X-ray Absorption Line Diagnostics of Quasar Outflows

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VIth Serbian Conference on Spectral Line Shapes in Astrophysics
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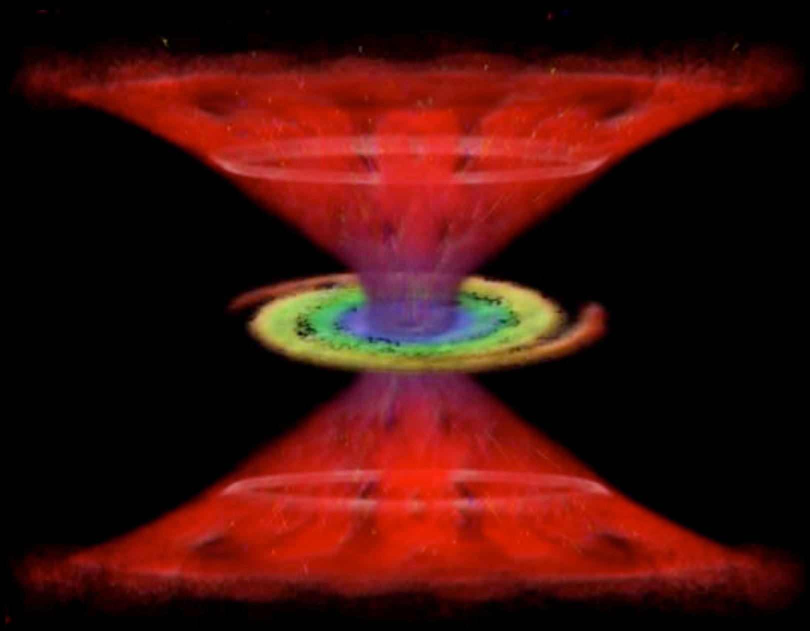
Quasar Outflows

Outline

- What are quasar outflows?
- How important are quasar outflows in regulating the growth of the black holes, in controlling structure formation and driving quasar evolution?
- X-ray absorption diagnostics of quasar outflows
- Future Prospects

Quasar Outflows

Radiation pressure will exert a force on gas rising up from the accretion disk through:



(a) Electron scattering (Thomson scattering)

$< \sigma_T/H > \sim 7\times10^{-25}$ cm$^2 x$ per H atom, where x is the ionization fraction

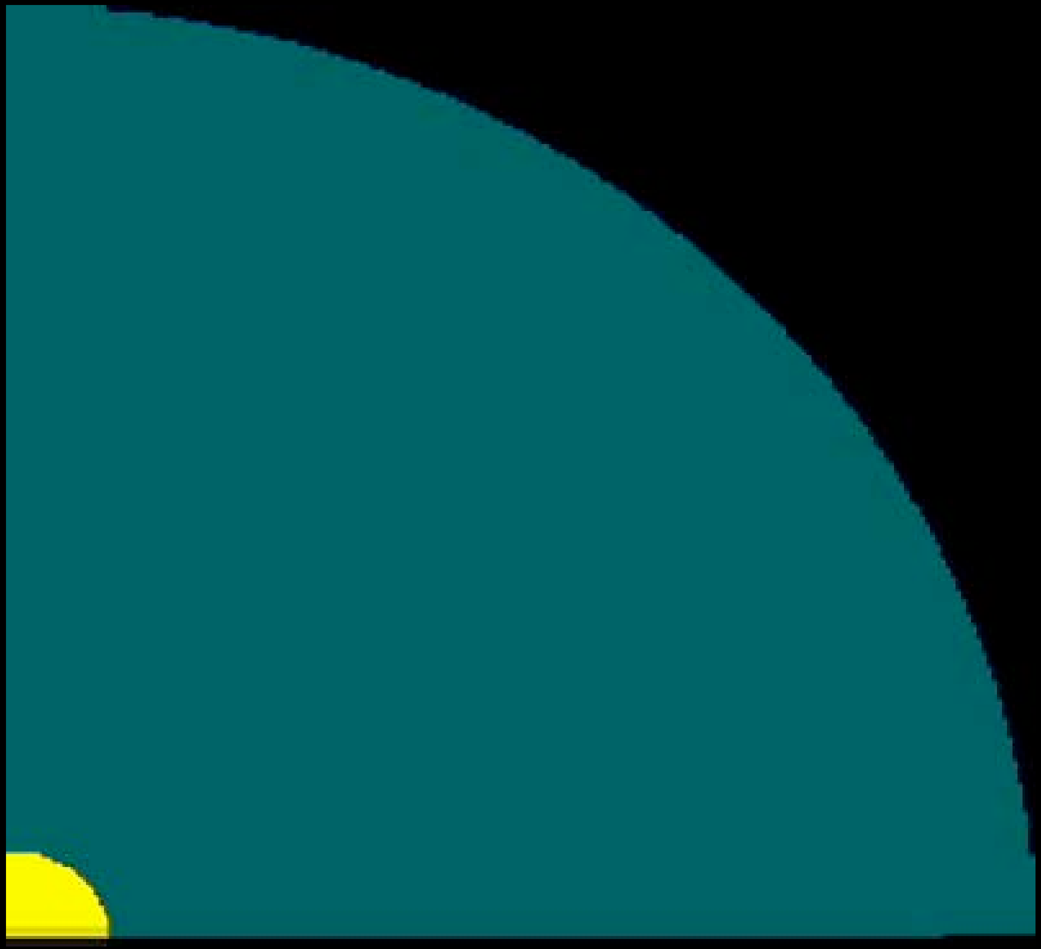
(b) Scattering by dust grains

$< \sigma_{dust}/H > \sim 10^5(\alpha/0.1\mu m)^{-1} < \sigma_T/H >$

where α is the grain size assuming a dust-to-gas ratio of 0.01

(c) Scattering in atomic resonance lines (line driving)

Quasar Outflows



Density evolution of disk wind driven by radiation pressure on spectral lines.

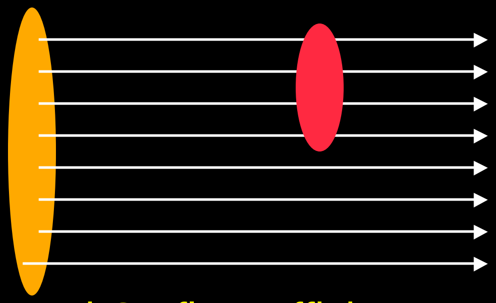
Proga Stone & Kallman (2000)

Quasar Outflows

How important are quasar winds in regulating the growth of SMBHs, for providing a feedback mechanism for kinetic energy injection into the IGM and for driving quasar evolution?

