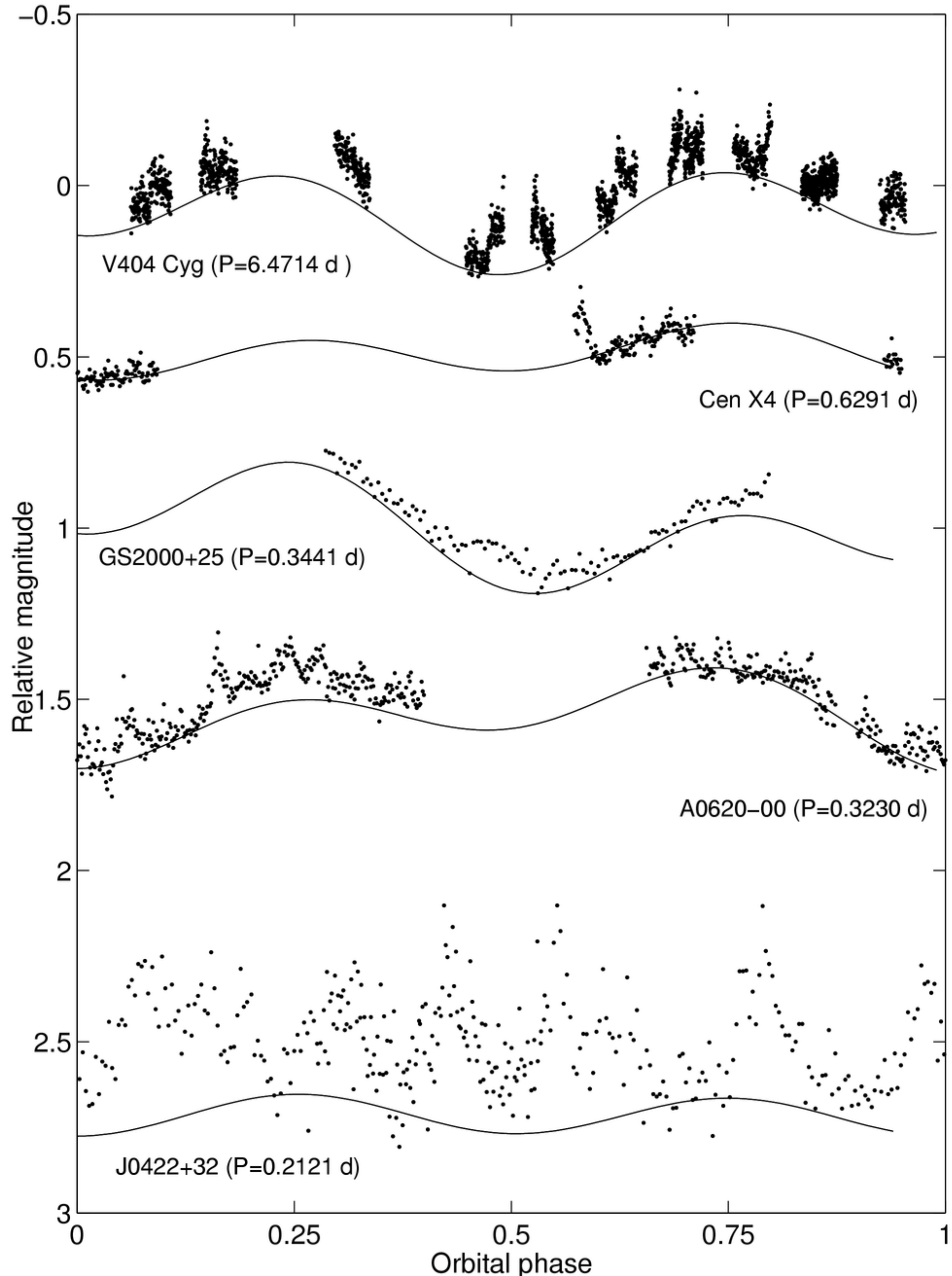
- Black-hole X-ray transients are LMXBs
- Very bright X-ray sources during rare outbursts, usually decades apart
- Optically brighten by up to 8^m (irradiation of companion and disc allows echo mapping)
- Can produce relativistic jets (micro-quasars)

- In quiescence very faint
- Companion star dominates
- RV + light curve → masses
- Nature of quiescent acc.flow?
- Evidence for *Event Horizon*?



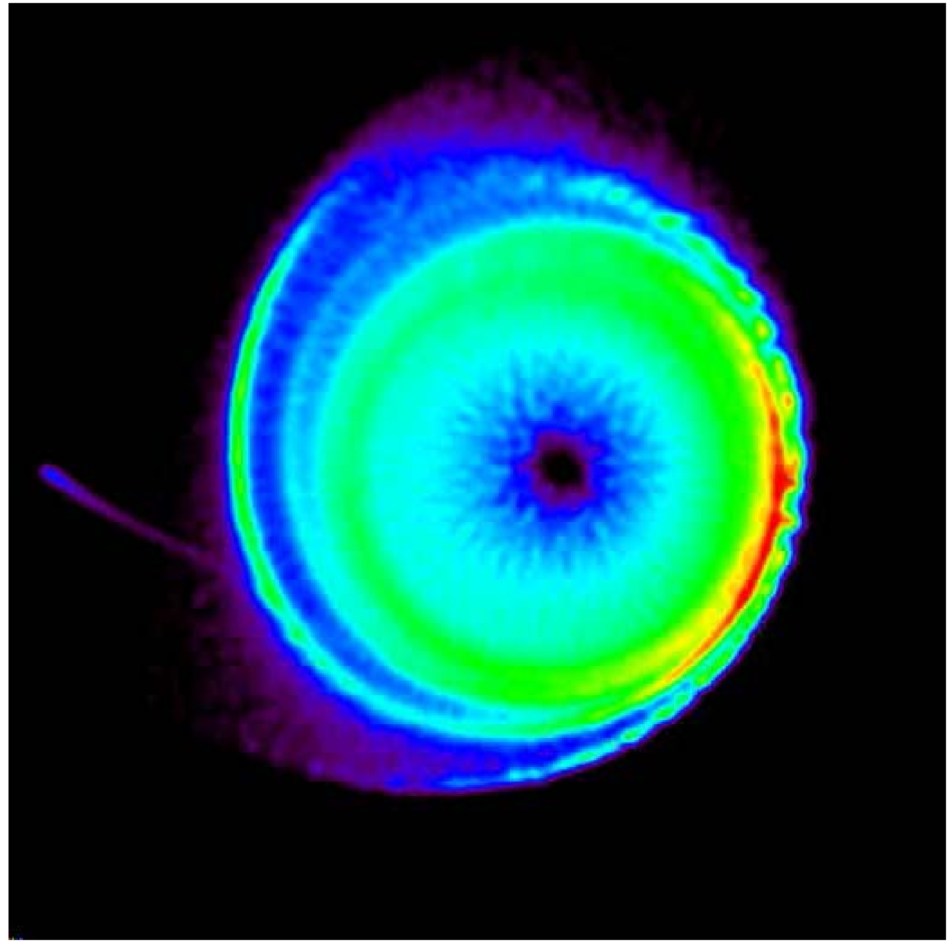


5 Quiescent Transient Optical Lightcurves



High q LMXBs/CVs → eccentric, precessing discs

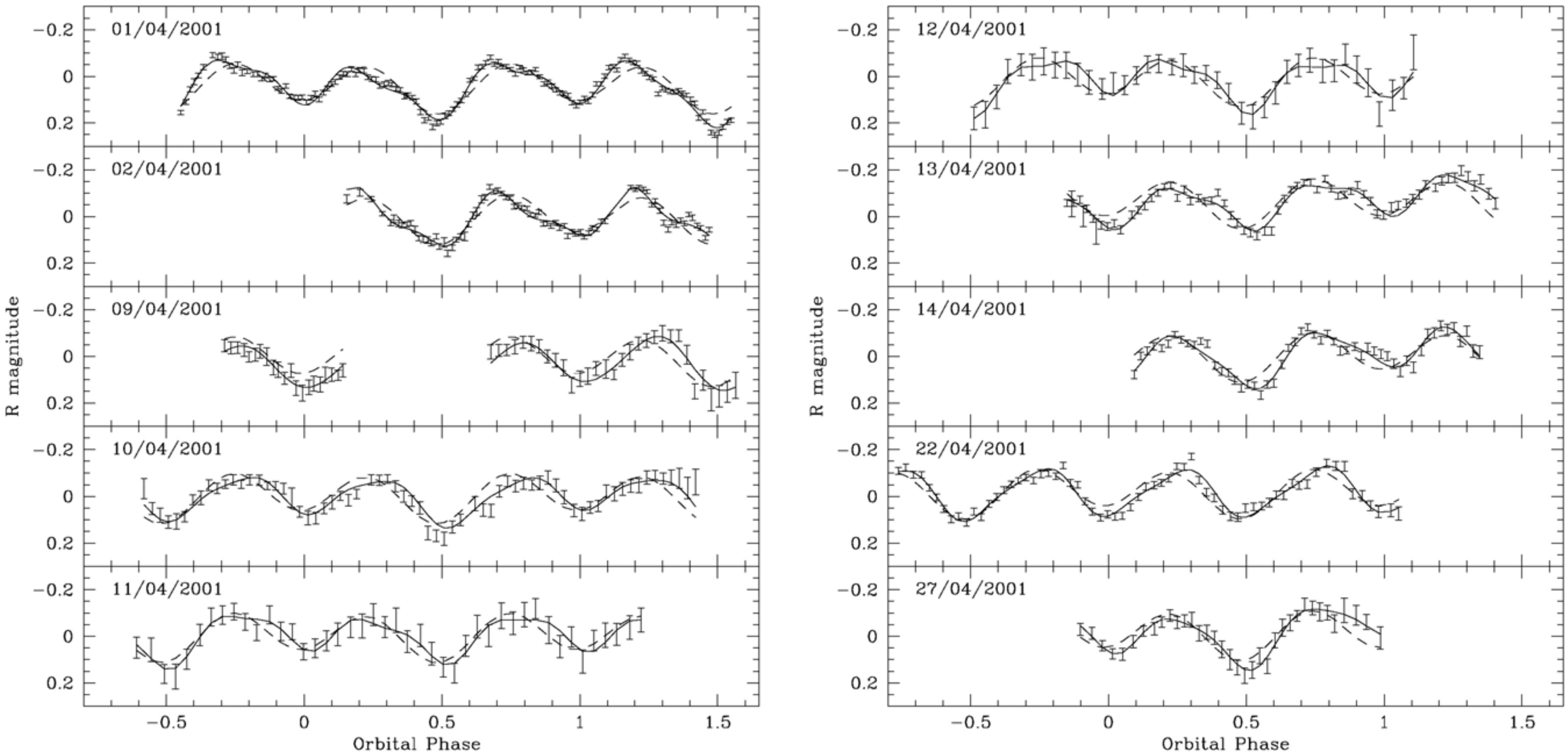
- Explanation for superhump P being few % longer than P_{orb}
- 3:1 resonance in disc only with stability radius at high q (Whitehurst 1988)
- All BH/NS SXTs, all short P LMXBs, all CVs < P gap satisfy this!
- Murray SPH simulation (www.star.le.ac.uk/jmu) of discs in high q binary



Origin of superhumps in SXTs

- Superhump features now seen in 5 SXTs (N Mus 91, GS2000+25, J0422+32, J1118+480, N Oph 93) see O'Donoghue & Charles 1996 MN
- But LMXBs are ~100x more luminous than CVs in optical – due to X-ray irradiation of disc
- →intrinsic disc luminosity is swamped by X-ray heating
- Therefore Haswell et al 2001 proposed that the disc shape (and hence area) is modulated on $P_{superhump}$ and hence so will reprocessed X-radiation
- Used SPH calculations of Murray for high mass ratio CVs

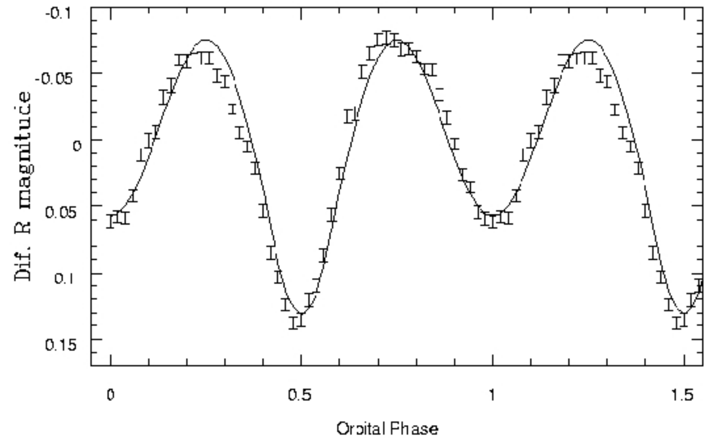
- Precessing disc in decline phase of J1118+480 (Zurita et al 2002)

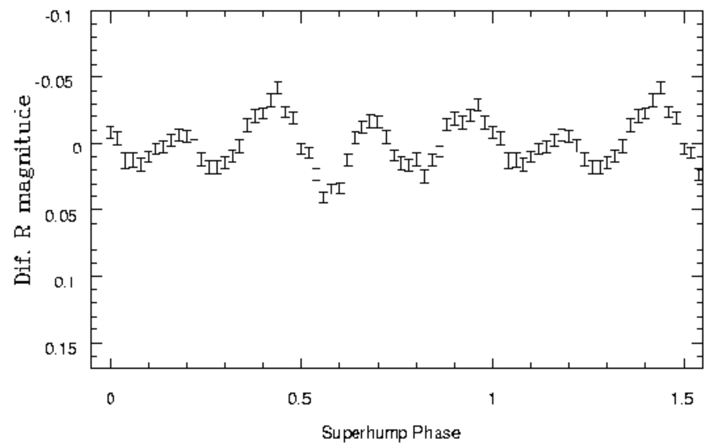


Zurita et al 2002 astro-ph/0202438

- Ellipsoidal modulation well defined over many months
- After subtraction, superhump P is present with differential of only 0.3% (wrt P_{orb})
- i.e. ~52d precession P (Hα→spectroscopic evidence for motion on this P)
- Simulations of precessing disc show that P differential is smaller if q is larger
- Hence photometry of SXTs in outburst → q constraints

