Chandra X-ray Spectroscopy of Winds in AGN

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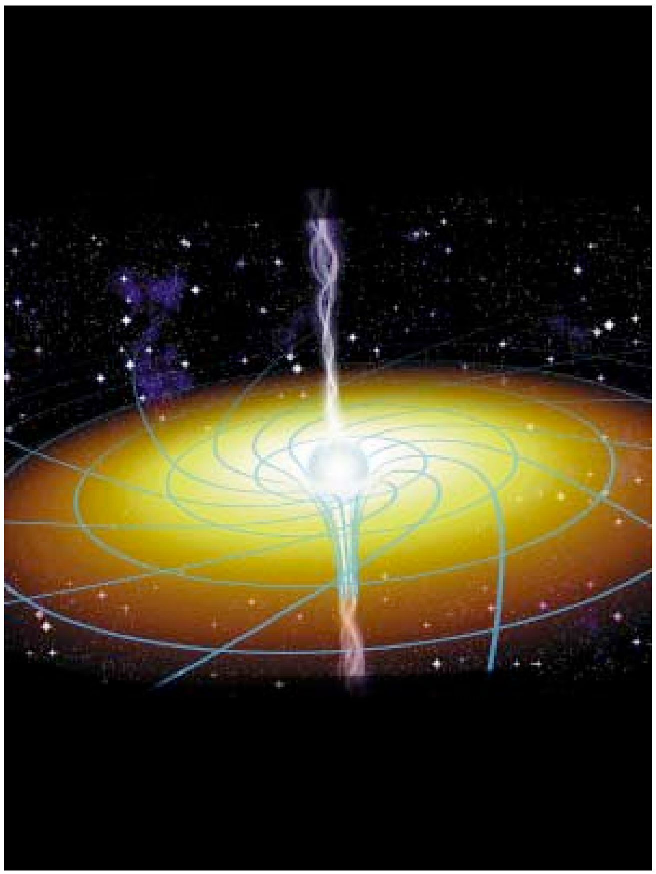


Based partly on work in

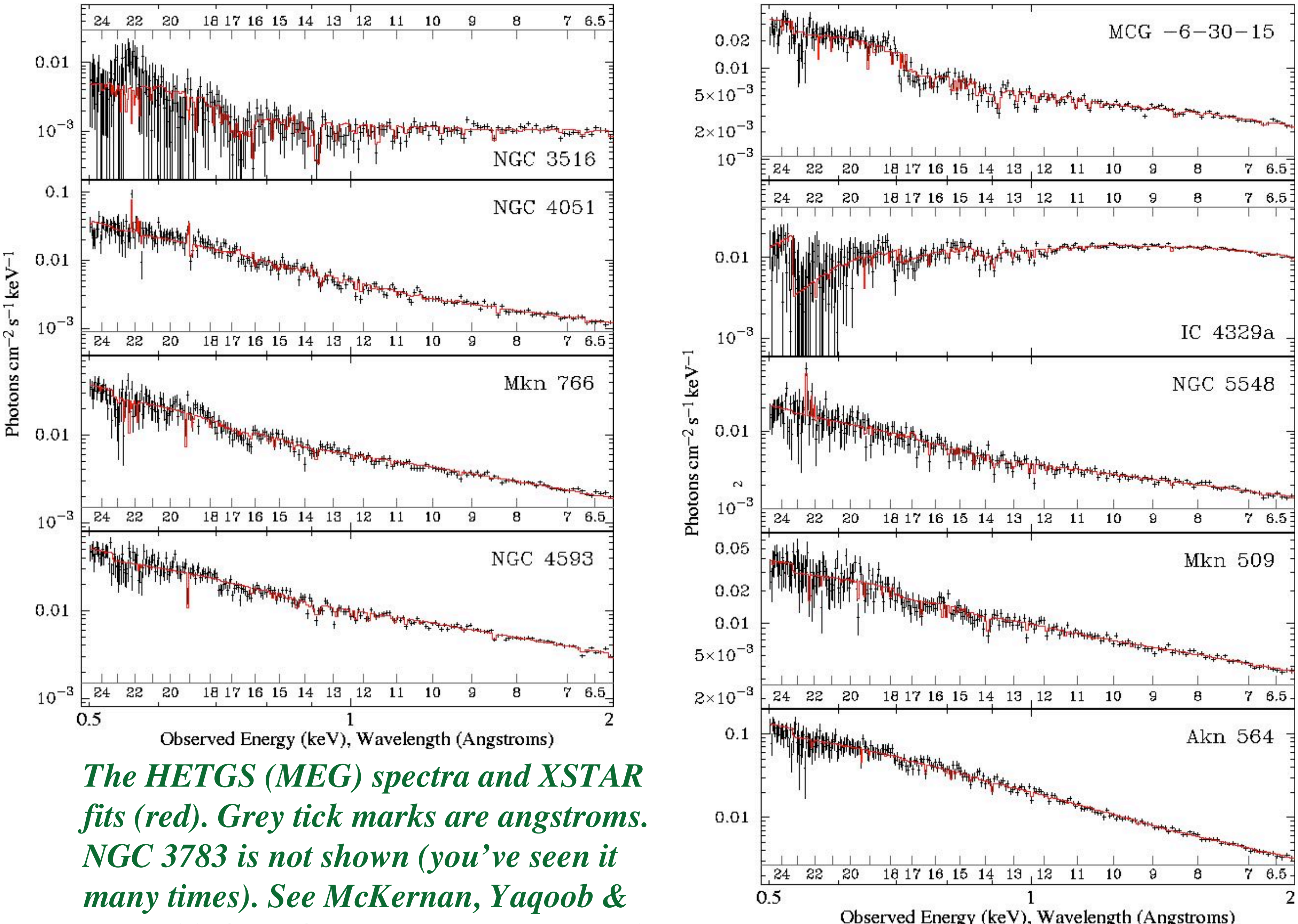
"A Soft X-ray Study of Type I AGN Observed with the Chandra HETGS'', by McKernan, Yaqoob, & Reynolds (2006, submitted), and

"Iron K Features in the Quasar E1821+643: Evidence for Gravitationally Redshifted Absorption?'' (Yaqoob & Serlemitsos, 2005, ApJ, 623, 112).

