X-ray processes in compact Galactic objects

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- Background
- Continuum
- Line spectra

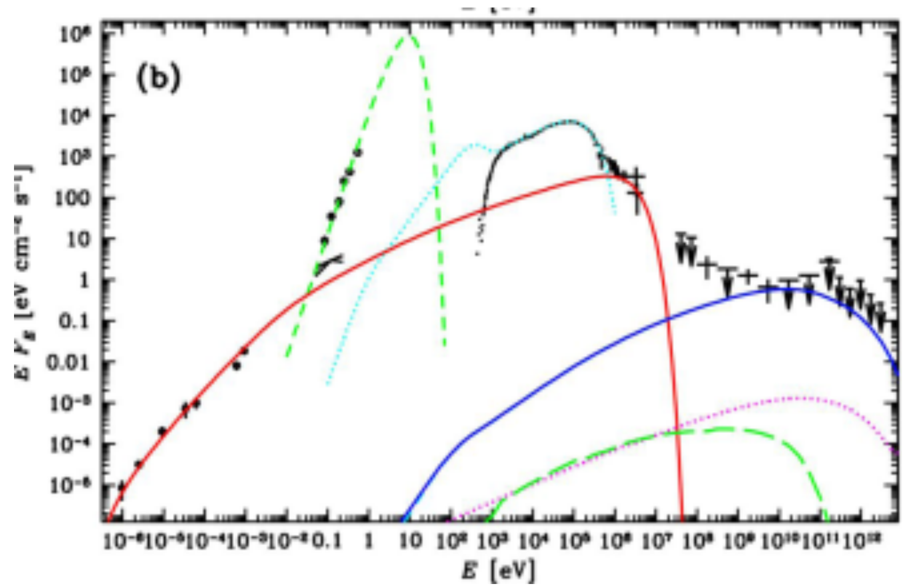
What are compact galactic objects?

- X-ray binaries
  - High mass; sfxts, be binaries, gamma-ray binaries…
  - Low mass: Black hole transients, bursters, accreting pulsars, ns transients….
- Cataclysmic variables,White dwarfs,novae …
- Radio/gamma ray Pulsars, isolated neutron stars
- A big subject, with many pieces that I do not know…
- this talk will be part journal club, part research note..
- I will concentrate on low mass X-ray binaries with black holes, but some results are applicable to other sources
- ‘If you ask me anything I don’t know, I’m not going to answer’ (Yogi Berra)

General properties of LMXBs and other accreting compact sources

- $L_x \sim 10^{38}$ erg s^{-1} → accretion powered
- Spectra ~ power law with cutoff >10 keV → emission mechanism
- Variability on timescales $>10^{-3}$s → size < 10^{7} cm
- Distances > kpc
- Binaries with periods <days → size < 10^{11} cm

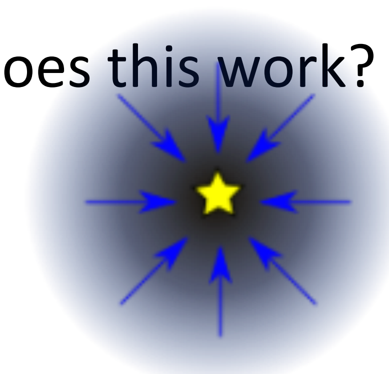
Broad band spectral energy distribution of Cyg X-1 in the hard state



(Zdziarski et al. 2014)

What is the emission mechanism?

- Accreting gas must convert its kinetic energy due to infall into light, X-rays
- Radial infall + larmor formula → very small emission
- The infalling gas must get thermalized somehow
- Simple virial arguments predict that $T > 10^{10}$K for $R \sim 10^6$ cm
- The details are uncertain; what can we tell from observations?
- Early spectra looked like bremsstrahlung. Does this work?



A simple model: bremsstrahlung from a uniform sphere of hot gas

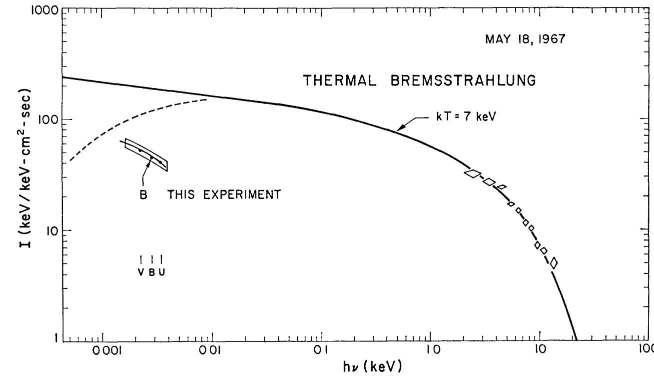
- Very Early data from eg. Sco x-1 was fit to bremsstrahlung emission from a uniform sphere of gas, T~10^8K

$$L = \frac{4\pi}{3} R^3 n^2 \sigma v k T$$

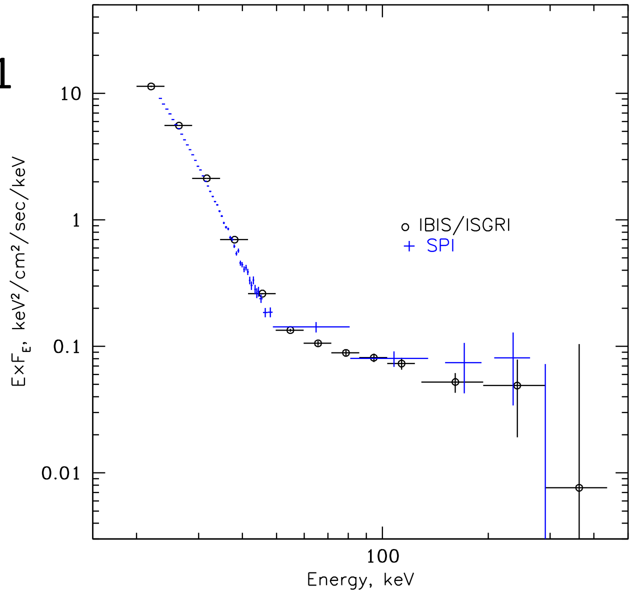
n=gas density, σ=brems cross section v=thermal speed

Works if n=$10^{11.5}$ cm^{-3}, R=10^{11}cm

- But does not allow for size implied by variability
- And, if R=10^6cm and n satisfies the constraint on L, then the optical depth to free-free absorption at ~1 keV is not small.
- → This is a generic problem for processes which scale in this way
- And in fact Sco X-1 can show much harder tail



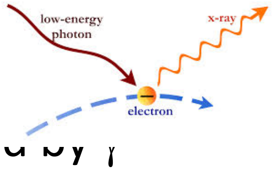
Chodil et al. 1968



(Revnitsev et al. 2014)