J1118+480 mean light curve

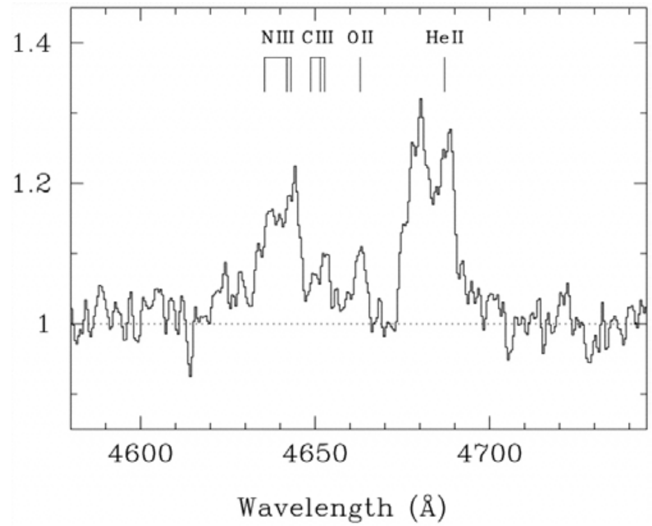


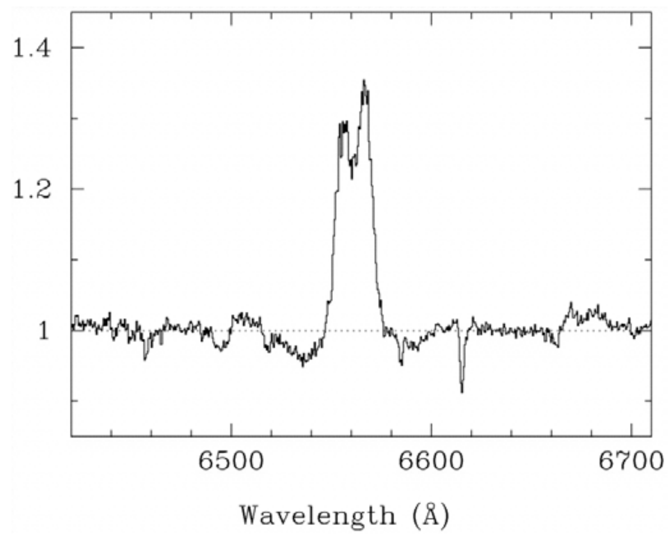


Other methods of mass determination

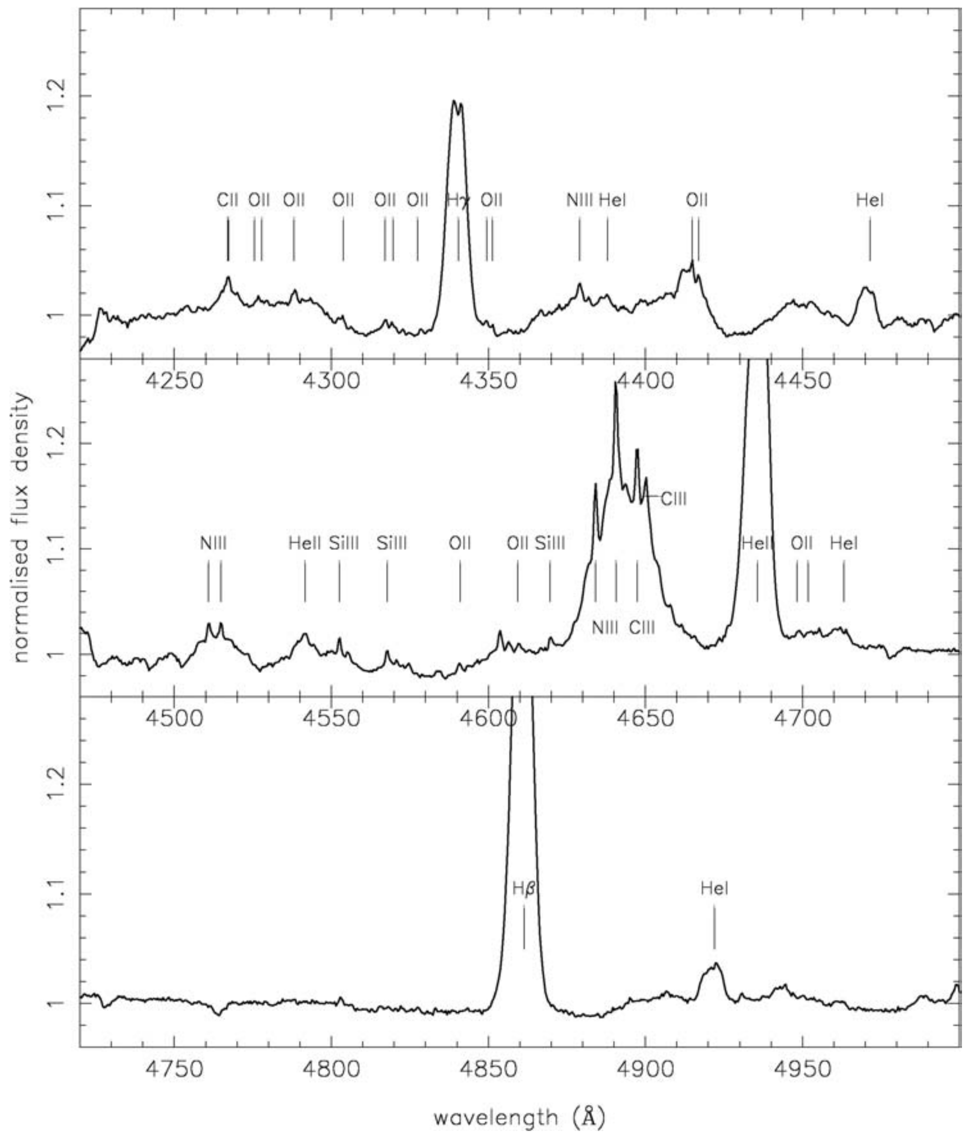
- Spectroscopy in outburst of all SXTs shows strong, complex emission lines
- e.g. J1655-60 (Soria et al 1998); very similar to J0422+32 (Harlaftis et al 1994)
- Classical double-peaked disc profiles

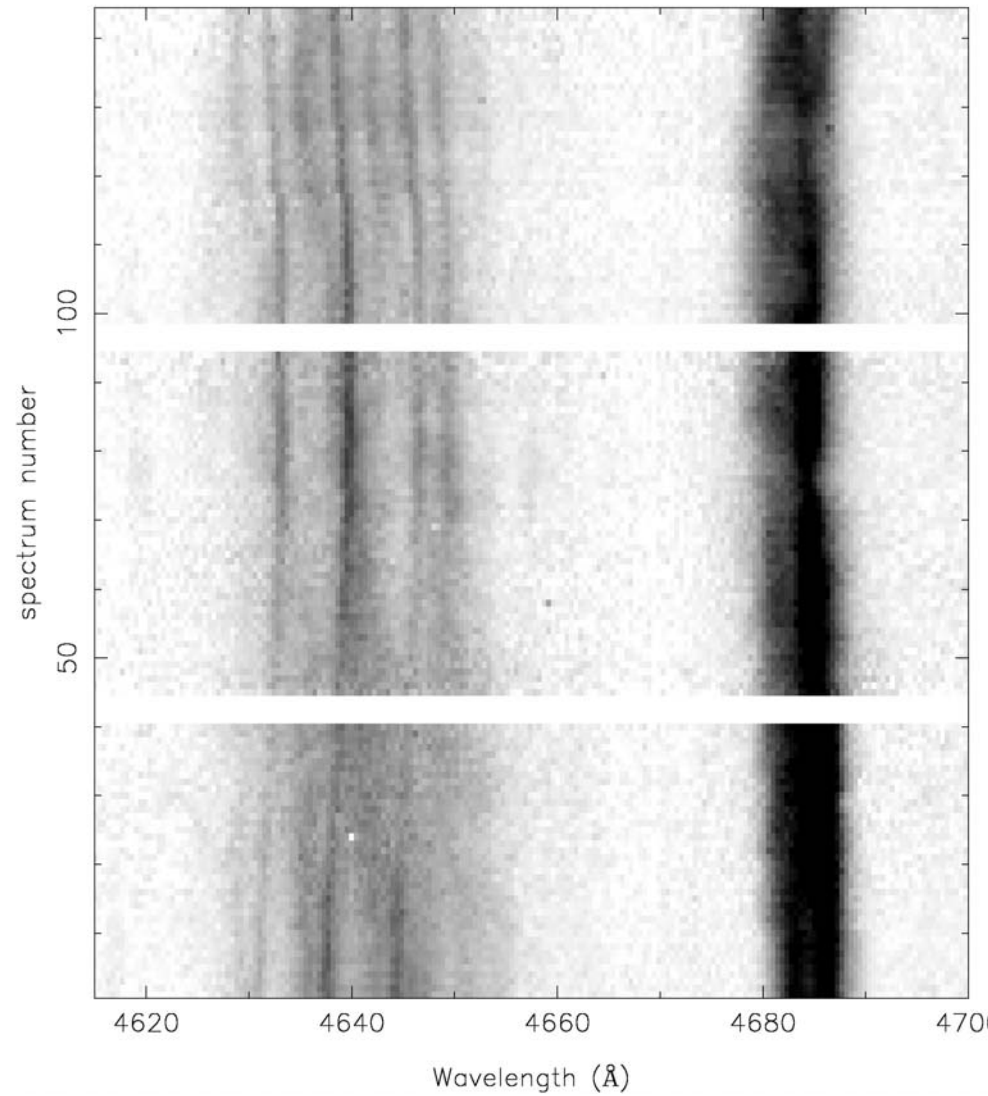
- But if resolution is high enough (spectral and temporal) then X-irradiation of secondary can be seen

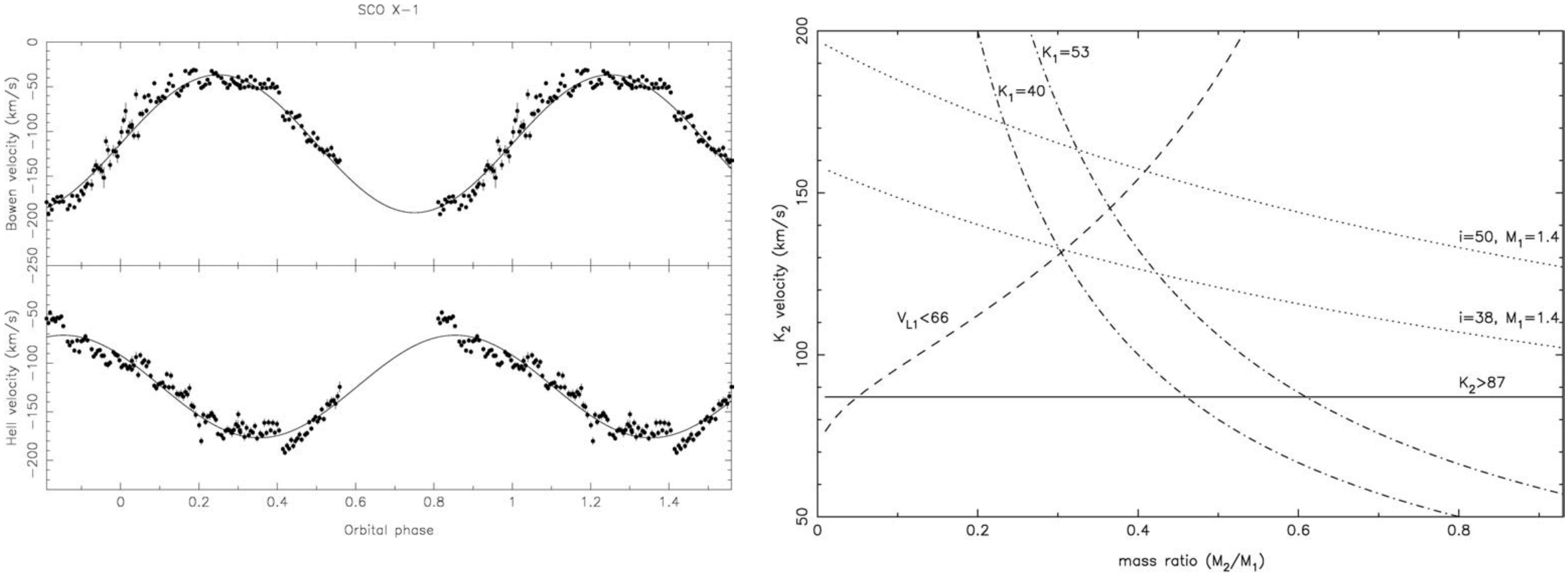




Mass of Sco X-1 (Steeghs & Casares 2001)

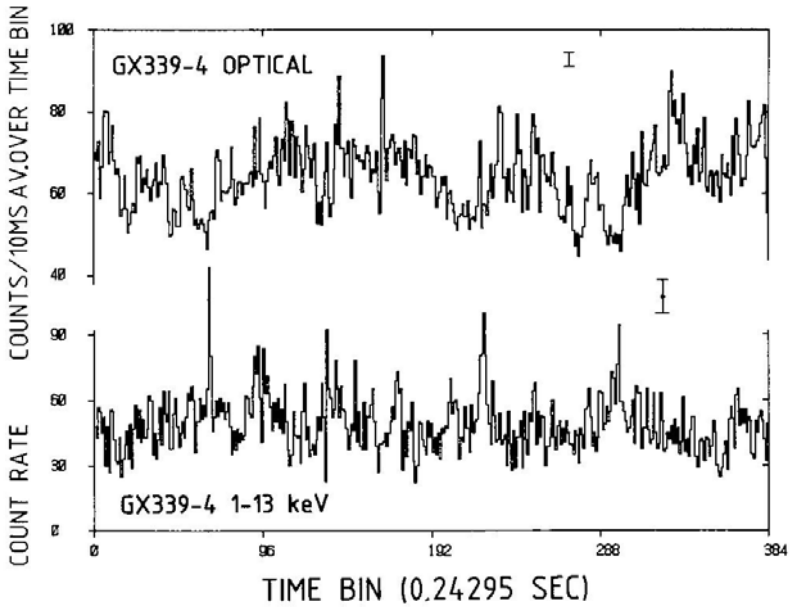


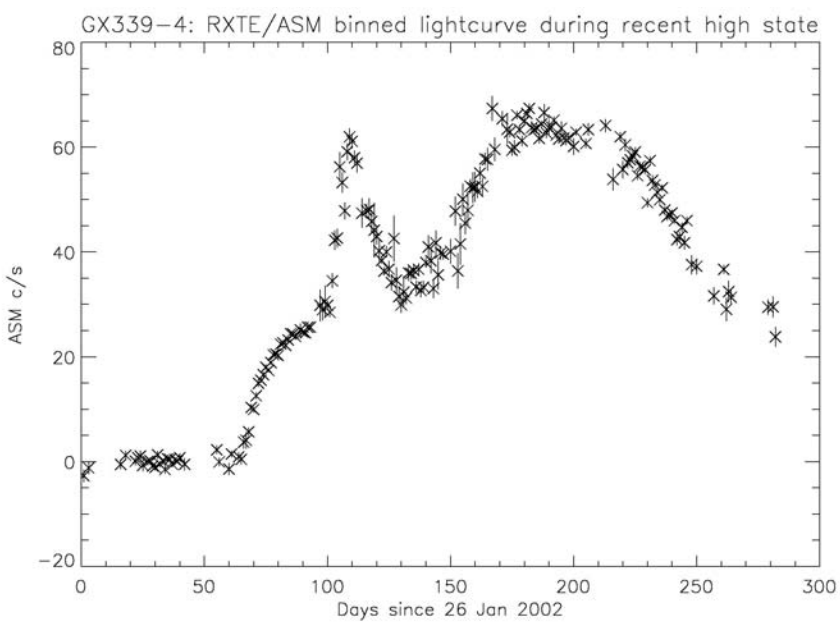




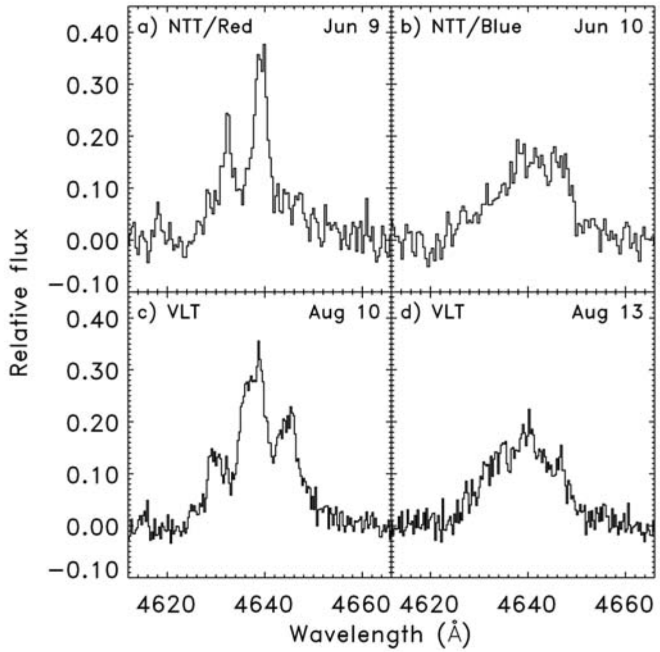
→First ever direct measurements of motion of companion in Sco X-1
→Can be used on SXTs in outburst
→Especially important for more distant or reddened systems

