The shocked outflow in NGC 4051 – momentum-driven feedback, ultrafast outflows and warm absorbers

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Accepted 2013 May 8. Received 2013 April 30; in original form 2013 February 5

ABSTRACT
An extended XMM–Newton observation of the Seyfert 1 galaxy NGC 4051 in 2009 revealed an unusually rich absorption spectrum with outflow velocities, in both Reflection Grating Spectrometers and EPIC spectra, up to \( \sim 9000 \, \text{km} \, \text{s}^{-1} \). Evidence was again seen for a fast ionized wind with velocity \( \sim 0.12 \, c \). Detailed modelling with the XSTAR photoionization code now confirms the general correlation of velocity and ionization predicted by mass conservation in a Compton-cooled shocked wind. We attribute the strong column density gradient in the model to the addition of strong two-body cooling in the later stages of the flow, causing the ionization (and velocity) to fall more quickly, and confining the lower ionization gas to a narrower region. The column density and recombination time-scale of the highly ionized flow component, seen mainly in Fe K lines, determine the primary shell thickness which, when compared with the theoretical Compton cooling length, determines a shock radius of \( \sim 10^{17} \, \text{cm} \). Variable radiative recombination continua (RRC) provide a key to scaling the lower ionization gas, with the RRC flux then allowing a consistency check on the overall flow geometry. We conclude that the 2009 observation of NGC 4051 gives strong support to the idea that a fast, highly ionized wind, launched from the vicinity of the supermassive black hole, will lose much of its mechanical energy after shocking against the interstellar medium (ISM) at a sufficiently small radius for strong Compton cooling. However, the total flow momentum will be conserved, retaining the potential for a powerful AGN wind to support momentum-driven feedback. We speculate that the ‘warm absorber’ components often seen in AGN spectra result from the accumulation of shocked wind and ejected ISM.

Key words: galaxies: active – galaxies: evolution – X-rays: galaxies.

1 INTRODUCTION
High-resolution spectra of the bright Seyfert 1 galaxy NGC 4051 obtained by Chandra, XMM–Newton and Suzaku over the past decade have detected soft X-ray absorption lines indicating an ubiquitous outflow with velocities in the range \( \sim 200–600 \, \text{km} \, \text{s}^{-1} \) (Collinge et al. 2001; Ogle et al. 2004; Pounds et al. 2004; Steenbrugge et al. 2009), with occasional reports of higher velocities of \( \sim 2340 \, \text{km} \, \text{s}^{-1} \) (Collinge et al. 2001) and \( \sim 4600 \, \text{km} \, \text{s}^{-1} \) (Steenbrugge et al. 2009). A substantially longer XMM–Newton observation in 2009 revealed a more complex soft X-ray absorption spectrum, with outflow velocities up to \( \sim 9000 \, \text{km} \, \text{s}^{-1} \) (Pounds & Vaughan 2011). While rare in the soft X-ray band, similar outflow velocities are frequently observed in Fe K spectra of NGC 4051, more sensitive to highly ionized matter (Pounds et al. 2004; Lobban et al. 2011). Moreover, in an archival XMM–Newton search of 42 radio quiet AGN, Tombesi et al. (2010) found evidence for still higher velocity outflows (\( v \sim 0.1c \)) in \( \sim 35 \) percent of their sample, including NGC 4051. An intriguing question is whether, or how, such ultrafast outflows (UFOs) are physically linked with the more weakly ionized and much slower outflows (‘warm absorbers’) which are also common in many bright AGN.

In an initial analysis of the 2009 XMM–Newton observation of NGC 4051, Pounds & Vaughan (2011a; hereafter Paper I) considered an apparent correlation of outflow velocity and ionization parameter in terms of a mass-conserved decelerating flow, perhaps resulting from strong Compton cooling after shocking of the high-speed primary wind with the interstellar medium (ISM) or slower moving ejecta (King 2010; Zubovas & King 2012). A wider relevance of the shocked flow scenario lies in the transformation of an energetic AGN wind into an outflow where the potential mechanism for galaxy feedback is the momentum thrust (King 2003, 2005).

