Anatomy of an outflow: mapping the Mrk 509 warm absorber

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Collaborators

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Main goal campaign

• Characterise warm absorber by stacked, high S/N, high-resolution RGS spectrum
• Measure / constrain any variability of the absorber by med-resolution, highly sensitive EPIC spectra
• From (lack of) variability, determine distance absorption components
Observation campaign Mrk 509

- Core: 10 x 60 ks XMM, spaced 4 days (RGS, EPIC & OM all used!)
- Simultaneous Integral 10 x 120 ks
- Followed by 180 ks Chandra LETGS, simultaneous with 10 orbits COS (HST)
- Preceded with Swift (UVOT, XRT) monitoring
- Supplemented with ground-based (WHT, Pairitel) photometry & grism
- Period: 4 Sept – 13 Dec 2009 (100 days)
- 7 papers published, 8 submitted/in progress
Lightcurve during 100 days

- Intense monitoring with XMM & Swift gives continuous ~4d sampling
- Outburst in middle XMM monitoring $\rightarrow$ ideal for reverberation
- Strong correlation UV & Soft X-ray $\rightarrow$ comptonisation soft excess (Mehdipour et al. 2011)
Spectral energy distribution

- DBB
- Soft excess
- Power law
Time-dependent SEDs
Sample high-resolution spectra
Discrete ionisation components?

- Fitting RGS spectrum with 6 discrete WA components (A1-C1, C2-E2)
- Alternative: fit individual column densities, then decompose that into discrete components A-E (integrated over v)
Continuous AMD model

- Fitted columns with continuous (spline) model
- Surprise: comps C & D pop-up as discrete components!
- Upper limits FWHM 35 & 80 %
- Component B (& A) too poor statistics to prove if continuous
- Component E also poorer determined: correlation $\xi$ and $N_H$

$\Rightarrow$ Discrete components
Pressure equilibrium? No!
Time-dependent photoionisation

- SED changes in complex way
- Absorber adjusts on timescale $t_{\text{rec}} \sim 1/n$
- Solve $t$-dependent equations:
  - $\frac{dn_i}{dt} = A_{ij}(t) n_j$
  - $A_{ij}(t)$ contains $t$-dependent ionisation & recombination rates

Simplified case: predicted change transmission for 0.1 dex increase $L$, At spectral resolution EPIC/pn
Example of time-dependent calculation
• Models for instantaneous response:
• No sign of predicted signal
• \( \rightarrow \) lower density
• RGS gives similar constraints
Long term variability

• Compare archival spectra to our 2009 spectrum
• Predictions for change in components C, D and E
• Only change seen for component D
Upper limits distance

- Recombination time scale yields density $n$
- Using $\xi = \frac{L}{nr^2} \Rightarrow r = \sqrt{\frac{L}{\xi n}}$
- Using measured column density $N = n\Delta r$
  with $\Delta r$ the thickness of the layer and $\Delta r < r$
  $\Rightarrow r < \frac{L}{N\xi}$
## Summary distance limits

<table>
<thead>
<tr>
<th>Component</th>
<th>Lower limit (pc)</th>
<th>Method</th>
<th>Upper limit (pc)</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>~3000</td>
<td>Direct imaging</td>
<td>~3000</td>
<td>Direct imaging</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[O III]</td>
<td></td>
<td>[O III]</td>
</tr>
<tr>
<td>B</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>C</td>
<td>71</td>
<td>pn &amp; RGS, Fe blend</td>
<td>9000</td>
<td>Δr/r&lt;1</td>
</tr>
<tr>
<td>D</td>
<td>4.7</td>
<td>RGS O VIII</td>
<td>33</td>
<td>Long-term pn</td>
</tr>
<tr>
<td>E</td>
<td>4.6</td>
<td>pn, Fe blend</td>
<td>21-400</td>
<td>Δr/r&lt;1</td>
</tr>
</tbody>
</table>
Physical parameters

• The mass outflow rate is very large:

• using $\dot{M} = \Omega m_p n r^2 v$ with $n r^2 = L/\xi$ gives:

• $\dot{M}/\Omega = 2000, 25, 22, 2.1$ and $0.6$ Msun/yr for components A-E

• Compare to accretion rate of about $0.5$ Msun/yr

• either small filling factor, super-Eddington or small solid angle

• Kinetic luminosity is very small (at most $10^{-4} \times$ the ionising luminosity)
Other highlights