The HETGS Seyfert 1 Sample

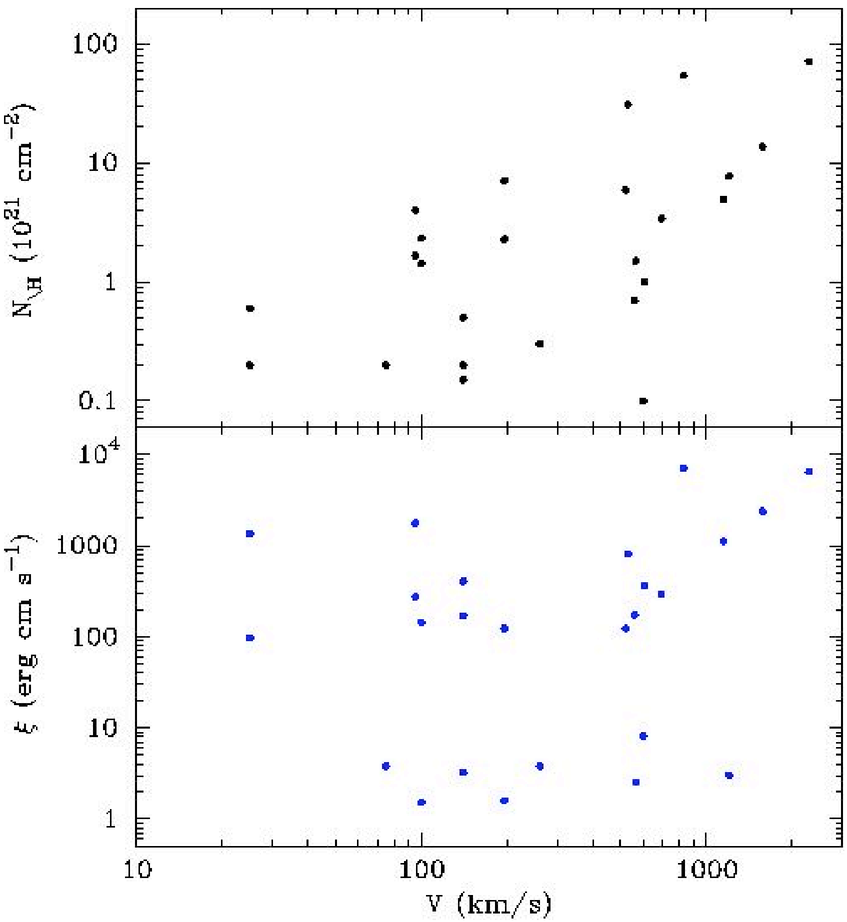
Source	RA (J2000.0)	Decl. (J2000.0)	Redshift (z)	Galactic N_H ($10^{20} cm^{-2}$) [a]	Observation Start [b]	Exposure[c] (ks)
Fairall 9	01 23 45.7	-58 48 21	0.04600	3.0	2001 Sep 11	80
3C 120[d]	04 33 11.0	05 21 15	0.03301	12.30	2001 Dec 21	58
NGC 3227	10 23 30.6	+19 51 54	0.00386	2.15	1999 Dec 30	47
NGC 3516	11 06 47.5	+72 34 07	0.00884	3.05	2001 April 9	200
NGC 3783	11 39 01.7	-37 44 18	0.00973	8.50	2001 Feb 24	850
NGC 4051	12 03 09.5	44 31 52	0.00242	1.31	2000 Mar 24	80
Mkn 766	12 18 26.5	29 48 46	0.01293	1.80	2001 May 7	90
NGC 4593	12 39 39.3	-05 20 39	0.00831	1.97	2001 Jun 29	79
MCG-6-30-15	13 35 53.3	-34 17 48	0.00775	4.06	2000 Apr 5	126
IC 4329a	13 49 19.2	-30 18 34	0.01605	4.55	2001 Aug 26	60
Mkn 279	13 53 03.5	+69 18 30	0.03045	1.64	2002 May 18	116
NGC 5548	14 17 59.5	25 08 12	0.01717	1.70	2000 Feb 5	82
Mkn 509	20 44 09.6	-10 43 23	0.03440	4.44	2001 Apr 13	60
NGC 7314	22 35 46.2	-26 03 01	0.00474	1.46	2002 Jul 19	97
Akn 564	22 42 39.3	29 43 31	0.02467	6.40	2000 Jun 17	50

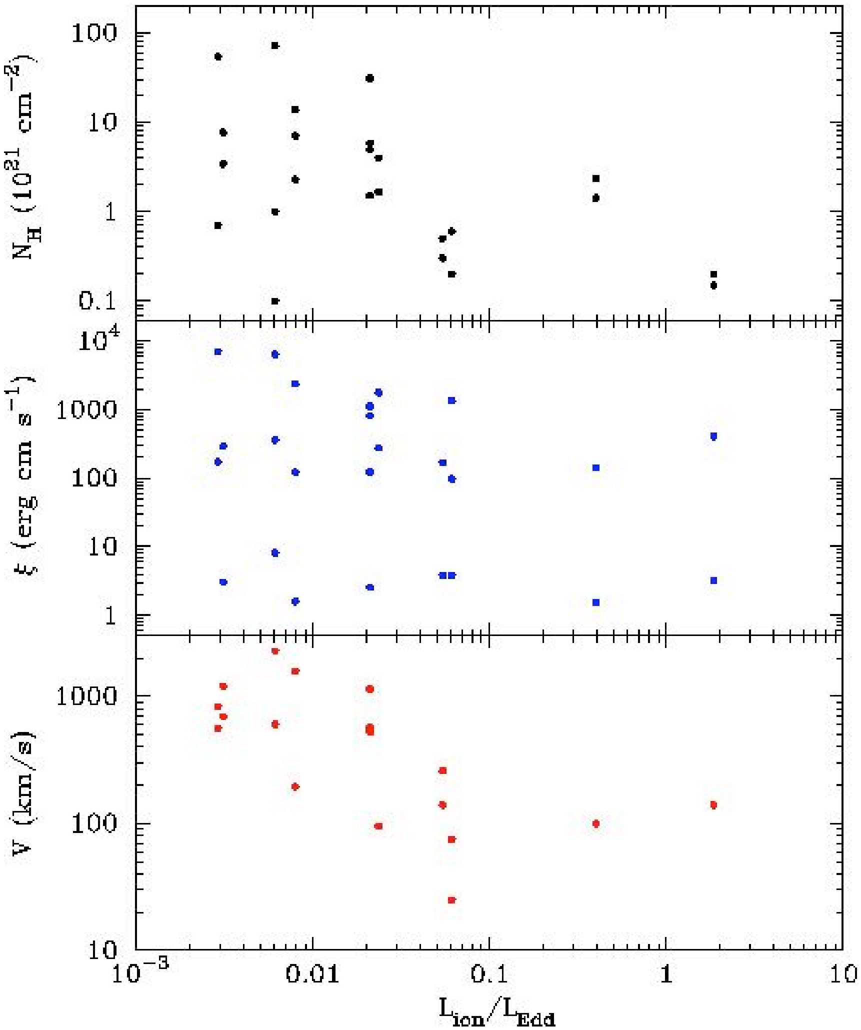
10/15 AGN in this sample exhibited definite signatures of photoionized absorption. Measurement of individual absorption and emission lines and XSTAR modeling described in McKernan, Yaqoob & Reynolds (2006). NGC 3227, NGC 7314 soft X-ray spectra too heavily absorbed. Significant intrinsic features not found in F 9, 3C 120 (but see Ogle et al. 2005), Mkn 279 (see Scott et al. 2004, Arav et al. 2005).