TOO application! GX339-4 turns back on

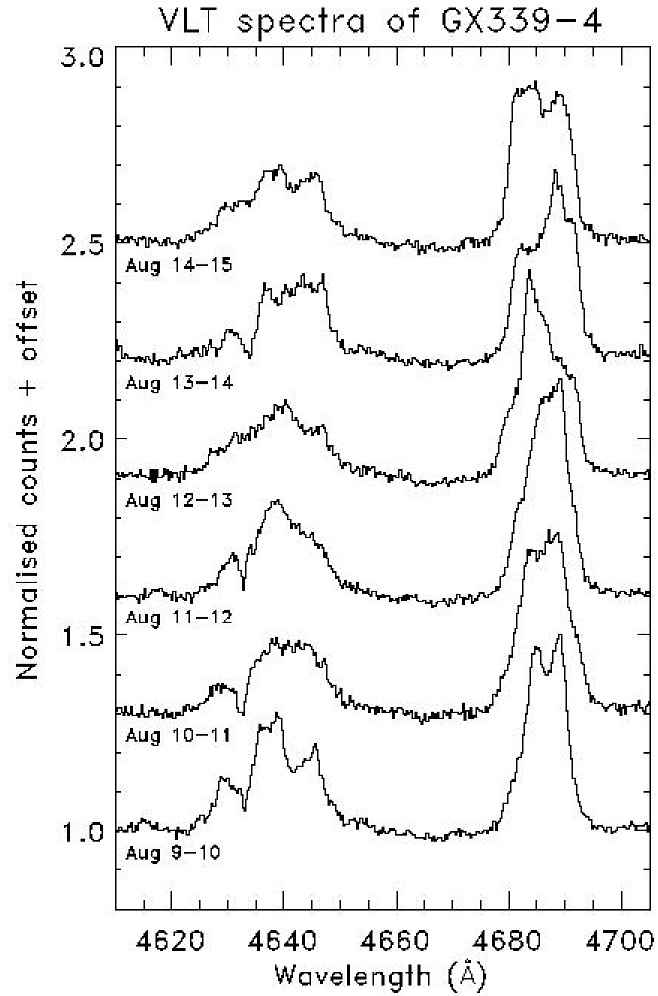


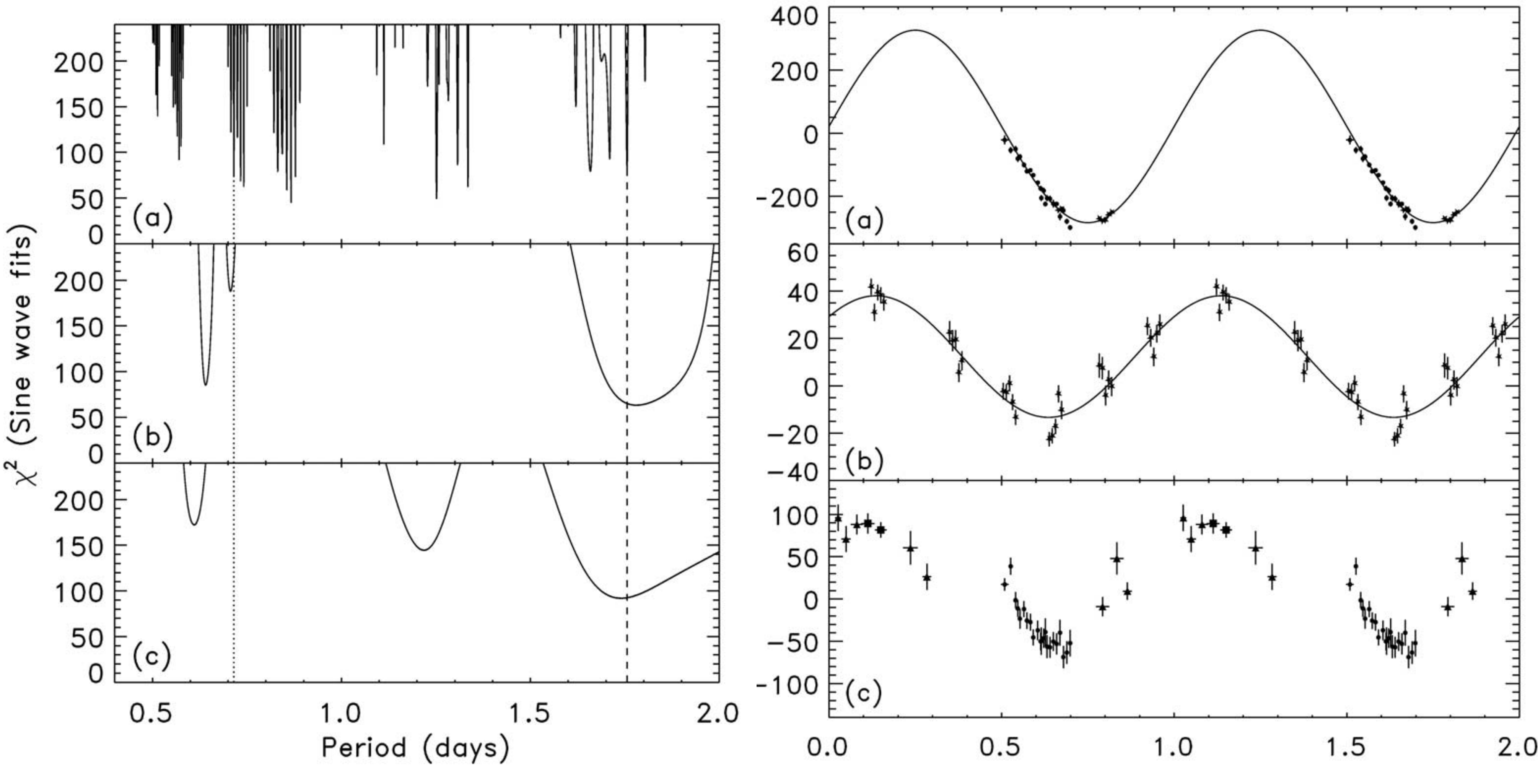


- ID'd 25y ago
- multiple X-ray states: high, low, "off" (V~15—21)
- X-ray flickering → BHC
- various P's proposed:
- 14.8hr (Callanan et al 92)
- 0.7d (Cowley et al 02)
- no secondary detected, even during last "off" state (Shahbaz et al 01)
- turned on again April 02
- → use irradiation of secondary?



NTT, VLT hi-res spectra of GX339-4
(Hynes, Steeghs, Casares, Charles, O'Brien 2002)

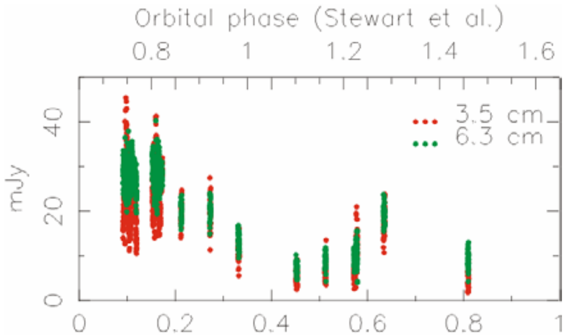




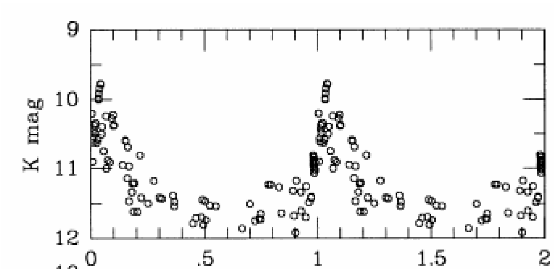
P = 1.76d → f(M) = 5.8M_O! i.e. BH as expected!

Cir X-1: An (Old/Young), (High/Low-mass) XRB

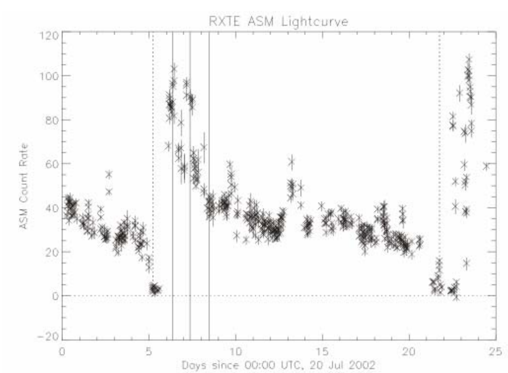
16.6 d Orbital Cycle



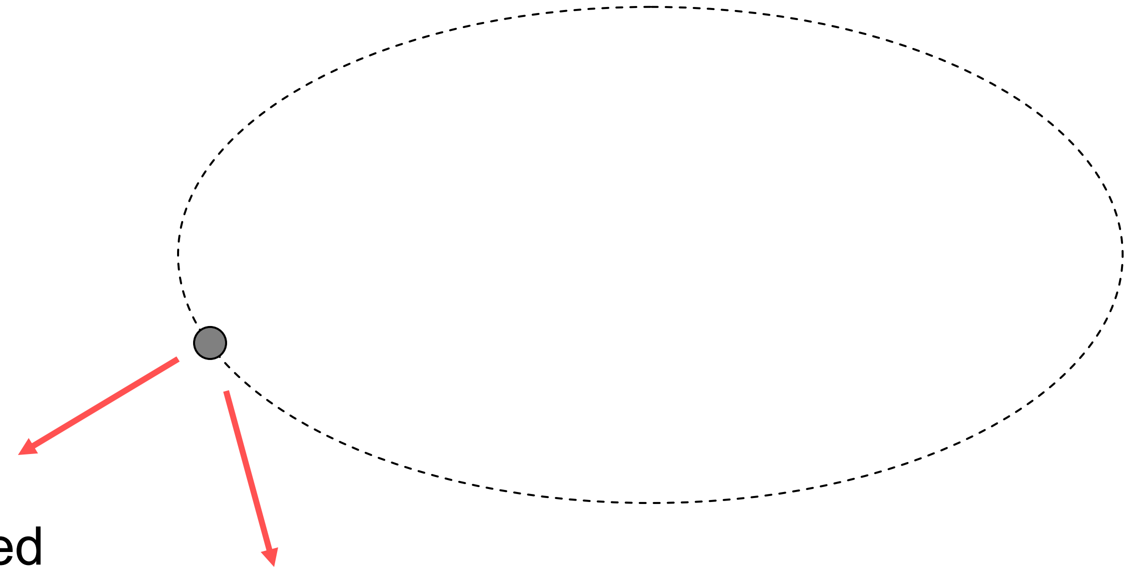
Radio



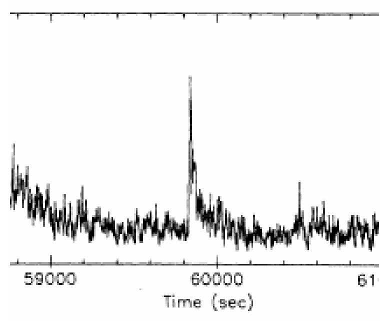
Infrared



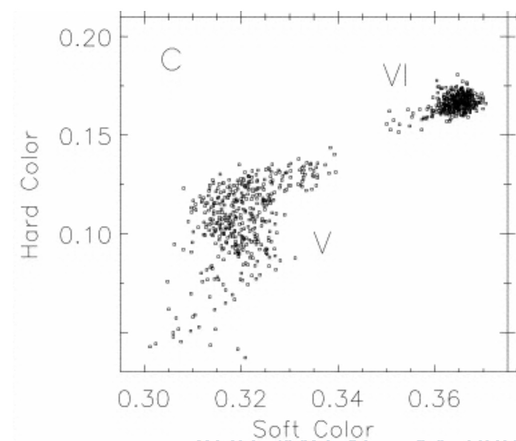
X-ray



Type I Bursts

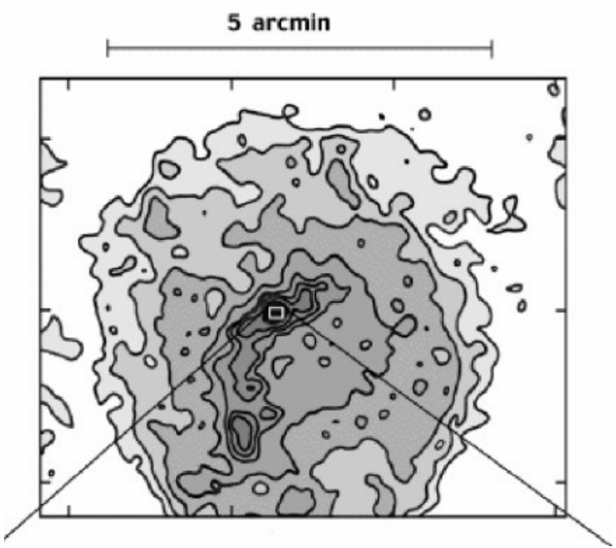


HB QPO's Present

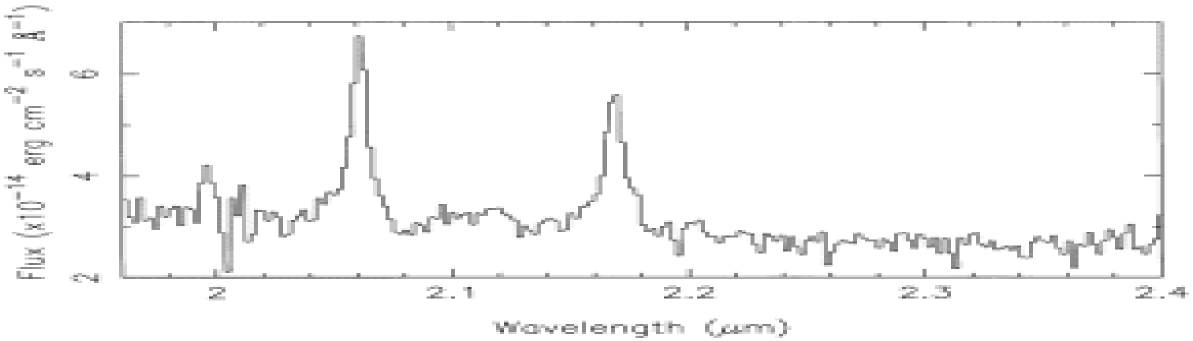


(Tennant et al 1986, Glass 1994, Fender et al 1998, Shirey et al 1998)

