X-ray astronomy and Eddington winds

Ken Pounds looks at how X-ray observations continue to transform our understanding of active galactic nuclei.

Twenty years ago, when the science programme for ESA's new X-ray observatory was being put together, there was no mention of how an over-fed supermassive black hole, lurking in an active galactic nucleus (AGN), would eject excess matter in the form of a powerful wind, although a check on Shakura and Sunyaev's classical 1973 paper on disc accretion would have found that prediction. In the event, the discovery of such winds, with implications for limiting the growth of supermassive black holes and of their host galaxies, has been a notable feature in the ongoing success of ESA's XMM-Newton mission, as the new observatory was named. The first detection of a highly ionized, subrelativistic wind was made, appropriately, in an early XMM-Newton study of quasars in the Palomar-Green survey, proposed by the lead scientist of the main European Photon Imaging Camera (EPIC), Martin Turner. My good fortune was to be on hand to volunteer to help Martin in analysing the rich data set. The subsequent discovery that such winds are common, with properties matching those expected from episodes of super-Eddington accretion, is the topic of this personal account, ending with a brief look a decade ahead to the exciting potential of high-resolution X-ray spectroscopy in the era of Athena, discussed in greater detail by Poshak Gandhi on page 6.24 of this issue.

A brief history

Unexpected discoveries have been the hallmark of the first half century of X-ray astronomy, beginning with the detection of an incredibly bright X-ray star, Scorpius X-1 (Giacconi *et al.* 1962), during a sounding rocket flight in New Mexico in 1962, a discovery that later led to the Nobel prize in physics for Riccardo Giacconi. Other surprises followed the launch of Uhuru (operating 1970–73), a small NASA satellite which surveyed 95% of the sky over 2.5 years. This satellite led to the discovery of 339 X-ray sources (Forman *et al.* 1978), and a new class of X-ray binary stars including the first strong stellar black hole candidate, Cygnus X-1 (Schreier *et al.* 1972), as well as extended X-ray emission from a hot intergalactic medium in the Virgo cluster of galaxies (Kellogg *et al.* 1967).

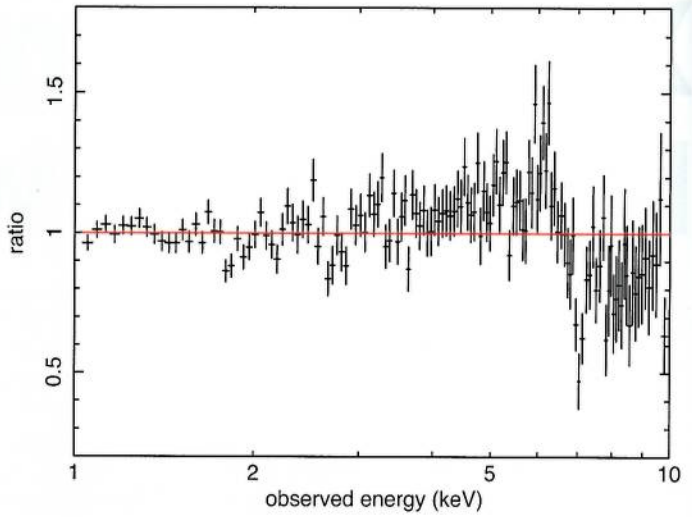
"EXOSAT allowed uninterrupted viewing of a target source for up to three days"

My own interest in AGN began with Ariel 5 (1974–80), the UK successor to Uhuru. Ariel 5 carried a payload of five instruments from UK universities, including the the Leicester Sky Survey Instrument, an array of collimated proportional counters proving to have sufficient sensitivity and positional resolution to identify numerous Uhuru and other newly discovered faint X-ray sources at high galactic latitude. Some were associated with additional galaxy clusters, while many others were identified with Seyfert galaxies (Elvis 1978). I had the satisfaction of explaining the real nature of the Unidentified High Galactic Latitude Sources from the first Uhuru survey at the 1976 Texas Relativistic Astrophysics meeting in Boston (Pounds 1977). The UHGLS turned out to be Seyfert galaxies, but they had been highlighted initially as a new type of "X-ray galaxy" in the scientific case for NASA's Advanced X-ray Astrophysics Facility (AXAF). My own role in the identification programme was marginal, with the astronomical lead provided by a group of enthusiastic young students mainly from the astronomy MSc course at Sussex.

I had a larger role (Harries 1999) in advocating a mission concept that led to Europe's first X-ray astronomy satellite, EXOSAT (1983–86), whose unique high-apogee orbit provided the first opportunity for uninterrupted viewing of a target source for up to three days. That new capability led directly to the remarkable discovery that the X-ray emission from several bright Seyferts exhibited large amplitude variability on timescales of hours (Lawrence *et al.* 1985, McHardy 1988), providing the first compelling evidence that radio-quiet Seyfert galaxies harboured massive black holes in their nuclei.