The HETGS (MEG) spectra and XSTAR fits (red). Grey tick marks are angstroms. NGC 3783 is not shown (you've seen it many times). See McKernan, Yaqoob & Reynolds for references to previous work.

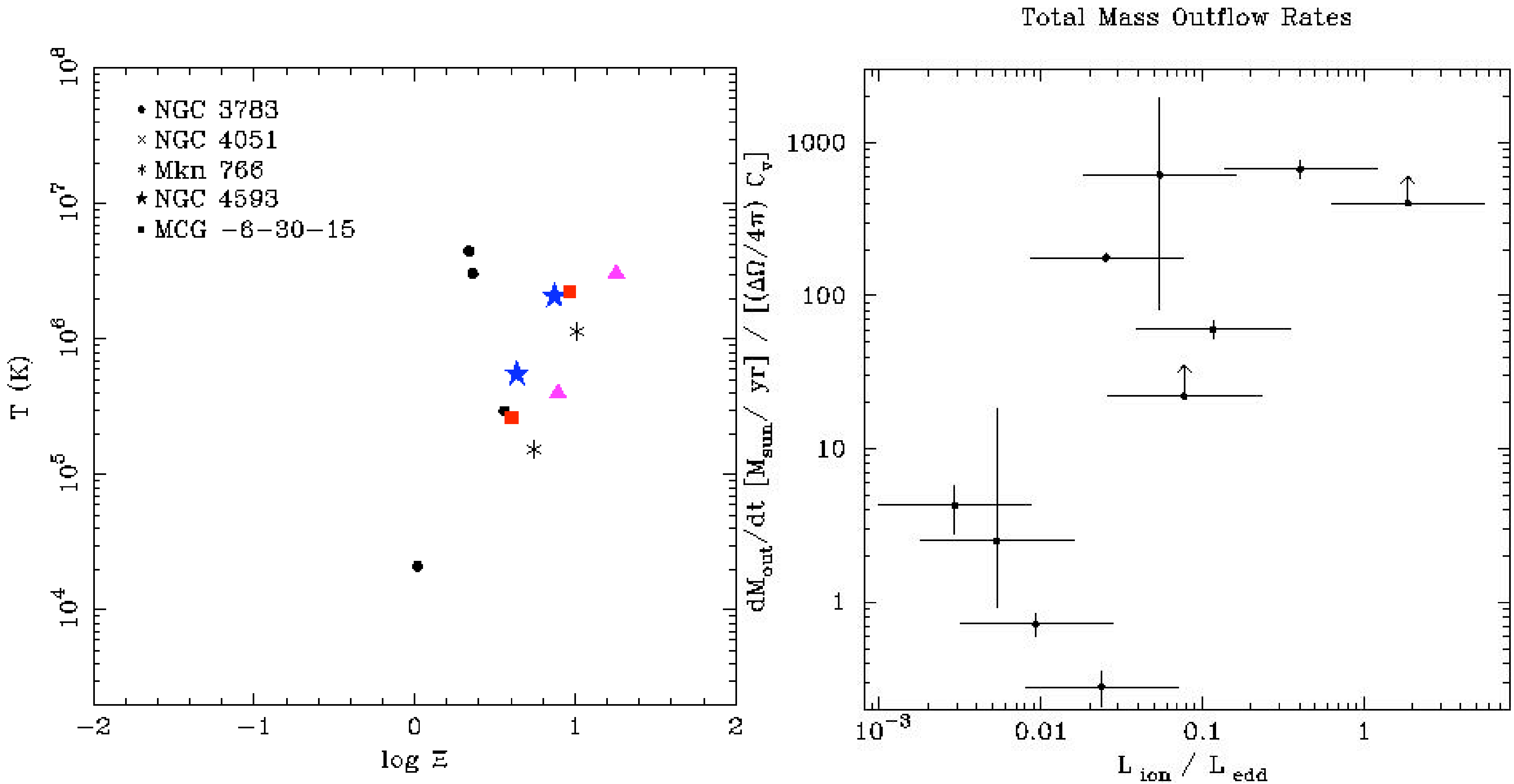
Correlations with Outflow Velocity & L_{ION}/L_{EDD}





- ❑ ***V bimodal? Anti-correlated with L_{ION}/L_{EDD}?***
- ❑ ***Correlation of N_H with outflow velocity, V?***
- ❑ ***N_H and ξ (high) not correlated with L_{ION}/L_{EDD}?***
- ❑ ***As noticed by others, the photoionized gas does not occupy intermediate values of ξ .***

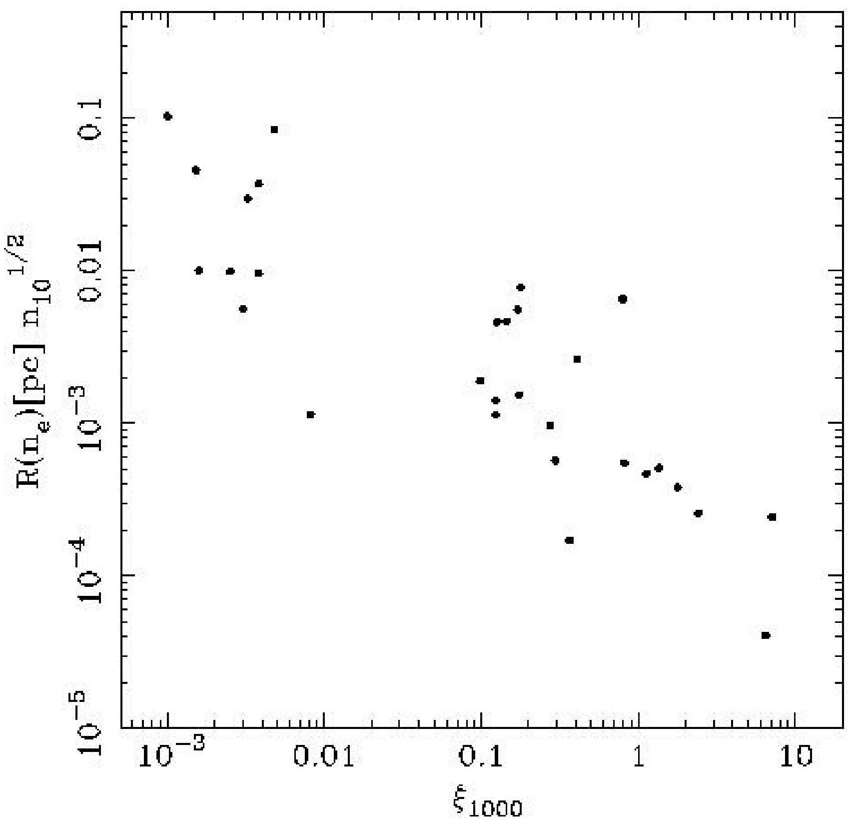
Some of the AGN have more than one warm absorber component. These plots show parameters of each component. See McKernan, Yaqoob, & Reynolds (2006) for details.