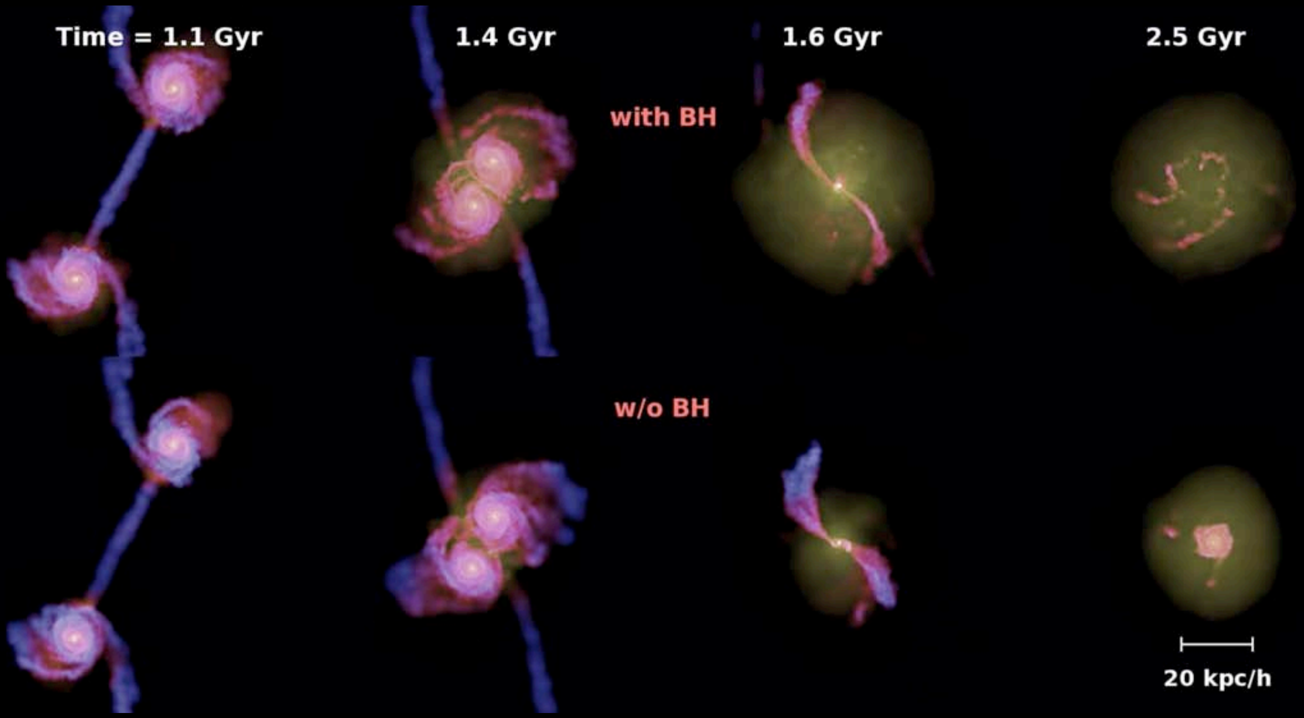
Observational constrains:

- Frequency of Quasar Outflows
- Kinematic and ionization (v, N_H, U) properties of AGN outflows
- Locations and driving mechanisms of the UV and X-ray outflows
- Covering Factors



→ Mass Outflow rates and Outflow Efficiency

Quasar Outflows



Simulations from Matteo, Springel & Hernquist, 2005

Quasar Outflows

Papers reporting fast outflows from quasars:

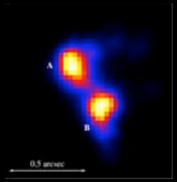
Object	z	v/c	Reference
APM 08279+5255	3.91	0.2 and 0.4	(Chartas et al. ApJ, 2002, ApJ, 579, 169)
H 1413+117	2.56	0.23 and 0.67	(Chartas et al. ApJ, 2007, 661, 678)
PG 1115+080	1.72	0.1 and 0.4	(Chartas et al. ApJ, 2003, 595, 85)
PDS 456	0.184	0.15	(Reeves et al. ApJ, 2003, 593, 65)
PG 1211+143	0.081	0.13	(Pounds et al. MNRAS, 2003, 345, 705) (1) (2)
PG 0844+349	0.064	0.2	(Pounds et al. MNRAS, 2003, 346, 1025) (3)
Mrk 509	0.034	0.1-0.2	(Dadina et al. A&A, 2005, 442, 461)
IRAS13197-1627	0.0165	0.11	(Dadina and Cappi, A&A, 2004, 413, 921)
IC 4329a	0.016	0.1	(Markowitz et al. 2006, ApJ, 646, 783)
MCG-5-23-16	0.0085	0.1	(Braito et al, 2006, AN, 327, 1067)

(1) Disputed by Kaspi et al., who claim the outflow may arise from a lower velocity, depending on the specific identification of lines in the spectrum.

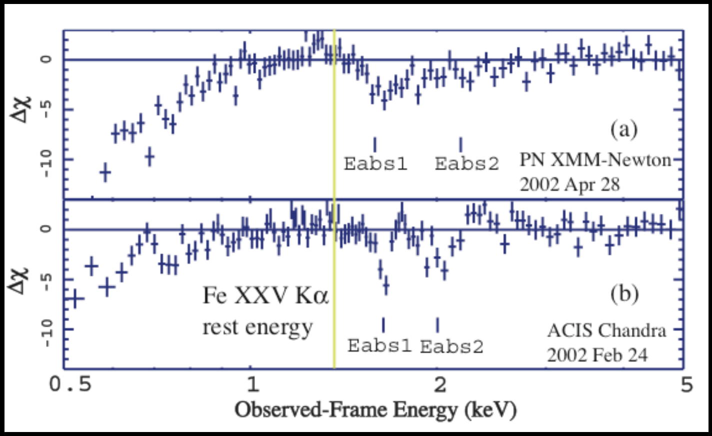
(2) Pounds & Page 2006 claim to confirm the high velocity outflow in PG 1211+143 in astro-ph0607099)

(3) Disputed on the basis of background subtraction in the EPIC/pn spectrum (Brinkman et al. 2005)

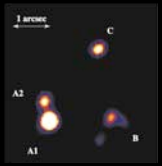
Quasar Outflows: Observations



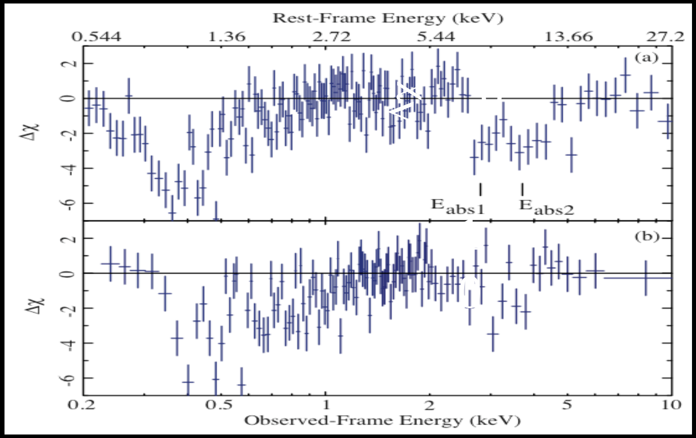
$z = 3.91$



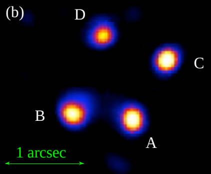
APM 08279+5255 (Chartas et al. 2002)