A further significant advance followed the launch of the Japanese GINGA satellite (1987–91), with the UK Large Area Counter (LAC) detector (Turner *et al.* 1989). The LAC had sufficient high-energy sensitivity to make the first astrophysical detection of "X-ray reflection" (Nandra & Pounds 1994), indicating the presence of dense matter (presumed to be the accretion disc) close to the continuum source. That discovery opened a new route to exploring the properties of matter and radiation close to the supermassive black hole, one that has since been productively exploited by the Cambridge X-ray group (Fabian & Ross 2010).

Finally, after the successful demonstration of focusing X-ray optics on NASA's Einstein Observatory and the German Rosat mission, the way was open for an orbiting X-ray telescope with capabilities comparable to those available at lower photon energies. In 1999, 37 years after the discovery of Scorpius X-1, two such X-ray observatories came along within a few months of each other. In July, NASA launched AXAF (renamed Chandra post-launch), with ESA's successor to EXOSAT



1 Ratio of EPIC pn data to a simple power law continuum for the 2001 XMM-Newton observation of PG1211, showing a deep absorption line near 7 keV and additional structure between ~1 and 4 keV. Deriving an outflow velocity requires the correct identification of the individual absorption lines, which ideally requires spectral modelling with a photoionized absorber. Note that photon energy is in the observer's frame.

following five months later. The large-aperture X-ray optics of the three XMM-Newton telescopes was to prove crucial to the spectral study of AGN, the most luminous non-transient objects in the universe.

Most astronomers had by then accepted that the centres of all but the smallest galaxies harbour supermassive black holes (SMBH). Powerful radio (and optical) jets and the aforementioned rapid X-ray flux were evidence for a highly compact source of extreme luminosity, with gravitational accretion onto the hole releasing some of its huge binding energy. About that same time, a remarkable correlation was emerging between the observed mass of a SMBH and the dispersion of velocities (a proxy for mass) in the stellar bulge of the host galaxy (Ferrarese & Merritt 2000, Gebhardt *et al.* 2000): the bulge mass is typically 1000 times that of the SMBH. But what was the physical link behind the so-called M–σ relation? The answer was blowing in the wind.

Much of the gravitational energy released by accretion is emitted as photon radiation, but observations show most of that light escapes from the active nucleus. However, a second form of energy release, that can couple much more efficiently to the bulge gas, is the mechanical energy of a high-velocity wind (King 2003, 2005). Such winds are highly ionized and invisible to ground-based telescopes; their discovery had to wait for the availability of X-ray spectroscopy.

A fast outflow

Prior to the launch of XMM-Newton, AGN X-ray spectra were well-described by a power law continuum, with a soft excess below 1–2 keV and evidence of reflection indicated by an Fe K fluorescence emission line at ~6.4 keV and the continuum scattering hump at ~10–30 keV. Martin Turner chose to study the nature of the strong soft excess in a sample of Palomar-Green (PG) quasars within his guaranteed observing time. For one of those targets, PG1211+143 (hereafter PG1211), a 50 ks observation in June 2001, revealed a bright, soft X-ray source with evidence of strong absorption structure superimposed on the hard power law distribution.

At a redshift of 0.0809 (Marziani *et al.* 1996), PG1211 is one of the brightest AGN at soft X-ray energies and should be more accurately classified as a narrow-line Seyfert 1 galaxy (FWHM Hβ of 1800 km s^{-1}) (Kaspi *et al.* 2000). A black hole mass of $3\times10^7\,M_\odot$ and bolometric luminosity 4×10^{45} erg s^{-1} indicate a mean accretion rate close to the Eddington limit.

Figure 1 shows the ratio of XMM-Newton data from the EPIC pn camera (Strueder *et al.* 2001) to a simple power law continuum, with a deep absorption line evident near 7 keV and additional spectral structure at ~1–4 keV. Fe is the only abundant element with atomic transitions at such a high photon energy, so the most likely candidates for the 7 keV absorption line were the resonance 1s–2p transitions in H-like Fe XXVI and He-like Fe XXV. With rest energies of 6.96 and 6.70 keV respectively, the observed absorption line indicated a large blueshift, with the X-ray continuum source being seen through a highly ionized outflow – a wind – moving at a velocity of ~0.09c or ~0.14c (Pounds *et al.* 2003).

The near-coincidence of the more conservative velocity with the AGN redshift gave some initial concern that the absorption was more local – and the wind therefore much slower – despite the uncomfortably large column of highly ionized Fe in the galactic interstellar medium implied by this scenario. Happily, the weaker absorption features at ~1–4 keV were successfully separated into H- and He-like resonance line pairs in the higher resolution data from the EPIC MOS camera (Turner *et al.* 2001), resolving the ambiguity in favour of the higher velocity (Pounds & Page 2006). That was confirmed by comparing the full X-ray spectrum with a grid of photoionized absorption spectra, finding a Doppler-corrected outflow velocity of $0.15\pm0.01c$, more than an order of magnitude faster than the "warm absorbers" seen in earlier AGN X-ray spectra (Blustin *et al.* 2005, McKernan *et al.* 2007).