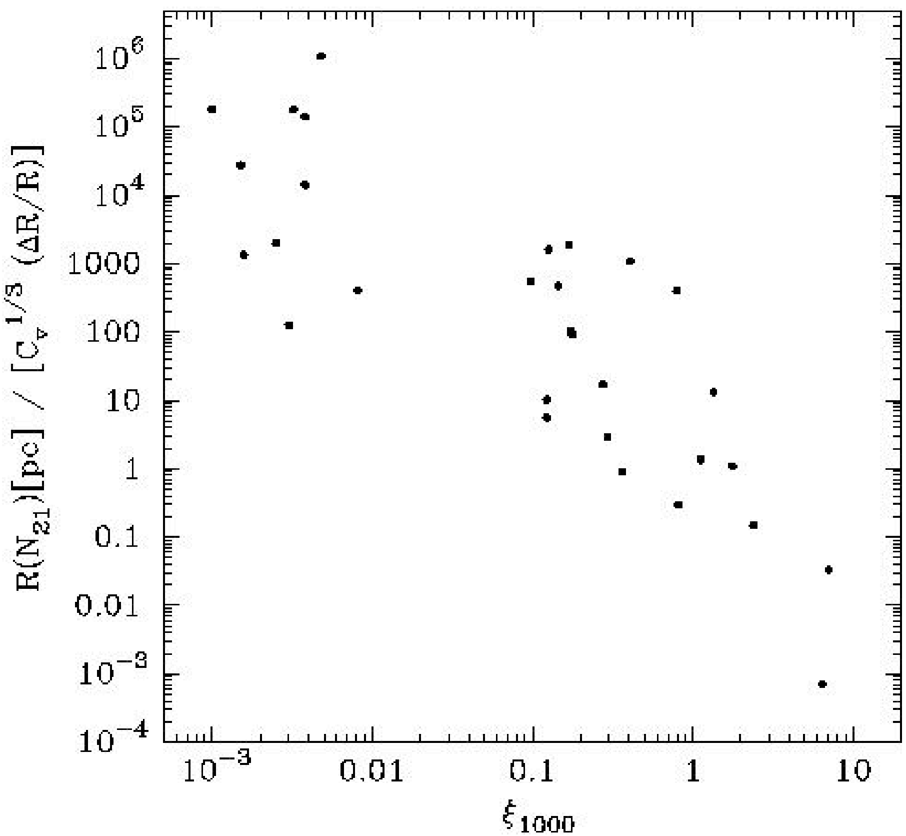
- *The different warm absorber components in a given AGN appear to be in approximate pressure equilibrium with each other.*
- *There appears to be no correlation between mass outflow rate and black-hole mass.*
- *Possible correlation of mass outflow rate with L_{ION}/L_{EDD}?*
- *Total mass outflow rate is critically dependent on the covering factor and the volume filling factor, C_V.*

Location of the Wind

$R(n_e)[pc] = 1.03\times10^{-3}\ n_{10}^{-1/2}\ [L_{ion,44}/\ \xi_{1000}]^{1/2}$



$R(N_{21})[pc] =$
$32.5\ [C_v^{1/3}\ (\Delta R/R)]\ [L_{ion,44}/(N_{21}\ \xi_{1000})]$



- ***Three additional AGN from Blustin et al. (2005) included (MR 2251-178, IRAS 13349+2438, NGC 7469). These are NOT correlation plots (look at the formulae).***
- ***Left: n_e unknown. High/Low ionization density ratio of ~100-10000 makes the different components co-spatial..consistent with conclusion about pressure equilibrium.***
- ***Right: Volume filling factor (C_V) and ΔR/R unknown. Gives "maximum" radius if ΔR/R<1 enforced. If the high & low ionization components are co-spatial, they must have different filling factors.***

Some Implications & Considerations

- The filling factor (C_v) is HIGHLY UNCERTAIN (in most cases unconstrained) but the mass outflow rate critically depends on it.
- Blustin et al. (2005) derive filling factors ~(0.03-8)%, (much less in a few cases), derived assuming momentum in outflow ~ momentum in radiation intercepted. This is an assumption which is not necessarily true. Indeed, using these derived filling factors Blustin et al. (2005) calculate a maximum distance of the warm absorber which is LESS than the minimum distance in FOUR sources!
- Independently of this, the Blustin et al. (2005) maximum warm absorber distances are in error: they should be larger by a factor $C_V^{-2/3}$ (an error of a factor ~5-218).
- Blustin et al. (2005) minimum distance of warm absorber calculated assuming outflow exceeds escape velocity - this is not necessarily true either.

Ratio of Mass Outflow Rate to the Accretion Rate

The ratio of the mass outflow rate to the accretion rate does not depend on the absolute luminosity or black-hole mass. It depends only on

