Inverse Compton X-ray signature of AGN feedback

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ABSTRACT
Bright AGN frequently show ultrafast outflows (UFOs) with outflow velocities $v_{\text{out}} \sim 0.1c$. These outflows may be the source of AGN feedback on their host galaxies sought by galaxy formation modellers. The exact effect of the outflows on the ambient galaxy gas strongly depends on whether the shocked UFOs cool rapidly or not. This in turn depends on whether the shocked electrons share the same temperature as ions (one-temperature regime, 1T) or decouple (2T), as has been recently suggested. Here we calculate the inverse Compton spectrum emitted by such shocks, finding a broad feature potentially detectable either in mid-to-high energy X-rays (1T case) or only in the soft X-rays (2T). We argue that current observations of AGN do not seem to show evidence for the 1T component. The limits on the 2T emission are far weaker, and in fact it is possible that the observed soft X-ray excess of AGN is partially or fully due to the 2T shock emission. This suggests that UFOs are in the energy-driven regime outside the central few pc, and must pump considerable amounts of not only momentum but also energy into the ambient gas. We encourage X-ray observers to look for the inverse Compton components calculated here in order to constrain AGN feedback models further.

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

1 INTRODUCTION
Supermassive black holes (SMBH) produce powerful winds (Shakura & Sunyaev 1973; King 2003) when accreting gas at rates comparable to the Eddington accretion rate. Such winds are consistent with the ‘ultrafast’ outflows (UFOs) $v_{\text{out}} \sim 0.1c$ detected via X-ray line absorption (e.g. Pounds et al. 2003a,b) and also recently in emission (Pounds & Vaughan 2011). The outflows must be wide enough to explain their ~40 per cent detection frequency (Tombesi et al. 2010a,b). UFOs may carry enough energy to clear out significant fractions of all gas from the parent galaxy (e.g. King 2010; Zubovas & King 2012a) when they shock and pass their momentum and perhaps energy to kpc-scale neutral and ionized outflows with outflow velocities of ~1000 km s$^{-1}$ and mass outflow rates of hundreds to thousands of $M_\odot$ yr$^{-1}$ (e.g. Feruglio et al. 2010; Rupke & Veilleux 2011; Sturm et al. 2011; Liu et al. 2013).

Most previous models of UFO shocks assumed a one-temperature model (‘1T’ hereafter) where the electron and proton temperatures in the flow are equal to each other at all times, including after the shock. Faucher-Giguere & Quataert (2012) showed that shocked UFOs are sufficiently hot and yet diffuse that electrons may be much cooler than ions (‘2T’ model hereafter). They found that for an outflow velocity of 0.1c and $L_{\text{edd}}$ = 10$^{46}$ erg s$^{-1}$, the ion temperature is 2.4 × 10$^9$ K but the electron temperature reaches a maximum of only $T_e \sim 3 \times 10^9$ K in the post-shock region. The 1T regime may however still be appropriate if there are collective plasma physics effects that couple the plasma species tighter (e.g. Quataert 1998). There is thus a significant uncertainty in how UFOs from growing SMBH affect their hosts, e.g. by energy or momentum (King 2010).

Here we propose a direct observational test of the 1T and 2T UFO shock scenarios. AGN spectra are dominated by thermal disc emission coming out in the optical/UV spectral region. The shocked electron temperature in both scenarios is rather high, e.g. $T_e \sim 10^7$ K (2T) to $T_e \gtrsim 10^9$ K (1T). Inverse Compton (IC) scattering of the AGN disc photons on these electrons produces either soft X-ray (2T inverse Compton; 2TIC) or medium to hard X-ray energy (1TIC) radiation. Provided that the shock occurs within the IC cooling radius, $R_{\text{IC}} \sim 500$ pc $M_{\text{BH}}^{1/2} \sigma_{200}$ (where $M_{\text{BH}}$ is the SMBH mass in units of $10^8 M_\odot$ and $\sigma_{200}$ is the velocity dispersion in the host in units of 200 km s$^{-1}$; Zubovas & King 2012b), essentially all the kinetic energy of the outflow, $L_k = (v_{\text{out}}/2c)L_{\text{edd}} \sim 0.05L_{\text{edd}}$ for $v_{\text{out}} = 0.1c$, should be radiated away. We calculate this IC spectral component and find it somewhat below but comparable to the observed X-ray emission for a typical AGN. Significantly, the IC emission is likely to be steady state and unobscured by a cold ‘molecular torus’, which, for the 1T case, is in contrast with typical AGN X-ray spectra. We therefore make a tentative conclusion that current X-ray observations of AGN are more consistent with the 2T picture. In view of the crucial significance of this issue to models of SMBH–galaxy co-evolution, we urge X-ray observers to search for the 1TIC and 2TIC emission components in AGN spectra to constrain the AGN feedback further.