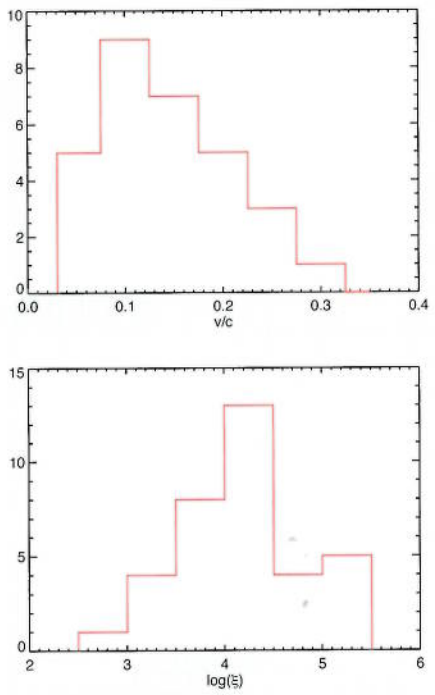
Modelling the full absorption spectrum using the XSTAR code of Kallman *et al.* (1996) also confirmed the high column density $N_H \sim 3.2\pm0.7\times10^{23}$ cm^{-2}, and high ionization parameter $\log\xi \sim 2.7\pm0.1$ erg cm s^{-1} of the absorbing gas. Importantly, the high velocity and column density suggested a significant mass outflow rate, perhaps having sufficient mechanical energy to disrupt star formation in the host galaxy and offer a mechanism to explain the remarkable M–σ effect.

"There was a clear need to find other examples of potentially powerful AGN winds"

There was a clear need to find other examples of potentially powerful AGN winds. Meanwhile, concerns were raised as to how such a highly ionized (low opacity) gas was accelerated to such a high velocity.

An Eddington wind

The solution lay in the argument used by Sir Arthur Eddington in predicting a limit to the luminosity of a star, beyond which the (outward) radiation pressure force on the stellar gas would exceed the local gravity at all radii and blow the star apart (although note that Shaviv [2001] shows how a steady state wind can be maintained in a bright nova where the stellar atmosphere is porous and the wind is clumpy). Using the spectral fit for PG1211, my colleague Andrew King noted the observed wind column density would have an electron scattering optical depth $\tau_{es} \sim 1$ when integrated to the Schwarzschild radius, R_{Sch}, raising the prospect of a highly ionized wind being driven by continuum radiation.



2 Distribution of primary outflow velocity and ionization parameter in 35 radio-quiet AGN with ultrafast outflows detected in the XMM-Newton or Suzaku archival surveys. The observed properties are consistent with the predictions of an Eddington wind. (From King & Pounds 2015)

In that scenario every photon emitted by the AGN will typically scatter once before escaping, giving up all its momentum to the wind. Equating the wind and photon momenta (King & Pounds 2003) then yields the relation:

$$\dot{M}_w v \simeq \frac{L_{Edd}}{c} \quad (1)$$

where $\dot{M}_w$ and v are the mass rate and velocity in the wind and L_{Edd} is the local Eddington luminosity.

Since the Eddington accretion rate:

$$\dot{M}_{Edd} = \frac{L_{Edd}}{\eta c^2} \quad (2)$$

we find continuum driving predicts an outflow velocity:

$$v \simeq \frac{\eta}{\dot{m}} c \sim 0.1c \quad (3)$$

where $\dot{m}$ is the accretion ratio, typically of order unity in SMBH growth episodes (King 2010), and η is the black hole accretion efficiency, of order 10%.

While the Eddington limit was originally derived for an isotropic spherical geometry, the classic paper of Shakura & Sunyaev (1973) considers a disc geometry, more likely in an AGN, where matter accreted at the outer edge of the disc becomes super-Eddington close to the black hole, with the excess matter being expelled from the disc in a quasi-spherical wind.

From a diagnostic viewpoint, it is useful to note that a highly ionized wind launched in this way will then coast, with the observed outflow velocity remaining of order of the escape velocity at the launch radius, offering a potential probe of the accretion structure feeding the SMBH from observations of the wind profile. For PG1211, a wind velocity of $v \sim 0.15c$ corresponds to $R_{launch} \sim 45 R_{Sch}$, suggesting such an Eddington wind is closely linked with the physics of the innermost accretion disc.