The high sensitivity of the 2009 XMM–Newton observation also found several strong, blueshifted and broad emission lines (BEL), all showing evidence of self-absorption near the line cores (Pounds
Broad soft X-ray emission lines have previously been reported for NGC 4051 (Ogle et al. 2004; Steenbrugge et al. 2009), and for several other Seyfert 1 galaxies (Kaastra et al. 2002; Costantini et al. 2007; Smith, Page & Branduardi-Raymont 2007), being interpreted by those authors as an extension of the optical/UV ‘broad-line region’, envisaged as optically thick ‘clouds’ circling the central black hole. Paper II outlined an alternative origin of the broad soft X-ray emission lines in NGC 4051, arising in a limb-brightened shell of shocked gas, and noted that self-absorption in the near-orthogonal flow could explain the low-velocity absorption component seen across a wide range of ionization states.

In this paper, we describe in Section 3 the detailed modelling of both Reflection Grating Spectrometers (RGS) and EPIC absorption spectra using the xstar photoionization code, with five RGS components confirming a linear correlation of outflow velocity and ionization parameter. While low-velocity/low-ionization absorption is only observed in the RGS data, the RGS and EPIC model parameters are in good agreement for the higher velocity/higher ionization absorption. A sixth RGS component lies off the main trend, and represents the low outflow velocity observed over a wide range of ionization. Intriguingly, a seventh RGS component has a small but significant net redshift, which we speculate might be due to shocked gas falling back towards the hole.

Section 4 uses the interorbit variability of Fe K absorption, reported in more detail in Pounds and Vaughan 2012 (hereafter paper III), to estimate the recombination time of the more highly ionized flow component (from changes in the Fe XXV to Fe XXVI ratio) and hence constrain the related particle density, which – with the corresponding absorption column density from XSTAR modelling – gives the thickness of the highly ionized post-shock shell. In Section 6, this value is compared with the theoretical Compton cooling length and used to derive an estimate of the shock radius.

At some point along the post-shock flow, two-body processes will become important, resulting in additional cooling (Appendix A), with the flow temperature (ionization and velocity) then falling more quickly. Section 5 examines strong radiative recombination continua (RRC) emission, with interorbit variability providing a recombination time-scale and corresponding mean particle density to allow scaling of this lower ionization flow component.

In Section 6, we outline a self-consistent physical picture of a highly ionized, high-speed wind, which shocks with the ISM at a sufficiently small radius for strong Compton cooling in the AGN radiation field to result in most of the mechanical energy in the flow being lost. The subsequent radial structure of the decelerating post-shock flow is determined by the competing cooling processes, which provide a physical basis on which to understand the complex X-ray absorption and emission spectra in the 2009 XMM–Newton observation of NGC 4051.

2 OBSERVATIONS

NGC 4051 was observed by XMM–Newton on 15 orbits between 2009 May 3 and June 15, yielding a total on-target exposure of ∼650 ks. This paper uses data from the Reflection Grating Spectrometers, RGS 1 and RGS 2 (den Herder et al. 2001), and the EPIC pn camera (Strüder et al. 2001). Detailed X-ray light curves are given in Alston, Vaughan & Uttley (2013) while mean RGS flux levels for each satellite orbit are shown in Fig. 1. Table 1 identifies the spacecraft revolution and respective orbit number, with corresponding observation start and end times. The overall observation was characterized by a generally high soft X-ray continuum over the first half (apart from orbit 4) with four successive high–flux orbits (5–8), followed by lower mean continuum levels from orbit 9 onwards.

3 MODELLING THE OUTFLOW WITH XSTAR

To quantify the overall photoionized absorption in the complex outflow in NGC 4051 the RGS and EPIC spectra for the sum of the four high-flux orbits 5–8 were modelled in xspec (Arnaud 1996) with alternative grids based on the xstar photoionization code (Kallman et al. 1996).

3.1 RGS data

For the RGS data, where most absorption lines appear intrinsically narrow, we chose grid 18 from the xstar library, which includes a fixed turbulent velocity of 100 km s$^{-1}$ to minimize computing time. Grid 18 covers an ionization parameter range in log$\xi$ from −4 to +4 erg cm s$^{-1}$, and column densities from 10$^{19}$ to 10$^{23}$ cm$^{-2}$.
Abundances of relevant metals from C to Fe were initially set to solar values, but allowed to vary in the final spectral fitting.