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2 INVERSE COMPTON FEEDBACK COMPONENT

2.1 General procedure to calculate the X-ray spectrum

In what follows, we assume that the UFO velocity is $v_{out}$, the total mass-loss rate is given by $M = L_{edd}/(c v_{out})$ and that the gas is pure hydrogen in the reverse shock and so $n_e = n_p$. Assuming the strong shock jump conditions, the shocked UFO temperature immediately past the shock is given by

$$k_B T_{sh} = \frac{3}{16} m_p v_{out}^2,$$

while the density of the shocked gas is

$$\rho_{sh} = 4 \times \rho_{out} = 4 \times \frac{M}{4\pi R^2 v_{out}^2} = \frac{L_{edd}}{\pi R^2 c v_{out}},$$

where $\rho_{out}$ is the pre-shocked wind density and $M$ is the mass outflow rate in the wind. The factor of 4 in the density above comes from the density jump in the strong shock limit (King 2010; Faucher-Giguere & Quataert 2012). The shock is optically thin for radii $R \gtrsim 4 G M_{sh} v_{out}^2 = 2 \times 10^{-3}$ pc $M_8$.

The dominant cooling mechanism of the shocked wind is IC scattering (King 2003). Soft photons produced by the AGN are up-scattered by the hot electrons of the shocked wind to higher energies (X-rays for the problem considered here). Given the input spectrum of the soft photons and the energy distribution ($F(\gamma)$) below, where $\gamma$ is the dimensionless electron energy, $E/m_e c^2$ of the hot electrons in the shock, one can calculate the spectrum of the IC up-scattered photons.

Consider first the case when the electron energy losses due to IC process are negligible compared with the adiabatic expansion energy losses of the shocked gas. In the zeroth approximation, then, we have a monochromatic population of photons with energy $E_0$ and total luminosity $L_0$ being up-scattered by a population of electrons with a fixed Lorentz factor $\gamma$. The typical energy of the up-scattered photons is given as $E_\gamma \approx (\gamma^2 - 1)E_0$. The emitted luminosity of these up-scattered photons is given by

$$L_{IC} = L_0 \frac{E_\gamma}{E_0} \tau,$$

(3)

$\tau$ is the Thompson optical depth of the shell, $\tau = k_s \rho \Delta R$, where $k_s$ is the electron Thompson scattering opacity, $\rho$ is the shocked gas density and $\Delta R$ is the shell’s thickness. To arrive at the total luminosity of the IC emission one needs to calculate $\tau$ as a function of time for the expanding shell. In any event, since we assumed that IC losses are small, $L_{IC} \ll L_0 = (v_{out}/2c)L_{edd}$, the kinetic luminosity of the UFO. This regime corresponds to the shock extending well beyond the cooling radius $R_{IC}$.

Here we are interested in the opposite limit, e.g. when the contact discontinuity radius is $R \lesssim R_{IC}$, so that IC energy losses are rapid for the shocked electrons. In this case, the luminosity of the IC emission is set by the total kinetic energy input in the shock, so that

$$L_{IC} = L_k.$$  

(4)

On the other hand, one cannot assume that the electron distribution of the shocked electrons is constant.

