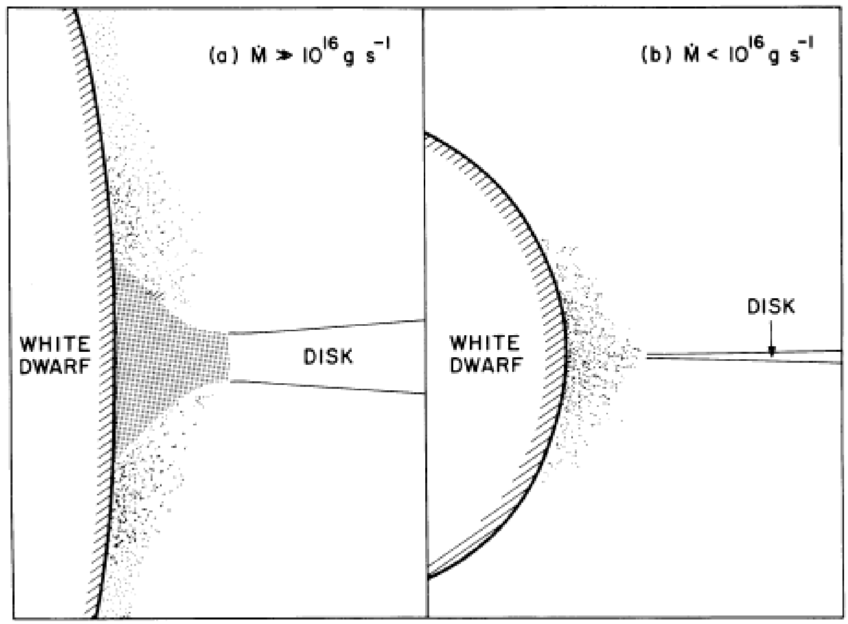
Neither Thick Nor Thin

The Role of Optical Depth in Accreting White Dwarf Binaries

Koji Mukai and Thomas Nelson

NASA/GSFC/CRESST and UMBC

Thick vs. Thin



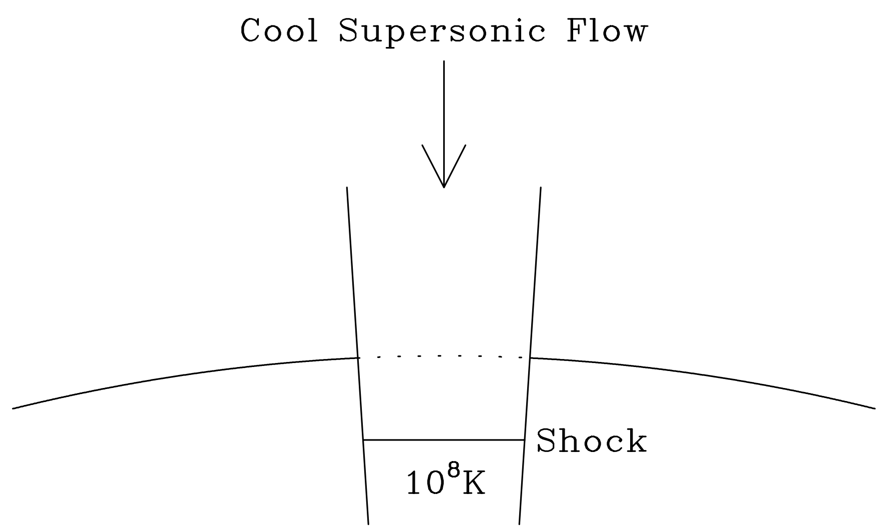
- "The surface of everything is optically thin" —but there must be a transition, in space and/or in time.