The composite high-flux RGS spectrum was first fitted by a power law plus blackbody to provide a smooth match to the continuum. Positive Gaussians (determined from fitting the sum of the low-flux spectra of orbits 4, 11, 13) were then added to the continuum to represent the main BEL and the strong Fe XVII emission lines near 17 Å. A number of RGS components were added to represent the stronger RRC, with the normalization of each left free to vary. Finally, guided by the intriguing observation that very few absorption lines in the RGS spectra appear to penetrate below ~50 per cent of the continuum, an unabsorbed fraction of the power law plus blackbody continuum was included in the model.

A sequence of photoionized absorbers from grid 18 was then added to achieve the best statistical fit over the whole 6–36 Å RGS waveband. The ionization parameter, column density and velocity (output as a modified redshift) were the primary free parameters of each absorber. In the event the recorded modelling was limited to (output as a modified redshift) were the primary free parameters of each absorber. In the event the recorded modelling was limited to the 10–36 Å waveband due to the low-RGS sensitivity at shorter wavelengths.

An initial fit to the RGS 1 data over the waveband 17–24 Å, dominated by absorption lines of O IV, V, VI, VIII and IX and largely independent of relative abundances, required two photoionized components, expressing the strong low (~500 km s⁻¹) and higher (~4000 km s⁻¹) velocity absorption in O VII and O VIII. The fit was then extended to 36 Å, to include the resonance lines of N VIII, N VI and C VI, and with both RGS1 and RGS2 data, and finally over the waveband 10–36 Å, covering the higher energy K-shell resonance transitions of Ne, and a potential complex of Fe L lines. For the full band fits, the abundances were allowed to vary, although being tied for the same element across the separate ionized components.

A total of seven photoionized absorbers yielded significant incremental improvements to the 10–36 Å fit, with an overall reduction from χ²/ν = 6785/4125 to χ²/ν = 5048/4094. Intriguingly, a further significant reduction to χ²/ν = 4996/4093 was found with 28 ± 5 per cent of the continuum unabsorbed. The parameters of this multi-absorber fit (illustrated in Fig. 2) are listed in Table 2.

The abundances of the more important elements in the best fit were C:0.29 ± 0.16, N:0.62 ± 0.35, O:0.68 ± 0.34, Ne: 0.41 ± 0.30 and Fe:1.9 ± 1.1. While these values are noted, only the over-abundance of Fe made a substantial difference to the fit parameters.

Components 1, 2 and 7 represent the high-velocity absorption observed most strongly in the soft X-ray data in O VIII and Ne X, and it is notable that they pick out similar velocities to the values obtained from Gaussian fits to the absorption in O VIII, N VII and C VI Lyman α (Paper I). Component 7 is the least significant, with a lower column density indicating a minor constituent at the highest post-shock velocities.

Components 3 and 4 represent the lower velocity/lower ionization absorption observed particularly strongly in absorption lines of O V, O VI and O VII and the Fe UTA at ~15–16.5 Å. The absence of an intermediate-velocity component is consistent with the absorption velocity profiles in Paper I, showing with a relative lack of absorption between ~3000 and ~1000 km s⁻¹.

Component 5 represents the low-velocity absorption seen across a wide range of ionization parameter, interpreted in Paper II as self-absorption in the BEL, where a high inclination to the line of sight constrains the projected flow velocities.

Component 6 was a surprise, but is strongly required by the fit. Although only hinted in individual spectra, the requirement of a redshifted absorption component at low velocity is interesting as a possible indicator of post-shock matter falling back from the contact discontinuity, having slowed to below the local escape velocity. The absence of a similar redshifted absorber in the comparable analyses of Steenbrugge et al. (2009) and Lobban et al. (2011) would argue against an alternative origin in a high-velocity cloud in the line of sight in the host galaxy, as reported for Mrk 509 (Ebrero et al. 2011). The outflow velocity and ionization parameter of components 1–5 and 7 are plotted in Fig. 4, together with the main absorbing ions located at the ionization parameter of maximum abundance for a gas in equilibrium.