Evidence for outflows from Cir X-1:

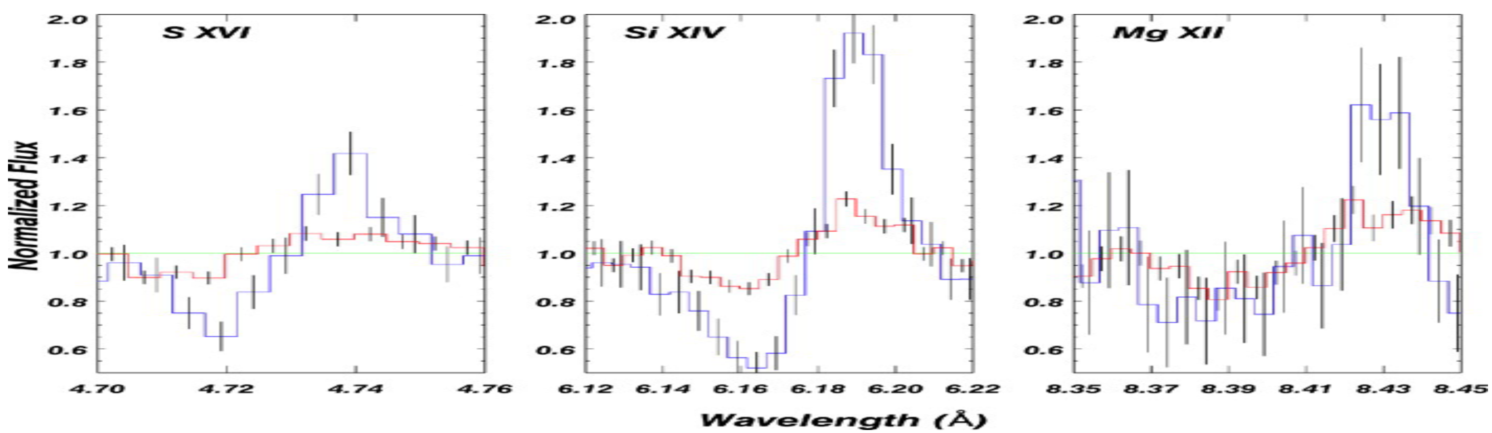


Fender et al 1998
(radio asymmetric jet, possible v~0.1c)



Johnston, Fender & Wu 1999

(strong IR emission lines, but no secondary detection)



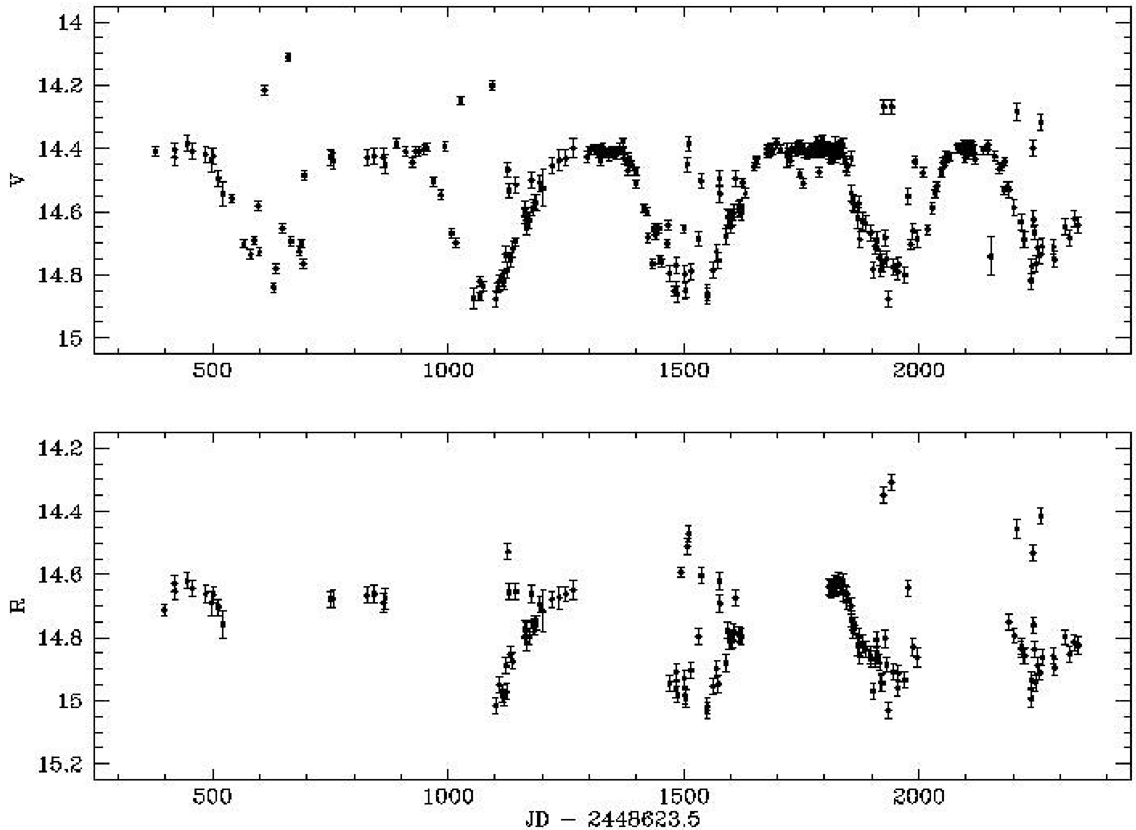
X-ray P Cyg lines (v~1-2,000 km/s)

Schulz & Brandt 2002

What is Cir X-1?

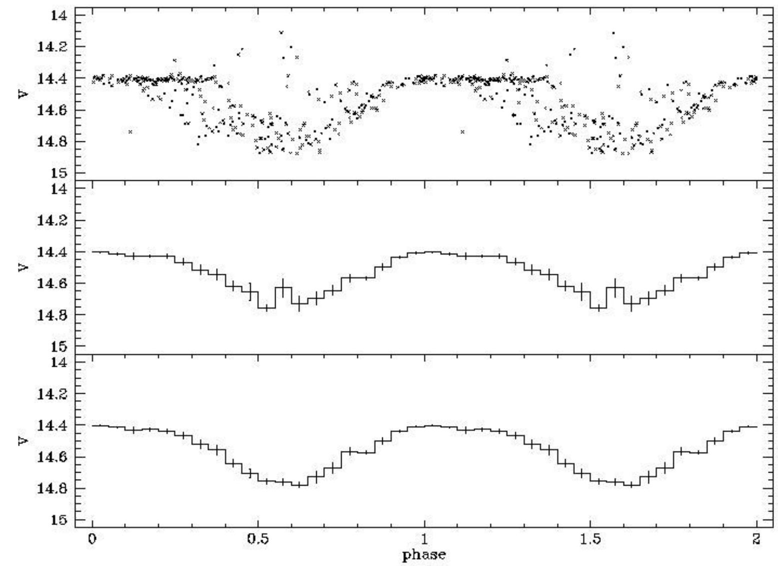
(but perhaps there are similarities with SS433?!)

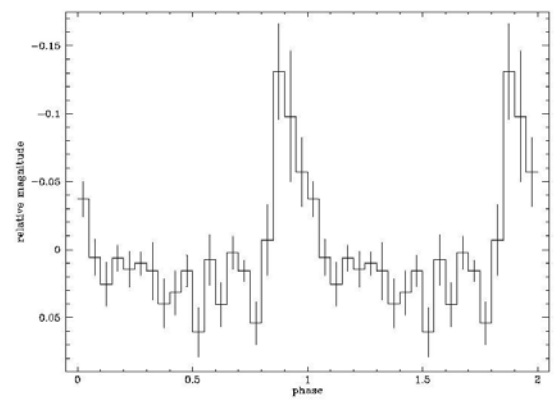
A0538-66 MACHO light curve



P_{orb}=16.6d; P_{long}=420d
(McGowan & Charles 02)

fold on P_{long}:





fold on P_{orb} (**only** during minima in 420d cycle!)

Ultra-luminous X-ray sources (ULXs)

• most luminous point-like extranuclear ULX located in nearby galaxies $L_x > 10^{39}$ erg/s

What are they ?

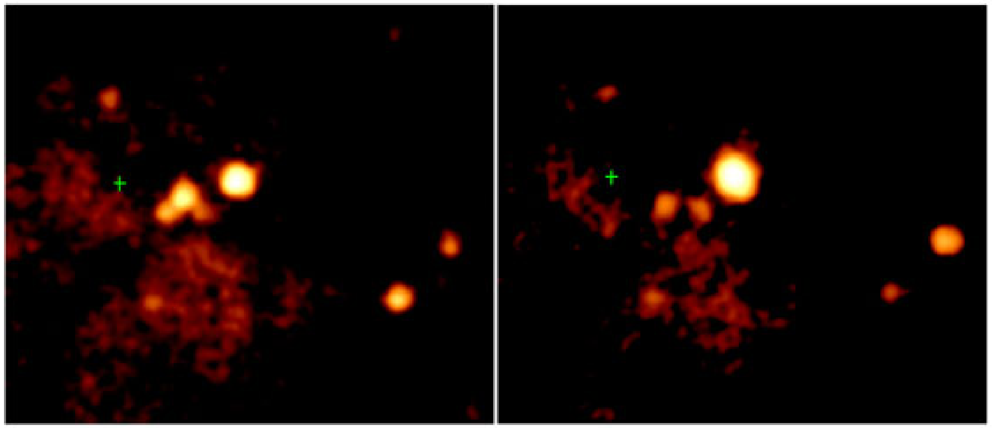
• new class of $10^2 - 10^5\ M_O$ black holes (Colbert & Mushotzky 1999)
• super-L_{Edd} from XRBs (Begelman et al 2002)
• anisotropic emission from XRBs (i.e. mild beaming; King et al 2002)

• strong association between ULX and star formation (Fabbiano et al 2001) → associated with young (HMXB) stellar systems

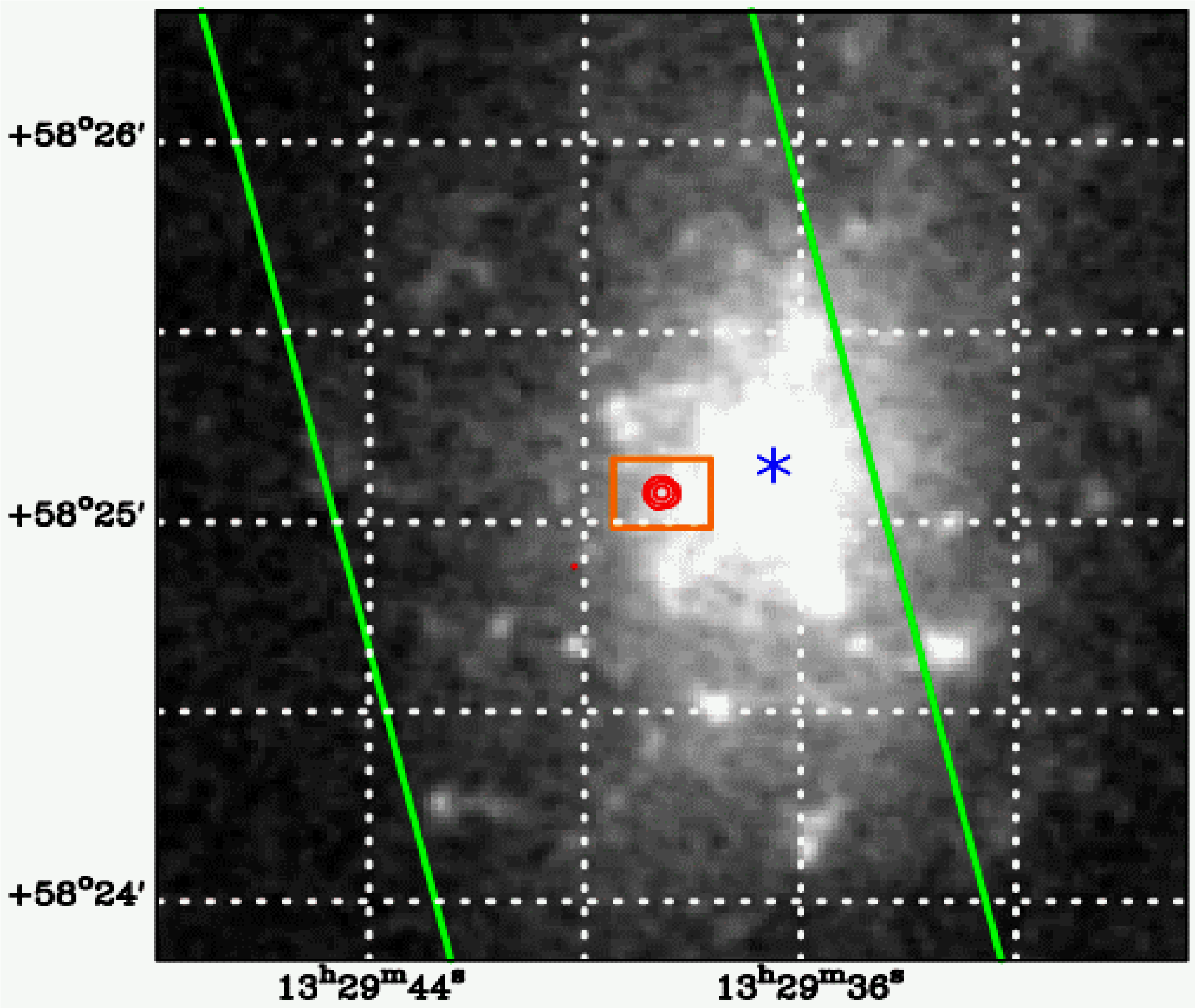
• but several ULX in nearby ellipticals → old (LMXBs) (King 2002)

Links between SXTs and ULXs?