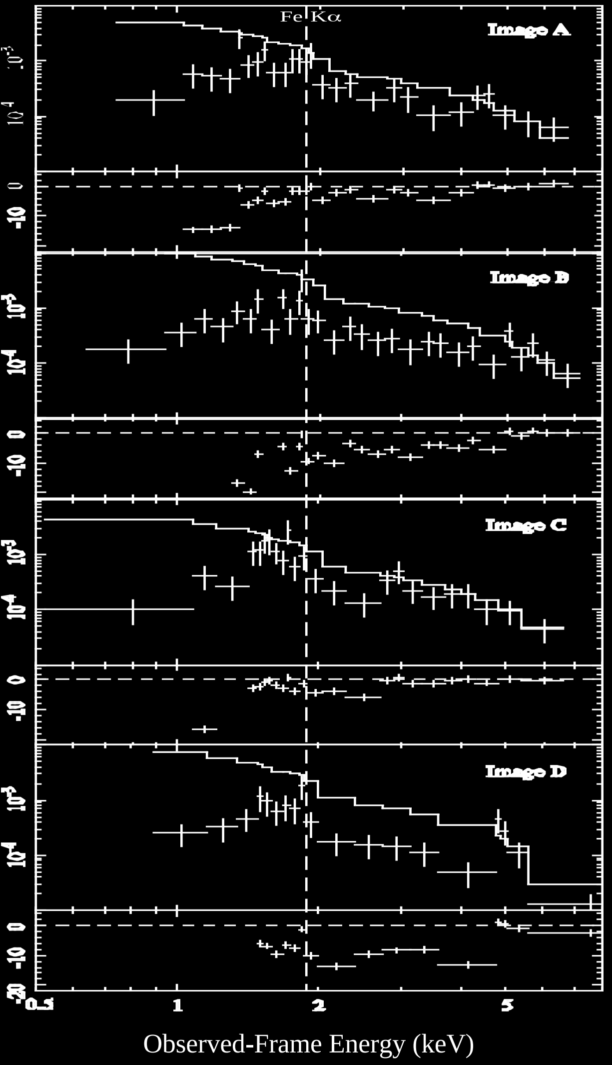
$z = 1.72$



PG 1115+080 (Chartas et al. 2003)

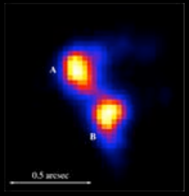


$z = 2.56$

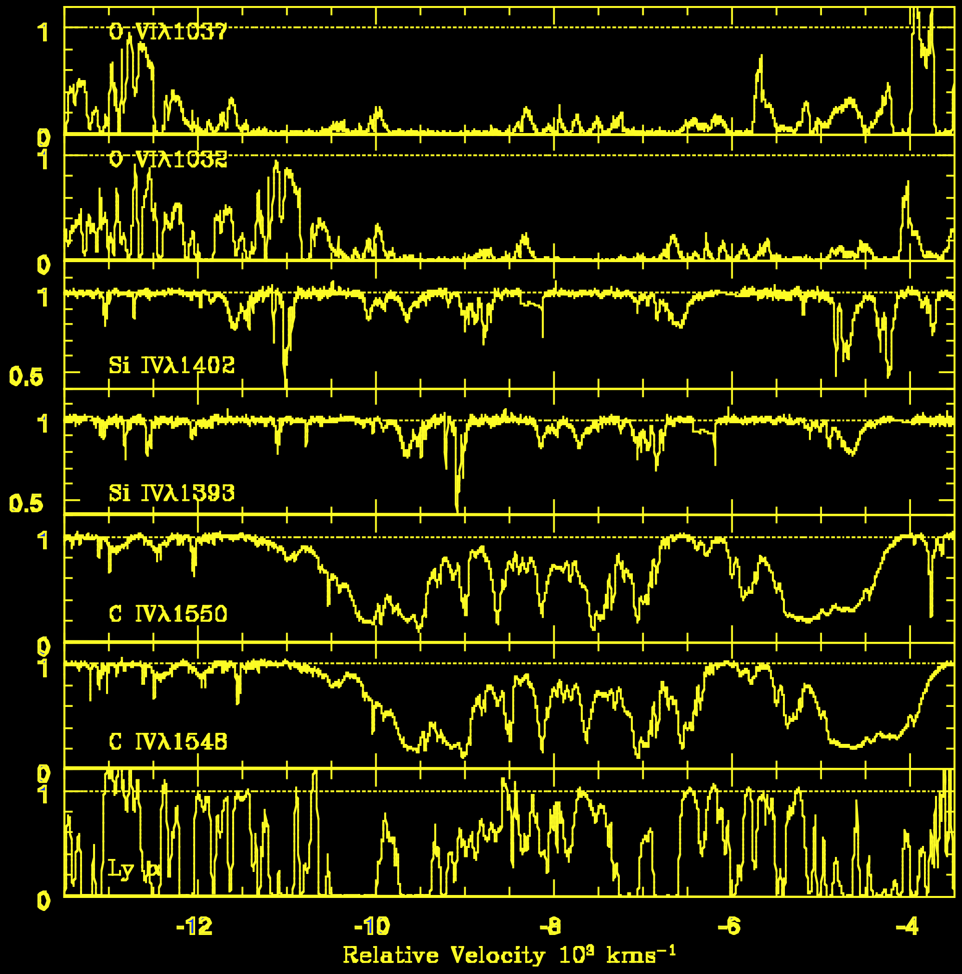


H 1413+117 (Chartas et al. 2007)