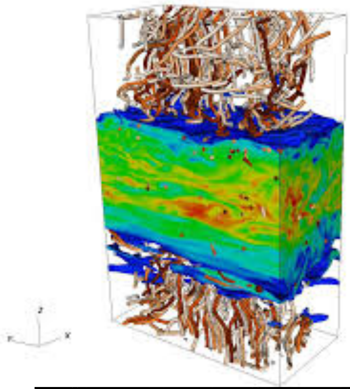
A better model: compton scattering

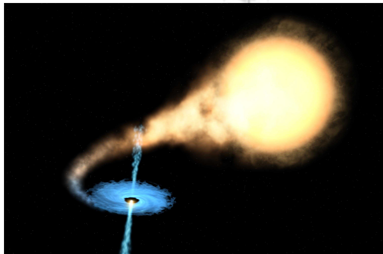
- Compton scattering of soft seed photons from energetic electrons
- Boosts photon energy by a fraction~kT/m_ec^2 per scattering in the electron rest frame
- what if the electron is relativistic?
  - Then the electron sees the flux of incident seed photons boosted by γ
  - and the energy of the photons in the lab frame is boosted by another power γ due to the motion of the electron



$$L \rightarrow L\gamma^2$$

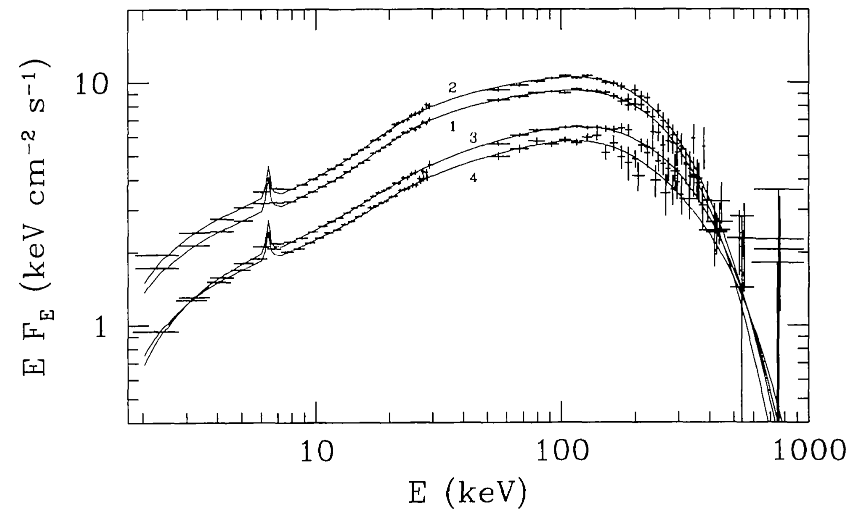
- This helps a lot
- But it's a bit surprising: accretion → relativistic particle comptonized spection
- and more likely is an mhd disk: accretion → dynamo+n field → particle acceleration → comptonized spection
- And synchrotron emission is also possible





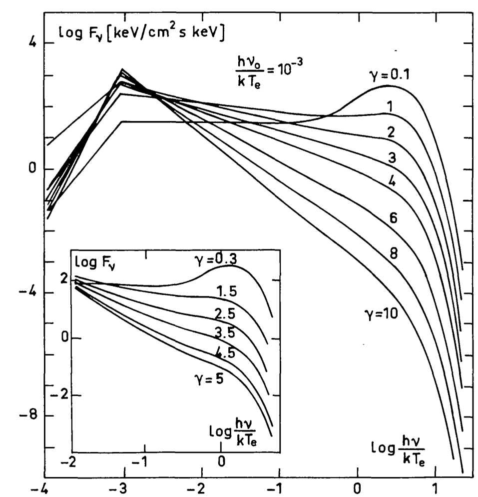
Hard state Spectra of black hole candidates fit to Comptonized model

Fit of broad band hard state
X-ray spectrum of Cyg X-1
to Comptonized model



Gierlinski et al. 1997

- Model depends on the extent of the Comptonization and the temperature of the electrons
- Parameterized by $y \sim \tau^2 T$
- For small y a high energy tail is created
- For large y a thermal peak is created near the kT of the electrons.



Sunyaev and Titarchuk 1980

$\gamma = \pi^2/3(\tau^2\, kT/m_e c^2)^{-1} \sim y^{-1}$

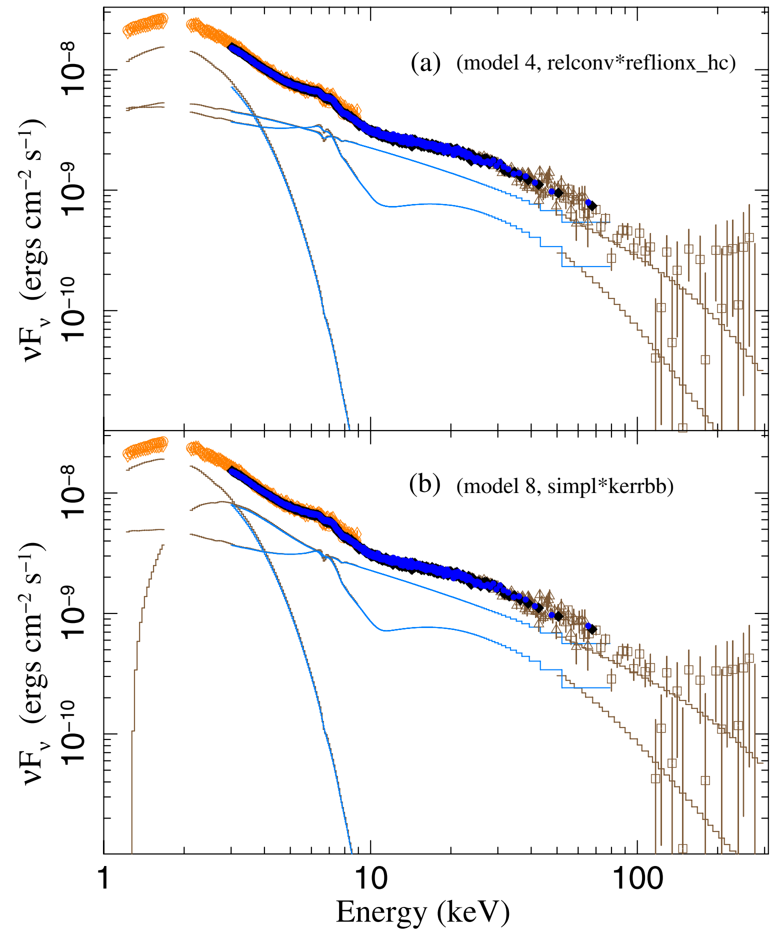
Soft state fits to blackbody plus comptonized component

- Crudely consistent with simple estimate:

$$R = \sqrt{\frac{L}{4\pi\sigma_{kb}T^4}}$$

$$\simeq 10^5 \mathrm{cm}\ L_{38}^{1/2} T_8^{-2}$$

- Neutron star sources also show blackbody components, consistent with emission from heated surface



Tomsick et al. 2010

We can get more insight by considering how radiation propagates

- What an observer receives is determined by two things:
  - Light emitted in the direction towards us
  - Light absorbed along the path
- Intensity we see is due to the sum of sources along our line of sight out to a place where the optical depth is ~1

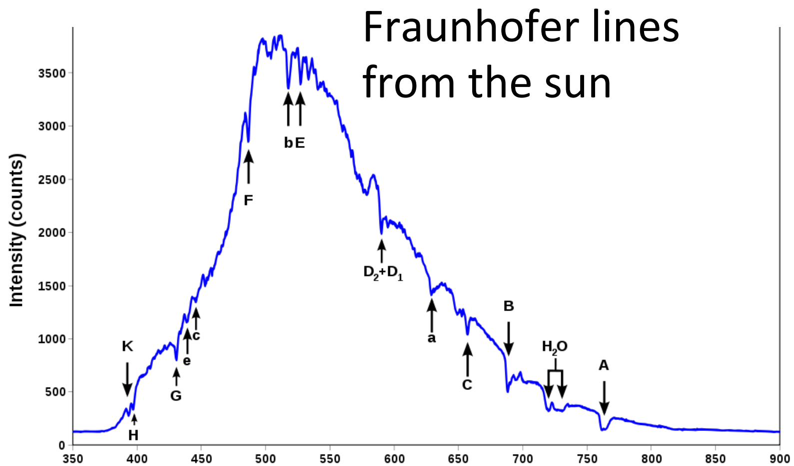
$$I_\varepsilon(s) = \int_{-\infty}^{s} ds' j_\varepsilon(s') e^{-\tau(\varepsilon;s,s')} + I_\varepsilon(-\infty) e^{-\tau(\varepsilon;s,-\infty)}$$