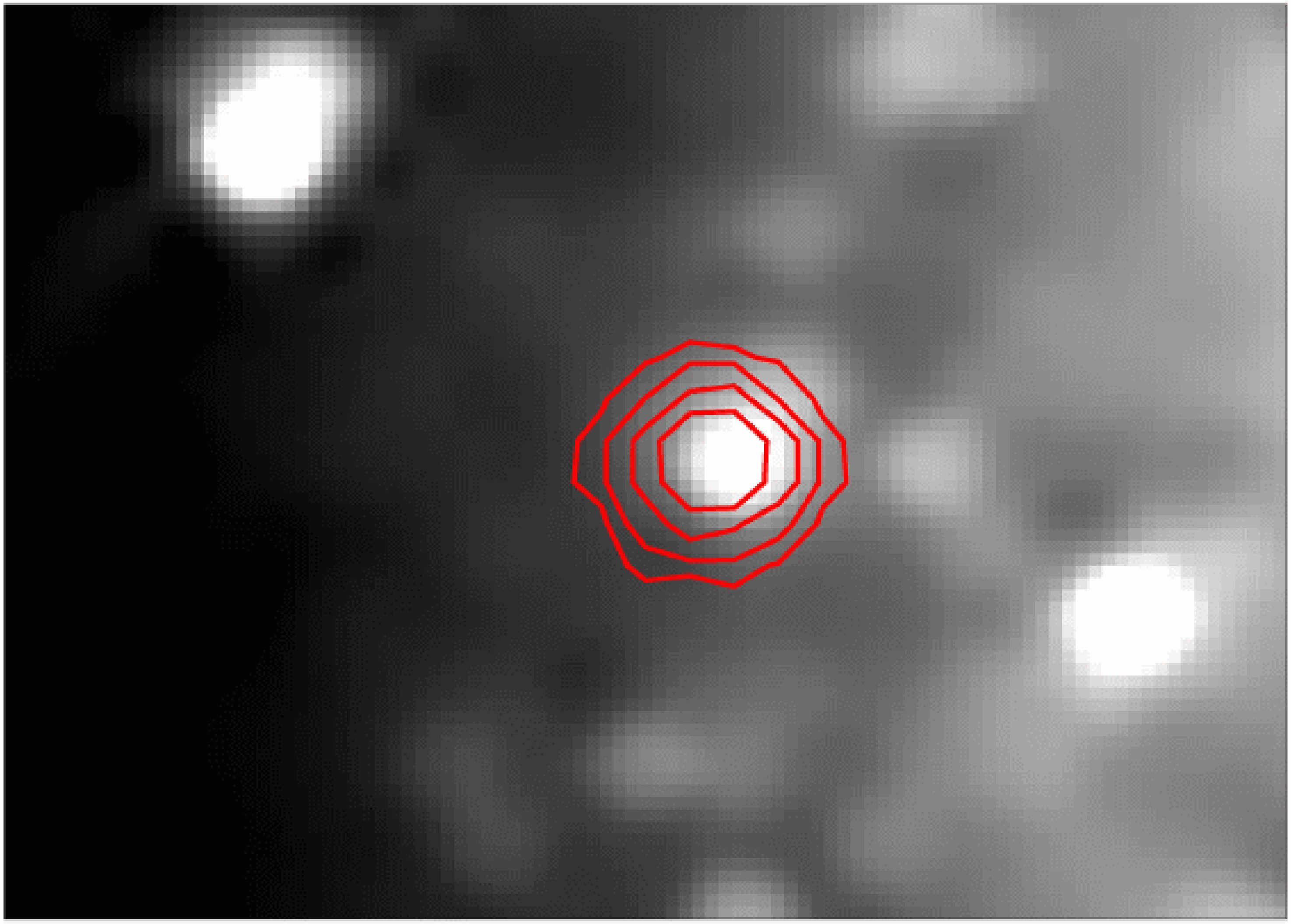
- Is GRS1915+105 our Galaxy's ULX? Heavy extinction → intrinsic L_X could be $>>10^{39}$ or even $>10^{40}$ erg/s
- ULXs in nearby galaxies (e.g. M82) are being suggested as $\sim 100 M_O$ BHs!
- Yet GRS1915+105's mass is only $\sim 15 M_O$ (Greiner et al 2001)
- But even this is lower than $33 M_O$ predicted from 67Hz X-ray QPO (Morgan et al 97) if this is orbital frequency of ISCO
- cf A0538-66 in LMC (peaks at $\sim 10 L_{Edd}$ for $1.4 M_O$ NS!)



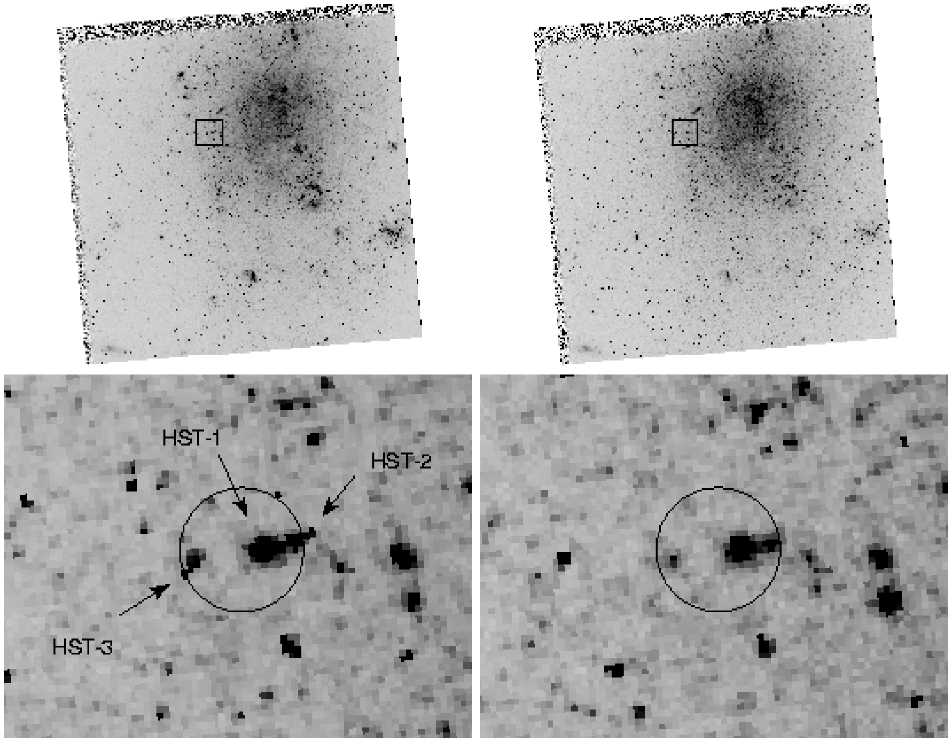
NGC 5204 X-1

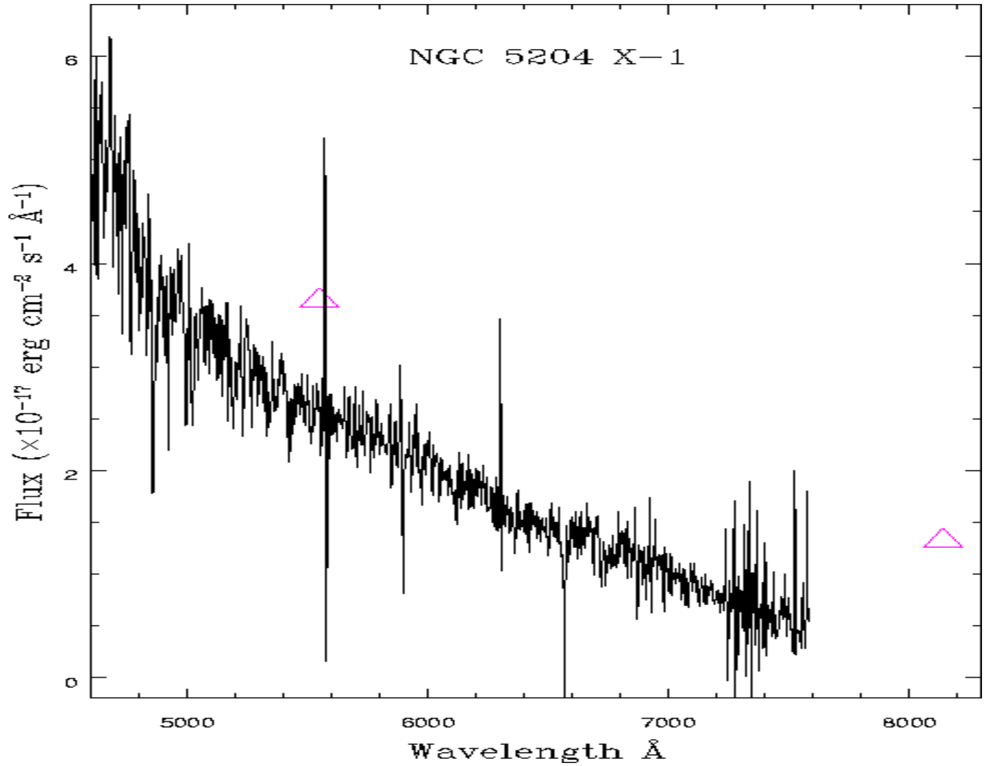


NGC 5204 X-1



WHT + INTEGRAL Red Continuum 6000 – 6200 A

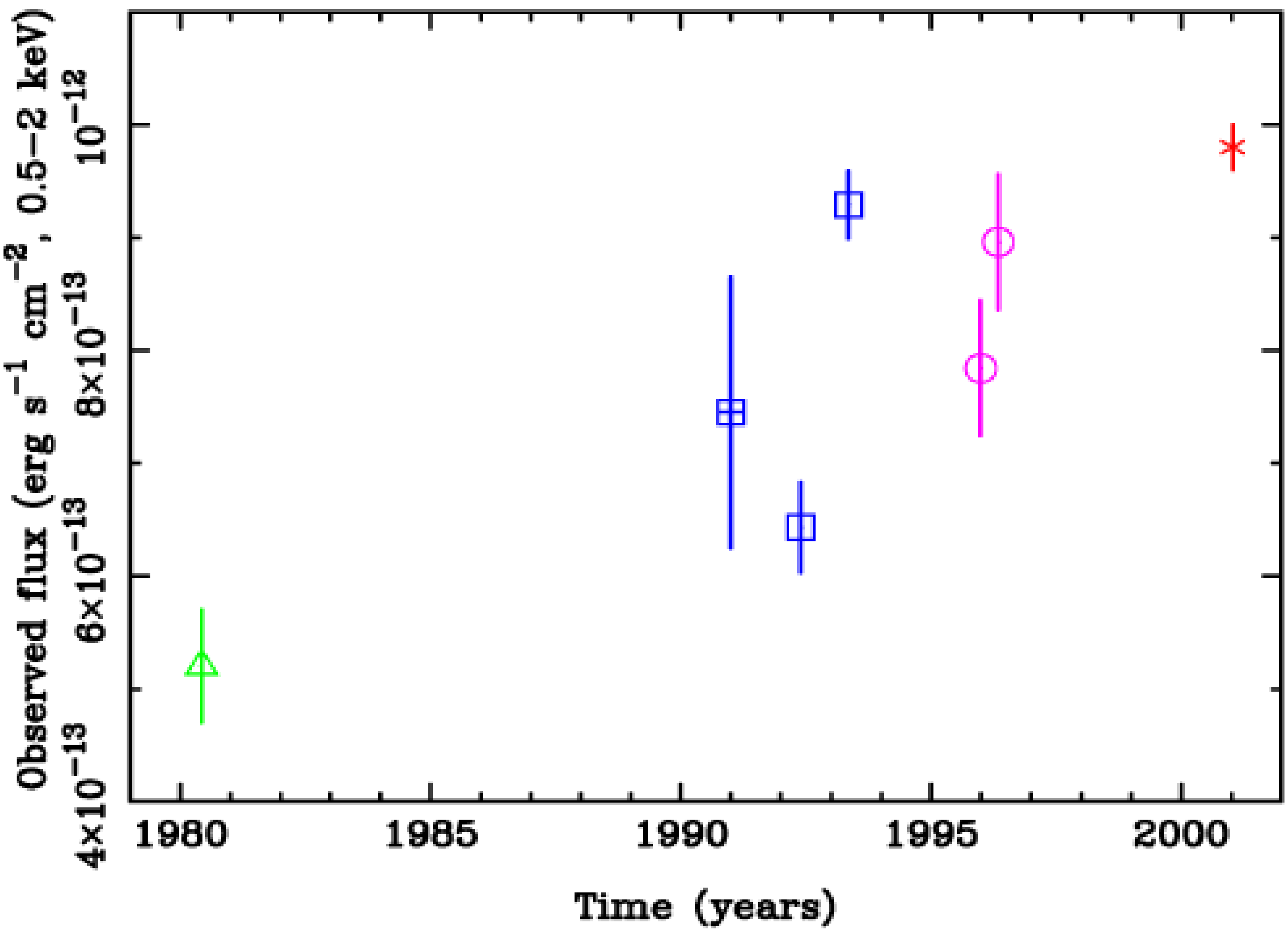




First optical ID of ULX in N5204 X-1 (Roberts et al 2001)

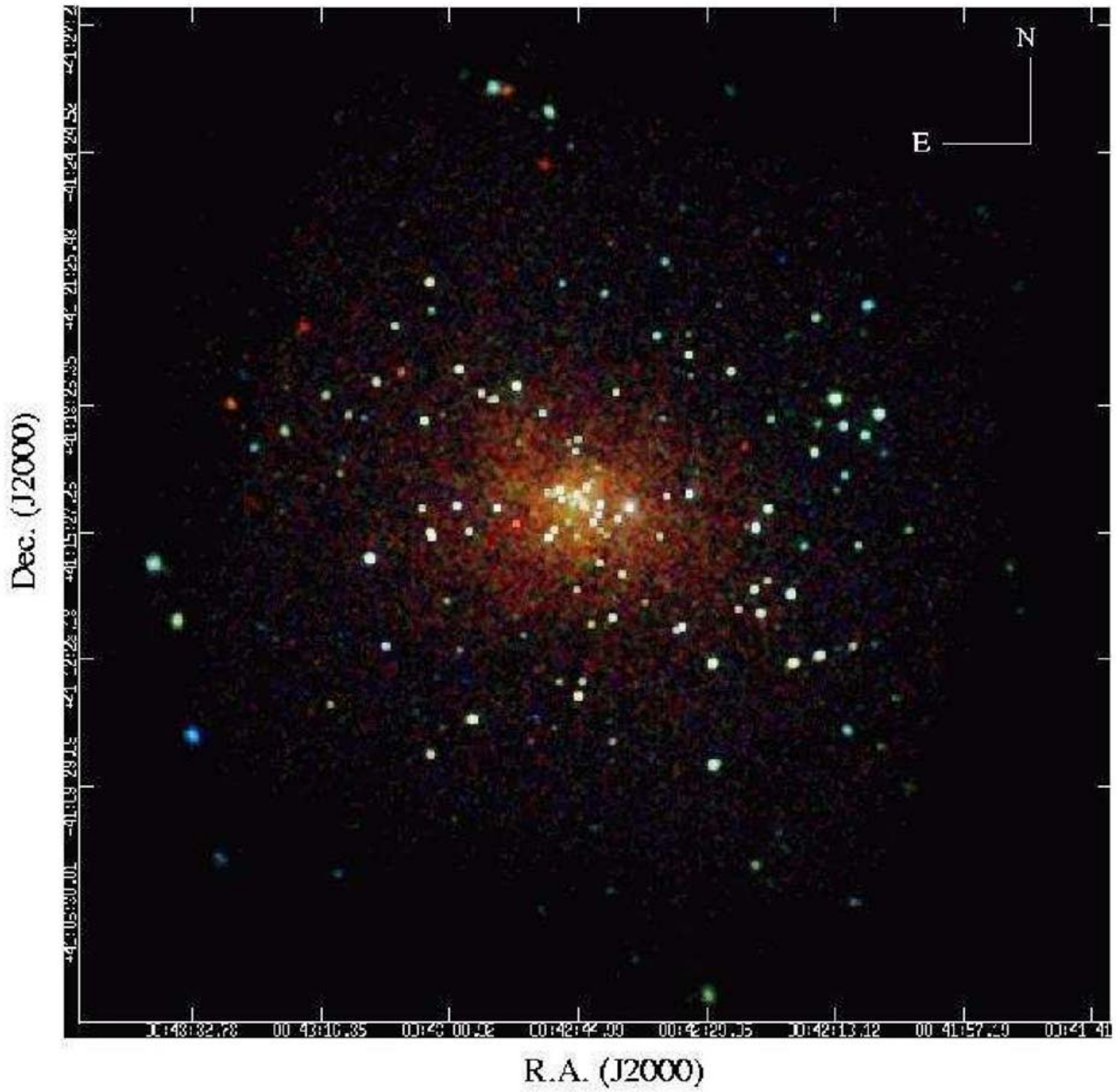
Very blue spectrum consistent with young stellar cluster ($<10^7$ yrs) (Goad et al 2002)