The high momentum and mass outflow rates in a continuum-driven wind, such as that of PG1211, lead naturally to a high ionization parameter. Such winds are most likely to be observed in X-ray spectra, currently by the high-throughput EPIC pn and MOS cameras on XMM-Newton.

High-speed winds are common

How frequently high-velocity winds were found in typical AGN remained unclear for several years, with blueshifted absorption lines in XMM-Newton observations of two broad absorption line (BAL) AGN (Chartas *et al.* 2002) and in the ultraluminous quasar PDS 456 (Reeves *et al.* 2003, O'Brien *et al.* 2005) considered to be rare objects. That situation began to change with the detection of a significant outflow of velocity $v \sim 0.1c$ in the Seyfert 1 galaxy IC4329A (Markowitz *et al.* 2006), and several outflow detections in the range $v \sim 0.14$–$0.2c$ in repeated observations of Mrk 509 (Dadina *et al.* 2005). An early review (Cappi 2006) listed seven non-BAL objects with outflows of $v \sim 0.1c$.

"The key interaction occurs when the wind hits surrounding gas in the host galaxy"

Final confirmation that a high-velocity wind was a common feature of active galaxies came from a search of AGN X-ray spectra in the XMM-Newton archive by Tombesi *et al.* (2010). They found evidence in 15 of 42 radio-quiet objects of one or (sometimes) two blueshifted Fe K absorption lines, where initial identification with Fe XXV and/or Fe XXVI resonance absorption lines indicated outflow velocities up to ~0.3*c*, with a median velocity of ~0.1*c*. A subsequent analysis based on broad-band modelling with XSTAR (Tombesi *et al.* 2011) confirmed that the outflows were also highly ionized, with $\log \xi \sim 3$–$6\,\mathrm{erg\,cm\,s^{-1}}$, and had high column densities in the range $N_H \sim 10^{22}$–$10^{24}\,\mathrm{cm^{-2}}$. A similar search of the Suzaku data archive (Gofford *et al.* 2013) yielded a further group of detections, finding highly ionized Fe K absorption in 20 (out of 51) AGN, with velocities up to ~0.3*c* and again a median value $v \sim 0.1c$.

Figure 2 summarizes modelled parameters from the 35 best-determined ultrafast winds from the XMM-Newton and Suzaku archival searches of bright AGN X-ray spectra, showing a distribution of wind velocity and ionization parameter entirely consistent with the expected values for an Eddington wind.

The energy and fate of the wind

As noted above, a key property of a fast AGN wind is its mechanical energy, providing a more effective way for the black hole to communicate with its host galaxy than photon radiation.

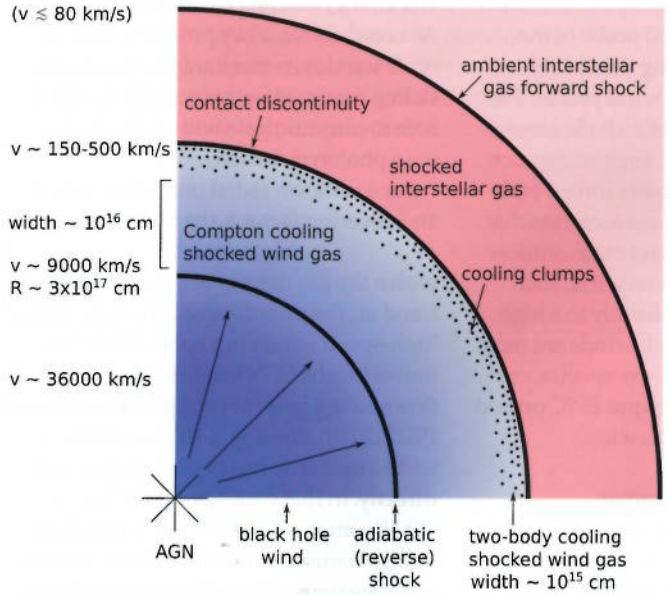
For a uniform radial outflow of velocity v and covering factor b, the mass rate is

$$\dot{M}_{out} \sim 4\pi b n r^2 m_p v \quad (4)$$

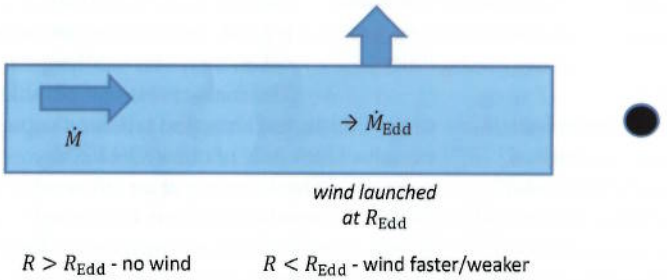
with n the gas density at a radial distance r, and m_p the proton mass. The detection of high-speed winds in a substantial fraction of bright AGN implies that many such flows have a large covering factor, although PG1211 remains one of the few where a wide-angle flow has been demonstrated directly. In that case, Pounds & Reeves (2009) compared the relative strength of ionized emission and absorption spectra to estimate the covering factor and collimation of the outflowing ionized gas, also finding a P Cygni profile – the classical signature of an outflow – for the Fe XXV resonance line, with emission and absorption components of comparable equivalent width. Both methods indicated a wide-angle outflow with b ($=\Omega/2\pi$) of 0.75 ± 0.25. Analysis of a Suzaku observation of PG1211 gave a similar result (Reeves *et al.* 2008).