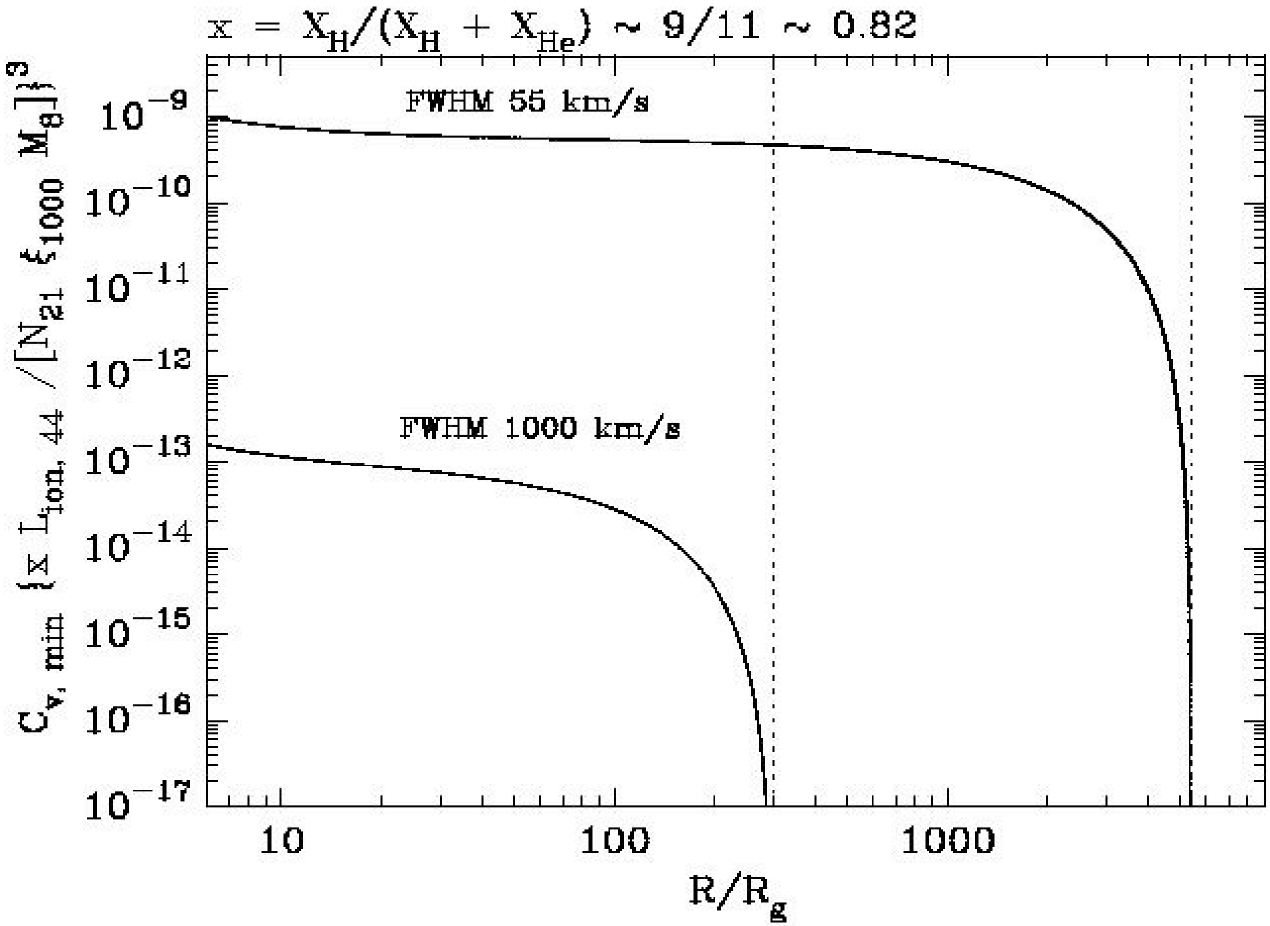
- The covering factor, $\Delta\Omega/4\pi$
- The volume filling factor, C_v
- The outflow velocity, v_{500} (units of 500 km/s)
- The ionization parameter, ξ_{1000} (units of 1000 erg cm s^{-1})
- The accretion efficiency, $\eta_{0.1}$ (units of 0.1)
- The ratio of the bolometric luminosity to the ionizing luminosity, $X = L_{\rm bol}/L_{\rm ion}$ (we will use $X_{10} \equiv X/10$)

$$\frac{\dot{M}_{\rm outflow}}{\dot{M}_{\rm accretion}} \sim 94 \left(\frac{\Delta\Omega}{4\pi}\right)\left(\frac{xy}{X_{10}}\right)\left(\frac{v_{500}}{\xi_{1000}}\right)\eta_{0.1}C_v$$

where x is the mean number of Hydrogen atoms per electron and y is the mean atomic mass per Hydrogen atom. For a gas consisting of only H and He, in which He is 10% abundant by number, $y = 1.3$ and $x = 9/11$, so $xy = 1.0636$.

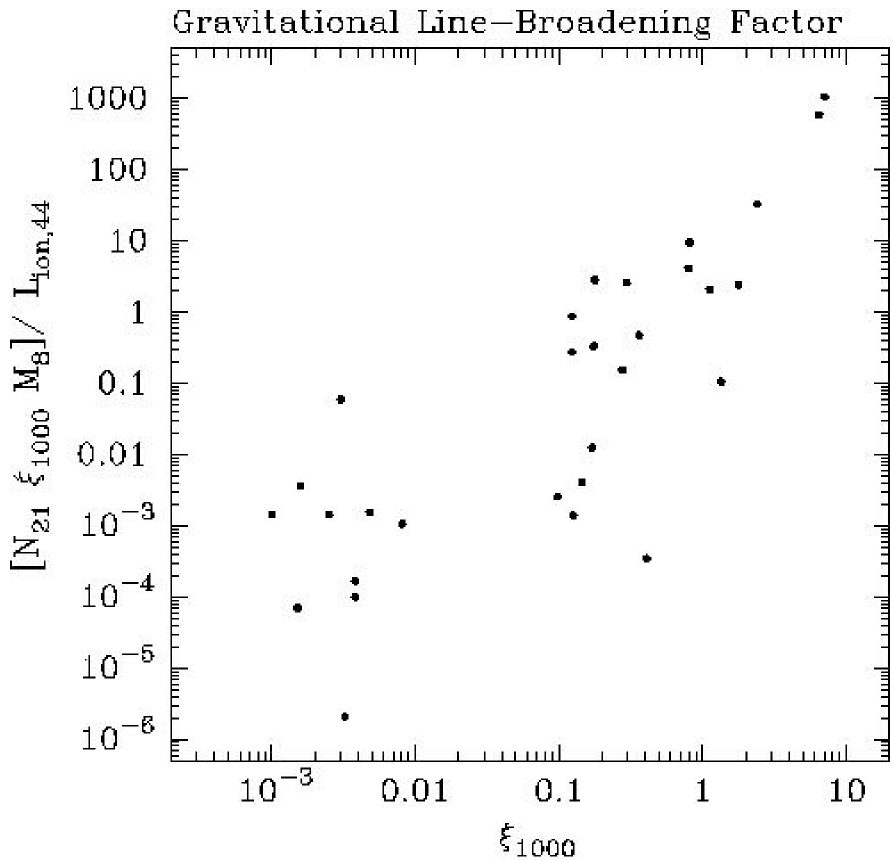
Observationally, for the 30 warm absorber components for 13 AGN, v_{500}/ξ_{1000} lies in the range ~ 0.04–840. Including only the high ionization components ($\xi > 90$), the range in v_{500}/ξ_{1000} is $\sim 0.04 - 13$. The mass outflow rate *may* be much larger than the accretion rate, BUT if the volume-filling factor remains unconstrained we cannot conclude that. $\Delta\Omega/4\pi$ is probably $\sim (2/3)(N_{\rm Sy1}/N_{\rm Sy2}) \sim 0.1$.