X-ray Variability of NGC 5204 X-1



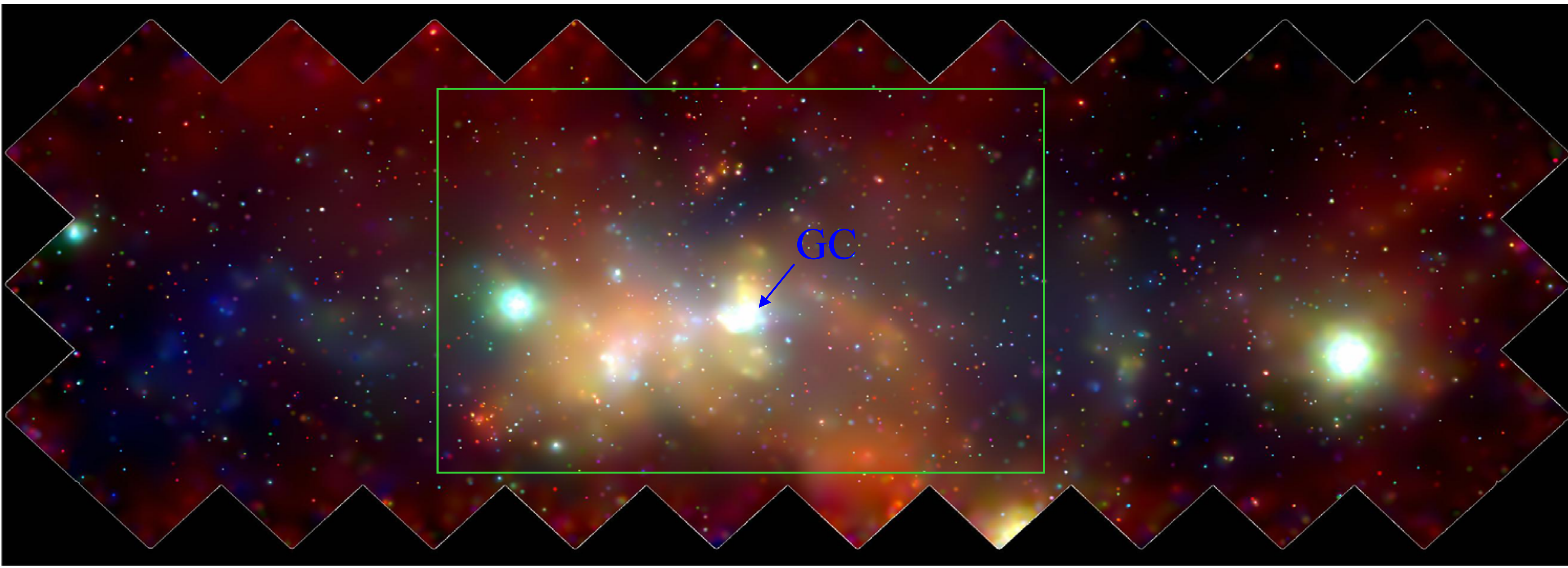
CXO/XMM work on ULXs:

- **population of extra-nuclear sources with Lx ~$10^{39\text{-}41}$ erg/s**
- **very unlikely to be 100-1000 M_O BHs**
- **alternatives: SN in dense environment or**
- **binary systems with mild beaming (e.g. King et al 2001)**
- **ULXs in ellipticals → likely 2 types (King 2002), since GRS1915+105 is LMXB**



CXO, XMM superb for population studies of XRBs in nearby galaxies (e.g. M31; Kong et al 2002)

Chandra Survey of the Galactic Center



Red: 1-3 keV Green: 3-5 keV Blue: 5-8 keV

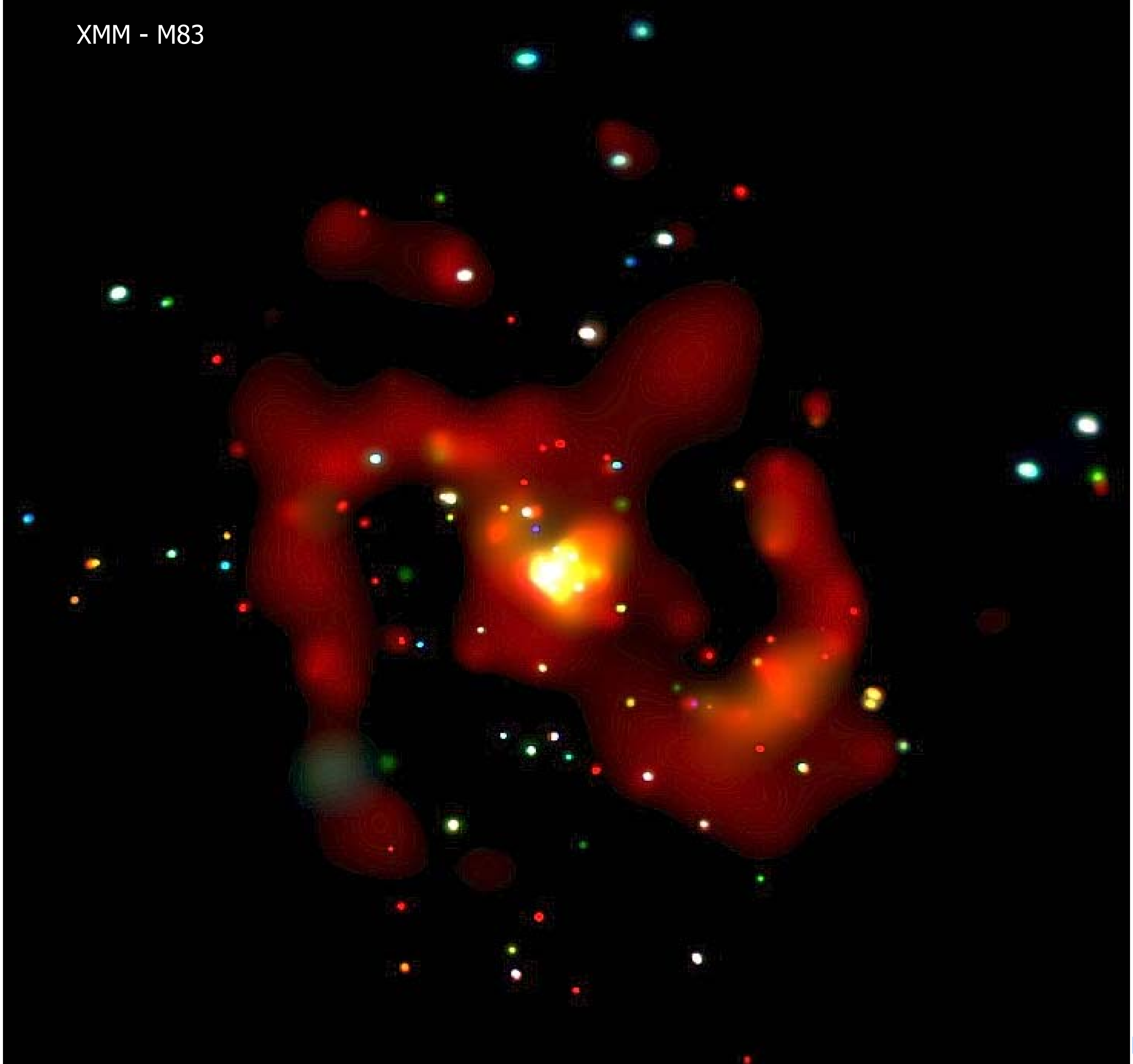
Wang et al (2002) Nature

X-RAY STUDIES OF NEARBY GALAXIES

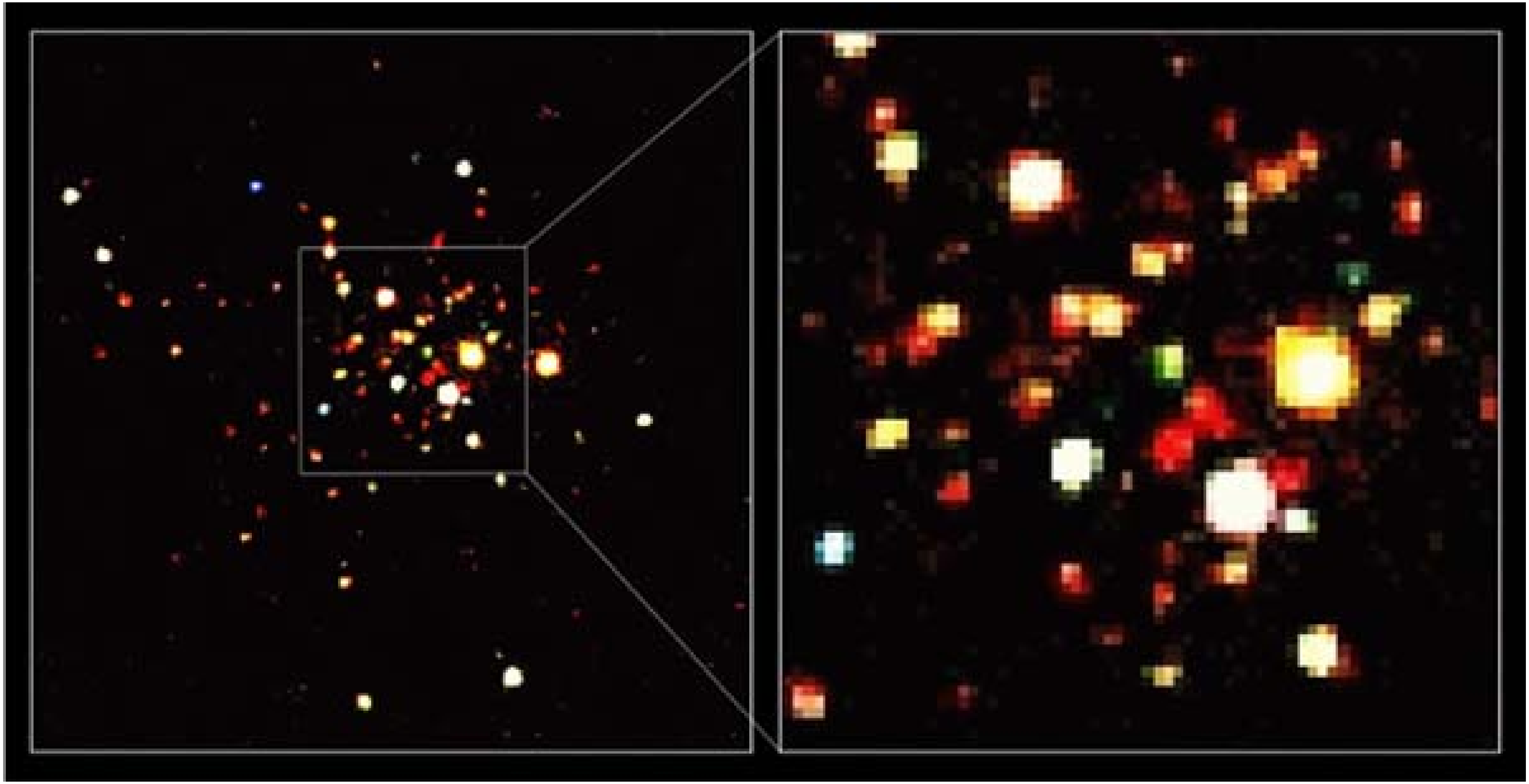
XMM ideal for faint, point sources – X-ray source population of entire galaxy (compact binaries, SNRs, diffuse emission)

(see Soria et al 2002)

Case study: M83 (d ~ 4 Mpc)