Below we calculate this cooling electron distribution and the resulting IC spectrum in both 1T and 2T regimes. We take into account that the input soft photon spectrum is not monochromatic but covers a range of energies and the electron population also has a distribution in $\gamma$. The spectral luminosity density, $L_{E\gamma}$, of the up-scattered photons, assumed to be completely dominated by the first scattering2 is given by (Nagirner & Poutanen 1994)

$$\frac{dL}{dE_{\gamma}} = c E_{\gamma} \int_1^{\infty} d\gamma' \frac{dF(\gamma')}{d\gamma} \int_0^{\infty} dE_0 \frac{d\sigma_{0i}}{dE_0} \left(\frac{d\sigma_0(E_i, E_0, \gamma)}{dE_i} \right),$$

(5)

where $d\sigma_0/dE_0 = (1/4\pi R^2 c E_0)(dL_{in}/dE_0)$ is the differential input photon number density at the location of the shock (radius $R$), and $d\sigma_0(E_i, E_0, \gamma)/dE_i$ is the angle-averaged IC scattering cross-section for a photon of energy $E_0$ to scatter to energy $E_i$ by interacting with an electron of energy $\gamma$ (Nagirner & Poutanen 1994).

The overall process to calculate the IC spectrum is as follows: in Sections 2.2 and 2.3 the electron energy distribution (EED) of the shocked electrons, $F(\gamma)$, is calculated. This part of the calculation is independent of the soft input spectrum; thus long as the up-scattered photons are much less energetic than the electrons that they interact with. In order to calculate the output spectrum, however, we need to introduce the soft photon spectrum explicitly. These are model dependent since the precise physics, geometry and emission mechanism of the AGN accretion flows remains a work in progress. We therefore try three different models for the soft photon continuum: a blackbody spectrum with $k_B T = 3$ eV, the UV region (1–100 eV) of a typical AGN spectrum taken from Sazonov, Ostriker & Sunyaev (2004) and the entire (1–100 eV) AGN spectrum taken from Sazonov et al. (2004). Finally, the integrals in equation (5) are calculated numerically and the total IC luminosity is normalized using equation (4).

2.2 The electron energy distribution in the 2T regime

In the 2T regime for the shock, Faucher-Giguere & Quataert (2012) show that, while cooling behind the shock, the electrons spend a considerable amount of time at a ‘temporary equilibrium’ state with temperature $T_{eq} \approx 2 \times 10^6$ K for $v_{out} = 0.1c$ (see fig. 2 Faucher-Giguere & Quataert 2012). Here we therefore make the approximation that in the 2T regime the electrons have a thermal EED at temperature $T = T_{eq}$, described by the Maxwell–Juttner distribution,

$$\frac{dF(\gamma)}{d\gamma} = n(\gamma, \theta) = \frac{\beta \gamma^2}{\theta K_2 (\frac{\gamma}{\theta})},$$

(6)

where $\theta = k_B T/(m_e c^2)$ is the dimensionless electron temperature and $K_2$ is the modified Bessel function of the second kind.

2.3 1T cooling cascade behind the shock

Now we turn to the 1T case, assuming that the electron and ion temperatures in the shocked UFOs are equal to one another at all times. In this case, there is no ‘temporary equilibrium’ state; behind the shock the electron temperature drops with time from $T = T_{sh}$ according to the IC cooling rate. The absolute minimum temperature to which the electrons will cool is given by the Compton temperature of the AGN radiation field, which is found to be $T_{IC} = 2 \times 10^7$ K by Sazonov et al. (2004). The cooling of the electrons leads to

1 Note that at low gas temperatures, $T < 10^7$ K, Compton processes instead heat the gas up (Ciotti & Ostriker 2007).

2 Since the wind shock is optically thin each photon should scatter once before escaping the system.
an electron temperature distribution being set up behind the shock (King 2010) which we calculate here.

The electron–electron thermalization time-scale is \( \sim m_e/m_p \) times shorter than the energy exchange time-scale with protons (Stepney 1983). One can also show that IC electron losses even in the 1T regime are not sufficiently large compared with electron self-thermalization rate to lead to strong deviations from the thermal distribution for the electrons (cf. equation 5 in Nayakshin & Melia 1998). We therefore assume that the electrons maintain a thermal distribution behind the shock at all times as they cool from the shock temperature \( T_{sh} \) to \( T_{IC} \). Our goal should thus be to calculate how much time electrons spend at different temperatures as they cool; this will determine \( P(\gamma) \) and the resulting IC spectrum.