From equation (4) the observed wind parameters of PG1211 in 2001 then yields a mass rate of $\dot{M}_{out} \sim 7 \times 10^{25}\,\mathrm{g\,m\,s^{-1}}$ ($\sim 2.5\,M_\odot\,\mathrm{yr^{-1}}$), and a mechanical energy $\sim 4.5 \times 10^{44}\,\mathrm{erg\,s^{-1}}$. The mass rate is comparable to the Eddington accretion rate for a supermassive black hole of mass $\sim 3 \times 10^7\,M_\odot$, assumed to be accreting at an efficiency of 10%. The outflow mechanical energy is ~6% of the Eddington luminosity, close to that predicted by continuum driving (King & Pounds 2003) and more than sufficient to unbind the gas of the host galaxy bulge if all the wind energy is efficiently communicated (Pounds 2014). However, is that the case for most of the fast winds currently detected?

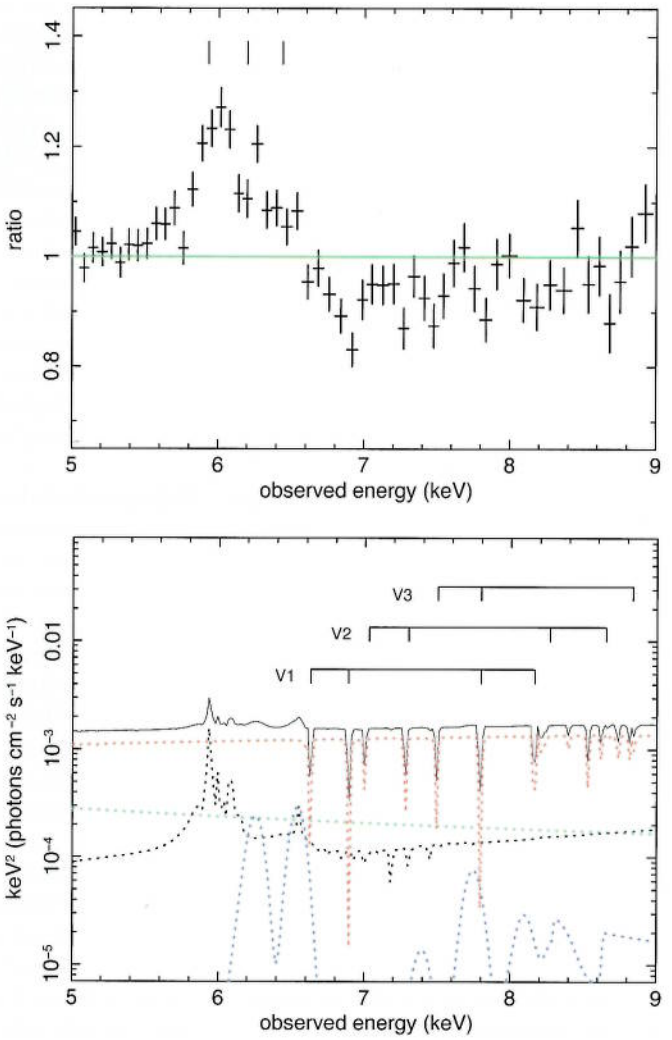
The key interaction occurs when the wind hits surrounding gas in the host galaxy, and is abruptly slowed in an inner (reverse) shock which heats the wind to a high temperature, and an outer (forward) shock pushing away the swept-up gas. If the impact occurs sufficiently close to the continuum source, it is likely that the shocks are narrow and cool rapidly, with only the ram pressure communicated to the outflow. King (2003, 2005) argued that such momentum-driven outflows probably establish the M–σ relation; once the black hole mass attains the critical M–σ value, the shocks move further from the AGN and the outflow becomes energy-driven, driving away much of the bulge gas, curtailing further growth and producing the



3 Shock pattern resulting from the impact of a black hole wind (blue) on the interstellar gas (red) of the host galaxy. The accreting supermassive black hole drives a highly ionized wind, observable in X-ray absorption lines. The wind collides with the ambient gas in the host galaxy and is slowed in a strong shock. Compton scattering in the AGN's radiation field rapidly cools the shocked gas, removing its thermal energy and strongly compressing and slowing it over a narrow radial extent. In the most compressed gas, two-body cooling becomes important, and the flow rapidly cools and slows over an even narrower region. In NGC 4051 this region is detected in the soft X-ray spectrum, where absorption (and emission) are dominated by the lighter metals. (From Pounds & King 2013)



4 The inflow of an incident of enhanced accretion. On reaching a critical radius in the disc where the accretion rate exceeds the local Eddington rate, a fast wind is launched, as described in the text. While there is no wind at larger radii, inwards of $R_{\rm Edd}$ a weaker, higher velocity wind might be seen.