Elements of this Talk

We do not have a theory for emissions from regions with $\tau \sim 1$ in accretion flows (boundary layer in particular) This talk includes:

- A brief review of existing works on magnetic CVs.
- Motivation: why do we want to think about $\tau \sim 1$ regions?
  - Answer: Compton cooling
- Two observational questions
- Initial application of Compton cooling model

The Aizu Model



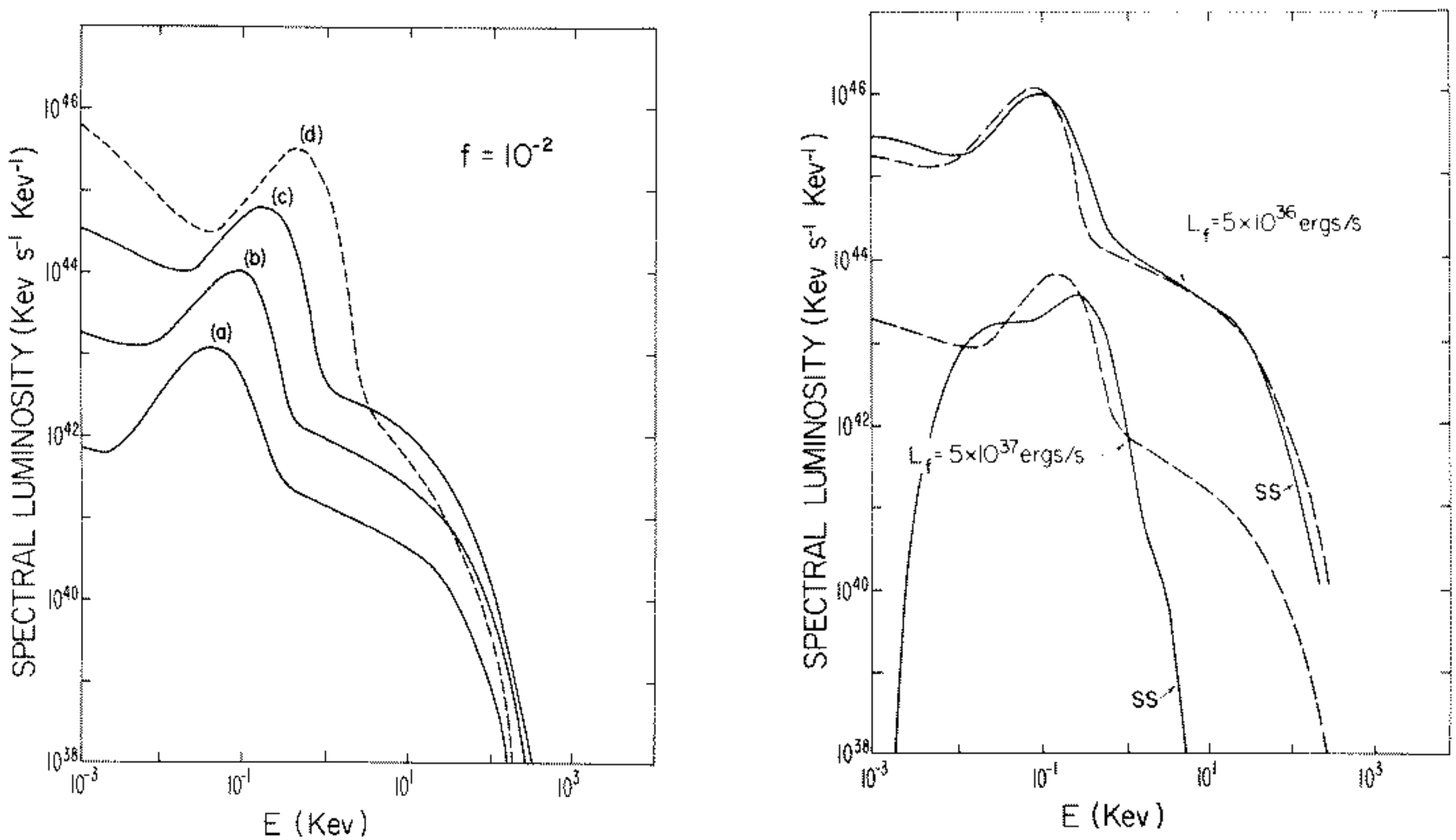
- Radial accretion, Bremsstrahlung cooling only
- Once shocked, little additional heating takes place (except the remaining kinetic energy - [1/4 $v_{ff}]^{1/2}$, or 1/16th of initial value)
- h_s determined by equating t_{cool} and settling time
- The integrated column density of post-shock material is around 2 g cm^{-2}, or $\tau \sim 0.35$ regardless of M_{wd} and for a range of local accretion rate.