<table>
<thead>
<tr>
<th>Comp</th>
<th>logξ</th>
<th>N_H</th>
<th>Velocity (km s⁻¹)</th>
<th>Δχ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.0 ± 0.1</td>
<td>4.3 ± 0.4 × 10²²</td>
<td>~5760 ± 500</td>
<td>488/3</td>
</tr>
<tr>
<td>2</td>
<td>2.5 ± 0.1</td>
<td>1.0 ± 0.1 × 10²²</td>
<td>~3720 ± 300</td>
<td>113/3</td>
</tr>
<tr>
<td>3</td>
<td>1.6 ± 0.2</td>
<td>7 ± 0.3 × 10¹⁰</td>
<td>~510 ± 150</td>
<td>94/3</td>
</tr>
<tr>
<td>4</td>
<td>0.8 ± 0.1</td>
<td>1.6 ± 0.3 × 10²¹</td>
<td>~120 ± 45</td>
<td>797/3</td>
</tr>
<tr>
<td>5</td>
<td>2.6 ± 0.2</td>
<td>2 ± 0.5 × 10²¹</td>
<td>~630 ± 350</td>
<td>174/3</td>
</tr>
<tr>
<td>6</td>
<td>~0.82 ± 0.1</td>
<td>4 ± 1.5 × 10²⁰</td>
<td>~360 ± 60</td>
<td>48/3</td>
</tr>
<tr>
<td>7</td>
<td>3.2 ± 0.2</td>
<td>1 ± 0.3 × 10²¹</td>
<td>~10290 ± 1000</td>
<td>23/3</td>
</tr>
</tbody>
</table>
3.2 EPIC data

Fitting the EPIC pn absorption spectra, again for the sum of the four high-flux orbits (5–8), allows an extension of the XSTAR modelling to heavier ions whose K-shell wavelengths fall outside the sensitive range of the RGS. The generally higher velocities and ionization levels seen in the EPIC spectrum led to a preference of grid 21 for XSTAR modelling, with a higher turbulent velocity of 1000 km s$^{-1}$, but otherwise a similar parameter range to grid 18. The continuum was first modelled by a partially covered power law plus reflection, the model \( p\text{cref} \) described in detail in Paper III. Positive Gaussians were added to represent the Fe K fluorescence line at \( \sim 6.4 \) keV and an apparent red wing.

Initially restricting the fit to the 1.3–5 keV band, covering the K-shell resonance lines of Mg, Si, S, Ar and Ca, the continuum model yielded a moderately good fit (\( \chi^2 = 743/735 \)). However, several absorption lines were clearly evident in the data:model ratio plot. The addition of a single XSTAR component of grid 21 matched the stronger of these features and provided an excellent overall fit (\( \chi^2 = 743/735 \)), with ionization parameter \( \log \xi = 3.2 \pm 0.1 \) and column density \( 1.8 \pm 0.2 \times 10^{22} \) cm$^{-2}$ (Fig. 3, top panel). The relative blue-shift of this more highly ionized component, \( 2.8 \pm 0.2 \times 10^{-2} \), corresponds to an outflow velocity of \( 9100 \pm 600 \) km s$^{-1}$, consistent with the strongest high-velocity component found in Ne X Lyman \( \alpha \) absorption in the RGS data (Paper I).

Extending the EPIC spectral fit to 10 keV includes the strong Fe K absorption lines. The continuum was again modelled with \( p\text{cref} \), but provided a poor fit (\( \chi^2 = 1829/1358 \)) with strong negative residuals near 7 keV. The addition of photoionized absorption with grid 21 produced a very substantial improvement (\( \chi^2 = 1445/1362 \)), due mainly to matching the resonance absorption lines of Fe XXV and Fe XXVI (Fig. 3, middle panel). The XSTAR fit over this wider energy band had a similar ionization parameter (\( \log \xi = 3.4 \pm 0.1 \)) and column density (\( 3.9 \pm 0.7 \times 10^{22} \) cm$^{-2}$), but a lower velocity (\( 7600 \pm 500 \) km s$^{-1}$). A probable explanation for this difference, which appears to go against the general velocity–ionization trend, is that the Fe K absorption lines are so strong as to dominate the fit, while the Fe Lyman \( \alpha \) absorption line appears unusually broad in the data and may not be well modelled with a single velocity. The lower panel of Fig. 3 illustrates the relevant structure of the Fe K absorption, where the ratio of data to continuum is modelled by Gaussians. It appears likely that the XSTAR fit is finding a mean value in a velocity range from \( \sim 5000 \) to \( 9000 \) km s$^{-1}$, perhaps tracing the post-shock flow across the main Compton cooling shell. In that context, \( \sim 5000 \) km s$^{-1}$ may then indicate the point where two-body cooling becomes important as the temperature falls below \( \sim 1 \) keV (Section 6 and Appendix A), and the highly ionized flow changes rapidly to a low-ionization flow.