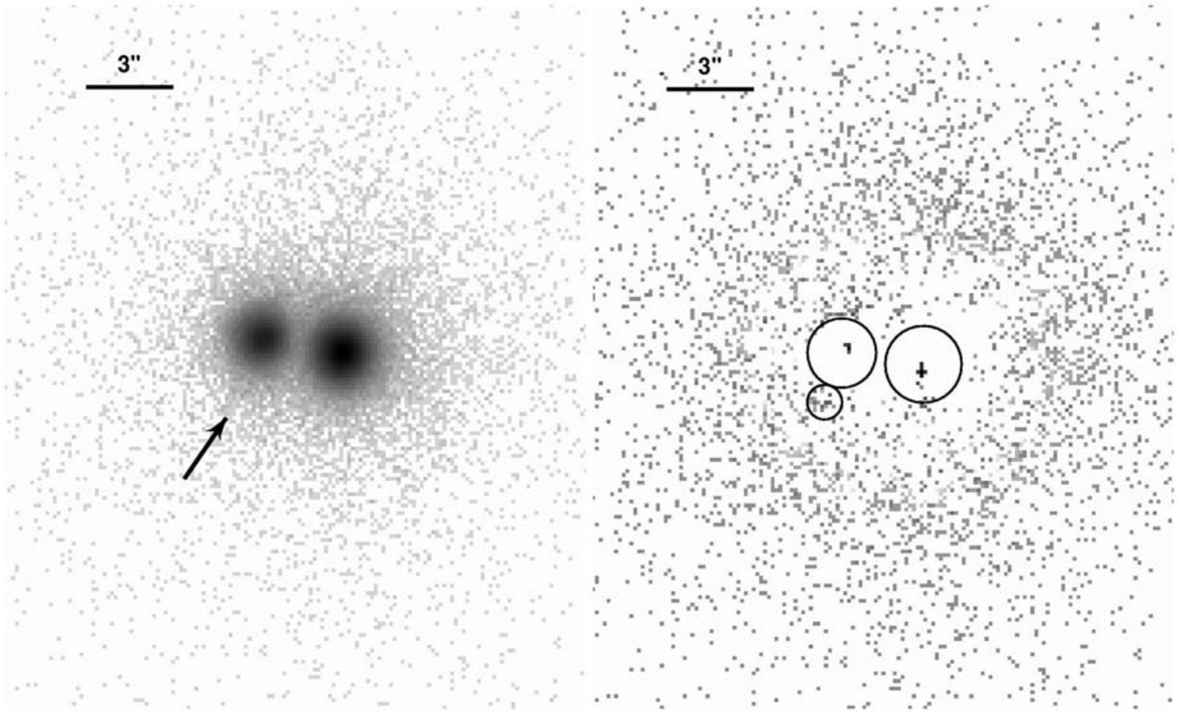

XMM - M83

X-ray source populations in globular clusters



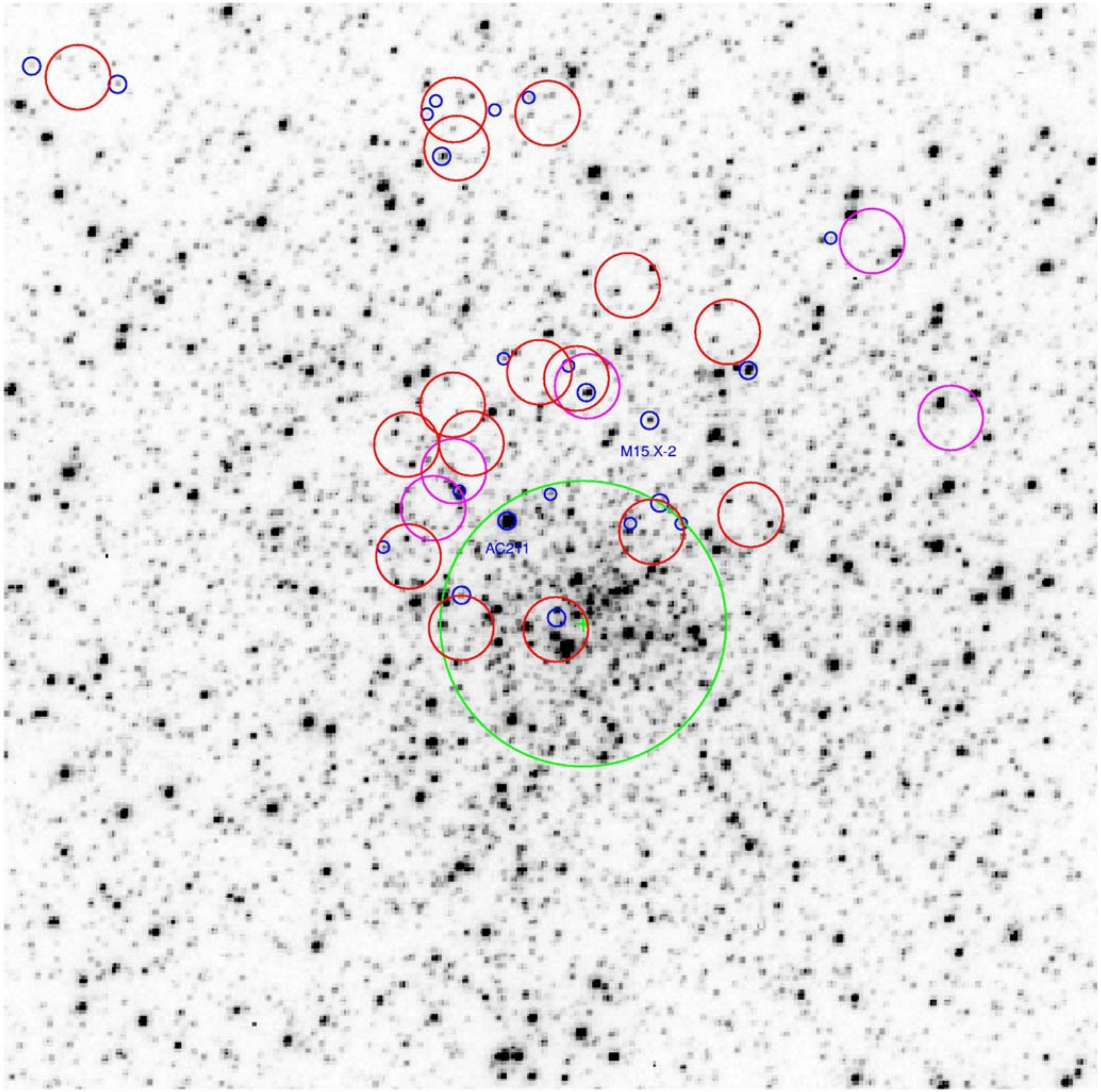
47 Tuc (Grindlay et al 2001)

HRC image of core of M15:

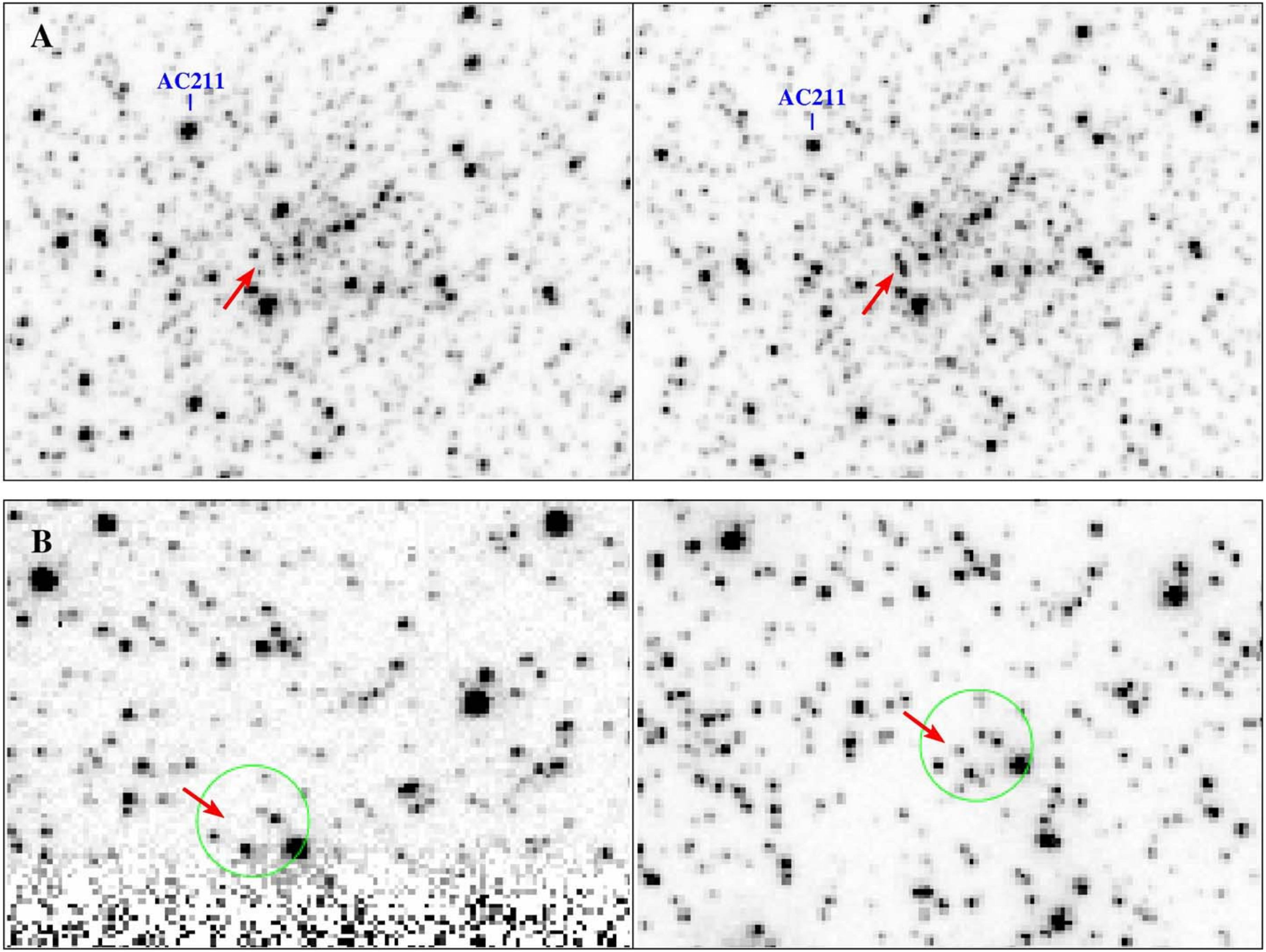


(from Hannikainen, Charles, van Zyl, et al 2002)

X2127+115 (P=17.1hr) ADC source
(White & Angelini 2001; Charles, Clarkson & van Zyl 2002)



HST U image of M15


A
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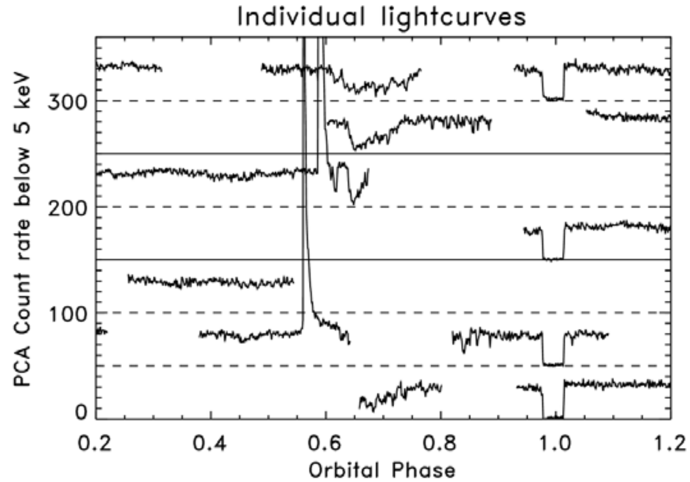
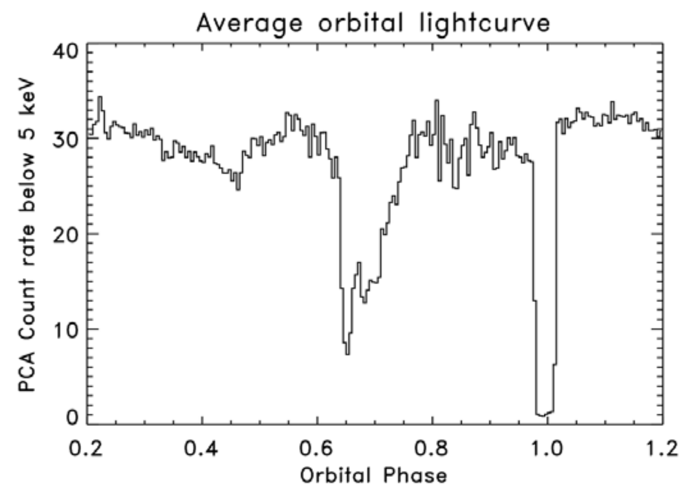
B

High i LMXBs ideal for studying disc structure

- Variable accretion disc geometry first seen in Her X-1
- 35d X-ray on/off cycle due to tilted/precessing disc (in 1.7d orbit) (established in mid-70s!)
- X-ray irradiation-driven models from Wijers & Pringle, Dubus & Ogilvie (important for AGN!)
- Expect disc precession in high q systems (cf superhumps in SU UMa systems in superoutburst)
- Observe these effects in X/opt with short P e.g. 0748-676

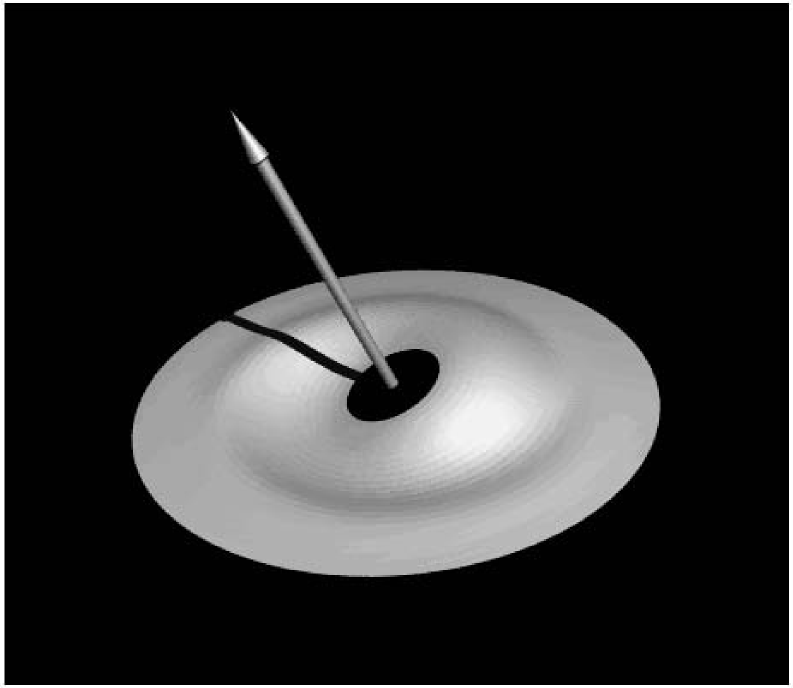




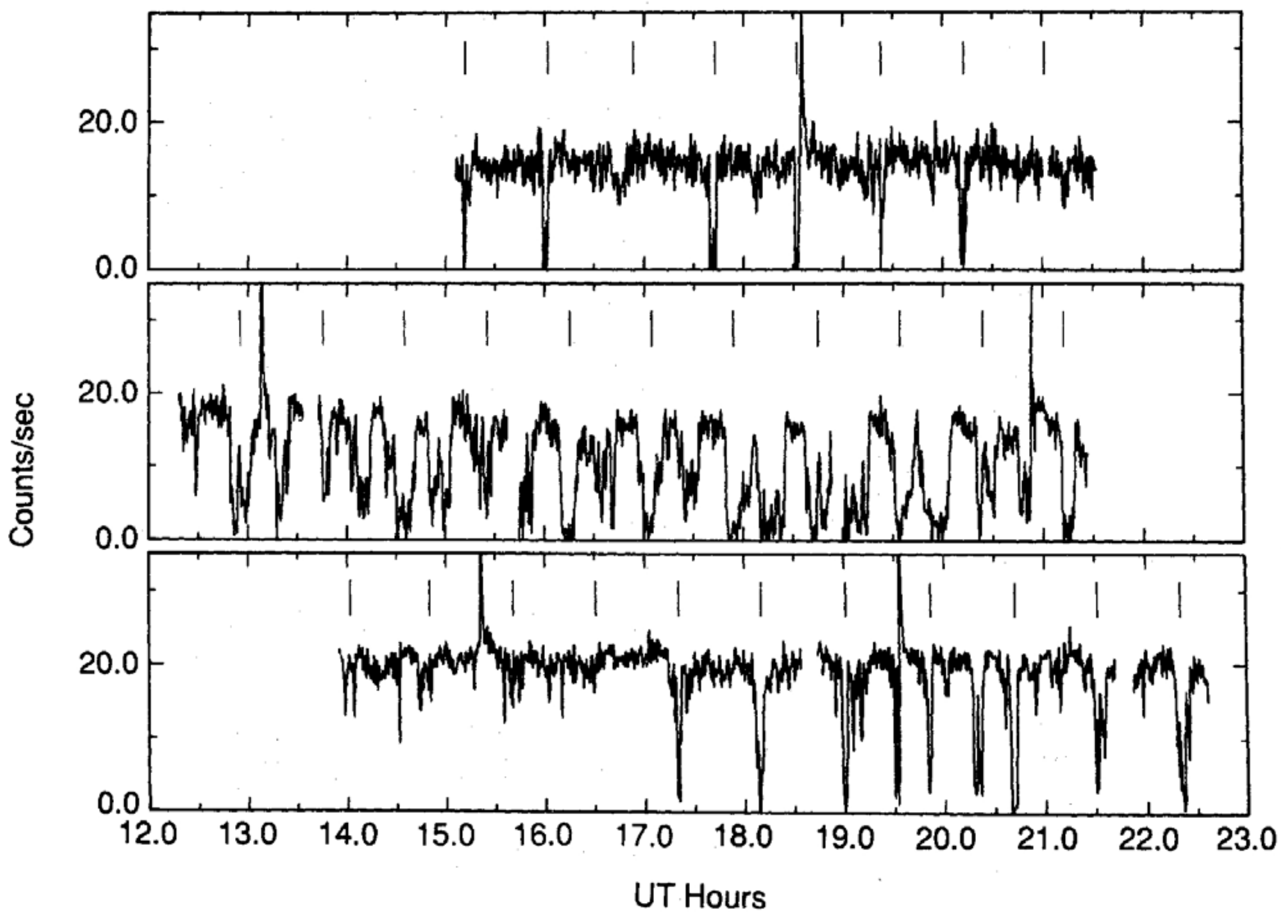
Earliest evidence for disc precession

Her X-1 discovered in early 70s to be "on" for only ~12 days out of every 35 days!