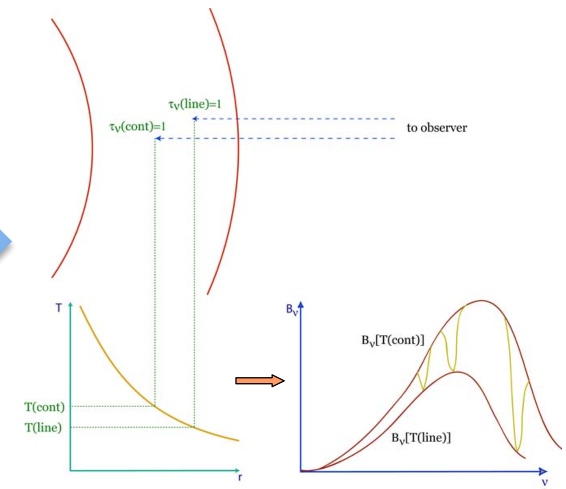
- → The Eddington-Barbier relation:

$$I_\varepsilon \simeq B_\varepsilon(T)\,\big|_{\tau=2/3}$$

- This allows us to interpret spectra in terms of
  - The microscopic conditions in the emitting gas
  - And the geometry
- This is illustrated by considering familiar paradigms taken from other branches of astronomy
- 'If you don't know where you are going, you might wind up someplace else'

Paradigm 1: optical lines in stellar atmospheres

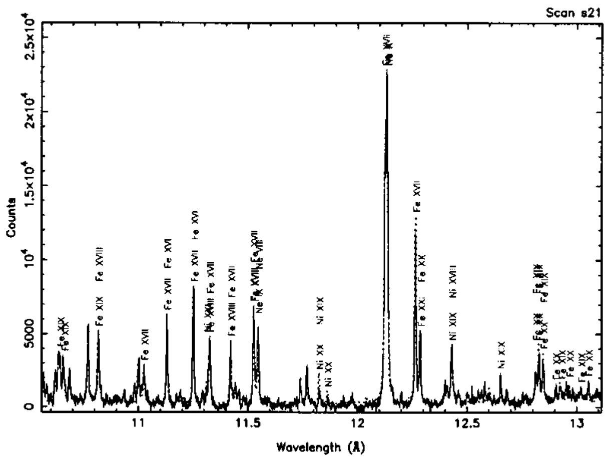




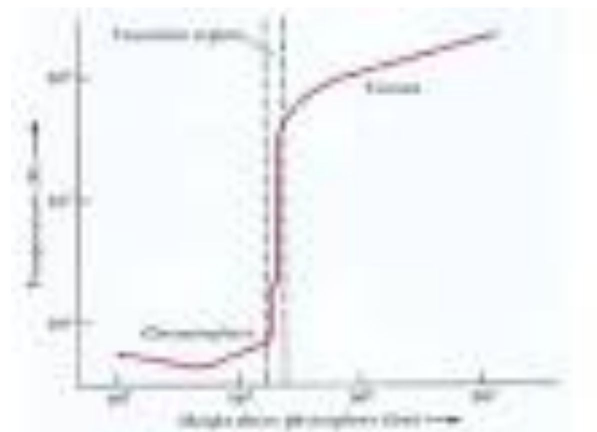
- Line opacity means we see less deep in stellar atmospheres
- Atomsphere is optically thick at all energies
- Decreasing temperature with height means lines appear in absorption

Paradigm 2: X-ray emission from stellar coronae

solar X-ray spectrum

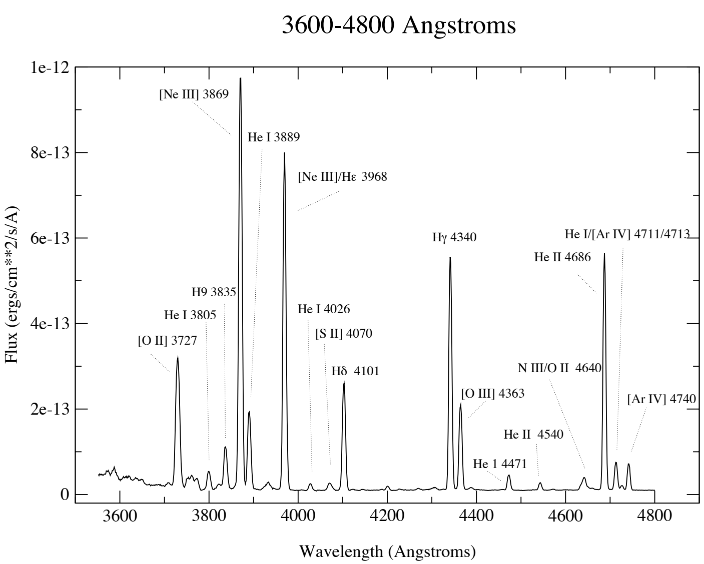


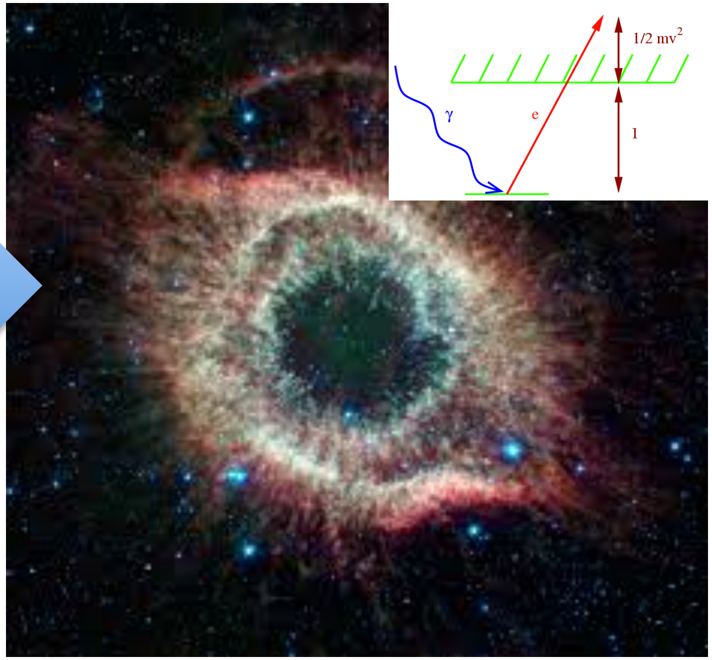
(Phillips et al.1999)



Temperature inversion causes X-ray lines to appear in emission
Lines have greater optical depth than continuum