Constraints from Gravitational Broadening Limits on the Absorption Lines



At a given radius from the central BH, an absorption line observed at "infinity" will be gravitationally broadened. This broadening has to be LESS than the observed line width because other broadening mechanisms will affect the line (e.g. dynamics). This EITHER means (R/R_g)> (c/FWHM) OR a lower limit on the volume filling factor (C_V) is imposed as a function of radius (see figure).

Gravitational Line Broadening Limits: Observations



$$k \equiv \frac{1.48 \times 10^{-7} N_{21} \xi_{1000} M_8}{x L_{\text{ion},44} f}.$$

where $f = C_V^{1/3}$; for $kr=k(R/R_g) << 1$,

$$\frac{\Delta \mathrm{E}}{\mathrm{E}_0} \sim k \left(1 - \frac{2}{r}\right)^{-\frac{1}{2}}$$

For $r >> 1$,

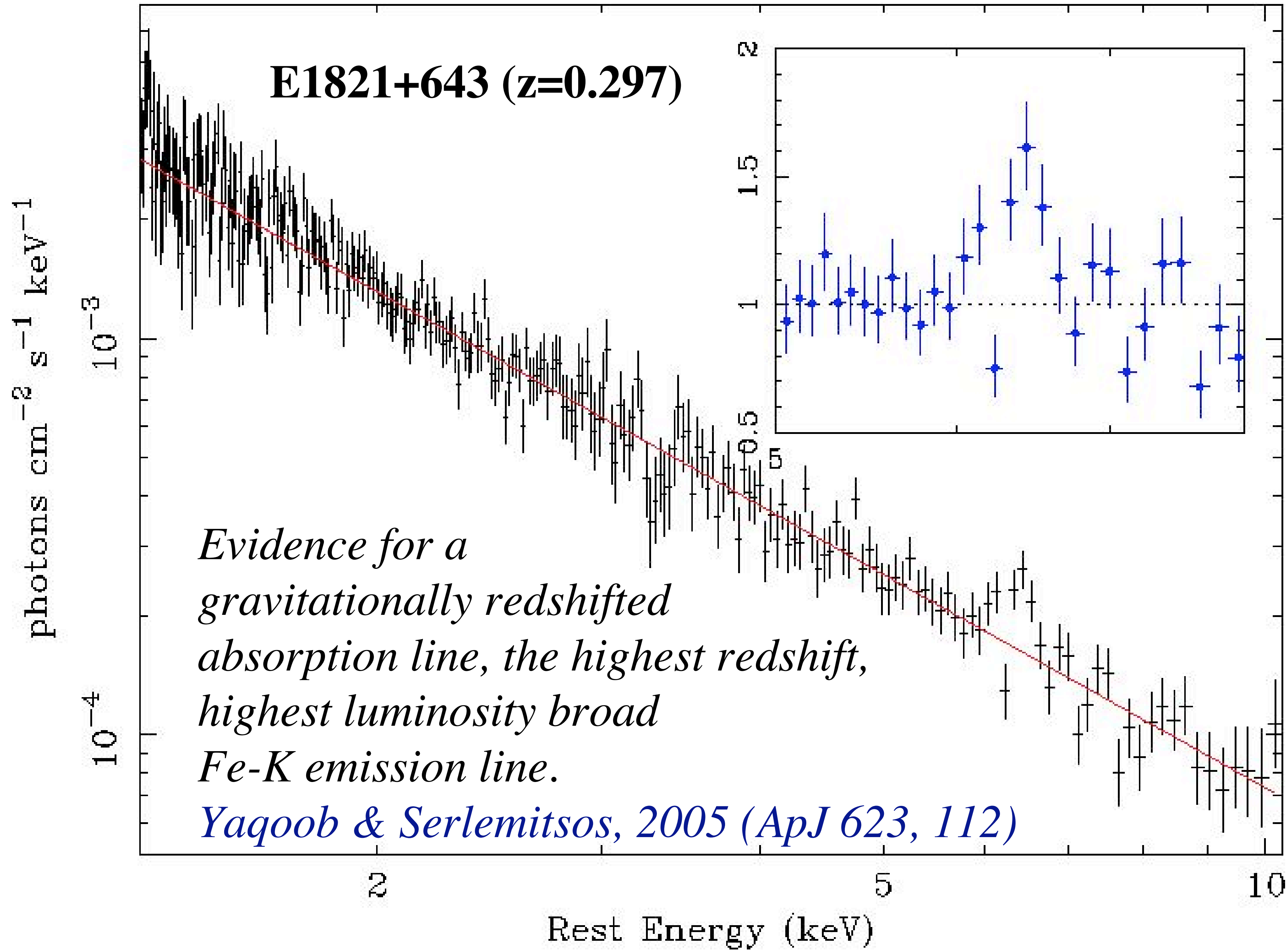
$$\frac{\Delta E}{E_0} \sim \frac{k}{1 + kr}.$$

For all r, the lower limit on the filling factor, for an observed line width, FWHM, is

$$C_v = \left[\frac{1.48 \times 10^{-7} N_{21} \xi_{1000}}{x L_{\text{ion},44}}\right]^3 \left[2\left(1 - \left[\left(\frac{\text{FWHM}}{c}\right) + \left(1 - \frac{2}{r}\right)^{\frac{1}{2}}\right]^2\right)^{-1} - r\right]^{-3} r^6$$

The factor $N_{21}\xi_{1000}M_8/L_{\text{ion},44}$, which determines the importance of gravitational broadening, ranges between $\sim 10^{-6}$ to $\sim 10^3$ for the 30 warm absorber components. In 8/13 sources, the factor is greater than unity. In two sources (NGC 4051 and NGC 5548) it is greater than 500.

The largest value is for NGC 5548 and in this case, using the fact that some of the absorption lines are not resolved with the *Chandra* MEG at a resolution of 300 km/s FWHM, we get a lower limit on the volume filling factor of 0.013 (1.3%). This then gives an absolute lower limit on the mass outflow rate of $0.057(\Delta\Omega/4\pi)\ M_\odot\ \text{yr}^{-1}$. The lower limit on the ratio of the mass outflow rate to the accretion rate is then $\dot{M}_{\text{outflow}}/\dot{M}_{\text{accretion}} > 8.4(\Delta\Omega/4\pi)(\eta_{0.1}/X_{10})$.


