Study of Outflows from Supermassive Black Holes

Our recent *Chandra*, *XMM-Newton* and *Suzaku* observations of several high redshift quasars have revealed the presence of massive outflows of highly ionized, high-metallicity material driven from near the black hole (a few gravitational radii, r_g) with velocities of up to 0.7c (see Figure 1; Chartas et al. 2002, ApJ, 579, 169; Chartas et al. 2003 ApJ, 595, 85; Chartas et al. 2007, AJ, 133, 1849; Saez et al. 2008 submitted to ApJ). The mass outflow rate in APM 08279+5255 ($\dot{M} \sim$ 1–10 $M_{\odot}$ yr^{-1}) is found to be comparable to its accretion rate and the fraction of bolometric energy released in the form of kinetic energy is $\epsilon_K \sim 0.02$–0.12.

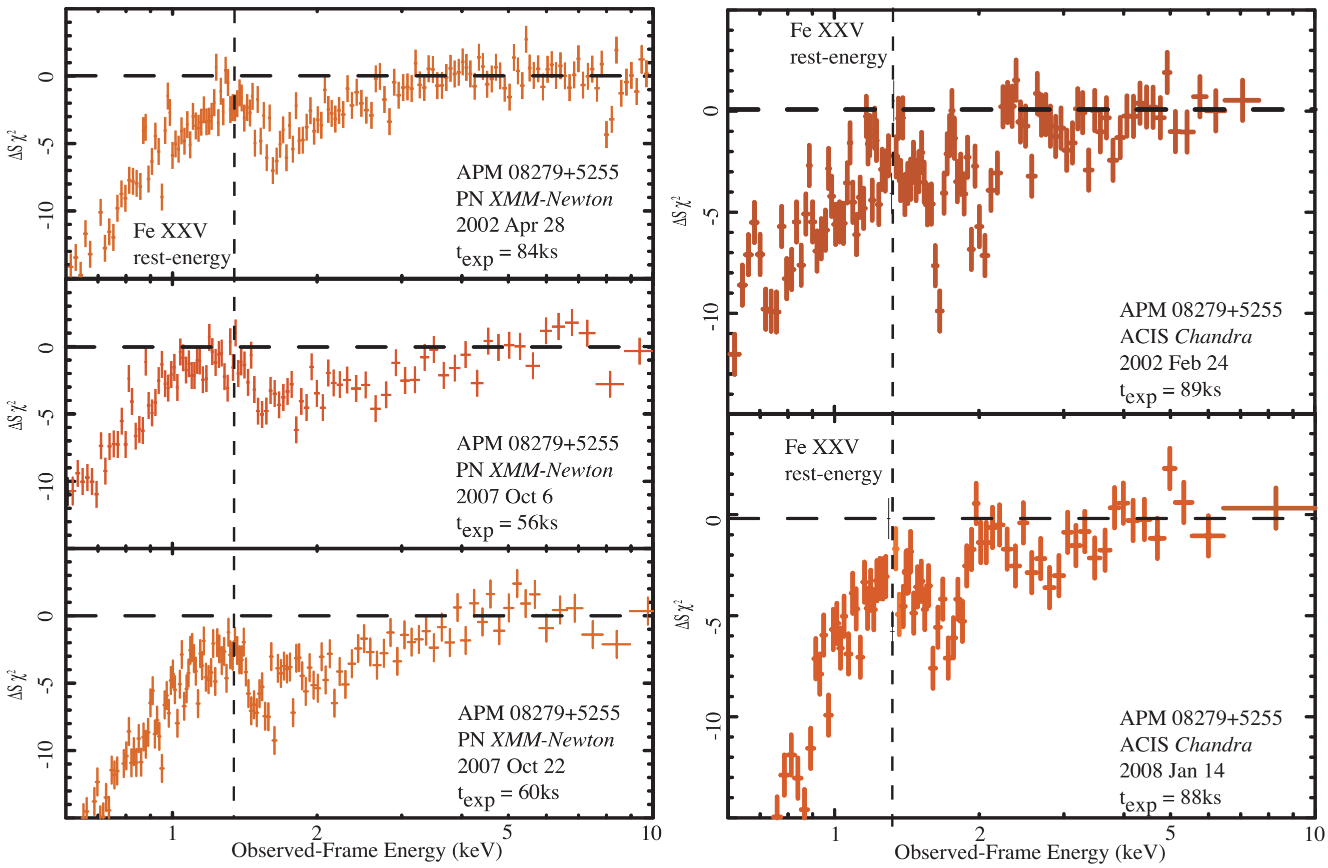

Figure 1: $\Delta\chi$ residuals between the best-fit Galactic absorption and power-law model and (a) the *XMM-Newton* pn spectra and (b) the *Chandra* ACIS spectra of APM 08279+5255. This model is fit to events with energies lying within the range 4–10 keV (observed frame) and then extrapolated to lower energies. The dashed vertical lines indicate the location of the rest-frame energy of the Fe XXV(1s-2p) resonance absorption line (6.7 keV). Note that the X-ray Broad Absorption Lines are clearly detected in all observations.

The potential importance of quasar outflows has been explicitly demonstrated in theoretical models of structure formation and galaxy mergers that incorporate the effects of quasar outflows [e.g., Scannapieco & Oh 2004, ApJ, 608, 62 (SO04); Granato et al. 2004, ApJ, 600, 580 (G04); Springel, Di Matteo, & Hernquist 2005, ApJL, 620, L79 (SDH05)]. A basic assumption in the models of SO04 is that all quasars host outflows. SO04 find that by choosing the fraction of the total bolometric energy released over a quasar's lifetime into the Interstellar Medium (ISM) and Intergalactic Medium (IGM) in the form of kinetic energy to be $\epsilon_{\rm k}$=0.05, they can successfully model the observed evolution of the B-band quasar luminosity function between redshifts of 0.25 and 6.25. Their adopted value of an average efficiency for quasar outflows of $\epsilon_k \sim 0.05$ is consistent with our estimated value based on the *Chandra*, *XMM-Newton* and *Suzaku* observations of APM 08279+5255. In a study SDH05 simulated the growth of black holes in gas-rich galaxies with and without the presence of accretion feedback. The feedback in their model is thought to occur through energetic quasar outflows that interact with the gas of the host galaxy. It is assumed that about 5% of the radiated luminosity is