5 (Top) Fe K emission and absorption profile in the stacked 2014 pn spectrum showing a weaker absorption line at ~7 keV compared with 2001, but additional absorption structure at higher energy and emission components at a small blueshift relative to markers indicating the rest energies of Fe K emission lines of neutral, He-like and H-like ions, respectively. (Lower) Model fit including three highly ionized absorption components. Colour coding is blue for the high-ionization emission, with the ionized reflection continuum and Fe K fluorescence line shown in black. The hard power law and unabsorbed power law components are in red and green, respectively. (From Pounds *et al.* 2017)

observed large-scale molecular outflows (e.g. Veilleux *et al.* 2009).

While the status of the majority of currently known AGN winds is unclear, statistical evidence of an evolutionary link with the slower "warm absorbers" (Tombesi *et al.* 2013) might be explained by the wind being shocked on hitting a shell of swept-up interstellar gas (King & Pounds 2014). Further, the relatively low SMBH masses of the bright, mostly low-redshift wind hosts, suggests that many are still in the momentum-driven, growth phase. An important exception appears to be IRAS F11119+3257, a luminous infrared galaxy (redshift 0.189) exhibiting both a powerful molecular outflow and a highly ionized wind of $v \sim 0.25c$ (Tombesi *et al.* 2015).

Meanwhile, two XMM-Newton observations of the low-mass Seyfert NGC 4051 have provided the first direct evidence of a fast ionized wind being shocked, with subsequent strong cooling leading to most of the initial flow energy being lost before it can reach the bulge gas.

"A critical point is where the local accretion luminosity reaches the Eddington rate"

Evidence for a shocked flow

NGC 4051 was found in the XMM-Newton archival search to have a high-velocity wind during an observation in 2002, with spectral modelling determining an outflow velocity $v \sim 0.20c$ (Tombesi *et al.* 2011).

A further XMM-Newton observation of NGC 4051 in 2009, extending over six weeks and with an on-target exposure of ~600 ks, broke new ground by finding an unusually rich absorption spectrum with multiple outflow velocities up to $v \sim 0.13c$ (Pounds & Vaughan 2011a). Inter-orbit variability was seen in both absorption and emission lines, with strong recombination continua and velocity-broadened resonance lines providing evidence of a shocked flow (Pounds & Vaughan 2011b). That interpretation was confirmed when modelling of both Reflection Grating Spectrometer (den Herder *et al.* 2001) and EPIC pn absorption spectra found a correlation of outflow velocity and ionization state, as expected from mass conservation in a cooling post-shock flow (Pounds & King 2013).

Rapid variations in the observed ratio of Fe XXV to Fe XXVI absorption line strengths

1 Parameters of highly ionized outflow in PG1211

component	log ξ	N_H (10^{23})	v/c	$L_{abs/em}$
abs 1	3.5 ± 0.1	2.6 ± 1.3	0.067 ± 0.003	11×10^{41}
abs 2	3.9 ± 0.6	1.5 ± 1.0	0.129 ± 0.006	6×10^{41}
abs 3	3.4 ± 0.2	0.5 ± 0.5	0.187 ± 0.003	3×10^{41}
emission	3.5 ± 0.1	0.1 (f)	0.015 ± 0.006	6×10^{41}

Parameters of the highly ionized outflow in PG1211+143 from an extended XMM-Newton observation in 2014, with three photoionized absorbers, defined by ionization parameter ξ (erg cm s^{-1}), column density N_H (cm^{-2}) and outflow velocity (v/c), together with a photoionized emission spectrum modelled by an ionization parameter and outflow velocity. Extracted or added luminosities for each photoionized component are over 2–10 keV.

(Pounds & Vaughan 2012) implied a short Compton cooling time, while detection of strong recombination continua in the soft X-ray spectra indicated an increasing density in the decelerating and cooling post-shock flow. The structure and scale of the shock geometry deduced from the observations and modelling of NGC 4051 are illustrated in figure 3.

If the majority of AGN with powerful winds are indeed in the momentum-driven phase we can confidently expect future observations to reveal other examples of short-range shocking, with strong recombination spectra being a likely signature.

"Observations support the view that the highest velocity AGN winds are transient"

Unique wind velocities

Figure 2 shows the distribution of wind velocity for 35 AGN detected in XMM-Newton and Suzaku spectra, implying a unique value in every case. As noted above, Shakura & Sunyaev (1973) first pointed out that a black hole supplied with matter at a super-Eddington rate will expel it from its accretion disc in such a way that it never exceeds the local Eddington luminosity.