Quasar Outflows: Observations



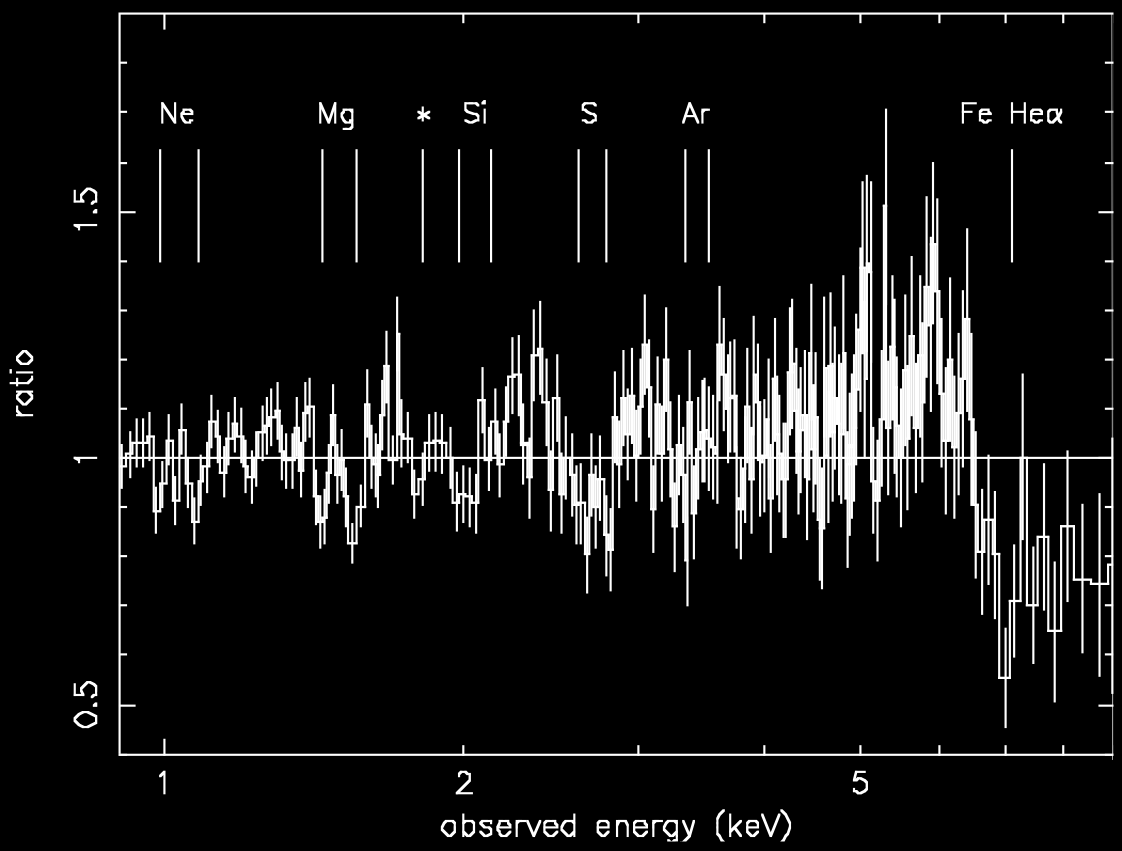
$z = 3.91$



UV BALs of APM08279+5255 due to various species. The spectrum of APM08279+5255 was obtained with the HIRES echelle spectrograph at the10m Keck-I telescope by Ellison et al. 1999.

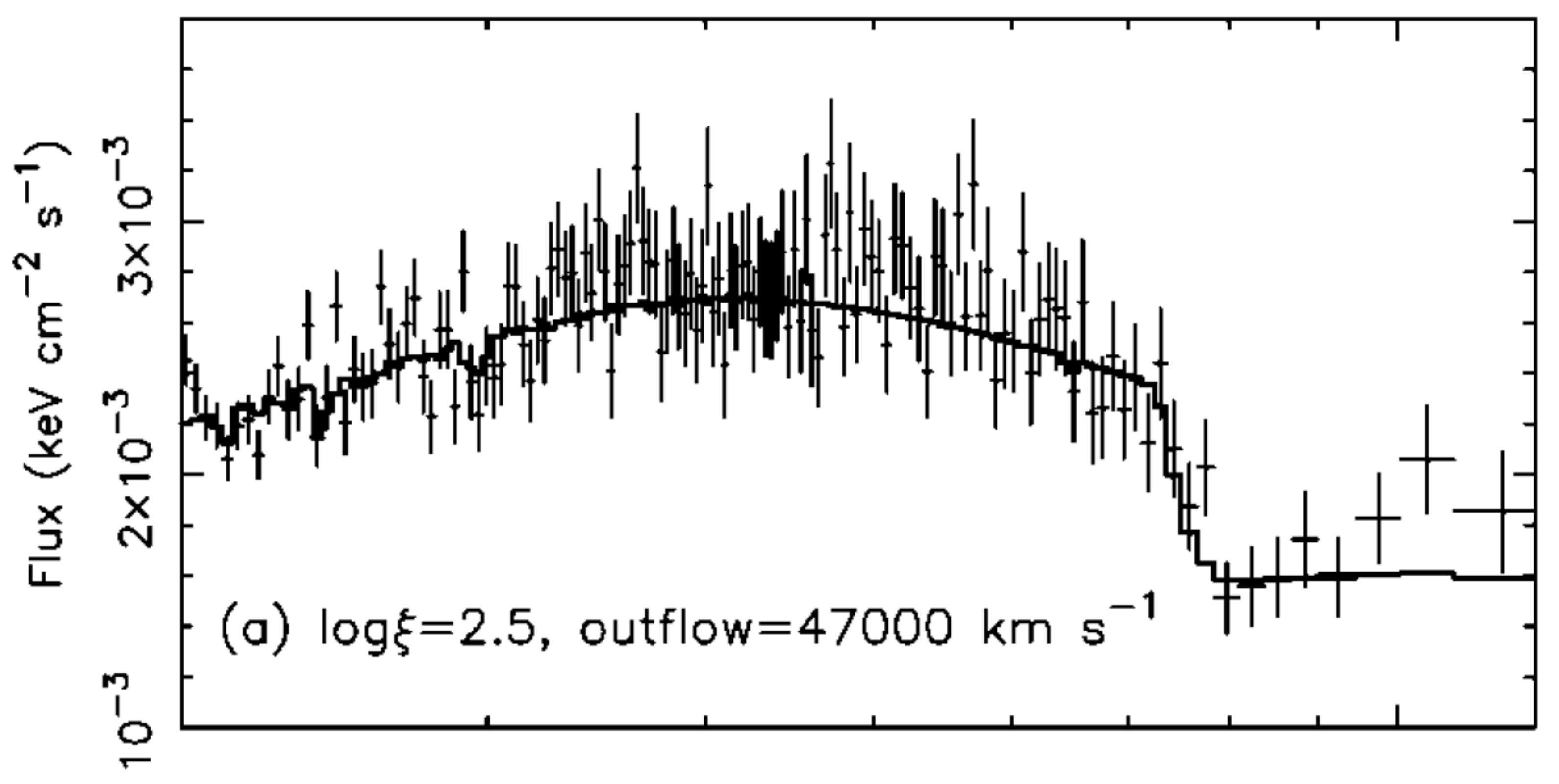
Figure from Srianand, R., & Petitjean, P. 2000.