In summary, XSTAR modelling finds the RGS and EPIC absorption parameters are in good agreement in the high-ionization/high-velocity region of overlap. The linear trend of velocity and ionization parameter is clearly seen in Fig. 4, as expected for a cooling post-shock flow. The weak high-velocity component in the RGS data may indicate density structure in the post-shock flow.

Finally, a seventh point is added to Fig. 4 to represents the pre-shock wind, with velocity \( v \sim 0.12c \) (Paper III) and an ionization parameter of \( \log \xi = 3.8 \), the latter assuming the factor of 4 increase in density (along with a similar decrease in velocity) expected across a strong shock.

An outstanding question for the mass-conserved shocked flow interpretation is raised by the strong column density gradient between the high and lower ionization XSTAR components. We interpret this in Section 6 in terms of the onset of additional two-body cooling, causing the flow to pass quickly through intermediate velocity and ionization stages.
Shocked outflow in NGC 4051

Figure 4. Outflow velocity and ionization parameter for each of the XSTAR photoionized absorbers derived from fitting to the RGS spectra, together with a high point representative of the pre-shock wind. The main trend is consistent with the linear correlation of velocity and ionization parameter expected for a mass-conserved cooling flow.

4 VARIABLE FE K ABSORPTION AND THE HIGHLY IONIZED FLOW COMPONENT

The strongest absorption lines in the EPIC spectrum are generally those of the resonance transitions of Fe XXV 1s–2p and Fe XXVI Lyman α (Fig. 3, middle panel). The ratio of line depths is a sensitive measure of ionization state, and a detailed examination of the Fe K absorption profile in Paper III showed that the line ratio – and implicitly the ionization – could change significantly between adjacent orbits.

Fig. 5 compares the Fe K absorption profile for orbits 6 and 7 (where similar spectra have been co-added for greater clarity) with that for orbit 8 where the ionizing flux $\gtrsim 7.1$ keV has increased by a factor of $\sim 2$, to the highest level of the 2009 campaign. While the two absorption lines are of similar depth in the first case, the 7.1 keV Fe XXVI Lyman α line is significantly the stronger in orbit 8, indicating the ionization state of the highly ionized flow component has changed on a time-scale of $\sim 2$ d (Table 1).

For an ionization front moving into a low-density medium, as here, the observed response time will be governed by the recombi-

nation time. Assuming a post-shock temperature for the more highly ionized flow of $\sim 1$ keV (Paper I), and a recombination coefficient of $\sim 5 \times 10^{-12}$ cm$^3$ s$^{-1}$ (Verner & Ferland 1996), the observed variability time-scale corresponds to an electron density of $\sim 4 \times 10^6$ cm$^{-3}$.

Comparing this measure of the particle density of the highly ionized flow with the corresponding column density from XSTAR modelling, $N_H \sim 4 \times 10^{22}$ cm$^{-2}$, yields a primary cooling shell thickness of $\sim 10^{16}$ cm. We use this value in Section 6 to estimate the shock radius.

5 RECOMBINATION CONTINUUMS FROM THE LOWER IONIZATION FLOW

Paper II reported a significant emission component from the N VII RRC (threshold wavelength 18.59 Å), though evidence for interorbit variability is affected by blending with high-velocity absorption in O VIII Lyman α (18.968 Å). The N VI RRC is strongly blended with O VII absorption, while the O VII RRC sits at the upper wavelength edge of a strong Fe UTA. Fortunately, both C v and C VI RRC lie in spectral regions relatively free from absorption lines. Velocity profiles of both carbon RRC for a composite of all 15 orbits are of a similar form, with distinct – though not identical variability – between individual orbits and groups of orbits with similar continuum levels. The 15-orbit sum and a representative set of emission profiles for C VI are shown in Fig. 6.