The rate of cooling due to the IC process is

\[
\left( \frac{du}{dr} \right)_{IC} = -\frac{4}{3}\sigma_TcU_{rad}\int_0^\infty (\gamma^2 - 1) n(\gamma, \theta) d\gamma.
\]

(7)

The plasma specific internal energy density, \( u \), is the sum of the ion contribution, \((3/2) n k T\), and that for the electrons. For convenience of notations we define \( u = a_e(\theta) \theta m_e c^2 \), where

\[
a_e(\theta) = \frac{3}{2} + \frac{(\gamma - 1)}{\theta}
\]

(8)

and \( \langle \gamma \rangle = \int_0^\infty \gamma n(\gamma, \theta) d\gamma \) is the average electron \( \gamma \) factor. Clearly, \( a_e = 3 \) and \( a_e = 9/2 \) in the non-relativistic and extreme relativistic electron regimes, respectively. Finally, \( U_{rad} = L_{Edd}/(4\pi R^2 c) \) is the energy density of the AGN radiation field. We neglect the contribution of stars to \( U_{rad} \).

We also need to include the compressional heating behind the shock front, so that

\[
\frac{du}{dr} = \left( \frac{du}{dr} \right)_{IC} - P \frac{dV}{dr},
\]

(9)

where \( P = (\Gamma - 1)/\theta m \) is the pressure of the gas, \( \Gamma \) is the adiabatic index and \( V = 1/\theta \) is the specific volume of the gas. Assuming that the flow velocity is much smaller than the sound speed behind the shock, the region can be considered almost isobaric. \(^3\) i.e. pressure \( \approx \) constant. One finds \( -P dV/dr = (1 - \Gamma) du/dr \), so that the electron temperature evolution is solved from

\[
m_e c^2 \frac{d}{dr} (a_e(\theta) \theta) = \frac{1}{\Gamma} \left( \frac{du}{dr} \right)_{IC}.
\]

(10)

This equation is solved numerically in order to determine \( \dot{\theta} = d\theta/dr \). One can define the dimensionless function \( G(\theta) \),

\[
G(\theta) = \frac{1}{t_e} \frac{\theta}{\dot{\theta}}
\]

(11)

where \( t_e = m_e c^2 / (\sigma_T U_{rad}) \), is a time-scale factor which happens to be the order of magnitude of the IC cooling time for non-relativistic electrons.

We call \( G(\theta) \) the inverse Compton 1T cooling cascade distribution, and plot it in Fig. 1. Note that the function is independent of the outflow rate, \( M \), the energy density of the AGN radiation field, \( U_{rad} \), or the soft photon spectrum as long as the up-scattered photons are much less energetic than the electrons themselves. The function \( G(\theta) \) is thus a basic property of the IC process itself.

\(^3\) The time it takes a sound wave to travel across the shocked wind is much less than the time it takes the shock pattern to propagate the same distance and so any fluctuations in the pressure will very quickly be washed out, see Weaver et al. (1977).
For comparison, a single temperature thermal electron distributions are also shown for $T = T_{sh}$ and $T_{IC} = 2 \times 10^7$ K with the dotted and dash-dotted curves, respectively.

thermal distribution $n(\gamma, \theta)$ with the electron cooling history (function $dN/d\theta$):

$$\frac{dF(\gamma)}{d\gamma} = \int_{\theta_{sh}}^{\theta_{IC}} n(\gamma, \theta) \frac{dN}{d\theta} d\theta,$$

(15)

where $\theta_{sh} = k_{B} T_{sh} / (m_e c^2)$ and $\theta_{IC} = k_{B} T_{IC} / (m_e c^2)$.

The cooling-convolved electron distribution function, $dF/d\gamma$, normalized per electron in the flow, is shown in Fig. 2. We assumed $v_{out} = 0.1c$ and hence, $T_{sh} = 2 \times 10^8$ K. For comparison, we also plot the single temperature EEDs, $n(\gamma, \theta_{sh})$, and $n(\gamma, \theta_{IC})$. This figure shows that in terms of number of electrons, the distribution is strongly dominated by the lower energy part, $\theta = \theta_{IC}$. This is because high energy electrons cool rapidly and then ‘hang around’ at $T \approx T_{IC}$. On the other hand, electron energy losses are dominated by $\theta \approx \theta_{sh}$, since these are weighted by the additional factor $\sim (\gamma^2 - 1)$ (cf. equation 7). Since the EED is power law like in a broad energy range, we expect the resulting IC spectra to be power law like in a broad range as well.