Quasar Outflows: Observations



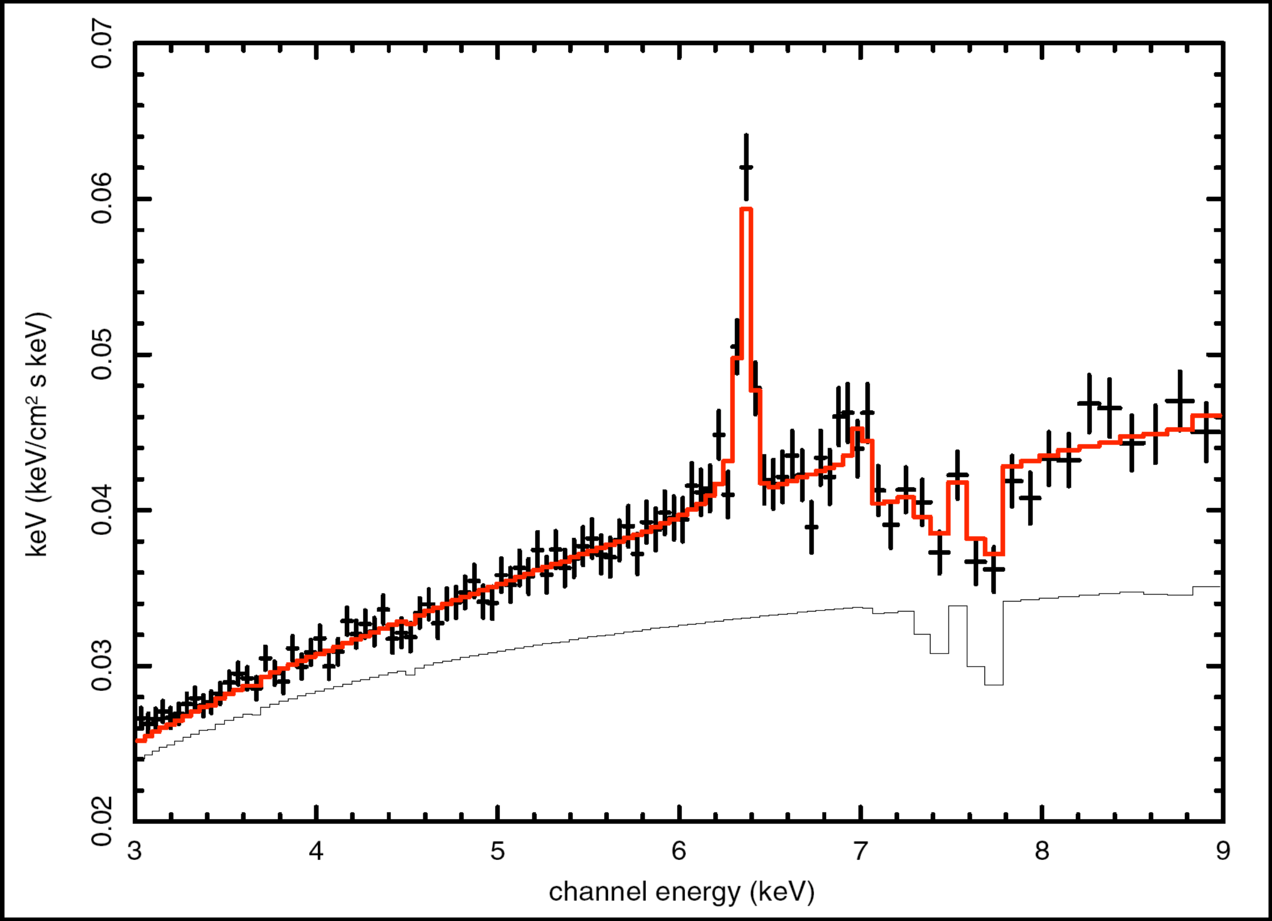
EPIC MOS data from the observation of PG 1211+143 compared with a simple power-law fit. Inferred outflow velocity of v = 0.130 +/- 0.003c (Pounds et al. 2007).

Quasar Outflows: Observations



The EPIC PN spectrum of PDS 456 fit with a warm absorber model. The best-fit model indicates an outflow velocity of about 50,000km/s and an ionization parameter of logξ = 2.5 (Reeves et al. 2003).

Quasar Outflows: Observations



The EPIC PN spectrum of MCG-5-23-16 fit with an Ionized absorber model. The best-fit model indicates an outflow velocity of about 0.1c (Fe XXVI Kα) and an ionization parameter of logξ = 3.6 (Braito et al. 2006).

X-ray Absorption Diagnostics of Quasar Outflows

Properties of the outflowing absorber that can be constrained from observed X-ray absorption lines:

1. Kinematic properties (ie. velocity, acceleration)
2. Structure of Outflows (ie. location of absorbers, launching radii, inclination angle)
3. Partial Covering Factor (ie. doublet method)
4. Effective Hydrogen Column Density (N_H)
5. Number Density of Absorber (n_e)
6. Ionization level (ξ; multiple ionization levels?)
7. Efficiency of Quasar Outflow (ie. quasar feedback)

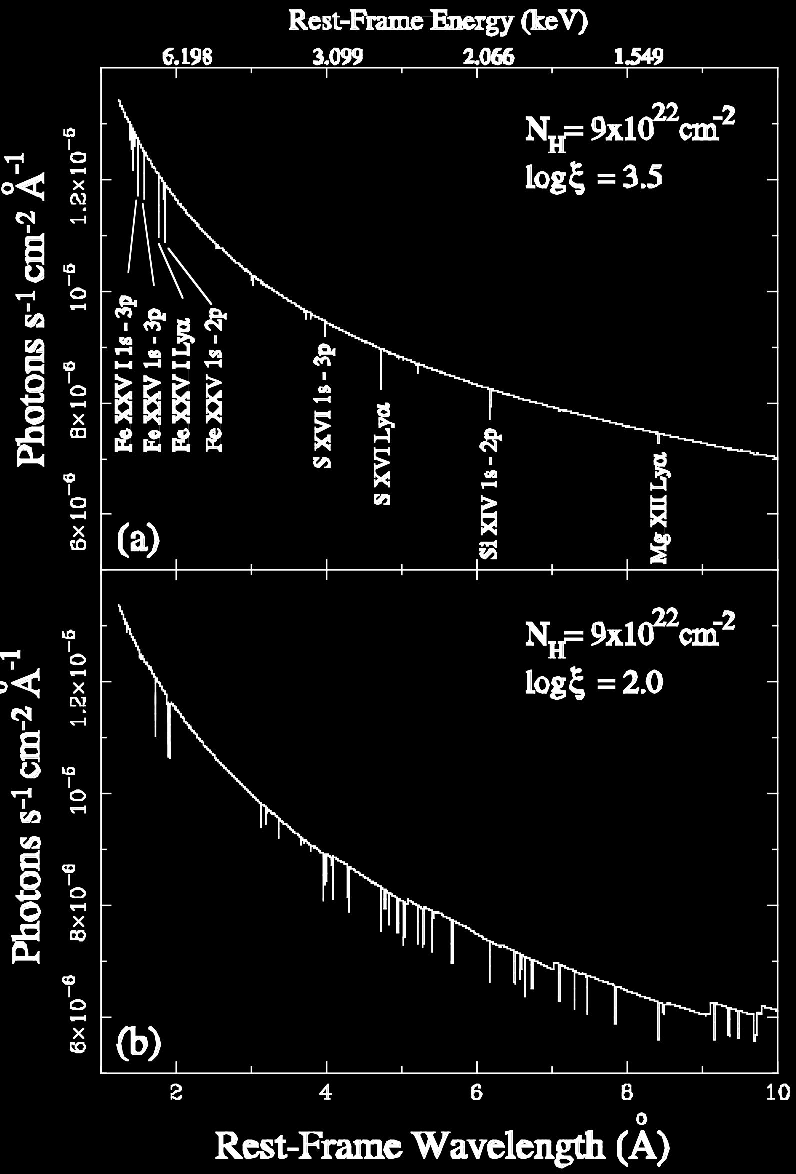
X-ray Absorption Diagnostics

KINEMATICS

Identify absorption lines in X-ray spectra

Search for possible blueshifts or redshifts of the absorption lines that would imply an outflow of infall, respectively.

The energy of the absorption line provides an estimate of the projected velocity of the outflowing or infalling absorber along the observed line of sight.