In such a situation, which should be relevant to a luminous AGN such as PG1211 where a comparison of bolometric luminosity and black hole mass indicates a mean accretion rate close to the Eddington rate, figure 4 traces the flow of matter accreted at the outer disc moving inwards on the local viscous timescale. While the disc successfully radiates accretion energy at large disc radii and there is no wind, a critical point arises where the local accretion luminosity reaches the Eddington rate. This defines the Eddington radius R_{Edd}, where

$$R_{Edd} = \dot{m}GM/L_{Edd} \quad (5)$$

The wind starts at R_{Edd}, with the correct (local escape) velocity. Mass loss from within this radius falls quickly, because the local accretion rate $\dot{M}(R)$ will scale so as to keep $GM\dot{M}(R)/R \simeq L_{Edd}$, and $\dot{M}(R) \propto R$. Hence there is less absorption from smaller radii, which may show as a higher velocity wing/tail to the primary outflow.

The discovery observation of PG1211 in 2001, with a dominant wind velocity of $v \sim 0.15c$, is consistent with this picture, even to the extent that (unpublished) modelling with a higher resolution grid finds evidence for a higher velocity wing/tail.

More recent observations have revealed that a unique wind does not always apply, with a new and extended study of PG1211 finding three primary wind velocities persisting over a five-week observation. In addition, a closer look at XMM-Newton and Suzaku archival data shows that where an AGN wind has been observed more than once, the derived velocity can vary significantly, with the reported value a (perhaps unphysical) mean.

The new PG1211 analysis is described below, followed by a brief discussion how such multiple wind velocities might arise from the random way in which AGN accrete. Thus an accreting cloud approaching at an oblique angle to the black hole spin plane will warp and break up the inner disc (Nixon *et al.* 2012), leading to a state of quasi-dynamical accretion that could, in principle, launch multiple winds over a short time interval.

A more complex wind

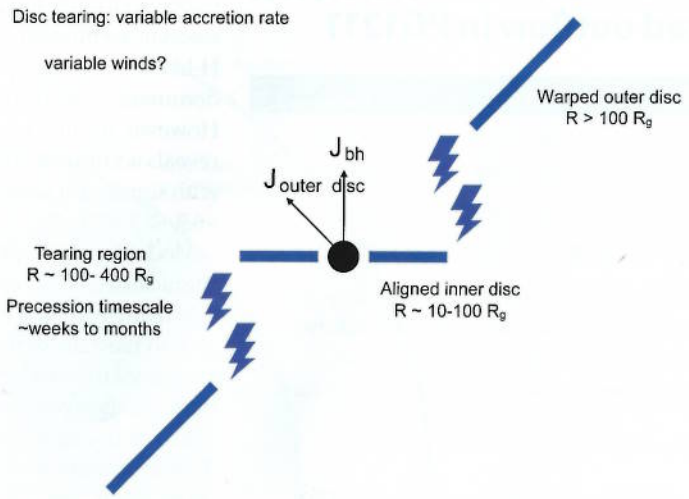
To clarify the properties of the archetypal Eddington wind, an extended XMM-Newton observation of PG1211 was undertaken over five weeks in 2014, with a total on-target exposure of ~680 ks, almost 15 times greater than the initial observation in 2001 and an order of magnitude more than for the typical archival detections. The new observation had surprising implications, with once again a high column, highly ionized wind, but one that showed a more complex velocity profile.

The top panel of figure 5 shows the relevant section of the stacked pn camera data from this 2014 observation. Comparison with figure 1 shows that the emission near 6 keV is now resolved, with component rest energies close to the neutral Fe K fluorescent emission line and the 1s–2p resonance emission lines of He-like and H-like Fe. The absorption line at ~6.9 keV, dominant in 2001, is now ~3 times weaker. However, the much longer exposure in 2014 reveals additional absorption structure, with significant absorption lines at ~6.6, ~6.9, ~7.3, ~7.5, ~7.8, ~8.2 and ~8.7 keV.

Modelling with XSTAR successfully characterized a photoionized emission spectrum matching emission features seen in the data, with the He- and H-like resonance line strengths in a ratio set by the ionization parameter. The Fe Lyman-β emission line can also be seen in both data and model at ~7.7 keV, with a similar blueshift. Separate absorption grids similarly matched the observed spectral structure, with model parameters corresponding to highly ionized outflows at ~0.066*c*, ~0.129*c* and ~0.188*c* (Pounds *et al.* 2016a). The lower panel of figure 5 shows that the principal (1s–2p, 1s–3p) transitions in H- and He-like Fe match all seven absorption lines in the stacked EPIC pn data. Crucial support for the Fe K analysis came from the higher resolution Reflection Grating Spectrometer spectra, finding absorption in comoving lower ionization counterparts to all three primary (high column) velocity components (Pounds *et al.* 2016b). The parameters of the primary, highly ionized flow are summarized in table 1 (Pounds *et al.* 2017).