### 3 RESULTING SPECTRA FOR 1T AND 2T SHOCKS

Fig. 3 shows the IC spectra in both the 2T and 1T regimes, as labelled on the figure. We assumed an SMBH of $M_{bh} = 10^{7} M_{\odot}$ and outflow velocity of $v_{out} = 0.1c$. The input spectrum is modelled by a blackbody of single temperature $k_{B} T = 3$ eV and bolometric luminosity $L = L_{bol} = L_{bh}$. This simple model assumes that the UV luminosity of the innermost disc is absorbed and reprocessed into a cooler blackbody spectrum (we remind the reader that we assume that the UFO shocks at ‘large’ distances from the AGN, e.g. $R \sim 0.1–100$ pc). Also shown on the plots, for comparison, is a synthetic spectrum of a type 1 AGN as computed by Sazonov et al. (2004) normalized to the same bolometric luminosity, $L_{bol} = L_{bol}$. This last spectral component demonstrates that both 1T and 2T spectral components are actually comparable to the overall theoretical AGN spectra without UFOs; the 1T in the $\sim 2–10$ keV photon energy spectral window, whereas the 2T shock could be detectable in softer X-rays.

To explore the sensitivity of our results to model parameters, in Fig. 4 we use observationally motivated soft photon spectra from Sazonov et al. (2004) for energies below 0.1 keV, and we also consider two additional values for the outflow velocity, $v_{out}/c = 0.05$ and 0.2; these black dashed and long-dashed curves show synthetic type 1 and type 2 AGN spectra from fig. 4 of Sazonov et al. (2004).

Sazonov et al. (2004) for energies below 0.1 keV, and we also consider two additional values for the outflow velocity, $v_{out}/c = 0.05$ and 0.2; this figure also shows a synthetic type II (obscured AGN) spectrum from Sazonov et al. (2004), shown with the long dashed curve.

The figures demonstrate that at high enough outflow velocities, $v_{out} \sim 0.2c$, the shocked UFOs produce power law like spectra similar in their general appearance to that of a typical AGN. In fact, we made no attempt to fine tune any of the parameters of the King (2003) model to produce these spectra, so it is quite surprising that they are at all similar to the observed type I AGN spectra. In view of this fortuitous similarity of some of our IC spectra to the typical AGN X-ray spectra, one can enquire whether IC emission from ~pc scale shocks do actually contribute to the observed spectra.

Let us therefore compare the model predictions and X-ray AGN observations in some more detail.
(i) Bolometric luminosity. Figs 3 and 4 are computed assuming 100 per cent conversion of the UFO’s kinetic power in radiative luminosity, e.g. $L_{IC} = L_{\text{IC}}$ (cf. equation 4) which is a fair assumption within the cooling radius, $R_{IC}$, for the reverse shock (which is $\sim$ hundreds of pc for the 1T and just a few pc for the 2T models, respectively; see Faucher-Giguere & Quataert 2012; Zubovas & King 2012b). The ratio between the X-rays and the soft photon radiation in our model is thus $\sim (v_{out}/2c)$, e.g. 0.05 for $v_{out} = 0.1c$, which is just a factor of a few smaller than it is in the typical observed AGN spectra. In terms of shear bolometric luminosity 1TIC and 2TIC are thus definitely observable.

When the shock front propagated farther than $R_{IC}$, the overall luminosity of the shock decreases. In the limit of extremely large $R_{cd}$, where $R_{cd}$ is the contact discontinuity radius, the primary outflow shocks at the radius $R_{v_{out}} \sim (1/5)R_{cd}$ (see the text below and equation 6 in Faucher-Giguere & Quataert 2012). When $R_{v_{out}} \gtrsim R_{IC}$, the outflow is in the energy-conserving mode. We estimate that the IC luminosity would scale as $\propto R_{IC}/R_{v_{out}}$ in this regime. In the intermediate regime, $R_{v_{out}} < R_{IC} < R_{cd}$, $L_{IC} \sim L_{K}$. A more detailed calculation is required in this regime to determine $L_{IC}$ than has been performed here.