thermally coupled via these outflows to the surrounding gas. They find that the growth of the black-hole mass is self-regulated and eventually saturates at a final value that depends on the initial amount of gas available for accretion. These authors also found that feedback from stars and quasars in their simulations of galaxy mergers can heat and expel gas from the centers of the merged galaxies.

One of the major unanswered questions in current theoretical and numerical models of quasar winds involves explaining how highly ionized outflows of X-ray absorbing material become accelerated to near-relativistic velocities. The main problem is that for radiatively driven winds the magnitude of the force on the absorbers is a function of the ionization state of the absorber. As the ionization parameter of the absorber increases, fewer resonance transitions are available to absorb photons from the source, thus resulting in a weaker driving force.

A clue to understanding the acceleration process of the wind in APM 08279+5255 is perhaps provided by the observed significant difference between the maximum velocities of the UV ($v_{\rm UV} \sim 0.04c$) and X-ray ($v_{\rm X-ray} \sim 0.44$–$0.74c$) absorbers of APM 08279+5255. If the X-ray absorbers are radiation-driven by photons from the hot corona we would expect to detect a correlation between the properties of the X-ray BALs (e.g., the equivalent width $W_{\rm BAL}$, $v_{\rm max}$) and the properties of the X-ray spectrum (e.g., X-ray flux $F_{\rm X}$, photon index Γ, column density $N_{\rm H}$). In particular, we might expect the maximum outflow velocity of the X-ray absorbers to depend on the shape on the X-ray spectrum. In Figure 2a I show the maximum outflow velocity as a function of X-ray photon index based on recent *XMM-Newton*, *Chandra*, and *Suzaku* observations of APM 08279+5255. There is a possible trend between the photon index and the maximum outflow velocity in the sense that flatter X-ray spectra appear to result in lower outflow velocities. If this trend is confirmed with follow-up observations it would imply that the dominant acceleration mechanism responsible for the near-relativistic velocities of the X-ray outflowing gas in BAL quasars is radiation-driving. The detected projected maximum outflow velocity of $v \sim 0.7c$ constrains the angle between the wind velocity and our line of sight to be less than $\sim$ 25 degrees (see Figure 2b). Such a small angle is consistent with the unification scheme of BAL and non-BAL quasars that posits that BAL quasars are viewed almost along the outflow direction.