X-ray Absorption Diagnostics

KINEMATICS

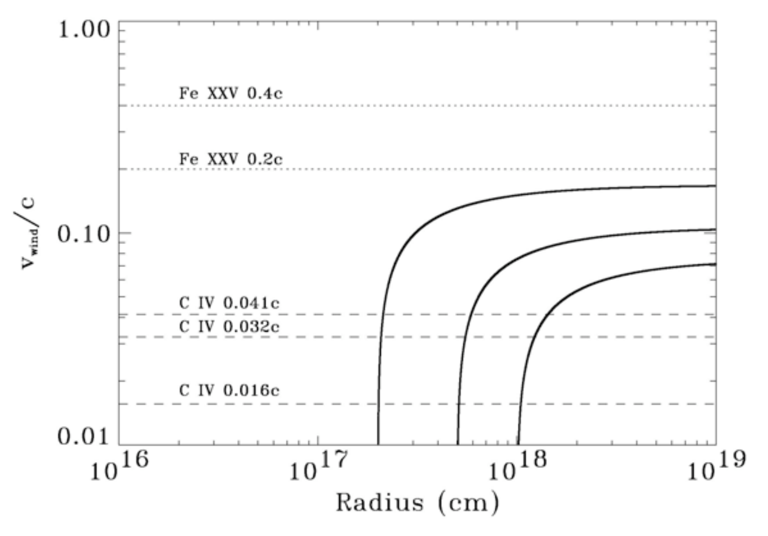
The terminal velocity (~ v_{obs}) is often approximated with the escape velocity from the region from which the wind is launched, resulting in the approximation :

$$R_{launch} \approx R_{sch}\left(\frac{c}{v_{obs}}\right)^2$$

The velocity of the outflow at a radial distance *R* produced by radiation pressure from a central source with a UV luminosity if L_{UV} and a mass of M_{bh} at some radial distance R is :

$$v_{wind} = \left[2GM_{bh}\left(\Gamma_f \frac{L_{UV}}{L_{Edd}} - 1\right)\left(\frac{1}{R_{in}} - \frac{1}{R}\right)\right]^{1/2}$$

Where, L_{edd} is the Eddington luminosity, Γ_f is the force multiplier, and R_{in} is the launching radius



Estimate of wind velocity in APM 08279+5255
Assumed Γ_f=100, L_{UV}=4x10^{46} erg/s, L_{Bol} = 2x10^{47} erg/s and L_{Bol}/L_{Edd} = 0.1.

X-ray Absorption Diagnostics

Radial Location of an Absorber

(1) light-travel time based on observed variability of absorption features

$$r \approx c\,\frac{t_{\mathrm{var}}}{(1+z)}$$

(2) Combining n_e and U provides an estimate of the radial location of the absorber.

$$r = \left[\frac{L(H)}{4\pi U n_e c}\right]^{0.5}$$

Where *L(H)* are the ionizing photons s^{-1} emitted from the central engine, *U* is the ionization parameter, and n_e is the number density of the absorber

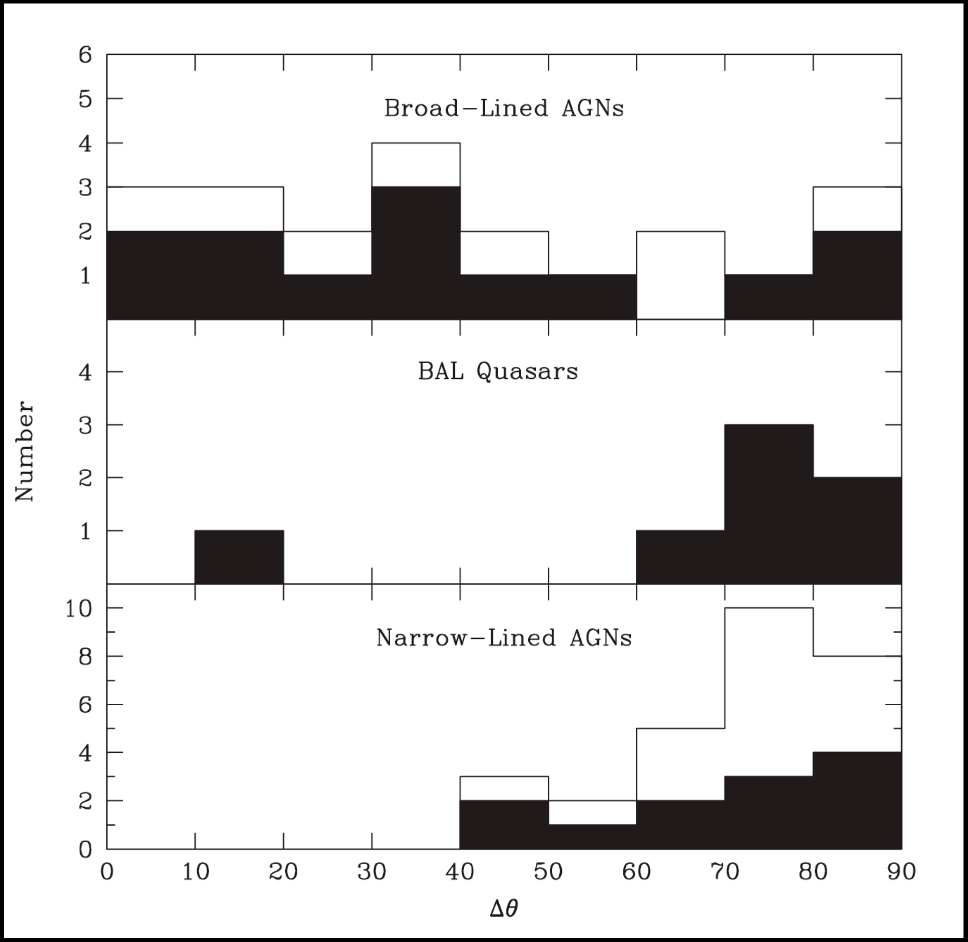
X-ray Absorption Diagnostics

Inclination Angle of Outflowing Stream

Methods of estimating inclination angle:

(1) Global covering factor (fraction of sources that show absorption)

(2) Using spectropolarimetry to determine the optical polarization and radio polarization angles.

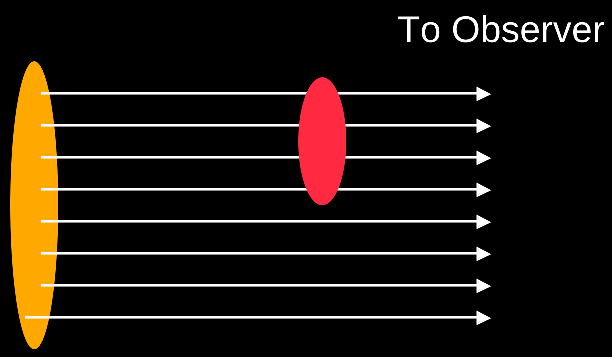


Distribution of Δθ (~ inclination angles) of outflow stream for broad line AGNs, BAL quasars, and narrow line AGNs. *From Brotherton, De Breuck, & Schaefer 2006, MNRAS 372, L58*