Photons vs. Electrons

If τ is only 0.35, only $\sim$30% of photons will Compton-scatter. However, there are usually far more seed photons than electrons.

- Shock is close to the surface; $\sim$half the accretion luminosity is thermalized on the white dwarf surface.
- Example: 0.6 $M_\odot$ WD, local $\dot{m}$ of 10 g cm^{-2}s^{-1} over 0.01% of WD surface, resulting in a 30eV blackbody radiation at 8.7 $\times 10^{32}$ ergs s^{-1}
- Such a blackbody emits 6.7 $\times 10^{42}$ photons per second, while accretion supplies 5×10^{39} electrons per second. So, if 30% of the photons Compton-scatter once, each electron experiences $\sim$300 Compton scattering events in the post-shock region.
- Quick & Dirty estimate of the electron-to-soft-photon ratio: electrons starts off at shock with kT$\sim$30 keV, and this energy is emitted as E$\sim$30 eV photons — so $\sim$1,000 soft photons per electron.

Resulting X-ray Spectra



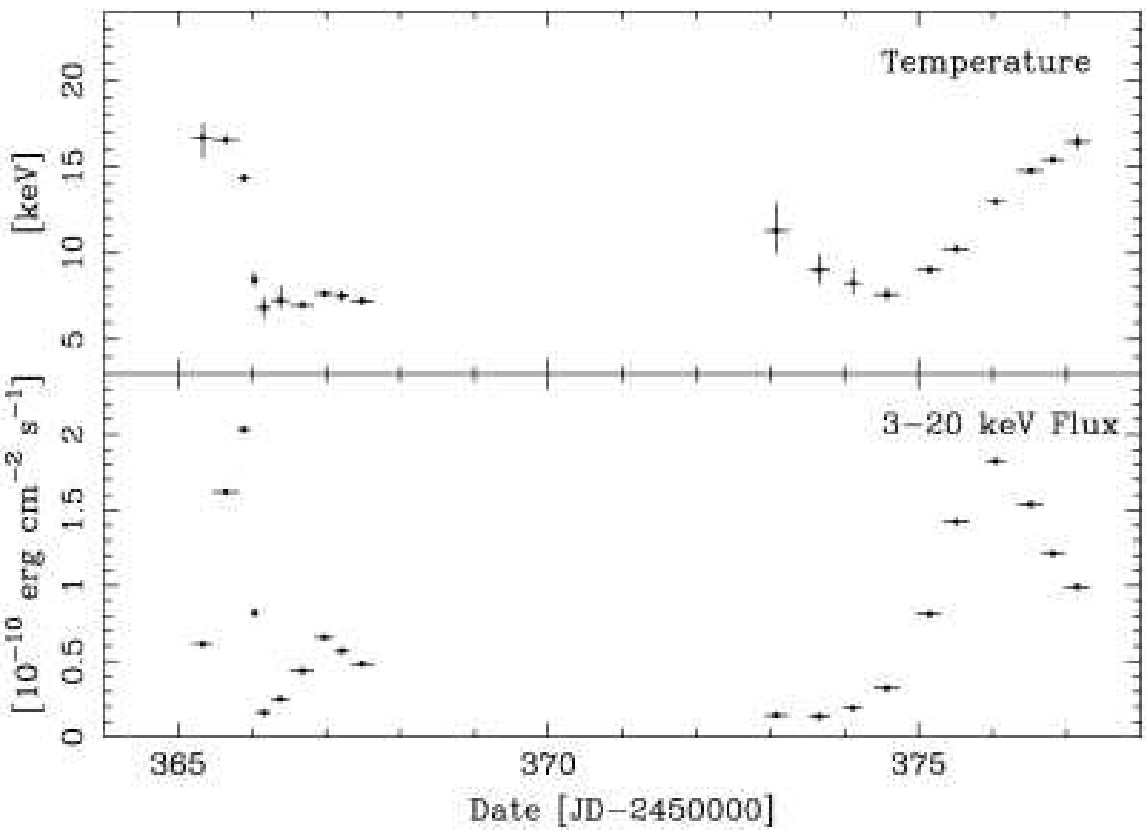
(from Imamura & Durisen 1983)

...limited applicability?