Paradigm 3: nebular line emission

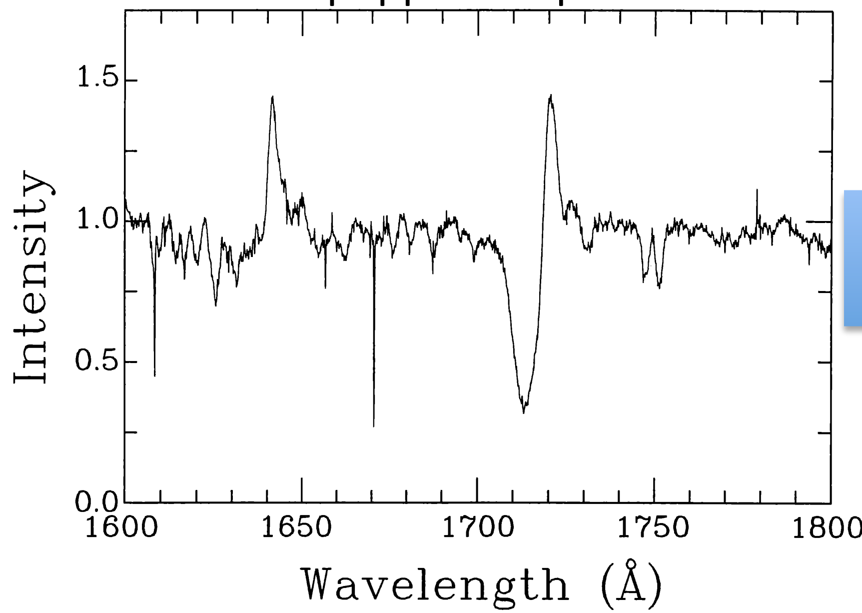




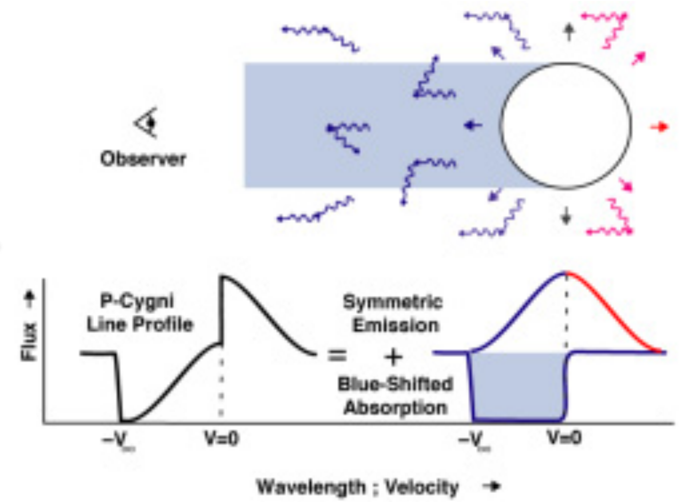
- Inelastic interaction (eg. Photoionization-recombination) between light from central star and extended atmosphere
- produces apparent line emission

Paradigm 4: Stellar wind scattering (resonance scattering)

Zeta puppis UV spectrum



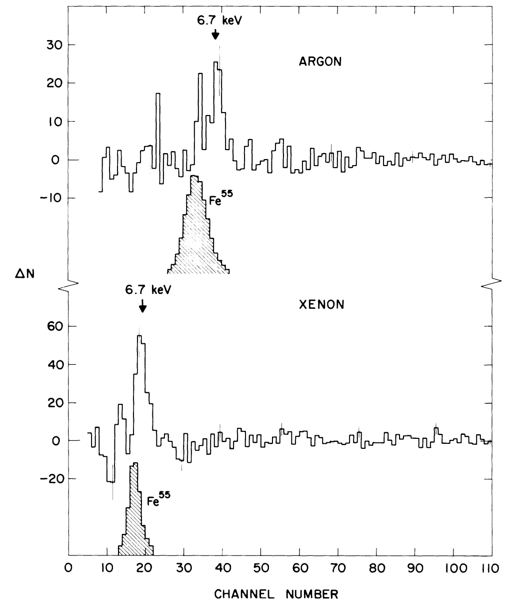
(Howarth and Prinja 1996)



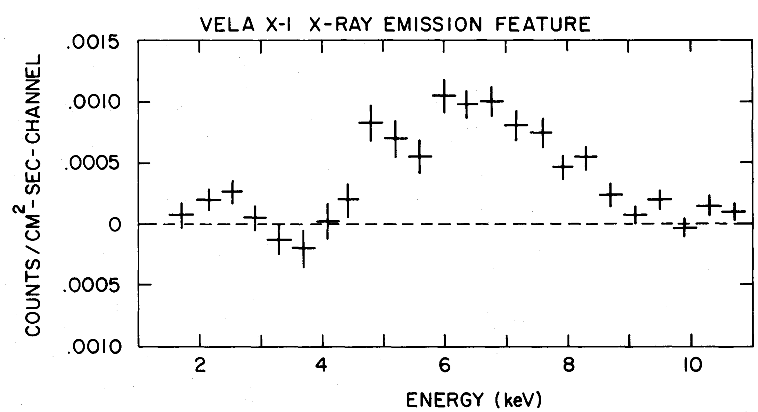
- Winds produce emission and absorption due to resonance scattering
- If the scattering gas were stationary then the emission and absorption would cancel

How do lines from X-ray binaries fit into this scheme?

- i.e. can we reuse these paradigms; ‘It’s déjà vu all over again’
- Iron lines were the first spectral features detected from X-ray binaries
- The majority of X-ray sources emit iron lines:
- Iron lines are diagnostic of
  - Ionization via energy
  - Dynamics via width or shift
  - Abundance and geometry via strength