We searched for X-ray BALs in other gravitationally lensed quasars and found such absorption features in the BAL quasar PG 1115+080 and the low-ionization BAL quasar H1413+117 (The Cloverleaf).

Specifically, in PG 1115+080 we detected significant variability of the X-ray BALs over a time-scale of just 1.8 weeks (proper-time). Our analysis implied that the X-ray absorber is launched closer to the black hole than the medium responsible for the UV absorption, thus the X-ray absorber may represent the shielding gas proposed in several theoretical studies of radiation-driven winds (e.g., Murray et. al. 1995, ApJ, 451, 498; Proga et al. 2000, ApJ, 543, 686).

In the LoBAL quasar H1413+117, the *Chandra* spectra of the individual images show high energy broad absorption features between rest frame energies of 6.4–15 keV. These features are especially significant in the spectra of images C and D where they extend from $\sim$ 6.4 keV up to energies of 9 keV and 15 keV, respectively (see Figure 3). If we interpret the X-ray broad absorption features as arising from absorption by outflowing highly ionized Fe XXV the observed maximum absorption energies in images C and D imply outflow velocities of $0.29c$ and $0.67c$, respectively. A schematic diagram of a possible outflow in H 1413+117 is shown in Figure 4.

Recent theoretical studies of the contribution of quasar winds on structure formation rely on input from observations that constrain quasar outflow efficiencies. The best candidates for estimating these efficiencies partly because of the significant flux magnification provided by the lensing magnification effect are the lensed BAL quasars PG 1115+080, APM 08279+5255 and H 1413+117. Our estimates

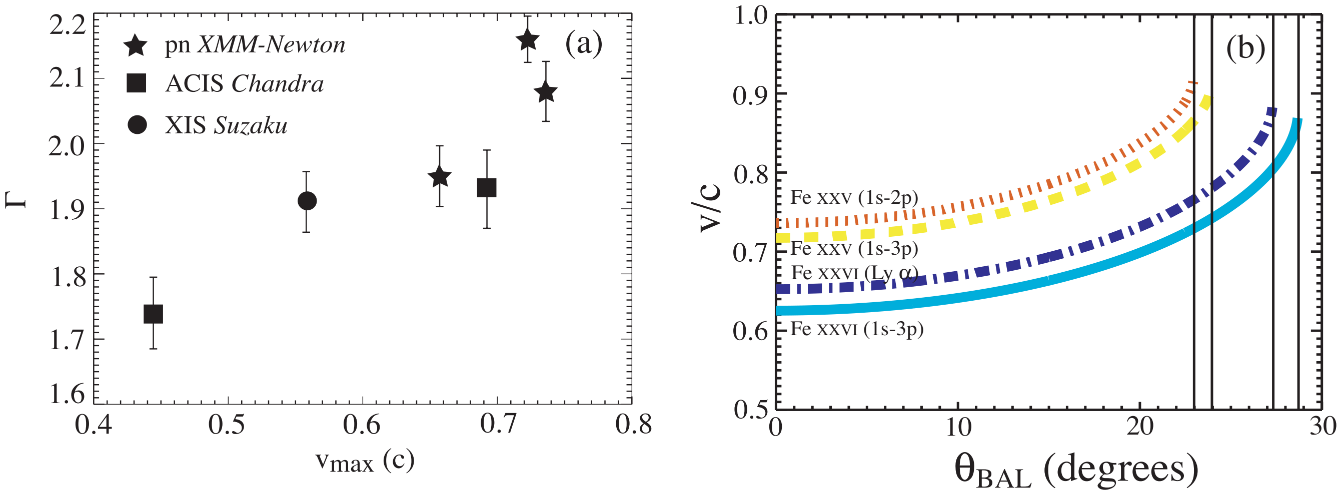

Figure 2: (a) Maximum outflow velocity of X-ray absorbers of APM 08279+5255 versus the X-ray photon index Γ. (b) Maximum outflow velocity as a function of angle between outflow direction and line of sight. Shown are the outflow velocities for the most likely resonance transitions responsible for the observed X-ray BALs in APM 08279+5255.