Fig. 6 (top-left panel) shows the composite velocity profile for the whole 2009 observation of NGC 4051, with zero velocity at the threshold wavelength of the C VI RRC (25.303 Å). The statistical quality of the composite data, plotted at high-velocity resolution (300 km s$^{-1}$), allows non-RRC features to be resolved and identified. To the blue side they include the low-velocity absorption component of N VI 1s–3p (seen near $-5000$ km s$^{-1}$) and multiple N VII Lyman α absorption components (near $-7000$, $-10 000$ and $-12 500$ km s$^{-1}$ in the plot). Positive and negative spikes at $\sim 8200$ and $\sim 5000$ km s$^{-1}$ are due to a dead pixel and a chip gap in the RGS CCDs.

The composite 15-orbit RRC emission profile is quite unlike the saw-tooth shape expected for stationary matter, and extends bluewards of the zero velocity threshold by $\sim 4000$ km s$^{-1}$. While some part of the RRC width will be a measure of the electron temperature in the recombining gas, the shape of the composite

Figure 5. Variable absorption profiles for the composite of orbits 6 and 7 and for the peak flux orbit 8, indicating an increase in ionization with higher continuum flux.
Figure 6. Left-hand panel, from top: composite velocity profile of the C vi RRC summed over the full 2009 observation. A strong RRC is visible, extending bluewards by $\sim 4000\,\text{km}\,\text{s}^{-1}$ from the rest-frame threshold. The sharp spikes at $-8200$ and $\sim 5000\,\text{km}\,\text{s}^{-1}$ are due to a chip gap and dead pixels in the RGS CCDs, while the absorption and emission structure beyond $-4500\,\text{km}\,\text{s}^{-1}$ is identified with low-velocity absorption in the N vi K$\beta$ line and the BEL and both low and higher velocity absorption in N vii Lyman $\alpha$. The middle and lower panels show the same profile, with velocity resolution degraded from 300 to 750 $\text{km}\,\text{s}^{-1}$, for orbits 1–3 and 4, respectively. Right-hand panel, from top: composite velocity profile of the C vi RRC with velocity resolution of 750 $\text{km}\,\text{s}^{-1}$, for orbits 5–8, 9, and 10. Note different y-axis scaling and see the text for discussion.

profile indicates a mean outflow velocity of $\sim 2000\,\text{km}\,\text{s}^{-1}$, similar to the velocity gap at $\sim 1500$–$3500\,\text{km}\,\text{s}^{-1}$ in the absorption profiles in the C, N and O Lyman $\alpha$ lines (Paper I), and interpreted in Section 6 as a consequence of a rapidly increased cooling rate.

The middle and lower-left panels of Fig. 6 show the same C vi RRC profile for a composite of the early orbits 1–3 and for orbit 4, when the mean continuum level has fallen (Fig. 1) by a factor $\sim 4$. The C vi RRC is of similar strength in both plots, setting a lower limit to the relevant recombination time of $\sim 2 \,\text{d}$ (Table 1).

The right-hand side of Fig. 6 continues the orbital sequence with the upper panel being a composite profile from the high-flux orbits 5–8, with the peak emission shifted still more strongly to the blue. In contrast, the high-velocity RRC component has essentially
disappeared by orbit 9 (right-hand side, middle panel), with an integrated flux lower than for orbits 5–8 by a factor of 4.5 ± 1.

Reference to the orbit timing data in Table 1 shows an interval of ∼6 d between orbits 8 and 9, providing a firm upper limit to the recombination time for the relevant flow component ≤5.5 d. However, additional Swift and RXTE monitoring (Alston et al. 2013) shows a high-continuum flux mid-way between orbits 8 and 9, further constraining the RRC decay time to ≤2.5 d. We assume below a recombination time of 2 d.

Assuming an electron temperature from the mean RRC profile of ∼4 eV, a C VI recombination coefficient of ∼10−11 cm3 s−1 (Verner & Ferland 1996) and the observed RRC decay time indicate a density of ∼3 × 109 cm−3. The related column density of ∼1022 cm−2 from XSTAR modelling then translates to an absorbing path length of 3 × 1015 cm for the lower ionization flow component.

Variability in the RRC contrasts with the lack of variability in the BEL of the same ions. The probable explanation lies in the higher blueshift of the RRC emission and a shorter light travel time. Since a substantial RRC flux implies a wide angle flow, a delayed response to a lower continuum will be a product of light travel time and intrinsic recombination time-scale, with the more blueshifted emission from matter observed at a smaller offset angle.

