Models for the multi-wavelength emission of accreting black hole X-ray binaries

Accretion disc

Jet

X-ray corona

Companion star

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Chaty et al. 2003

SED of X-ray binary XTE J1118+480
Radiation processes in the corona

**Inverse Compton**

**X-ray radiation**

If \( \tau_T = n_e \sigma_T R \geq 1 \): Comptonisation

**Soft seed photons?**

- \( \checkmark \) blackbody emission from accretion disc
- \( \checkmark \) synchrotron emission
Comptonisation models

- Soft seed photons (blackbody)
- Compton radiation

Thermal electron energy distribution (Maxwellian)

Power law electron distribution

$E_e \sim kT$
Emission from the accretion flow

**HARD STATE:**
- (compact radio jet)
- disc blackbody: weak / Corona: THERMAL electrons

**SOFT STATE:**
- disc blackbody: strong / Corona: NON-THERMAL electrons

Zdziarski et al 2003
Hybrid thermal/non-thermal comptonization models

Comptonising electrons have similar energy distribution in both states:
Maxwellian+ non-thermal tail

- **HARD STATE**: $kT \sim 50-100$ keV, $\tau_T \sim 1-3$: Thermal comptonisation dominates
- **SOFT STATE**: $kT \sim 10-50$ keV, $\tau_T \sim 0.1-0.3$: Inverse Compton by non-thermal electrons dominates

Lower temperature of corona in soft state possibly due to radiative cooling by soft disc photons

EQPAIR

(Poutanen & Coppi 1998; Coppi 1999; Gierlinski et al. 1999, Zdziarski ..., Done ... )
Hybrid models with magnetic field

Effects of magnetic field:

- Cyclo-synchrotron radiation = seed photons for comptonization, enhanced cooling of the Maxwellian electrons
- Cyclo-synchrotron self-absorption = fast electron thermalisation

BELM: a code to model radiation and kinetic processes in the corona

Evolution of electrons and photon energy distributions in a fully ionised, magnetised plasma (radiation, acceleration and Coulomb processes)

- Solve coupled time-dependent kinetic equations (one zone) for leptons and photons (no assumption on the shape of the electron distributions)

(Belmont, Malzac & Marcowith, A&A 2008; see also Vurm & Poutanen 2009)
Effects of magnetic field: the Synchrotron boiler

(Ghisellini, Guilbert and Svensson 1988)

Electrons injected with $\gamma = 10$ in an empty (but magnetised) region

Synchrotron self-Compton emission

High energy $e^{-} \rightarrow$ synchrotron photons $\rightarrow$ self-absorbed by lower energy $e^{-}$

- transfer of energy between particles
- ‘thermalizing’ effect on the electron distribution
- At steady state: hybrid thermal/non thermal lepton distribution

Pure non-thermal SSC models (steady state)

- Magnetic field $B$ at $\sim$equipartition with radiation, $l_B=(\sigma_T/m_e c^2) R B^2/(8\pi)$
- Continuous POWER-LAW electron injection $\Gamma_{\text{inj}}=3$, $l_{\text{nth}}=(\sigma_T/m_e c^2) L/R$
- Cooling and thermalisation through synchrotron self-Compton + e-e Coulomb
- Equilibrium distribution: Maxwellian+ non-thermal tail
- Spectra look like hard state!

(Malzac & Belmont MNRAS 2009)
Effect of external soft photons

Add soft thermal photons:

- temperature of Maxwellian electrons decreases
- Compton emission increasingly dominated by non-thermal electrons
- looks like a state transition!
All spectral states consistent with pure non-thermal acceleration models

Spectral transitions: thermal disc photons cool down the corona in softer states

Spectral fits with BELM: first constraints (upper limits) on coronal magnetic field $B$ and ions temperature $T_{\text{ions}}$ in all spectral states

In bright hard state magnetic field is weak ($B \sim <10^4$ G) and $T_{\text{ions}}/T_e < 10$

- cannot be produced by standard corona/hot flow models
- multi-zone models needed (Malzac 2012)

Comparison with observations

BeppoSAX+CGRO

INTEGRAL
A two-component model for the LHS?

- Thermal comptonisation component dominates hard X-ray emission
- Non-thermal component reproduces soft X-ray excess and MeV emission
- Changes in the relative luminosity of thermal and non-thermal regions lead to state transitions

(Malzac, IJMP, 2012)
Observed Spectral Energy Distribution of Compact Jets

- Neutron star (4U 0614+091)
- Black hole X-ray binary (GX 339-4)

Gandhi et al. 2011
see also Corbel & Fender 2002, Chaty et al. 2011; Rahoui et al. 2012; Corbel et al. 2013; Russell et al. 2013...

Migliari et al. 2010

AGN

Bloom et al. 1994
Energy losses neglected $\Rightarrow$ constant specific internal energy:

$$\tilde{\varepsilon}(z) = \tilde{\varepsilon}_0 \Rightarrow B^2 \propto n \propto E_{\text{int}} \propto V^{-1} \propto r^{-2} \propto z^{-2}$$

$$F_\nu \propto \nu^\alpha \Rightarrow \alpha_{\text{thick}} = 0$$

$$\alpha_{\text{thin}} = \frac{1 - p}{2}$$
What about adiabatic expansion losses?