E1821+643 (z=0.297)
photons cm^{-2} s^{-1} keV^{-1}
10^{-3}
10^{-4}
2
5
10
Rest Energy (keV)
2
1.5
1
0.5
5
Evidence for a gravitationally redshifted absorption line, the highest redshift, highest luminosity broad Fe-K emission line.
Yaqoob & Serlemitsos, 2005 (ApJ 623, 112)

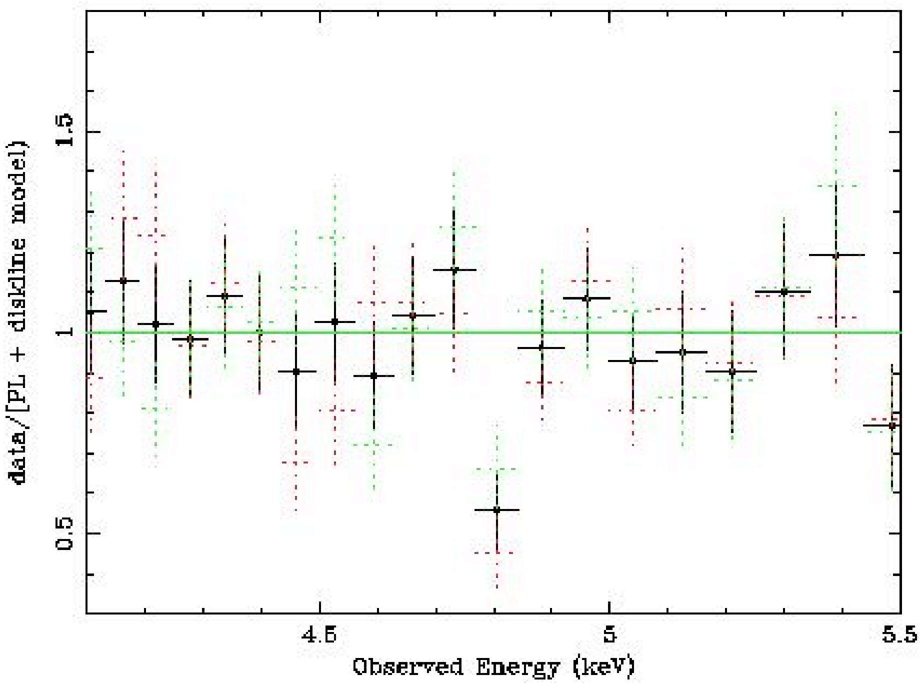
E 1821+643 : Fe–K Absoprtion Feature

Reality of the Absorption Feature

Absorption feature is present in BOTH plus and minus arms of the Chandra High Energy Grating (HEG).

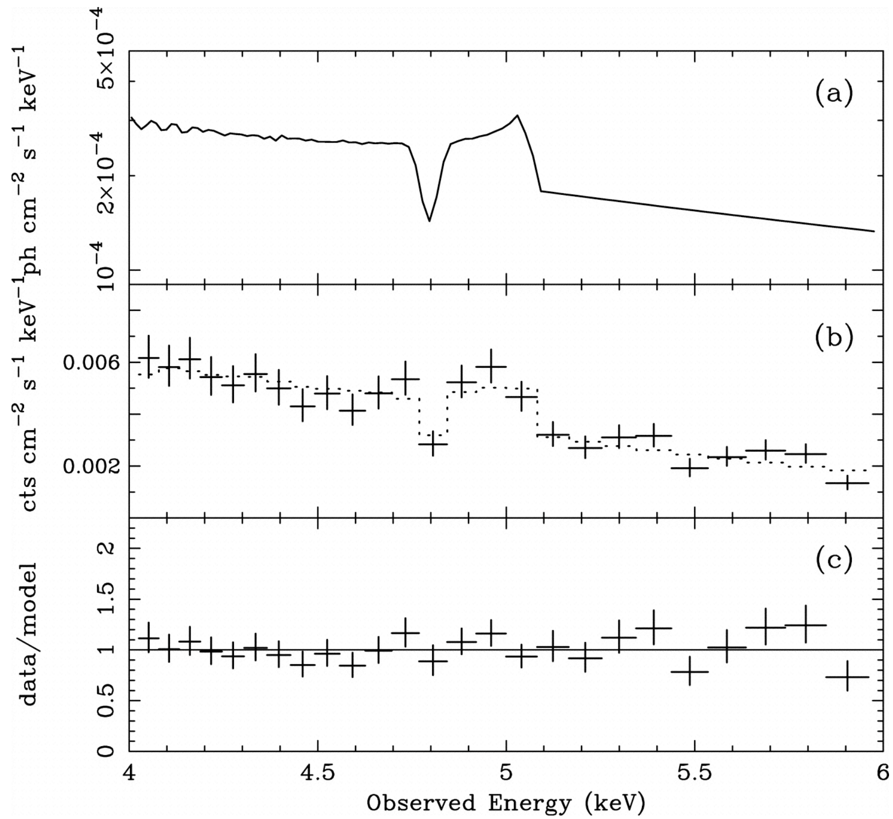
Black: Combined plus & minus orders

Red: –1 Order ***Green: +1 Order***

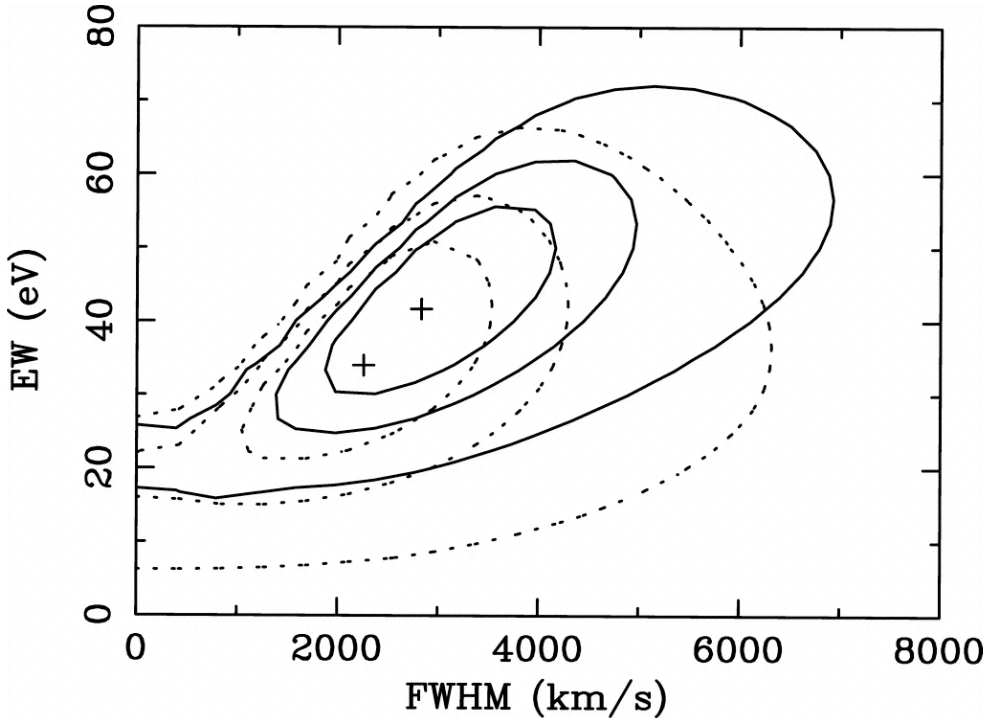


Significance of absorption line (from Monte Carlo simulations) is 2-3σ , depending on assumptions.