However, little attention has been paid to Compton cooling in accreting white dwarf binaries in the last 20 years because Imamura and others found:

- High local accretion rate is required for Compton cooling to be important
- Geometry is important — photons can escape from the side of the column
- High white dwarf mass is necessary — the ratio of two cooling mechanisms just below the shock is $\frac{free-free}{Compton} = 6.5 f_{soft}^{-1} m_1^{-2} R_9^2$ and free-free becomes more important at lower temperatures/higher densities.

Q1: Dwarf Novae in Outburst

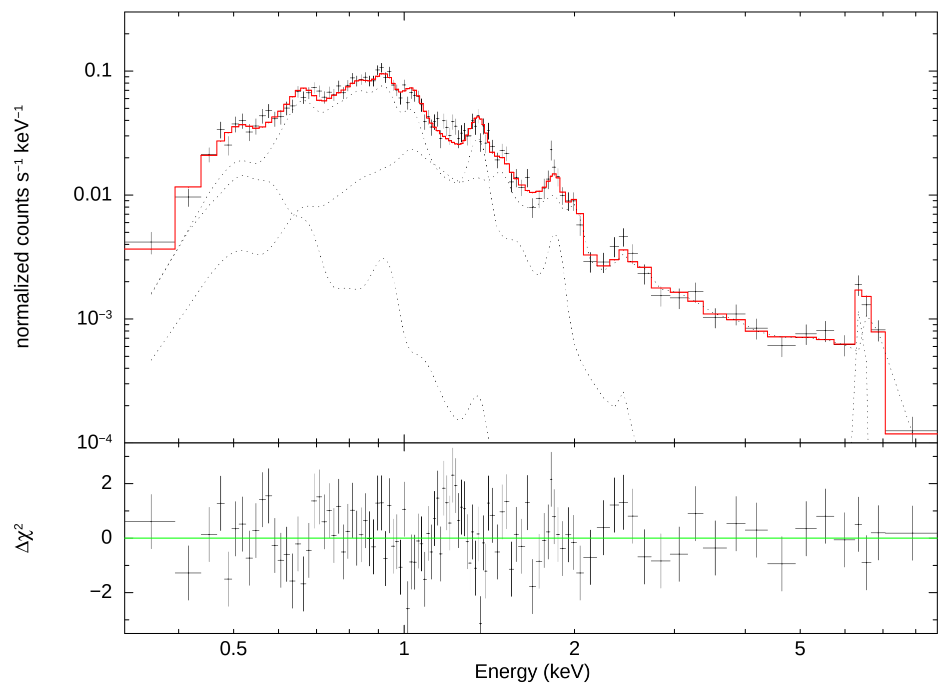


(from Wheatley, Mauche & Mattei 2003)

Why softer?

- In the Patterson & Raymond (1985) picture, both quiescent and outburst hard X-rays are from the optically thin (part of) boundary layer.
- The gravitational potential is the same, and the shock height should be roughly similar.
  - Single-temperature fits to Ginga and RXTE data result in kT$\sim$17 keV in quiescence and kT$\sim$7 keV in outburst
  - Cooling-flow fits to ASCA data result in kT$_{max} \sim$ 36 keV in quiescence and 10.5 keV in outburst
  - Temperature decrease by a factor of 2.5–3.5 needs explanation.
  - The luminosity also decreases.