In the model of King (2003), while the SMBH mass is below its critical $M_{bh}$ mass, the outflows stall in the inner galaxy, $R \lesssim R_{IC}$. Once $M_{bh} > M_{cr}$, however, the outflow quickly reaches $R \sim R_{IC}$ and then switches over into the energy-conserving mode, which is far more efficient. Therefore, we would expect that the 1TIC shock emission should be a relatively widespread and relatively easily detectable feature in this scenario. In the 2TIC case, however, $R_{IC}$ is just a few pc. Furthermore, since the outflow is much more likely to be in the energy conserving mode, even SMBH below the $M_{cr}$ mass may clear galaxies. We would expect that shocks in this model spend most of the time in the regime $R_{cd} \gg R_{IC}$, being much dimmer than shown in Figs 3 and 4. The 2TIC component is thus harder to detect for these reasons.

(ii) Variability. The IC shocks are very optically thin, so that the observer sees an integrated emission from the whole spherical shocked shell. Accordingly, the IC shell emission cannot vary faster than on time-scale of $R_{cd}/c \sim 30$ years $R_{cd}/(10$ pc). The shock travel time is even longer by the factor $c/v_{out} \sim 10$. This therefore predicts that IC shock emission must be essentially a steady-state component in X-ray spectra of AGN. In contrast, observed X-ray spectra of AGN vary strongly on all sorts of time-scales, from the duration of human history of X-ray observations, e.g. tens of years, to days and fractions of hour (e.g. Vaughan et al. 2003). This rapid variability is taken to be a direct evidence that observed X-rays must be emitted from very close into the last stable orbit around SMBHs.

(iii) No molecular torus obscuration in X-rays. Nuclear emission of AGN, from optical/UV to X-rays, is partially absorbed in ‘molecular torii’ (Antonucci 1993) of $\sim$pc scale (Tristram et al. 2009). This obscuration produces the very steep absorption trough in soft X-rays seen in type II AGN as compared with the type I sources (cf. long dashed versus dashed curves in Fig. 4). If a sizeable fraction of X-ray continuum from AGN were arising from the IC shocks on larger scales, then that emission would not show any signatures of nuclear X-ray absorption. While Gallo et al. (2013) report one such ‘strange’ AGN, it is also a very rapidly varying one (cf. their figs 9 and 10), which again rule out the 1TIC model. There are also examples when soft X-ray absorption varied strongly on short time-scales (e.g. Puccetti et al. 2007), indicating that X-ray emission region is as small as $10^{-4}$ pc.

(iv) No reflection component. Compton down scattering and soft-X-ray absorption by circumnuclear gas produces the reflection component or ‘Compton hump’ observed in many AGN at $\sim$30 KeV (Guilbert & Rees 1988; Pounds et al. 1990). In addition, the fluorescent Fe K-$\alpha$ line emission is associated with the same process and is frequently detected in X-ray spectra of AG (Nandra & Pounds 1994). Since the shocks that we study occur on large scales, the IC emission would likely impact optically thin cold gas and thus result in much weaker X-ray reflection and Fe K-$\alpha$ line emission than actually observed.

Given these points, we can completely rule out the most extreme assumption that the X-ray emission of AGN is due to UFO shocks alone. The next question to ask is whether having the 1TIC or 2TIC emission from the UFOs in addition to the ‘nuclear’ X-ray corona emission of AGN (Haardt & Maraschi 1993) would be consistent with the present data. To address this, we calculate the 1TIC and 2TIC emission as for Fig. 4, but now including the part of the Sazonov et al. (2004) spectrum above 0.1 keV, which means that we now also include IC scattering of the higher energy radiation from AGN in the UFO shocks (rather than only the disc emission). The resulting spectra are shown in Fig. 5.