A similar examination of the emission profiles of the C VI RRC supports this conclusion, with the 15-orbit composite showing a clearer separation into two velocity components. While the higher velocity component varies in a similar way to C VI, the low-velocity component in C VI appears to vary little with overall flux level, similar to the BEL.

6 DISCUSSION

Modelling the RGS and EPIC pn absorption spectra from the 2009 XMM–Newton observation of NGC 4051 confirms a general correlation of outflow velocity and ionization, consistent with mass conservation in a cooling shocked wind (King 2010, Paper I), while also quantifying the strong gradient in column density with ionization level. Interorbit changes in the ratio of Fe XXV and Fe XXVI absorption lines allow an estimate of the mean particle density in the highly ionized post-shock flow, with similarly rapid variability in strong RRC emission constraining the density in the lower ionization flow. In this section, we outline a model incorporating the above data, while providing a physical basis for identifying a fast ionized wind and a ‘warm absorber’ as early and late stages in a continuous, mass-conserved flow.

Fig. 7 illustrates the envisaged scenario, assuming spherical symmetry and a uniform radial flow. The highly ionized wind collides with the ISM sufficiently close to the AGN for strong Compton cooling of the shocked gas to define a shell where the ionization level remains sufficiently high for ionized Fe K absorption. At a critical juncture along the flow, two-body processes become important (see Appendix A) and the flow cools more rapidly over a narrower region, where X-ray absorption (and emission) is dominated by the lighter metals (O, N, C).

For the highly ionized flow, a density estimate from observed variability in the Fe K absorption line ratio (Section 4), and an absorption column from the XSTAR modelling indicate an absorption length of ∼1016 cm. A comparison with the theoretical Compton cooling time for NGC 4051 of ∼600 R2 yr (from Appendix A, equation (2), with M = 1.7 × 106 M⊙), and assuming a mean velocity for the highly ionized flow of 6000 km s−1, finds the observed cooling length to correspond to a shock at a radial distance R = 0.03 pc (∼1017 cm) from the black hole.

Repeated variability in the C VI RRC flux (Section 5) indicates a recombination time for the lower ionization matter of ∼2 d. Together with a related column density from XSTAR modelling, this indicates an effective absorbing path length of 4 × 1014 cm for the lower ionization flow component.

Given these estimates of shell radius and thickness, the RRC emission measure provides an overall consistency check on the above scaling. A C VI RRC flux from the spectral fit to orbits 5–8 of ∼10−4 photons cm−2 s−1 and recombination rate of 10−11 cm3 s−1, assuming 30 per cent of recombinations direct to the ground state, corresponds to an emission measure of ∼4 × 1020 cm−3, for a Tully–Fisher distance to NGC 4051 of 15.2 Mpc.

For a mean density of ∼3 × 109 cm−3, the emission volume (4πR2ΔR) is then ∼1050 cm3. With the derived values of recombining shell thickness δR ∼ 3 × 1014 cm, and shell radius R ∼ 1017 cm, we find that the measured RRC flux is re-produced within a factor of 2. Given the approximate nature and essential averaging of many observed and modelled parameters, the self-consistency check is remarkably good.

Finally, we note that all momentum-driven outflows in AGN will ultimately stall (King 2003, 2010), while the measured column densities in UFOs show they must be variable on relatively short time-scales (King 2010a). The repeated shocks will leave behind heated and compressed gas (both wind and ISM), which can linger for some time before dispersing or falling back towards the black hole (note: the escape velocity for NGC 4051 at R ∼ 1017 cm is ∼500 km s−1).

We suggest that this matter, observed here as the low-velocity/low-ionization component, may form much of the warm absorber frequently observed in AGN (Tombesi et al. 2013). The low-ionization, redshifted absorption component indicated in our XSTAR modelling offers an intriguing prospect of tracking the circulation of the stalled wind and the ISM that has been progressively removed from smaller radii.

7 SUMMARY

Combining the analysis of emission and absorption spectra with XSTAR modelling provides a picture of the overall NGC 4051 outflow consistent with a fast primary wind being shocked at a radial distance of the order of 1017 cm, well within the zone of influence of a supermassive black hole of mass 1.7 × 106 M⊙. While the analysis necessarily involves substantial simplifications, with a few discrete components providing a coarse description of a quasi-continuous and rapidly evolving flow, the resulting picture appears robust and physically attractive.