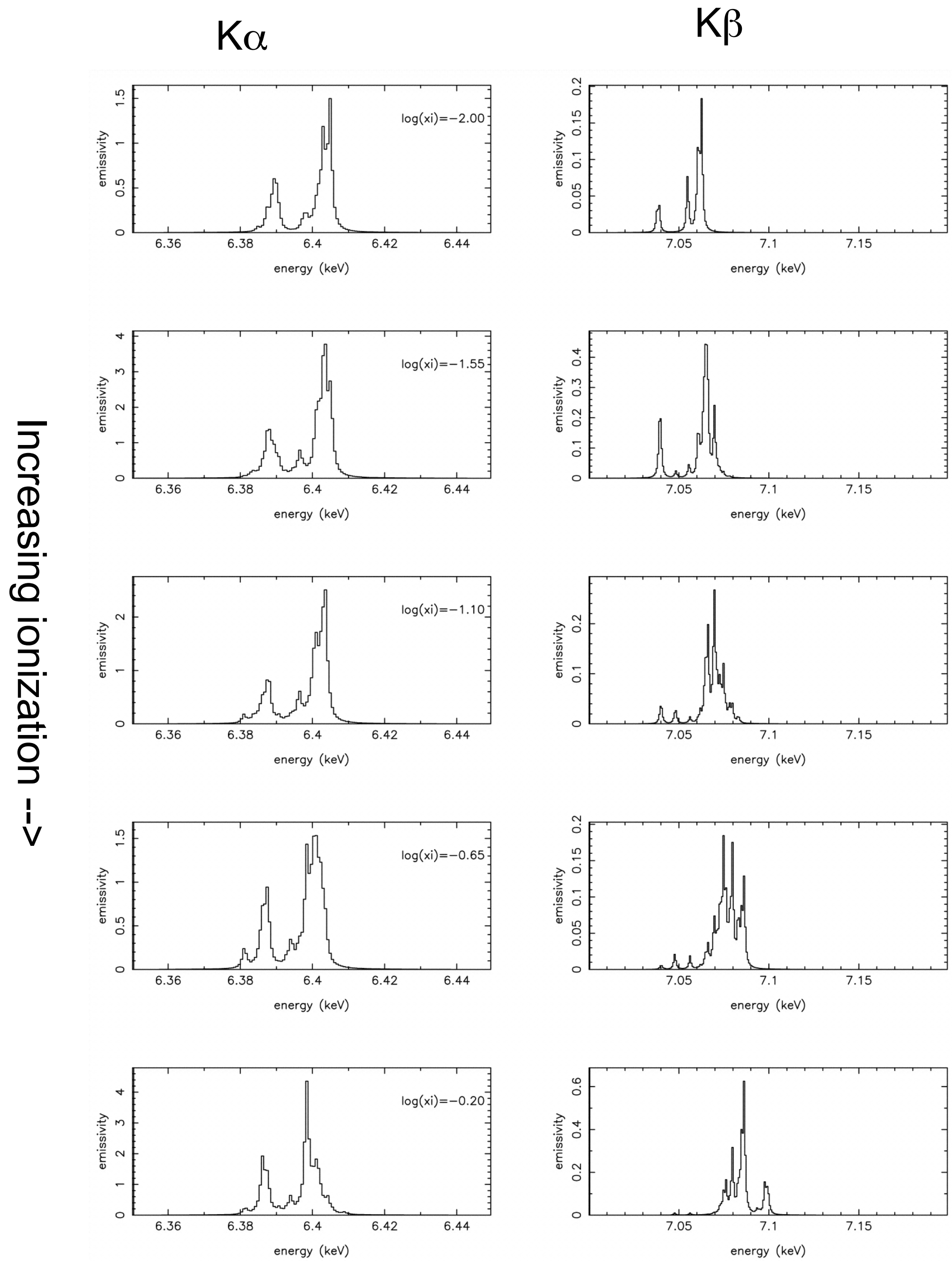
Cyg X-3; Serlemitsos et al 1975



Becker et al. 1978

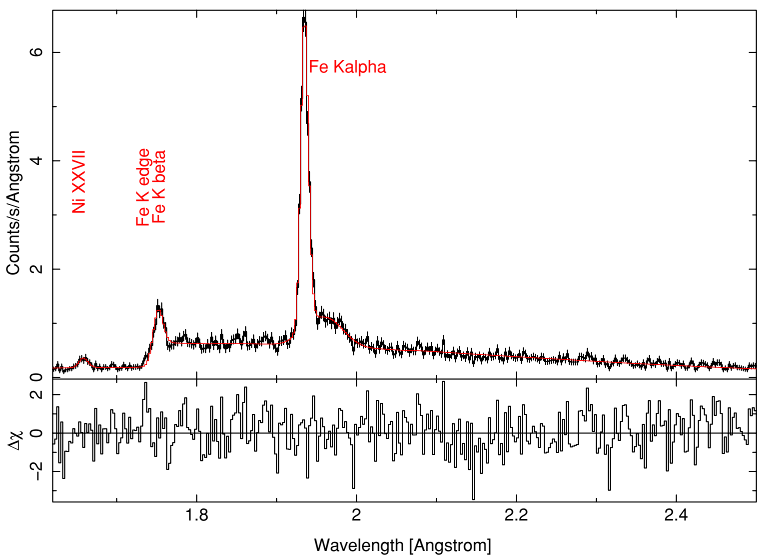
Iron K fluorescence is characteristic of photoionized gas

- Lines can be emitted from gas in all ionization states
- Iron is the a relatively abundant
- The line is in a clean part of the spectrum
- Iron K line shape and energy changes according to the ionization state of the gas
- $K\beta$ is more sensitive to ionization state than $K\alpha$

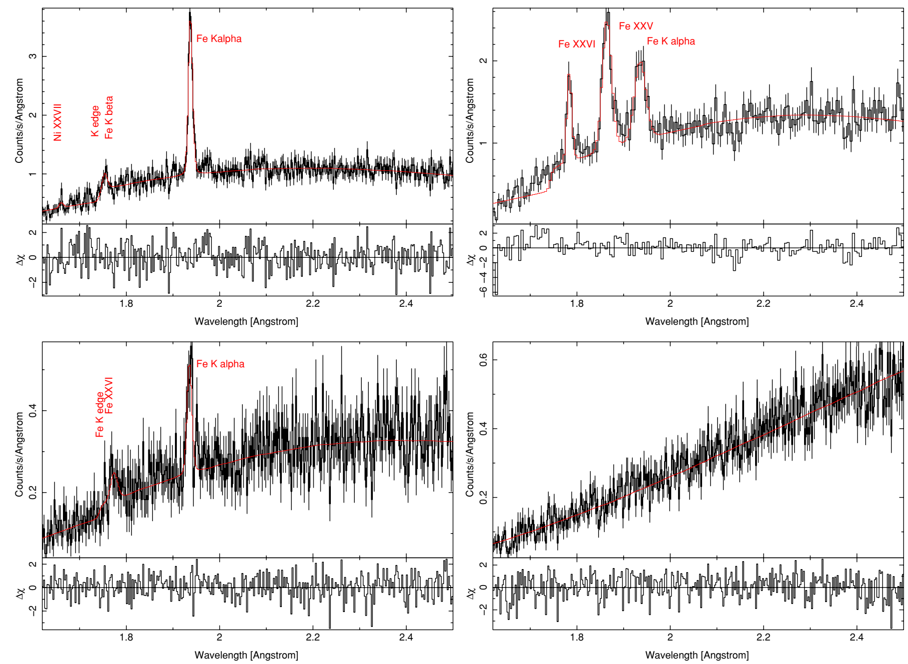


Chandra spectra show a variety of different iron line properties

GX301-2



Vela x-1 | cyg x-3

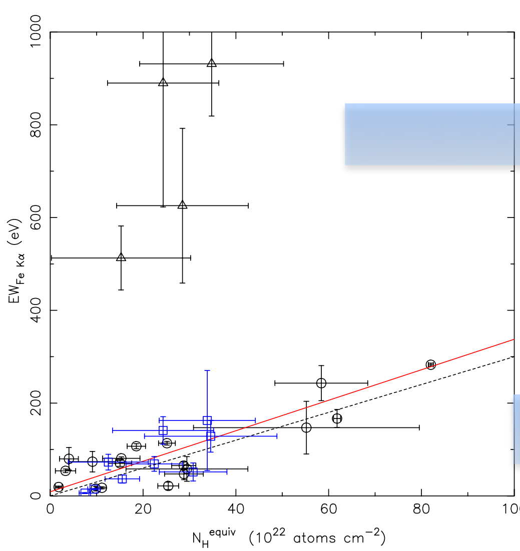


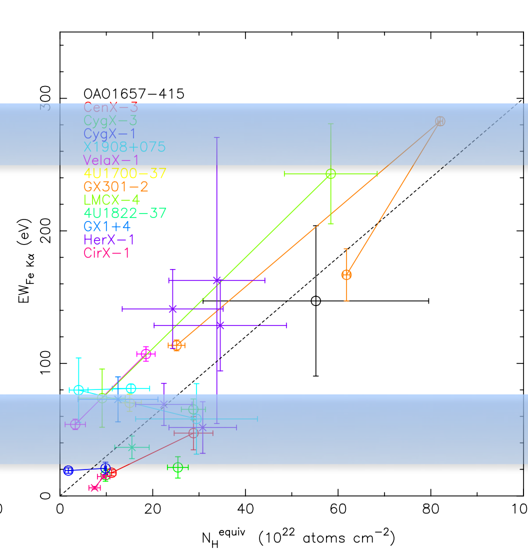
4u1822-37 | 4u1957+11

(Torrejon et al. 2010)

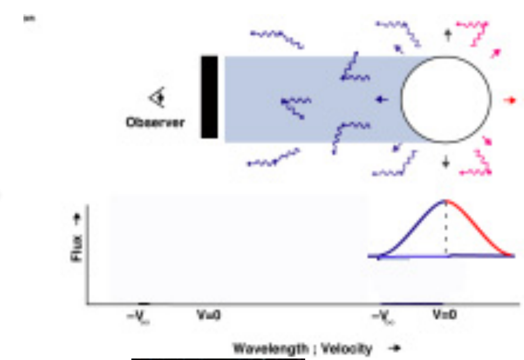
Which paradigm applies to iron K?

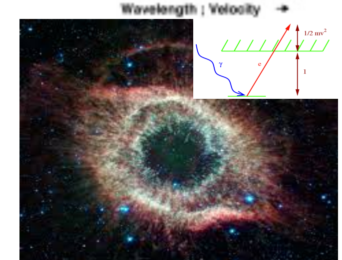
- The nebular paradigm predicts that the iron line equivalent width increases with the column density
  - More matter → more line
  - Spherical geometry implies we can measure the matter via NH
  - from the low energy photoelectric absorption
- Results for a sample of X-ray binaries: good correlation for many but not all.. → blocked wind (emission) paradigm is better for some objects