Q2: RS Oph in Quiescence



(from Nelson et al. 2010, submitted)

- The fit requires a soft component, probably from the nova shell, and a harder component, from accretion

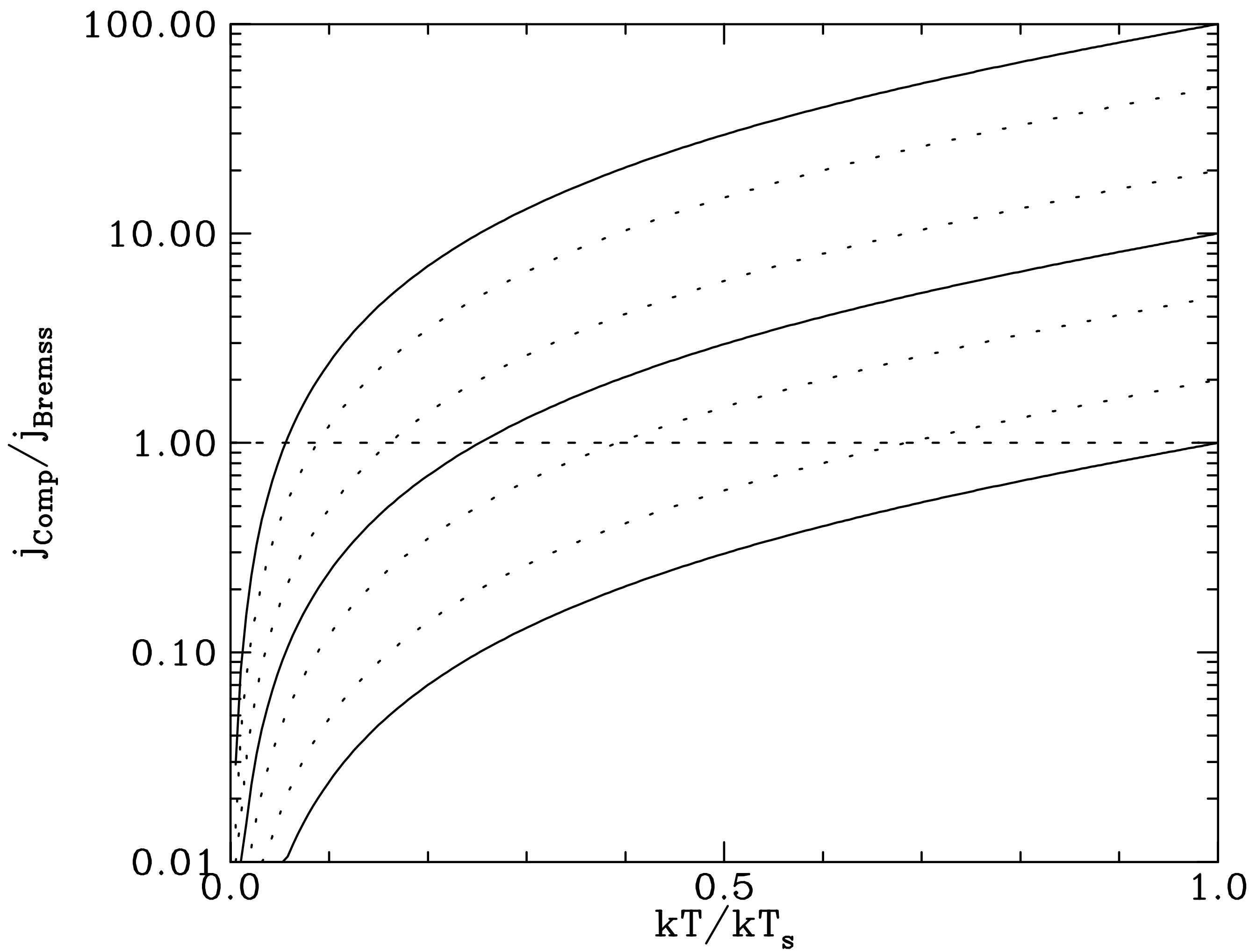
Why faint, and why soft?