The shocked gas initially cools in the strong radiation field of the AGN, with a Compton cooling length essentially determining the absorption columns of Fe and the other heavy metal ions. Two-body processes provide additional cooling as the density rises downstream, rapidly becoming dominant. Absorption (and emission) in the soft X-ray band then maps this thinner, outer region of the post-shock flow ahead of the contact discontinuity.

The inclusion of an unabsorbed continuum in the best-fitting XSTAR model may be evidence for denser cooling clumps in the flow (Fig. 7). Although our analysis has assumed a uniform radial flow, any density variations at the shock will be enhanced by differential cooling. Cooling radiation from the flow may also contribute significantly to a partially covered soft X-ray continuum.
Figure 7. Structure of the NGC 4051 outflow, not to scale, showing a highly ionized wind colliding with the ISM at a radius $\sim 10^{17}$ cm, the strong shock causing a sudden factor of 4 drop in velocity. Strong Compton cooling of the shocked gas defines a thin shell where the velocity continues to fall but the ionization state remains sufficiently high for strong Fe K absorption. Further along, when two-body processes become important, the flow cools more rapidly and slows over a narrower region where absorption (and emission) are dominated by the lighter metals seen in the soft X-ray spectrum. Although not used in the analysis, density variations in the shocked gas will be enhanced later in the flow and are pictured as cooling clumps.

We note that shocking with the ISM or other matter in the vicinity of the AGN, as found for NGC 4051, may provide the link between UFOs (Tombesi et al. 2010) and the equally common ‘warm absorbers’ in such objects. In that scenario, the onset of strong two-body cooling would result in the intermediate column densities being relatively small and difficult to see with less sensitive observations than in the present case.

An important consequence of powerful AGN winds losing much of their energy by radiative cooling after shocking against the surrounding gas is that feedback from such winds will be momentum driven, consistent with the observed form of the observed $M-\sigma$ relation (King 2003).

ACKNOWLEDGEMENTS

The work reported here is based on observations obtained with XMM–Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA (NASA). Simon Vaughan was PI of the 2009 observation of NGC 4051. We thank the anonymous referee for encouraging greater clarity in the text.

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Costantini E. et al., 2007, A&A, 461, 121
APPENDIX A

Immediately after the (adiabatic) shock, slowing the fast wind from $v \sim 0.12c$ to 1/4 of this speed, the free–free and Compton cooling times are

$$t_{ff} \approx 3 \times 10^{11} \frac{T^{1/2}}{N} \text{ yr}$$

and

$$t_C = 10^{-4} \frac{R_{16}^2}{M_8} \text{ yr},$$

respectively (see King, Zubovas & Power 2011: here $T$, $N$ are the post-shock temperature and number density, $R_{16}$ is the shock radius in units of 10$^{-16}$ cm, $M_8$ is the black hole mass in units of 10$^8 M_\odot$, and $m \sim 1$ is the Eddington factor of the mass outflow rate).

After the adiabatic shock, the gas cools rapidly from $T \sim 1.6 \times 10^{10}$ K by inverse Compton cooling, while its density rises as $N \propto T^{-1}$ (isothermal shock – pressure almost constant). So

$$t_f \propto T^{1/2} \frac{N}{N_s} \propto T^{3/2},$$

which means that the free–free cooling time decreases sharply while the Compton time does not change. When $T$ has decreased enough below the original shock temperature, free–free (and all the other atomic two-body processes) becomes faster than Compton.

From (A1) and (A2) above, this requires

$$\left(\frac{T}{T_s}\right)^{3/2} < 5 \times 10^{-5}$$

or

$$T < 2 \times 10^7 \text{ K},$$

showing that the temperature of ionization species forming around a few keV is determined by atomic cooling processes rather than Compton cooling. As the temperature falls further, two-body cooling becomes dominant, with the subsequent flow cooling still more rapidly and both velocity and ionization level falling quickly. This strong cooling phase is traced in the present observation by absorption and emission in the lighter metals (C, N, O) through increasingly narrow shells prior to the build up of low-velocity/low-ionization matter ahead of the contact discontinuity.

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