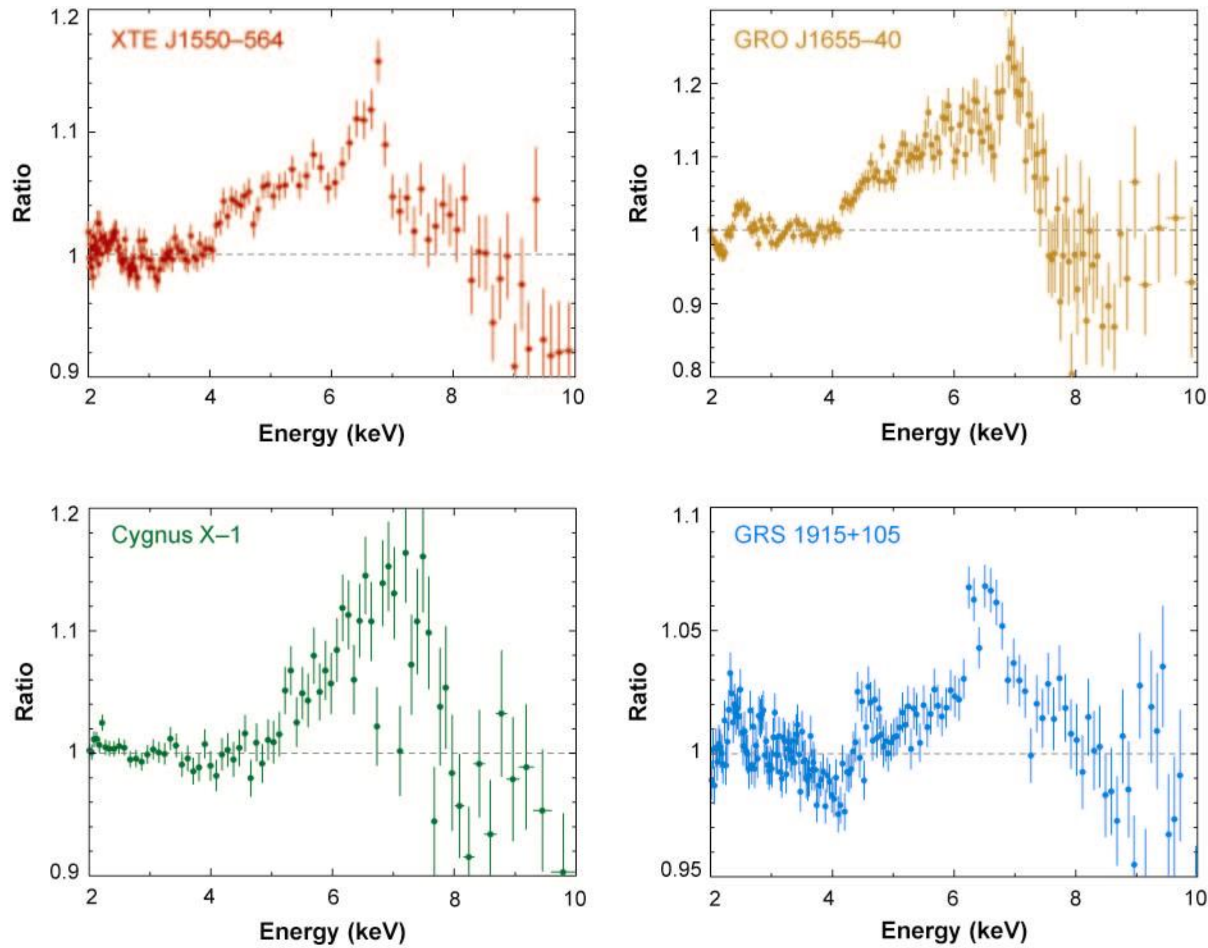
Torrejon et al. 2010





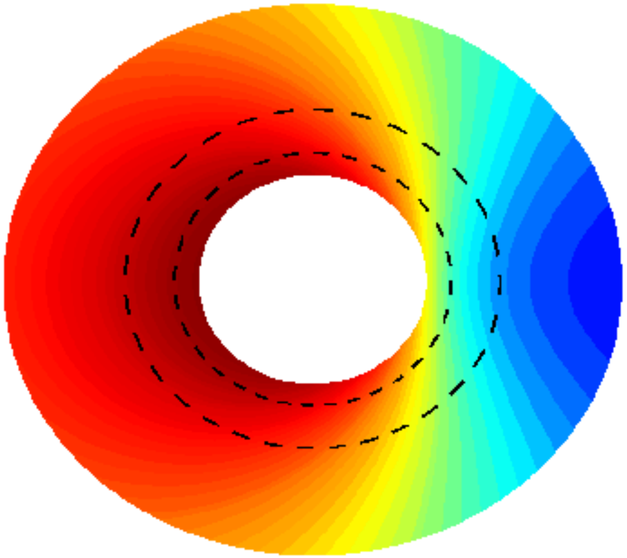
Relativistically broadened iron lines are observed from X-ray binaries

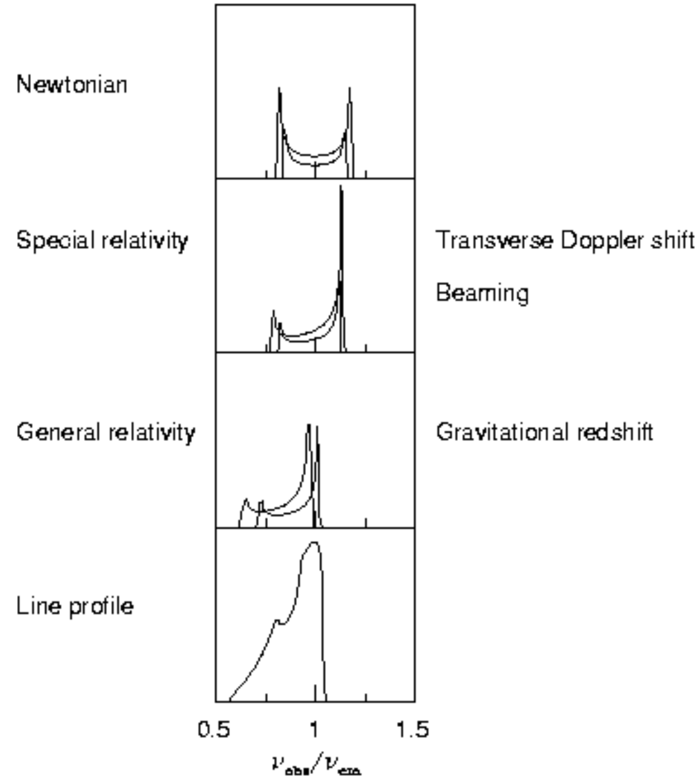
- Line is broadened by disk rotation
- Special relativity boosts the blue wing, more at high i
- General relativity redshifts the extreme wings
- Yields constraints on inclination, emission region location



Miller JM. 2007.
Annu. Rev. Astron. Astrophys. 45:441–79

Line Broadening by Black Hole Disk Emission



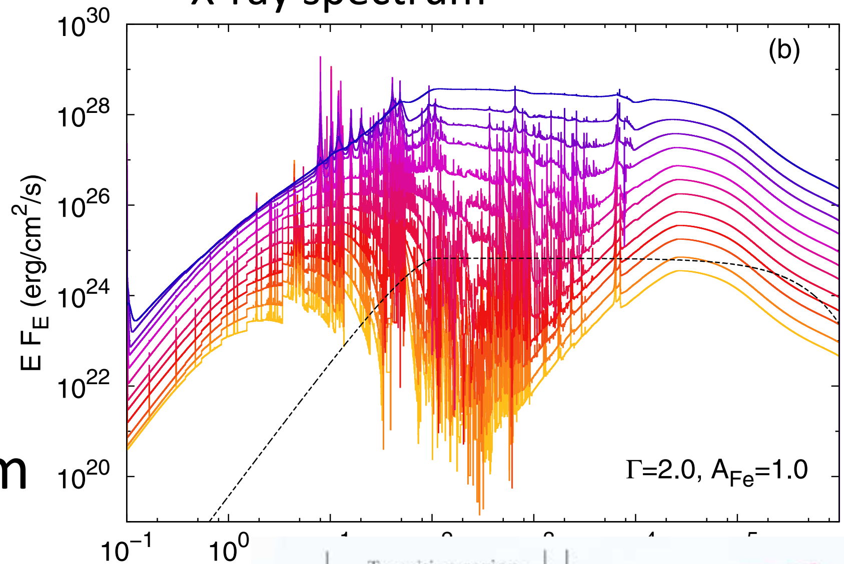


Fabian et al. 2000

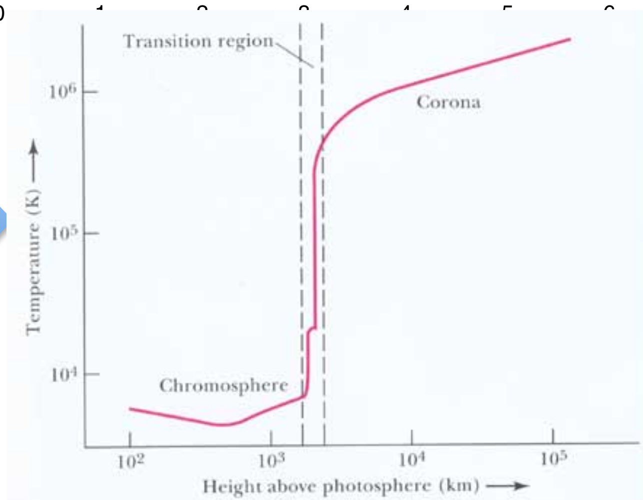
Broad iron lines are evidence for reflected emission from a rotating disk