X-ray Absorption Diagnostics

Velocity Dependent Covering Factors

For the case of partial coverage we have:



$$I_1'(v) = (1 - C(v))I_0 + C(v)I_0e^{-\tau_1}$$
$$I_2'(v) = (1 - C(v))I_0 + C(v)I_0e^{-\tau_2}$$

$$I_1(v) = (1 - C(v)) + C(v)e^{-\tau}$$
$$I_2(v) = (1 - C(v)) + C(v)e^{-2\tau}$$

where the covering factor *C(v)*, is the fraction of emission intercepted by the absorber over the line of sight. This method is applied in the case of an absorption doublet with normalized intensities in the weaker and stronger line troughs of I_1 and I_2

Solving the above equations we have:

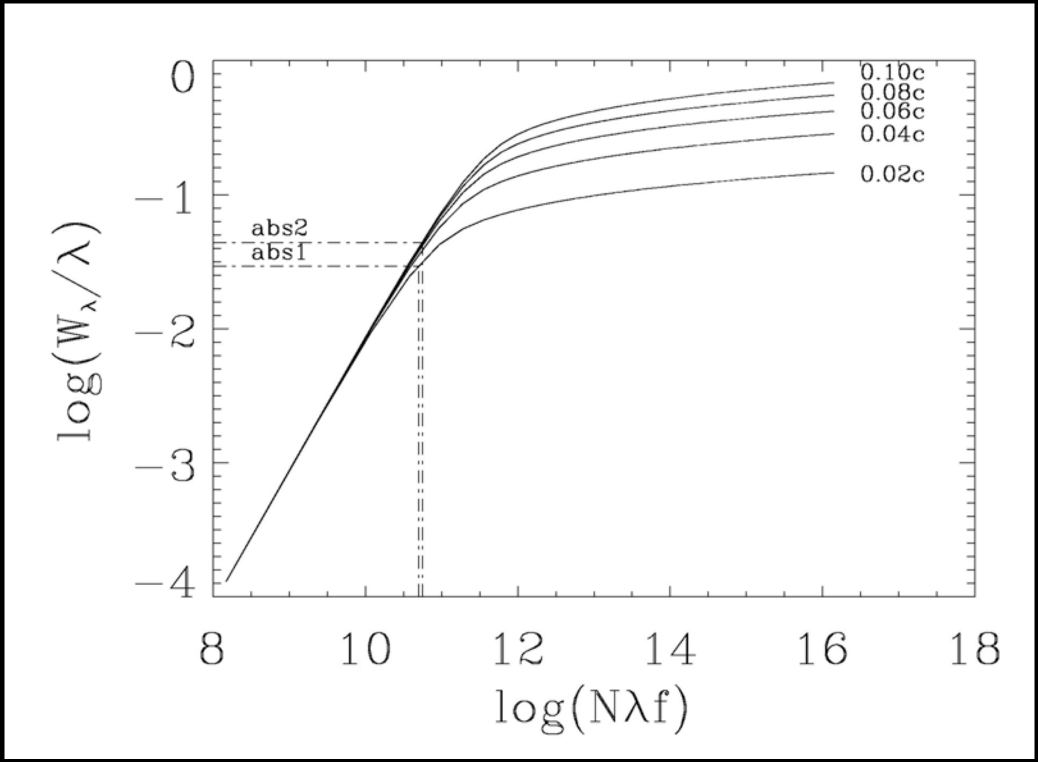
$$C(v) = \frac{I_1(v)^2 - 2I_1(v) + 1}{I_2(v) - 2I_1 + 1}, \quad \tau(v) = -\ln\left(\frac{I_1(v) - [1 - C(v)]}{C(v)}\right) = -\ln\left(\frac{I_1(v) - I_2(v)}{1 - I_1(v)}\right)$$

X-ray Absorption Diagnostics

Effective Hydrogen Column Densities

$N_{FeXXVabs1} \sim 3.4 \times 10^{18} cm^{-2}$

$N_{FeXXVabs2} \sim 3.8 \times 10^{18} cm^{-2}$



Using a curve of growth analysis one can estimate the hydrogen column densities implied by the observed equivalent widths of the two absorption lines at 8.05 and 9.79 keV.
We assumed that the ion species responsible for the X-ray BALs is Fe XXV and *b* parameters of the order of the observed widths of the lines ($b = \sqrt{2}\sigma_u$).

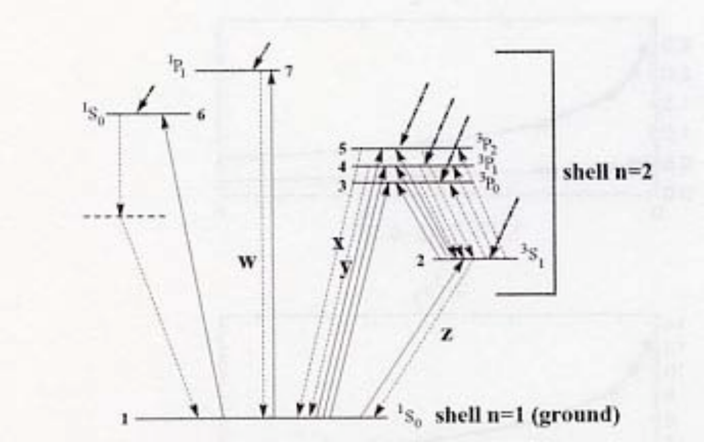
X-ray Absorption Diagnostics

Number Density of an Absorber *n*

the ratio of the forbidden lines to intercombination lines is a function of n_e

$$R(n_e) = \frac{z}{x+y}$$

$$G(T_e) = \frac{z+(x+y)}{w}$$



Where

w represents the resonance line $1s^2\ ^1S_0 - 1s2p\ ^1P_1$

x,y represents the intercombination lines $1s^2\ ^1S_0 - 1s2p\ ^3P_{2,1}$

z represents the forbidden line $1s^2\ ^1S_0 - 1s2s\ ^3S_1$

X-ray Absorption Diagnostics

Ionization Parameter

It is commonly thought that the outflowing gas observed in absorption is photoionized by a central source. The degree of ionization of the absorber is characterized by the ionization parameter

Two commonly used definitions of the ionization parameter

(1) The ionization parameter U represents the number of ionizing photons at the ionizing face of the absorbing gas divided by the number density of the gas (number density of H nuclei or free electron density)

$$U = \int_{\nu_0}^{\infty} \frac{L_\nu h\nu}{4\pi r^2 nc} d\nu$$

(2) The ionization parameter ξ, represents the ionizing flux at the face of the gas divided by the number density of free electrons.

$$\xi = \frac{4\pi F}{n}$$

X-ray Absorption Diagnostics

Ionization Parameter

The ionization parameter *U* for the outflowing absorbers in Seyfert 1s is found to span a large range (even within an individual AGN).