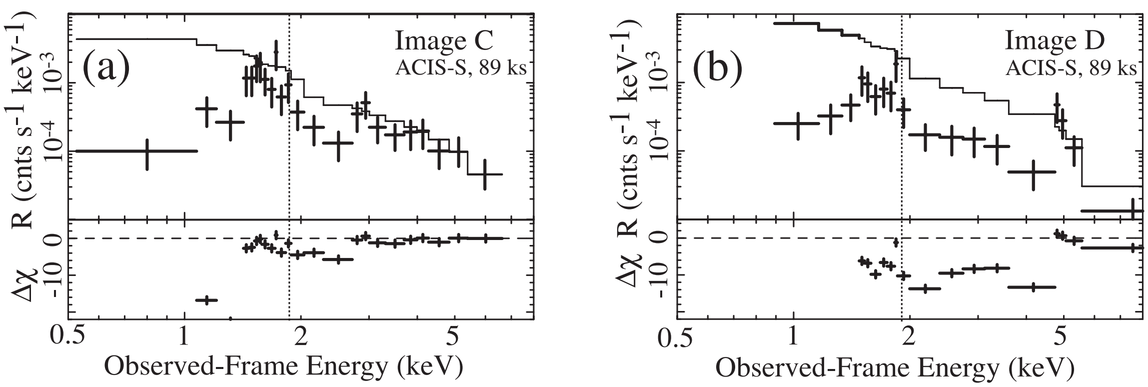

Figure 3: (a) The spectra of image C, and (b) of image D of H1413+117 (The Cloverleaf) fit with a Galactic absorption and a power-law model. The dashed vertical line indicates the location of the rest-frame Fe Ka emission line.

of the efficiency of the outflows in BAL quasars PG 1115+080 and APM 08279+5255, when compared to values predicted by models of structure formation (SO04; G04; SDH05), imply that these winds will have a significant impact on shaping the evolution of their host galaxies, perhaps explaining the M_{BH}–σ relation, and in regulating the growth of the central black hole. Additional future plans include monitoring the time variability of the Fe absorption features in these BAL quasars and thus place constraints on the acceleration mechanism of quasar winds.

I am presently establishing collaboration with teams designing future X-ray missions. Our simulations indicate that the calorimeter onboard the International X-ray Observatory (*IXO*) will provide the higher energy resolution and larger effective area needed to resolve the complex structure of many more X-ray BALs and to constrain better the kinematic, ionization, and absorption properties of the observed outflows.

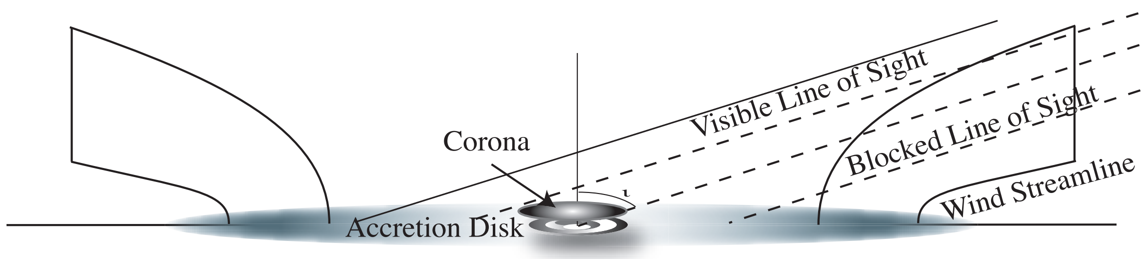

Figure 4: Schematic diagram of a possible outflow in the Cloverleaf quasar.