- Rotation provides Doppler shifts
- Disk geometry provides thick reflection atmosphere
- Energy source is the Compton continuum
- Consistent with coronal paradigm
- temperature inversion comes from the X-ray heating
- But Why do inferred parameters cluster around i~30-45°, Iron abundances > solar ?
- Do we really understand the geometry and energy source in disk reflection?
- Missing energy input?

Grid of models for reflected X-ray spectrum

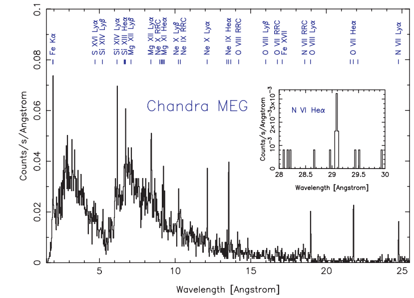


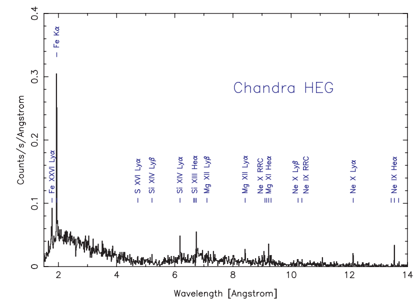
(Garcia et al. 2013)



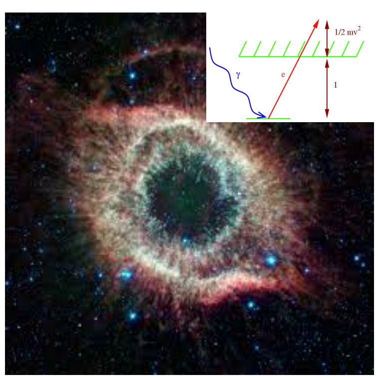
At energies <2 keV line emission is observed from sources such as HMXBs or high inclination sources

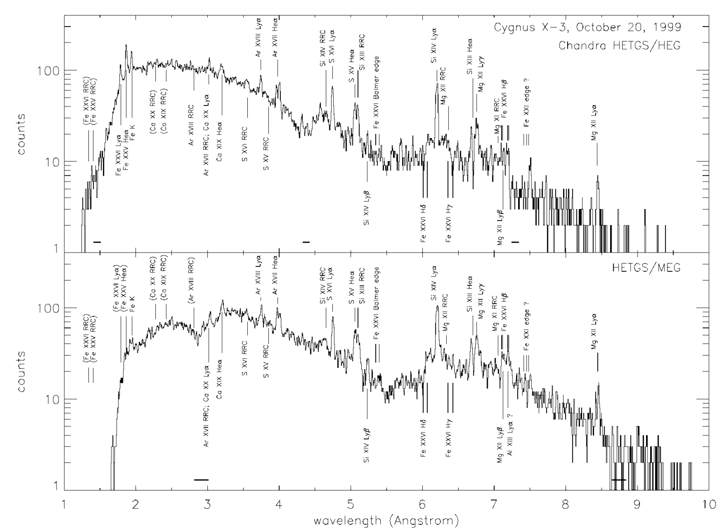
- Lines include strong resonance lines from many ions
- Recombination and thermal emission is strong
- → emission nebula paradigm is favored





(Jimenez-Garate et al 2003)

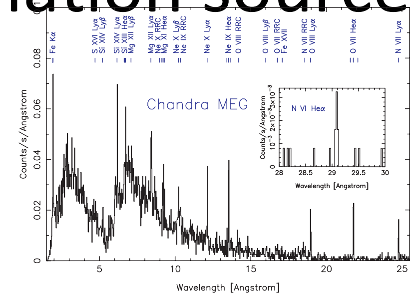


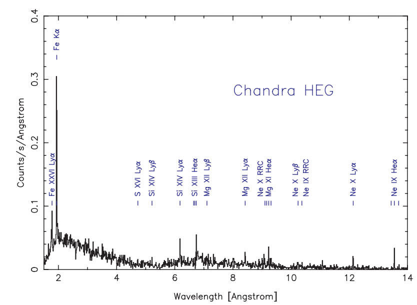


(Paerels et al. 2000)

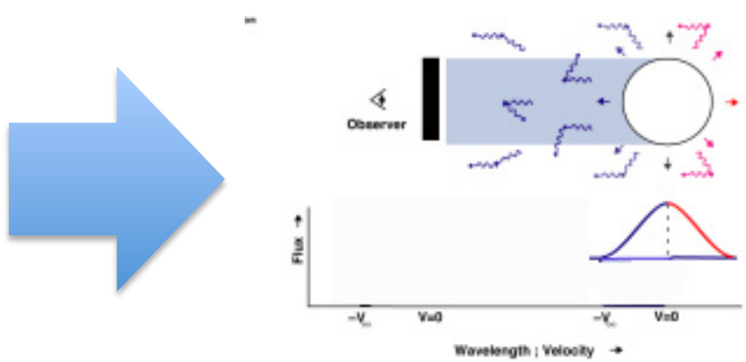
At energies ~0.5-2 keV line emission is observed from sources such as HMXBs or high inclination sources

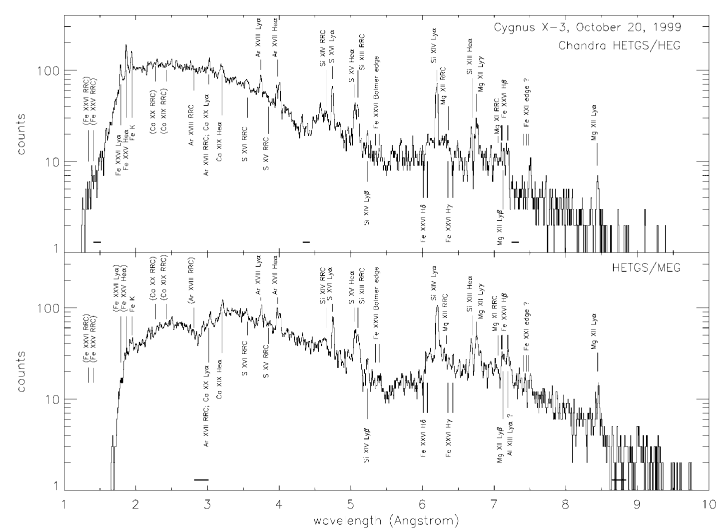
- Lines include strong resonance lines from many ions
- But Equivalent widths are greater when total flux is low
- → blocked wind (emission) paradigm may apply





(Jimenez-Garate 2003)