Pressure work against external medium as flow expands in conical geometry:

\[ d\tilde{W} = Pd\tilde{V} = (\gamma_a - 1)m\tilde{\epsilon}\frac{d\tilde{V}}{\tilde{V}} \approx \frac{2m\tilde{\epsilon}}{3} \frac{dR}{R} \]

\[ \Rightarrow \text{Specific internal energy decreases: } \tilde{\epsilon} \propto R^{-2/3} \propto z^{-2/3} \]

\[ \Rightarrow \alpha_{\text{thick}} = \frac{2p + 13}{4p + 18} \approx 0.65 \]

Spectrum is strongly inverted: need to compensate for losses.
Jet= ‘shells’ ejected a time intervals $\sim t_{\text{dyn}}$ with randomly variable velocities
Faster shells catch up with slower shells and collide
Shocks, particle acceleration, and emission of synchrotron radiation

Velocity fluctuations of smaller amplitudes and longer time-scales merge (and dissipate) at larger distances

Aim: study how results depend on the properties of Fourier PSD of fluctuations

Combining two approaches:
- Monte-Carlo simulations
- Analytical/Semi-analytical model
Response to white noise fluctuations

\[ f \times \text{Power Spectral Density} \]

\[ \text{Dissipation profile} \]

\[ \text{Specific energy profile} \]

\[ \text{Spectral energy distribution} \]

\[ \Rightarrow \alpha_{\text{thick}} = \frac{2p + 13}{4p + 18} \sim 0.65 \]

\[ \tilde{\epsilon} \propto z^{-2/3} \]
\[ P(f) \propto f^{-\alpha} \]

- **PSD of Lorentz factor fluctuations**
  - \( f \times \text{Power Spectral Density} \)
  - \( \alpha = 0, 0.6, 1, 1.2, 1.5 \)

- **Dissipation profile**
  - \( \frac{d\varepsilon}{dt} \times z \) [c^2]

- **Spectral energy distribution**
  - \( F_\nu \) [mJy]
  - \( \nu \) [Hz]

- **Specific energy profile**
  - \( \tilde{\varepsilon} \propto z^{-\frac{2(1-\alpha)}{3-\alpha}} \)

\[ \Rightarrow \alpha_{\text{thick}} = \frac{(2p + 13)(1 - \alpha)}{4p + 18 - \alpha(10 + 2p)} \]
Application to black hole binaries

\[ P(f) \propto \frac{1}{f} \quad \text{for} \quad 10^{-3} < f < 50 \quad \text{Hz} \quad \text{rms} = 30\% \]

\[ P_{\text{kin}} = 0.01L_E, \quad \Gamma = 2, \quad \phi_j = 1^\circ, + \text{ equipartition} \]

- Base of emitting region: \( z_0 \sim 10^{10} \text{cm} \)
- Magnetic field at base: \( B_0 \sim 10^4 \text{G} \)
- Flux of flat component: \( F_{v0} \approx 84 \frac{\delta^2}{D_{\text{kpc}}^2} \text{ mJ} \)
- High frequency break: \( \nu_T \sim 2 \times 10^{13} \text{Hz} \)
- Low frequency break: \( \nu_s \sim 1 \text{ GHz} \)

Malzac 2013
Fast Jet Variability

Observations of GX 339-4

Optical

Infrared

Gandhi et al. 2010

Casella et al. 2010
Fast Jet Variability

Model

Malzac et al. in prep.
IR /X-ray correlation

**Observations**

- **GX 339-4**
  - Casella et al. 2010

**Simulation**

- Assuming X-ray flux $\propto 1/\Gamma$
  - Malzac et al., in prep
Why flicker noise?

Accretion disks may produce 1/f noise (Lyubarskii 1997; King et al. 2004; Mayer & Pringle 2006...)

X-ray power spectra of X-ray binaries close to flicker noise:

\[ P(f) \propto f^{-1.3} \text{ at low frequencies} \]

+ band limited (Lorentzians) at high frequencies in HS

Gilfanov 2010
Using observed X-ray PSD as input PSD of jet Lorentz factor fluctuations

[Graph showing Lorentz factor Fourier PSD and photon SED]
Conclusions

- Emission from the X-ray corona well understood in terms Comptonization models.
- During state transitions the dramatic changes in disc luminosity drives the observed thermal vs non-thermal appearance of the Comptonized emission.
- Magnetic field may play a crucial role in thermalising electrons
- In hard state, hot accretion flow models favoured, but require that MeV tail is produced somewhere else: multi-zone corona ? jet ?

- Internal shocks can account for the canonical SED of compact jets provided the power spectrum of injected fluctuations is close to \( P(f) \propto f^{-1} \)
- Internal shocks produce strong, frequency dependent, variability similar to that observed.
- Possible connection between X-ray POWER spectrum and Radio-IR PHOTON spectrum.
Thanks !