- Excellent UV spectra with COS (see talk Jerry Kriss)
- Accurate abundances of the outflow (Steenbrugge et al.)
- Fe-K studies (Ponti et al.)
- Continuum emission modeling, including soft excess (Mehdipour et al., Petrucci et al.)
- Broad X-ray emission lines (Costantini et al.)
- Interstellar foreground absorption (Pinto et al.)
- Etc.
Conclusions

• Deep, multi-wavelength monitoring campaigns (AGN) are rewarding:
• High quality spectra, not limited by statistics
• “Continuous” light curves, allowing to monitor the variations
Spare slides
Photoionisation modelling

- Radiation impacts a volume (layer) of gas
- Different interactions of photons with atoms cause ionisation, recombination, heating & cooling
- In equilibrium, ionisation state of the plasma determined by:
  - spectral energy distribution incoming radiation
  - chemical abundances
  - ionisation parameter $\xi = L/nr^2$ with $L$ ionising luminosity, $n$ density and $r$ distance from ionising source; $\xi$ essentially ratio photon density / gas density
Photoionisation models

- Models for transmission of a thin slab
- Continuum & line absorption calculated
- slab model: ion columns independent
- xabs model: ion columns coupled through xstar/cloudy runs
- warm model: continuous distribution of $N_H(\xi)$
X-ray analysis

- Fit spectra using a power law + modified blackbody (or even a spline) continuum
- Where needed, add emission lines: relativistic, BLR or NLR X-ray lines
- Fit warm absorber using a model (see previous slide) → ionic or total column densities
- Using photo-ionisation model, derive $N_H$ and $\xi$ distribution
- Spectral fits done with SPEX, global fits
Decomposition into separate $\xi$: evidence for 5 components

- Use column densities Fe ions from RGS data
- Measured $N_{\text{ion}}$ as sum of separate $\xi$ components
- LETGS results similar
- Need at least 5 components
Separate components in pressure equilibrium?

- Not all components in pressure equilibrium (same $\Xi \sim \xi / T \sim F / p$)
- Division into $\xi$ comps often poorly defined
- $\Rightarrow$ Continuous $N_H(\xi)$ distribution: see next slide
Column density versus $\xi$
Density estimates: reverberation

- If $L$ increases for gas at fixed $n$ and $r$, then $\xi = \frac{L}{nr^2}$ increases
- $\Rightarrow$ change in ionization balance
- $\Rightarrow$ column density changes
- $\Rightarrow$ transmission changes
- Gas has finite ionization/recombination time $t_r$ (density dependent as $\sim \frac{1}{n}$)
- $\Rightarrow$ measuring delayed response yields $t_r \Rightarrow n \Rightarrow r$
COS spectrum Mrk 509
RGS analysis

- Because of excellent quality, many new steps developed
- *Example*: combining spectra with variable hot pixels
- Several other instrumental issues resolved (separate paper) ($\lambda$-scale, effective area, response $2\text{Gb} \Rightarrow 8 \text{Mb}$, rebinning...)

![Graph showing spectrum analysis](image)
Stacked RGS spectrum

- See Galactic O I edge
- Several narrow absorption lines
No O I from host galaxy

O I host galaxy
(not detected,
$N_H < 5 \times 10^{18} \text{ cm}^{-2}$)

Wavelength (Å)
Ejection/outflows: Blue-shifted absorption lines/edges - Variability
Absorbers variabiliy on timescales 1000-10000s

NGC1365

Obs1
Obs2
Obs3

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Cappi et al., 2009
Dadina et al. ’05

Risaliti et al. 2005
(See also Krongold et al. 2007 on NGC4051)

Mrk 509 (long-look, 200ks)
Mass loss through the wind

\[ \dot{M}_{\text{loss}} = \Omega m_p n r^2 v \]

\[ n r^2 \cdot v = (L / \xi) \cdot v \]

\[ \dot{M}_{\text{loss}} < \dot{M}_{\text{acc}} \]

\[ L = \eta \dot{M}_{\text{acc}} c^2 \]

\[ \Omega < \frac{(\xi / v)}{\eta m_p c^2} \]

<table>
<thead>
<tr>
<th>ξ (km/s)</th>
<th>-166</th>
<th>-1040</th>
</tr>
</thead>
<tbody>
<tr>
<td>ξ=1</td>
<td>0.0007</td>
<td>0.0001</td>
</tr>
<tr>
<td>ξ=1000</td>
<td>0.7</td>
<td>0.1</td>
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