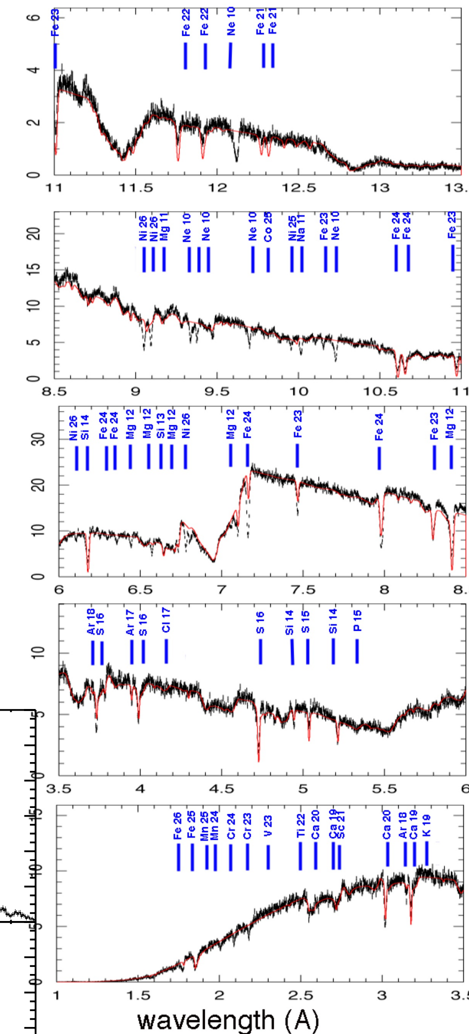


(Paerels et al. 2000)

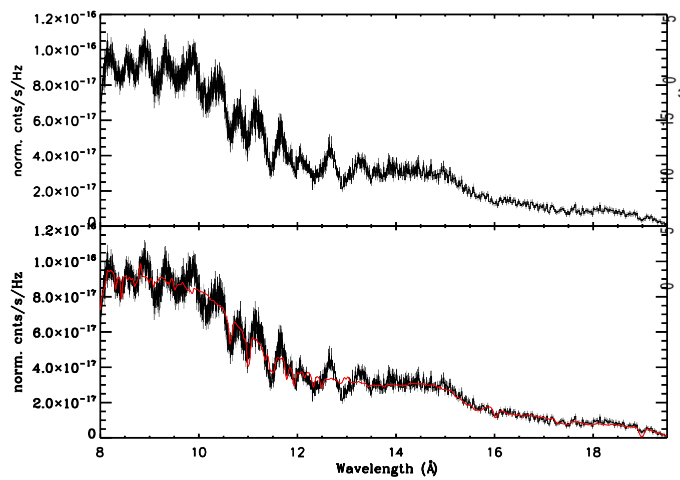
black hole transients in outburst prduce absorption

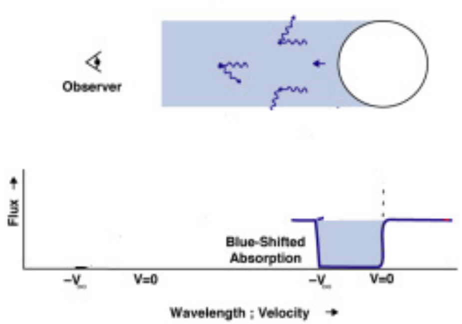
- No evidence for emission
- Suggests blocked wind (absorption)
- If so, should see equivalent width ~constant
  - Not the case: appearance of features do not correlation with outburst state
  - Spectra do not always fit to simple absorption

GROJ1655-40



Maxi J1305-704



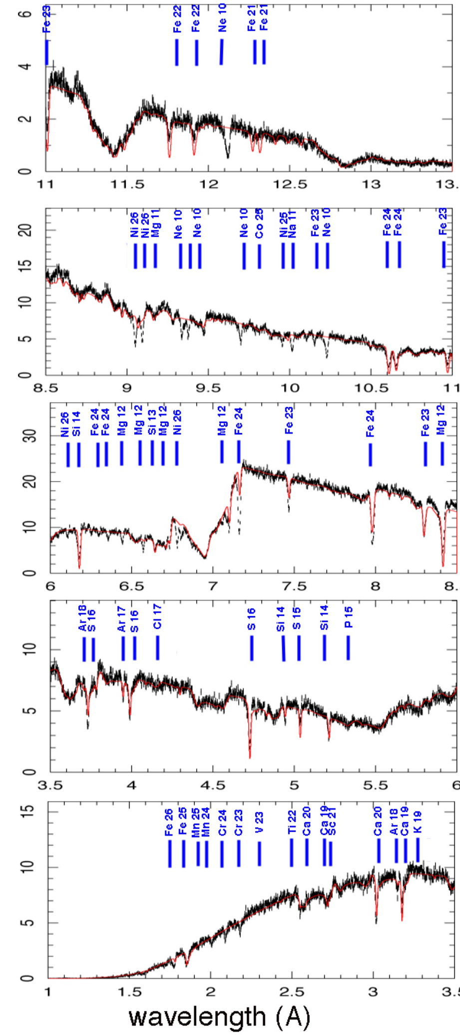


(Miller et al. 2015)

black hole transients in outburst produce absorption

- No evidence for emission
- Suggests blocked wind (absorption)
- If so, should see equivalent width ~constant
  - Not the case: appearance of features do not correlate in detail with outburst state
  - Spectra do not always fit to simple absorption
  - Maybe cool photosphere paradigm is better?
  - If so there is more material, but maybe at smaller radius?

GROJ1655-40



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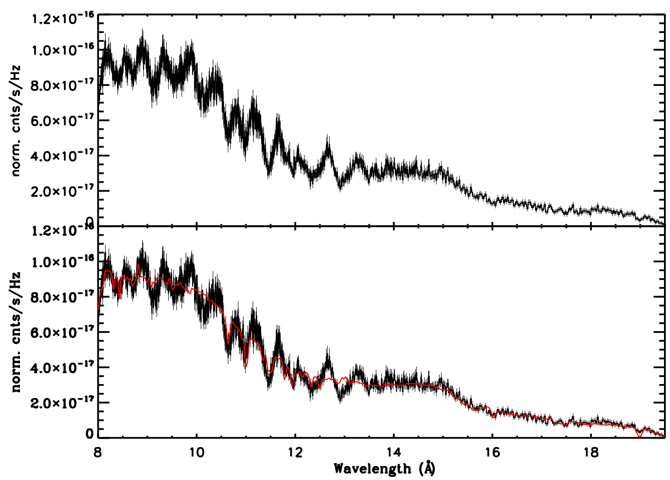

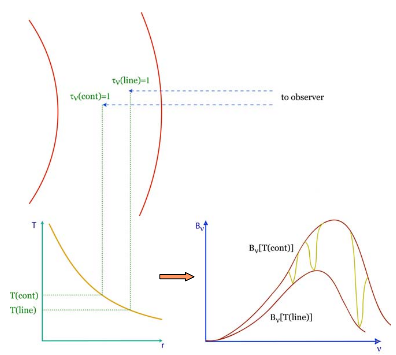

(Miller et al. 2015)

Reexamining paradigms for X-ray binary line spectra ('When you come to a fork in the road, take it')

feature	Current paradigm	New paradigm
Broad iron K	Corona	Blocked wind (emission)
<2 keV band line emission	Emission nebula	Blocked wind (emission)
Narrow Iron K emission	Emission nebula	Blocked wind (emission)
Bht absorption	Blocked wind (absorption)	cool photosphere

- problems remain with commonly used scenarios for X-ray binary line spectra
- 'Nobody goes there anymore; it's too crowded'
- These provide hints about the possible other things which may be going on:
  - additional sources of energy
  - partial obscuration of the radiation responsible for reprocessed or scattered emission
  - breakdown of standard assumptions about geometry or optical

How to better characterize the location of line emitting gas and geometry?

- Variability: correlated variability between line and continuum provides evidence for nebular or wind scattering connection. → variability campaigns and instruments with greater sensitivity
- Iron K band: search for emission/absorption features in sources with blocked winds;
- Higher spectral resolution: resolving the line widths provides clues about location of gas

X-ray binary science with astro-H

- Black hole iron lines: line vs. reflection hump
- Wind absorption: better s/n at low energy
- Search for weak features , dynamics at > 6 keV
- Other surprises… ULXs, Cyg X-3, SS433
- ‘It ain’t over till it’s over’