In the context of Eddington winds, the simultaneous detection of three primary velocity components indicates independent shells of gas in line-of-sight to the continuum X-ray source, none of which can unambiguously be linked with the dominant 0.15*c* wind that was observed in 2001. The implication is that an individual wind burst may be relatively short-lived; this has some support from the archival search results of Tombesi *et al.* (2011) and Gofford *et al.* (2013). Although including only a few repeated observations, they support the view that the highest velocity AGN winds are transient. Mrk 509 is the best sampled case in the XMM-Newton data, with measured wind velocities of ~0.173*c*, ~0.139*c* and ~0.196*c*, separated by five years and six months respectively (Cappi *et al.* 2009).

While the high detection rate shows that Eddington winds are common in bright, nearby AGN, the new PG1211 data indicate a more turbulent and dynamic inner disc in AGN than that considered by Shakura and Sunyaev (1973) and illustrated in figure 4. While the implied accretion variability might be due to instabilities intrinsic to the disc, an intriguing extrinsic factor could be the essential difference in the way AGN accrete compared to binary star systems.



6 Cartoon showing how the innermost region of an accretion disc misaligned to the black hole spin plane will warp and eventually tear off. Collision between successive rings then leads to shocks, cooling and loss of rotational support, with the resulting dynamic accretion being a potential source of a new, short-lived Eddington wind.

Probing inner disc accretion

Because gas in a galaxy typically falls from far outside the radius of gravitational influence of the SMBH, and with essentially random orientations, the accretion disc in an AGN will, in general, orbit in a plane misaligned to the spin of the central black hole (King & Pringle 2006, 2007). The inner disc will then be subject to Lense–Thirring precession, causing misaligned orbits to precess around the black hole spin vector, with orbits at smaller radii precessing faster and leading to the warping and potential tearing away of independently precessing rings of gas (figure 6). Nixon *et al.* (2012) derive an approximate radius within the disc at which this can occur, finding that, for typical AGN disc parameters, the tearing radius is of order a few hundred gravitational radii from the black hole – putting it in the same region from which the escape-velocity indicator suggests Eddington winds are launched.

Computer simulations (http://www.astro.le.ac.uk/~cjn/tearing.html) show that, as each torn-off ring precesses on its own timescale, two neighbouring rings will eventually collide, with the shocked material losing rotational support and falling inwards to a new radius defined by its residual angular momentum. The material added to the inner disc from the disc-tearing region is likely to cause a substantial and probably short-lived increase in the local accretion rate, leading a previously sub-Eddington flow to become briefly super-Eddington, with the probable launch of a new wind component. This scenario raises the exciting prospect that future observations of Eddington winds, together with parallel advances in theory and computation, could provide unique insights on accretion in AGN and on the growth of SMBH between mergers.

"Different wind velocity profiles suggest a gusty rather than steady wind"

Importantly for for relevance to galaxy feedback, the high detection rate of winds in the archival searches – and their comparable luminosity in absorbed and re-emission spectra – confirm that the integrated wind energy remains significant and proportional to the mean accretion rate. With precession timescales of order weeks for a radius of 50 R_g, to a few years for radii of order 200 R_g (assuming a $3 \times 10^7 M_\odot$ black hole with spin parameter 0.5; Nixon *et al.* 2012), the different wind velocity profiles of PG1211 in 2001 and 2014 suggest a gusty rather than steady wind. In that context it is relevant to note that the observability of an expanding high-velocity shell can be of order of months to a few years, depending on the launch radius and outflow velocity (King & Pounds 2015).

Finally, it is interesting to note that recent XMM-Newton observations have found similar highly ionized winds from several ultraluminous stellar X-ray sources (Middleton *et al.* 2014, Pinto *et al.* 2016), in which hyper-Eddington accretion (King & Muldrew 2015) offers an alternative to earlier claims for a class of stellar black holes of mass ~10^3–$10^5 M_\odot$, intermediate with that of SMBH.

Hitomi, XMM-Newton and Athena

Looking ahead, the planned reflight of the Japanese Hitomi mission will introduce the next major advance in X-ray spectroscopy, with the few eV spectral resolution of a microcalorimeter well matched to study complex high-energy spectral structure of the highly ionized matter characteristic of Eddington winds. Together with an extended XMM-Newton programme, such new data will provide the best opportunity for further exploration of both super- and hyper-Eddington accretion prior to the launch of the European-led Athena X-ray Observatory in 2028 (http://www.the-athena-x-ray-observatory.eu). •

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