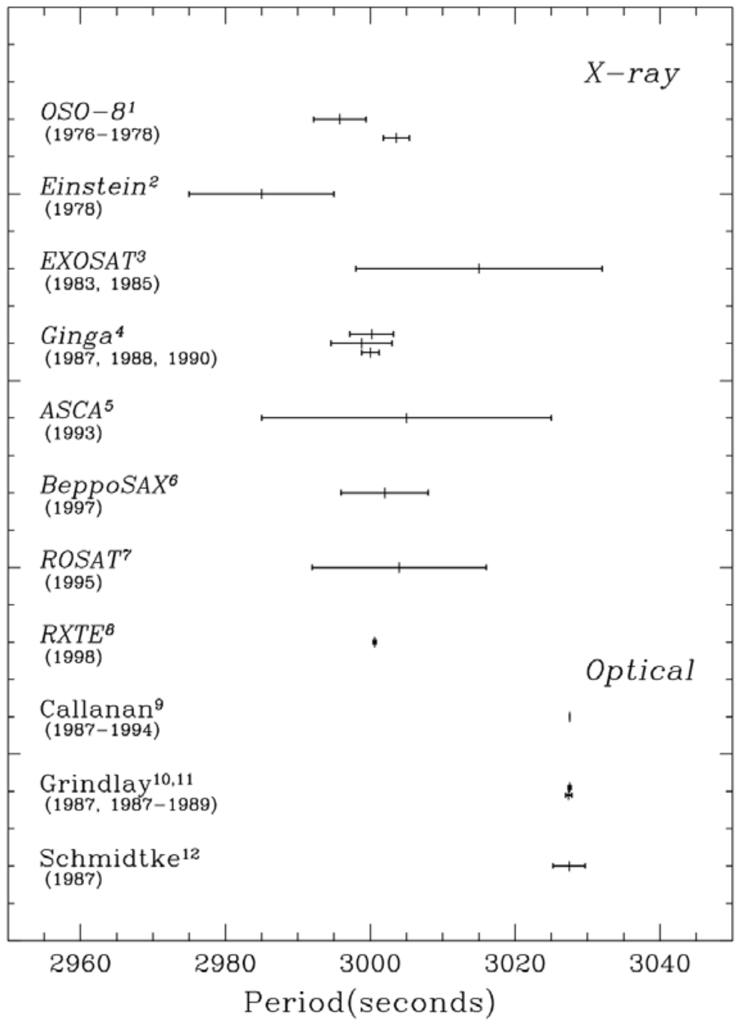
Explanation: tilted, precessing disc (Petterson 1975 ApJ)

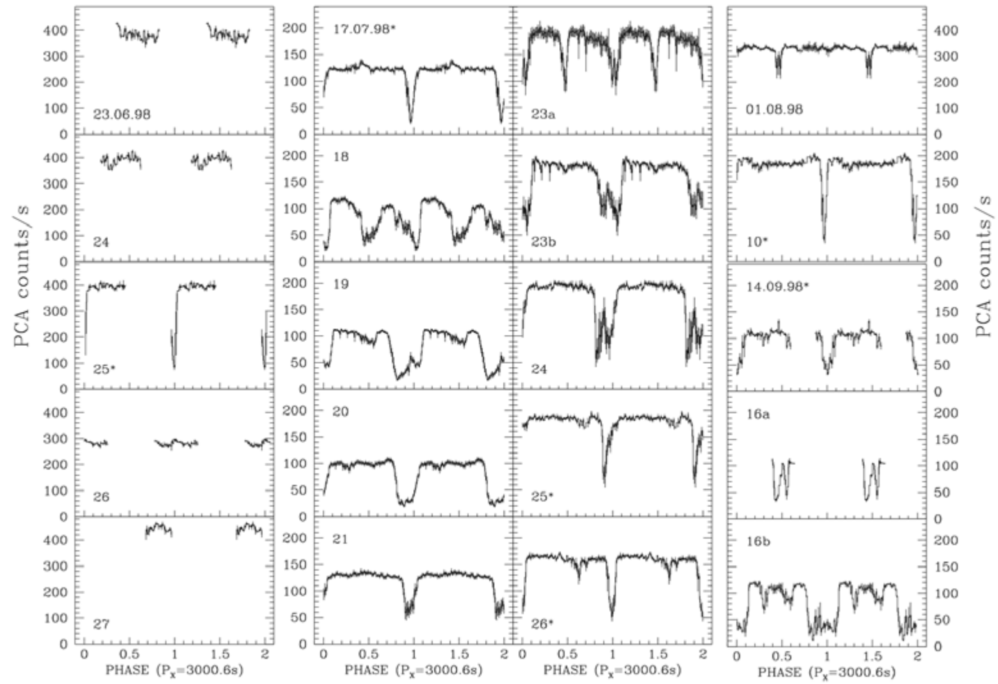


EXOSAT light curve of X1916-05



X1916-05: 50 min double degenerate LMXB





Superorbital variations in XRBs

- RXTE All-Sky Monitor (ASM) operating 1996-present
- ~10 “dwells” per day per source
- Daily averages posted on MIT RXTE web site (rxte.mit.edu)
- Perfect for studying nature of long-term variations in bright X-ray binaries
- Perform ~300d running-average periodogram
- E.g. Cyg X-2 (luminous LMXB)

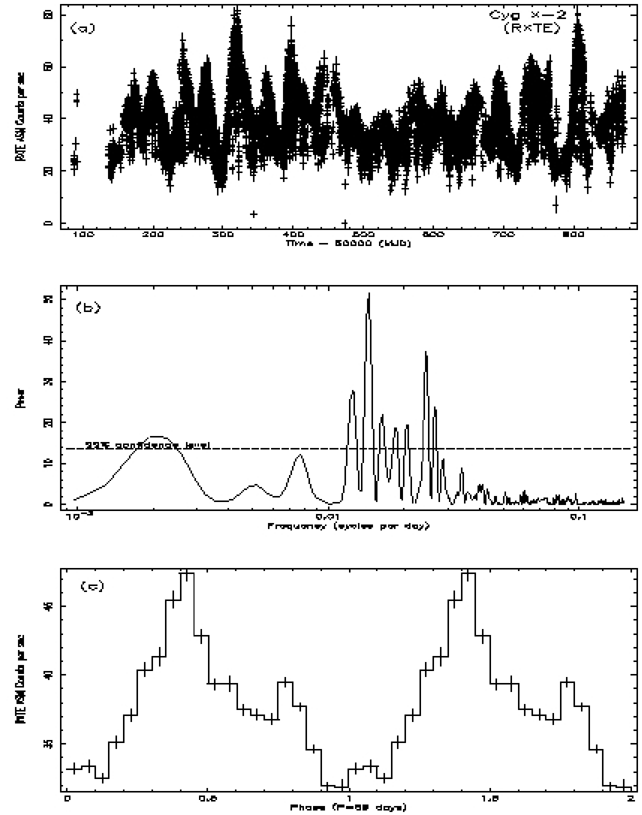
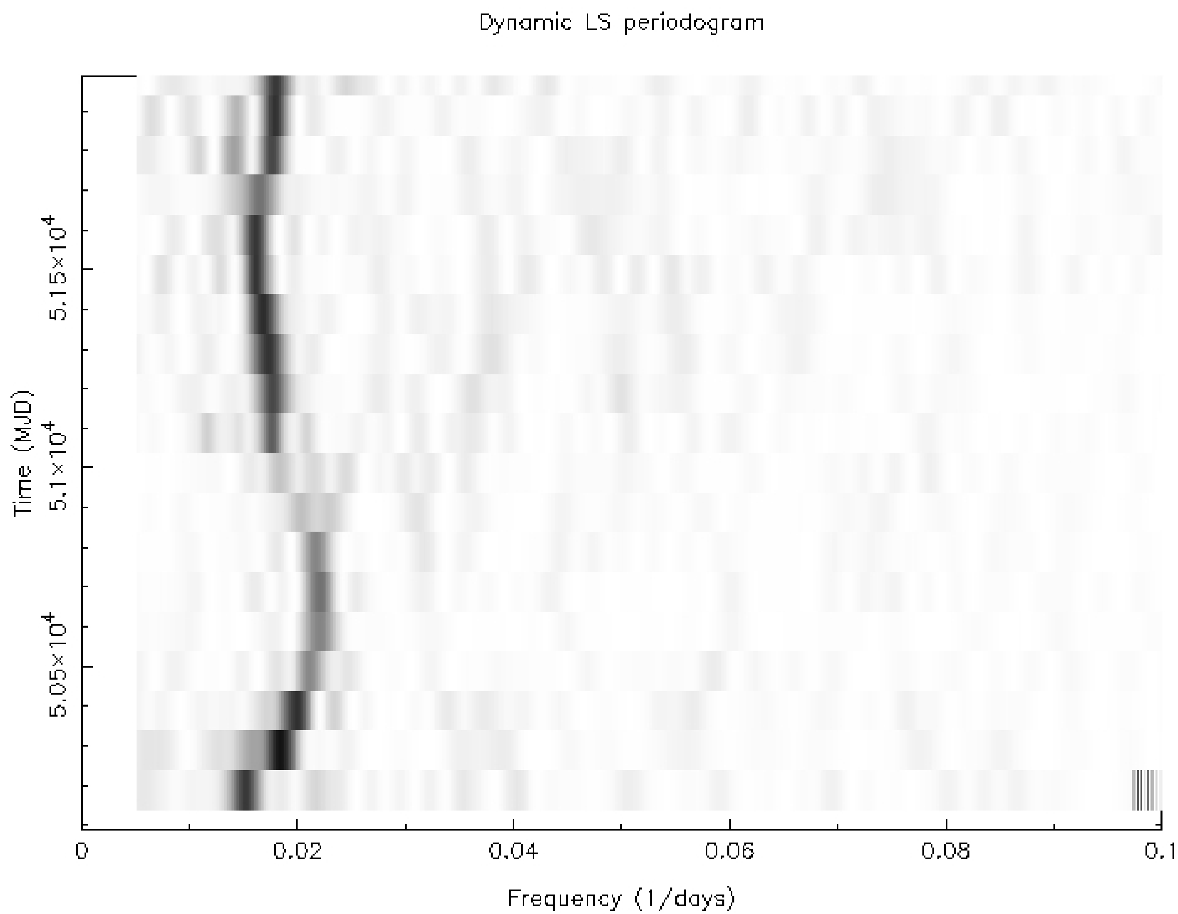


Fig. 3. a) *RXTE* ASM light curve of Cyg X–2 from 1996 February to 1998 February. b) Lomb-Scargle periodogram of the *RXTE* ASM data on Cyg X–2 showing a strong peak at ~ 69 days. The 99% confidence level is shown for reference. c) Folded light curve of the *RXTE* ASM data of Cyg X–2 with period 69 days. Phase zero is arbitrary set at the time of the first data point (JD2450087.8)

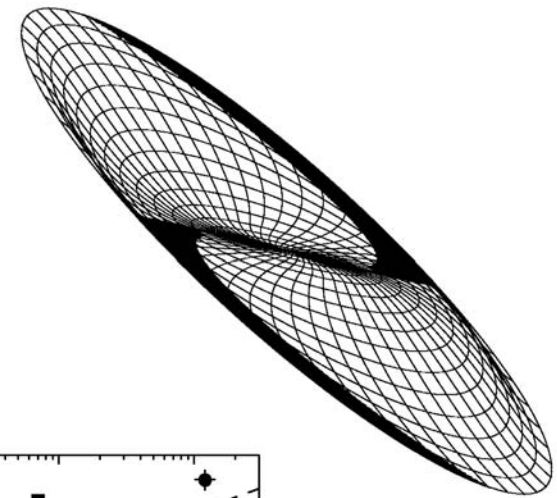
Superorbital variations in XRBs

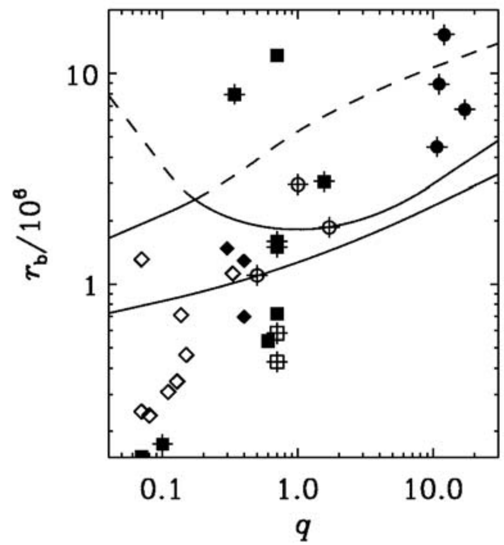


- But SMC X-1 (0.7s X-ray pulsar in 3.9d orbit about B0I primary) has "moving" ~60d variation (cf Her X-1?) (Clarkson et al 02 MN)

Irradiation-driven warping

- Ogilvie & Dubus 2001 MN → applied irradiation calculations to follow stability of disc as a function of component masses and separation
- Showed that there are regions where disc warping is expected (e.g. Her X-1, SMC X-1)
- But change in period was not expected!





Future XRB research areas:

- SXTs in quiescence and outburst for BH/NS accretion physics
- Simultaneous X-ray/GB spectroscopy of quiescent SXTs to locate emitting regions → constrain size of inner disc and hence nature of quiescent accretion flows (possible with CXO/XMM e.g. J2123-058 – partially eclipsing)
- INTEGRAL γ-ray spectroscopy of outburst SXTs to determine nature of the 500keV "annihilation" feature (redshifted 511keV; Li spallation; jet features)
- Search for X-ray emission lines predicted by ADAF models (Narayan & Raymond 99)
- Relationship to ULXs? (HST)
- Theory of disc precession/warping