We see that the 1TIC spectra would be ruled out in deeply absorbed type II AGN spectra, because the 1TIC component would be very obvious in these sources below a few keV. The 2TIC component, on the other hand, would not be so prominent except in very soft X-rays where interstellar absorption is significant. We therefore preliminarily suggest that X-ray emission from 1T UFO shocks may contradict the data for type II AGN, whereas 2TIC spectra would probably be comfortably within the observational limits.

4 DISCUSSION AND CONCLUSIONS

We calculated X-ray spectra of 1T and 2T IC shocks resulting from UFOs from AGN colliding with the ambient host galaxy medium. We concluded that 1TIC spectra could be detectable in AGN spectra and distinguishable from ‘typical’ AGN spectra actually observed by the absence of rapid variability, Compton reflection and Fe K-$\alpha$ lines. This disfavours 1T models for AGN feedback in our opinion. We must nevertheless caution that the quoted typical observed AGN spectra and properties may be dominated by local objects that are simply not bright enough to produce a significant kinetic power in outflows, which our model here assumed. We therefore urge X-ray observers to search for the unabsorbed and quasi-steady emission.
components presented in our paper in order to clarify the situation further.

It is interesting to note that the 2TIC comes out mainly in the soft X-rays where it is far less conspicuous as this region is usually strongly absorbed by a cold intervening absorber. In fact, it is possible that the 2TIC emission component calculated here does contribute to the observed ‘soft X-ray excess’ feature found at softer X-ray energies (< 1 keV) but not yet understood (Gierliński & Done 2004; Ross & Fabian 2005; Crummary et al. 2006; Scott, Stewart & Mateos 2012). The 2T spectral component in Fig. 3 is close to the observed shape of the soft excess and would provide a soft excess that is independent of the X-ray continuum, a requirement suggested by, e.g. Rivers et al. (2012). The observed soft excess does not vary in spectral position over a large range of AGN luminosities (Walter & Fink 1993; Gierliński & Done 2004; Porquet et al. 2004). The 2TIC model may account for this as well since fig. 2 of Faucher-Giguere & Quataert (2012) shows that $T_{eq}$ is quite insensitive to the exact value of the outflow velocity. Finally, the 2TIC emission would exhibit little time variability. Uttley et al. (2003) and Pounds & Vaughan (2011) reported a quasi-constant soft X-ray component in NGC 4051 which could only be seen during periods of low (medium energy) X-ray flux, which is qualitatively consistent with the 2TIC shock scenario.

Therefore, we conclude that general facts from present X-ray observations of AGN not only disfavour 1TIC component over 2TIC component but may actually hint on the presence of a 2TIC one in the observed spectra.

Whether the electrons thermally decouple from hot protons is vitally important for the problem of AGN feedback on their host galaxies. Because of their far larger mass, the ions carry virtually all the kinetic energy of the outflow. At the same time, ions are very inefficient in radiating their energy away compared with the electrons. In the 1T model, the electrons are able to sap away most of the shocked ions energy and therefore the AGN feedback is radiative, that is, momentum driven, inside the cooling radius (King 2003). In this scenario, only the momentum of the outflow affects the host galaxy’s gas. In the 2T scenario, the outflow is non-radiative, so that the ions retain most of their energy. The AGN feedback is thus even more important for their host galaxies in this energy-driven regime (Faucher-Giguere & Quataert 2012; Zubovas & King 2012a).

If the outflows are indeed in the 2T mode, then one immediate implication concerns the recently discovered positive AGN feedback on their host galaxies. Well-resolved numerical simulations of Nayakshin & Zubovas (2012) and Zubovas et al. (2013a) show that ambient gas, when compressed in the forward shock (to clarify, the shock we studied here is the reverse one driven in the primary UFO), can cool rapidly in the gas-rich host galaxies. The nearly isothermal outer shock is gravitationally unstable and can form stars. In addition, Zubovas et al. (2013b) argue that galactic gas discs can also be pressurized very strongly by the AGN-driven bubble. In these cases, AGN actually have a positive – accelerating – influence on the star formation rate in the host galaxy. Within the 1T formalism, the AGN-triggered starbursts occur outside $R_{IC}$ ~ hundreds of pc only (Zubovas et al. 2013b). If outflows are 2T then AGN can accelerate or trigger star bursts even in the nuclear regions of their hosts.

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