For the UV absorbers : log(*U*) ~ -4 to 0

For the X-ray absorbers: log(*U*)~-1.4 to 1.0

The outflowing UV and X-ray absorbers appear to be more highly ionized than the BELR and NELR which have ionization parameters in the range log(*U*) ~ -3 to -1

Computer programs for calculating the physical conditions and emission spectra of photoionized gases:

XSTAR: http://heasarc.gsfc.nasa.gov/docs/software/xstar/xstar.html

Cloudy : http://www.nublado.org/

X-ray Absorption Diagnostics

The mass outflow rate is:

$$\dot{M} = 4\pi r\left(\frac{r}{dr}\right)N_H m_p v_{wind} f_c$$

The outflow efficiency is:

$$\varepsilon_{k,i} = \frac{1}{2}\frac{\dot{M}_i v_{wind,i}^2}{L_{Bol}} = 2\pi f_{c,i} R_i \left(R_i / \Delta R_i\right) N_{H,i} m_p \frac{v_{wind,i}^3}{L_{Bol}}$$

Quasar Outflows: Mass Outflow Rates and Efficiencies

Assumptions:

f_c : 0.1 - 0.3

$r/\Delta r$: 1 - 10

R_{launch} = 3 - 15 R_s

N_H : from curve of growth analysis

Results:

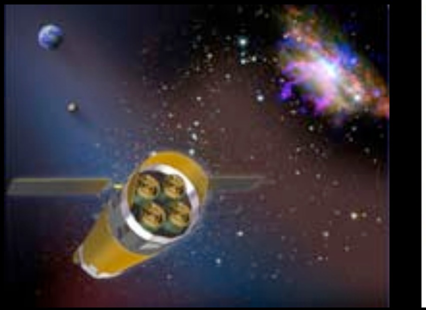
PG 1115+080

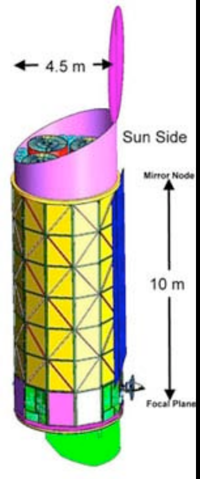
Comp	N_H cm^{-2}	v_{abs}	Mdot M_{sol}/year	ε_k
abs1	4e22	0.09c	0.1(-0.07,0.09)	7.2(-4.6,6.3)e-4
abs2	4e23	0.4c	4.6(-2.9,4.0)	6.3(-4.0,5.5)e-1

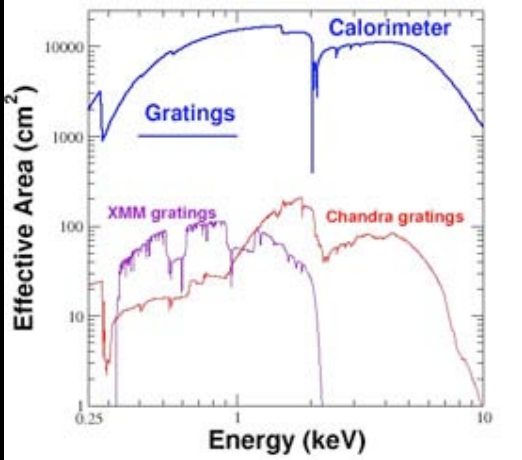
APM 08279+5255

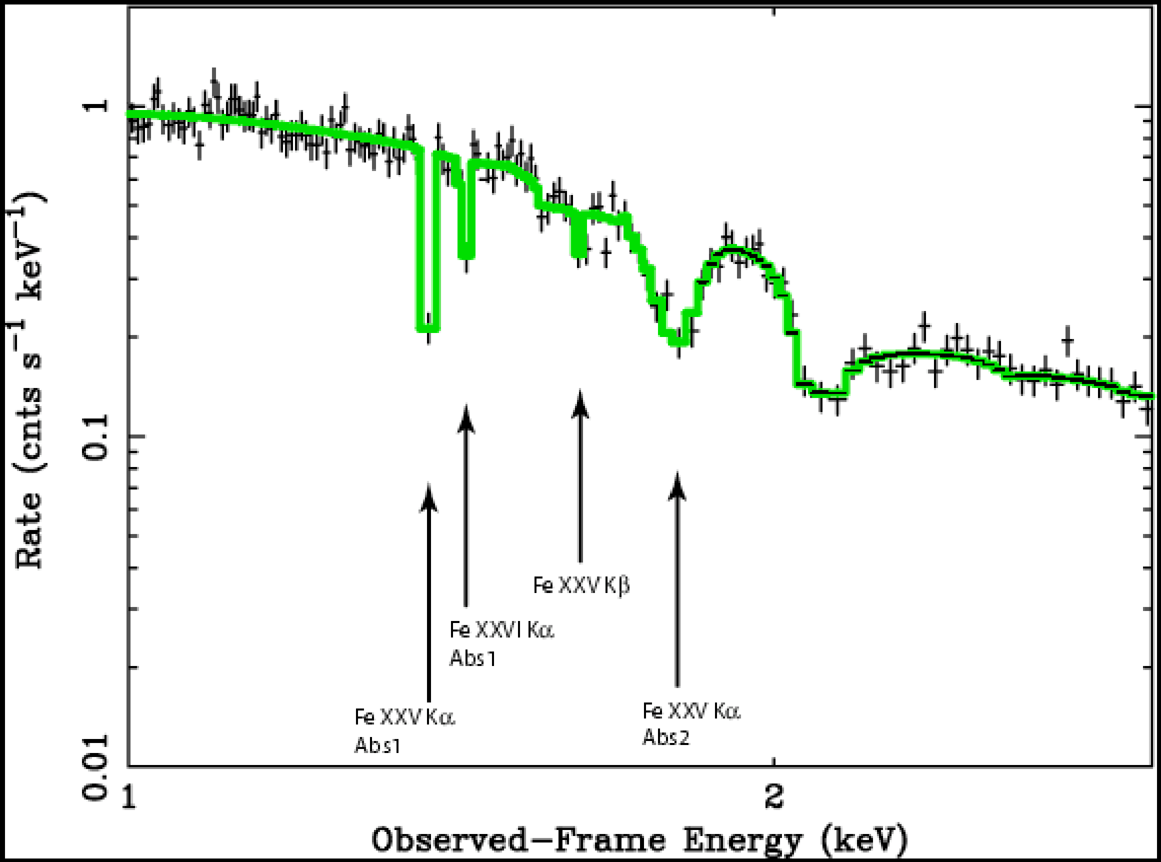
Comp	N_H cm^{-2}	v_{abs}	Mdot M_{sol}/year	ε_k
abs1	1e23	0.2c	1.7(-1.0,1.4)	1.0(-0.6,0.8)e-2
abs2	1e23	0.4c	3.3(2.1,2.9)	0.8(-0.5,0.7)e-1

What Lies Ahead?









Simulated Constellation-X Calorimeter Spectra of Variable X-ray BALS in APM08279+5255

Conclusions

- Sub-relativistic outflows of highly ionized gas have been detected in several quasars.

- X-ray absorption lines can be used to constrain the properties of quasar outflows (N_H, n_e, ξ, v, f_c, n_e, $Mdot$, ε_k)

- Mass outflow rates in APM08279 (~5 M_s/y) and PG 1115 (~5 M_s/y) is found comparable to their accretion rates.

- Fraction of bolometric energy released in the form of kinetic energy
  ε_K ~0.09 (-0.05,+0.07), APM 08279+5255
  ε_k ~ 0.64 (-0.40,+0.52), PG1115+080

- The confirmation of relativistic outflows in most quasars would imply that quasar outflows have a significant impact in inhibiting their own growth, halting star formation, shaping the evolution of their host galaxies and driving quasar evolution.

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