- RS Oph is a recurrent nova, and thought to have a $\sim$1.3 $M_\odot$ white dwarf, accreting at a high rate.
- T CrB, another recurrent nova, is detected in the BAT survey at an estimated $L_{X,bol} = 2 \times 10^{34}$ ergs s^{-1} (Kennea et al. 2009), with kT$\sim$18 keV for a 1-T model fit.
- Yet the the X-ray luminosity of RS Oph is lower ($L_{0.3-10keV} \sim 2 \times 10^{33}$ ergs s^{-1}) and the temperature is significantly lower (1-T fit: kT$\sim$2.4 keV; cooling flow fit: $kT_{max} \sim 5$ keV, where 60 keV is expected for an 1.3 $M_\odot$ WD).

Proposed Solution

- Addition of extra soft photons will tip the balance towards Compton cooling.
  - τ is still low, but each electron interact with more photons.
  - Additional L_{soft} due to (current or recent) nuclear burning, or inhomogeneous accretion
- We do not have a full model of the boundary layer
  - Assume Aizu model column laid on its side
  - Assume strong shock but from v_{Kep}, not v_{ff}
  - Add second cooling term, using the Wu et al. (1994) prescription with α=1/2, β=3/2 as appropriate for Compton cooling.
- The relative importance of Compton cooling is a function of physical position within the post-shock region/kT/ρ.

kT Dependence



Consequences

For the case which starts with j$_{Comp}$/j$_{Brems}$=10.0 at just below the shock

- Cooler regions are denser, and j$_{brems}$ $\propto n_e^2 kT^{1/2}$ — the ratio becomes progressively smaller as density increases.
- Cross-over occurs at kT$\sim$0.25 kT$_s$
- Approximation: Plasma cools from kT$_s$ to 0.25kT$_s$ exclusively via Compton cooling, the rest exclusively via Bremsstrahlung
- Observed L$_X$ is also $\sim$25% of what it would have been without Compton cooling
- If cooling flow fit is used, kT$_{max}$ $\sim$ 0.25 kT$_s$; normalization (accretion rate) corresponds to L$_{Brems}$+L$_{Comp}$.

Application: SS Cyg in Outburst

- Wheatley, Mauche & Mattei (2003) reports $L_{soft} \sim 7.5 \times 10^{33}$ ergs s^{-1}, presumably from the optically thick boundary layer
- $L_{Brems} \sim 2.0 \times 10^{32}$ergs s^{-1} and $kT_{max,q} \sim 3.5\times$ $kT_{max,o}$. In our picture, then, L_{Brems}+$L_{Comp} \sim 7.0 \times 10^{32}$ ergs s^{-1}.
- So the use of the curve that starts near j_{Comp}/j_{Brems}=10.0 is self-consistent.
- The Compton cooling interpretation passes the sanity check, as long as the X-ray source is right next to the soft source, with little geometrical dilution of soft photons.

(Luminosities scaled to a fiducial distance of 166 pc)

- This implies, however, that outburst X-rays in SS Cyg would be eclipsed when viewed from a high inclination angle.
- The inclination of Z Cha may be so high ($i = 81.8^\circ$) that any boundary emission is hidden from our view at all phases in outburst by the thickened rim of the disk (cf. UX UMa at 71°).

Application: RS Oph in Quiescence

- The observed temperature is ~10% of what is expected. This requires $j_{Comp}/j_{Brems} \sim 50$ at shock.
- The soft luminosity in RS Oph is poorly constrained, due to the much higher interstellar N_H than towards SS Cyg.
- In addition to the optically thin boundary layer, the residual heat from the 2006 recurrent nova eruption (which made this a supersoft source for several months) can provide the seed photon for Compton cooling
- The key difference for T CrB is the much longer age since the last nova outburst, hence lower kT_{eff} of the white dwarf.

Conclusions

- Post-shock regions in CVs and symbiotic stars have small but non-negligible τ
- When there is an additional source of soft photons, Compton cooling can become significant, which may explain dwarf novae in outburst, RS Oph in quiescence, supersoft sources, and polars with blobby accretion
- Wanted: theorists to work on a proper theory of the boundary layer including Compton cooling