Disk Emission Line Plus Gaussian Absorption Line Fit.



Absorption Line Parameters



Relativistic Disk-Line Fits to *Chandra* HEG Data for E1821+643

Parameter	Value
C-statistic	1014.5
Degrees of freedom	966
Disk-line rest energy (keV)	$6.57^{+0.01}_{-0.01}$ (6.51–6.68)
Disk-line emissivity index, q	$2.69^{+0.19}_{-0.19}$ (2.36–3.08)
Outer disk radius, $R_{\rm out}$	>930 (>18)
Disk inclination, $\theta_{\rm obs}$ (deg)	$0.0^{+0.4}_{-0.0}$ (0–27)
Disk-line intensity (10^{-5} photons cm^{-2} s^{-1})	$7.0^{+1.9}_{-1.7}$ (3.6–10.2)
Disk-line EW (eV)	209^{+51}_{-57} (107–305)
Absorption line center energy (keV)	$6.220^{+0.018}_{-0.013}$
Absorption line Gaussian width, σ (keV)	$0.021^{+0.012}_{-0.008}$
Absorption line velocity width, FWHM (km s^{-1})	2385^{+1440}_{-950}
Absorption line EW (eV)	34^{+13}_{-13}
Power-law photon index, Γ	$1.84^{+0.03}_{-0.03}$
2–10 keV Observed flux (10^{-11} ergs cm^{-2} s^{-1})	1.2
2–10 keV Luminosity, quasar frame (10^{45} ergs s^{-1})	3.3

- **68%, 90%, 99% confidence contours. Absorption line modeled with a Gaussian. Solid: Emission line modeled with a Gaussian. Dotted: Emission line modeled with a relativistic disk line (see table).**
- **All spectral fitting parameters are in the quasar frame.**
- **Absorption line is only marginally resolved (i.e. unresolved by the HEG at 99% confidence).**
- **Redshift corresponds to effective velocities ~21000 km/s (Fe XXV) or 32000 km/s (Fe XXVI).**

Redshifted Absorption Lines in other Quasars

- **PG1211+143 (Reeves et al. 2005): Chandra LEG data. Two absorption lines, V~ 0.23c and 0.35c (if Fe XXVI Lya, 0.20c & 0.32c Fe XXV). Line widths poorly constrained, upper limit 7800 km/s FWHM.**
- **Mkn 509 (Dadina et al. 2005): XMM-Newton EPIC data. V~ 0.21c (if Fe XXVI Lya, 0.18c if Fe XXV).**
- **Q0056-363 (Matt et al. 2005): XMM-Newton EPIC data. V~ 0.23c (if Fe XXVI Lya, 0.20c if Fe XXV).**
- ***Compare with V~ 0.11c (Fe XXVI) or ~ 0.07c (Fe XXV) for E1821+643.***
- ***In all cases, the EWs range from tens to ~100 eV.***
- **Curve of growth analysis for E1821+643 gives a lower limit on the optical depth at the center of the resonance line, and a lower limit on the column density of the ion responsible for the absorption. We get $N > 9 \times 10^{16}$ cm^{-2} and $\tau > \tau_0$(1000/FWHM [km/s]) where $\tau_0 = 0.174$ or 0.321 for Fe XXV or Fe XXVI respectively.**
- ***Column density and optical depth limits for PG 1211+143, Mkn 509, and Q0056-363 are similar to those obtained for E1821+643 because of the similar EWs and the fact that the absorption lines are not clearly resolved.***
- **Note: identification with lines other than from Fe creates a problem with predicted Fe lines (for "regular" abundances), which are not observed.**

Inflow or Outflow?

Could the absorption line in E1821+643 be due to gravitationally redshifted outflow?

Photoionized outflows with v ~ hundreds of km/s have been found to be common in type 1 AGN by Chandra gratings.

High velocity outflows found by XMM in two quasars:

PG 1211+143: v ~ 25,000 km/s; R ~ 260 Rg
PG 0804+349: v ~ 60,000 km/s; R ~25Rg

(Lower v ~ 3000 km/s claimed by Kaspi et al. 2005 for PG 1211+143).

Both outflows are optically thick.
Thick photosphere near BH in ~Eddington accretors may be common.

If absorption line in E1821+643 is gravitationally redshifted outflow (due to H–like Fe absorption) then

R ~ 9.7 Rg for v ~ 1000 km/s
R ~ 4.3 Rg for v ~ 25,000 km/s
R ~ 6.2 Rg for v ~ 60,000 km/s

Mass flow rate depends on the (unknown) filling factor.

Summary

- Photoionzed wind found in 2/3 of HETGS Sy 1 sample.
- Wide range in N_H and ξ but gas with ξ ~10-100 is "missing".
- Some sources have multiple components in approximate pressure eqm.
- Outflow velocities typically ~0-1000 km/s: bimodel distribution?
- Distance of absorber requires knowledge of n_e or the volume filling factor & NOT the covering factor. (Variability studies by Krongold et al. imply a "compact" absorber in NGC 3783 and NGC 4051, fractions of a pc).
- Mass outflow rate also depends critically on the unknown filling factor.
- Limits from gravitational absorption-line broadening give a lower limit on the volume filling factor, which may be interesting limits in a few cases (e.g. NGC 5548, NGC 4051). The method gives limits which are independent of the dynamics of the wind & can also be used for the UV absorption lines, which will give tighter limits. Otherwise, only limits on *emission* lines can give information on the volume filling factor.
- Ratio of mass outflow rate to accretion rate again critically depends on the unknown volume filling factor.
- Redshifted (1+z ~ 0.07-0.11c) absorption line, probably due to Fe XXV or Fe XXVI, found in the RQ high-luminosity (L[2-10 keV] ~ 3 x 10^{45} erg/s), high z (0.297) quasar E1821+643. May be redshifted *outflow, not inflow*. The broad Fe K *emission* line in this quasar kills the "X-ray Baldwin Effect".

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