Lyman edges in supermassive black hole binaries

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ABSTRACT
We propose a new spectral signature for supermassive black hole binaries (SMBHBs) with circumbinary gas discs: a sharp drop in flux bluewards of the Lyman limit. A prominent edge is produced if the gas dominating the emission in the Lyman continuum region of the spectrum is sufficiently cold \(T \lesssim 20,000\) K to contain significant neutral hydrogen. Circumbinary discs may be in this regime if the binary torques open a central cavity in the disc and clear most of the hot gas from the inner region, and if any residual UV emission from the individual BHs is either dim or intermittent. We model the vertical structure and spectra of circumbinary discs using the radiative transfer code TLUSTY, and identify the range of BH masses and binary separations producing a Lyman edge. We find that compact supermassive \((M \gtrsim 10^8 M_\odot)\) binaries with orbital periods of \(\sim 0.1\)–\(10\) yr, whose gravitational waves are expected to be detectable by pulsar timing arrays, could have prominent Lyman edges. Such strong spectral edge features are not typically present in AGN spectra and could serve as corroborating evidence for the presence of an SMBHB.

Key words: accretion, accretion discs – black hole physics – galaxies: active.

1 INTRODUCTION
Supermassive black holes (SMBHs) are present in the centres of most, if not all, nearby galaxies (see reviews by e.g. Kormendy & Richstone 1995; Ferrarese & Ford 2005). If two galaxies containing SMBHs merge, this should then result in the formation of an SMBH binary (SMBHB; e.g. Begelman, Blandford & Rees 1980). Thus, given the hierarchical model for structure formation, in which galaxies are built up by mergers, one would naively expect SMBHBs to be quite common.

Many candidates for binary BHs have been identified on kiloparsec scales, including two galaxies with spatially resolved active binary nuclei (Komossa et al. 2003; Fabbiano et al. 2011, see e.g. the review by Komossa 2006 and Shen et al. 2013, and references therein). At parsec scales, however, there is only one clear example: a radio observation of a BH pair with a projected separation of \(\sim 7\) pc (Rodriguez et al. 2006). There remain no confirmed binary BHs at subparsec separations.

The lack of observational evidence for binaries at small separations suggests that the SMBHs either remain inactive during the merger, or that they merge within a small fraction of a Hubble time and are consequently rare (Haiman, Kocsis & Menou 2009b). Another possibility is that the spectrum of a compact binary differs significantly from those of single-BH active galactic nuclei (AGNs).

A better understanding of the spectral energy distributions (SEDs) and light curves from circumbinary discs is necessary to determine whether binaries may therefore be missing from AGN surveys or catalogues (Tanaka 2013).

Gravitational waves (GWs) from a merging SMBHB may be detected in the next decade by pulsar timing arrays (PTAs; Biziouard et al. 2013). Identifying the GW source in EM bands would also have considerable payoffs for cosmology and astrophysics (e.g. Phinney 2009). Unfortunately, GWs yield limited precision on the sky position. For a PTA source, of the order of \(10^3\) (and perhaps as many as \(10^4\)), plausible candidates may be present within the 3D measurement error box (Tanaka, Menou & Haiman 2012). Concurrent EM observations would then be necessary to identify the GW source.

Many different EM signatures have been proposed for SMBHBs. These include periodic luminosity variations commensurate with the orbital frequency of the source (Haiman et al. 2009a and references therein) and broad emission lines that are double-peaked and/or offset in frequency (Shen et al. 2013 and the references therein). Additionally, the evacuation of a central cavity by the binary could lead to a spectrum that is a distinctively soft (Milosavljević & Phinney 2005; Tanaka & Menou 2010), and has unusually weak broad optical emission lines, compared to typical AGN (Tanaka et al. 2012). Other work (Gültekin & Miller 2012; Roedig, Krolik & Miller 2014) describes spectral signatures of discs with partial cavities, which may show up in the SED as broad, shallow dips.

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We here propose that, in addition to the above signatures, the presence of a central cavity in a circumbinary disc could produce distinct absorption edges in the optical/UV (in particular, at the Lyman limit). This is analogous to the prominent Lyman break in galactic spectra $\geq few \times 10^{4}$ Myr after a starburst, when the composite emission is dominated by less massive stars with cooler atmospheres (Leitherer et al. 1999; Schaerer 2003). Physically, such an edge would be present if the disc is cold enough ($T_{\text{eff}} \lesssim 20,000 \text{ K}$) to have sufficient neutral (ground-state) hydrogen to absorb Lyman continuum photons. The disc should also be hot enough (conservatively $T_{\text{eff}} \gtrsim 10,000 \text{ K}$); for yet cooler discs, the continuum emission redwards of the Lyman limit may be obscured by metal absorption features.

This Letter is organized as follows. In Section 2, we describe the details of our disc and emission models. In Section 3, we show examples of spectra for binary BH discs, and compare these to those of single-BH discs. In Section 4, we discuss caveats, including emission from mini-discs around each of the individual BHs that could mask the Lyman edge. We summarize our main conclusions and the implications of this work in Section 5.

2 DISC MODELS

In order to model disc spectra, we must begin with a model for the disc. In particular, we need the energetics (i.e. how much energy is dissipated by tidal torques and viscous heating throughout the disc). We here adopt the analytic models in Kocsis, Haiman & Loeb (2012, hereafter KHL12). These are modified versions of a standard Shakura & Sunyaev (1973) accretion disc, to incorporate the angular momentum transfer and the corresponding heating of the disc by the binary torques. The models self-consistently track the co-evolution of the disc and the binary orbit, through a series of quasi-steady, axisymmetric configurations.

There are several qualitatively different solutions for such a system, depending on the parameters of the binary (i.e. masses and orbital separation) and the disc (i.e. viscosity and accretion rate). For the purposes of this Letter, we concentrate on regions of parameter space in which a central cavity is opened and maintained, as the lack of the hot inner regions is responsible for the Lyman edges in the spectrum. Our conclusions on Lyman edges simply rely on emission from disc patches with effective temperature $T_{\text{eff}} \approx 10,000-20,000 \text{ K}$ dominating the composite UV spectrum, and should not be sensitive to model details.

Fig. 1 shows illustrative examples of radial profiles of the effective temperature (defined by $\sigma_{\text{SB}} T_{\text{eff}}^4 \equiv F$, where $\sigma_{\text{SB}}$ is the Stefan–Boltzmann constant, and $F$ is the total dissipation rate per unit disc surface area, including both viscous and tidal heating). The solid curve shows $T_{\text{eff}}(r)$ for a circumbinary disc around a $M_{\text{tot}} = M_1 + M_2 = 10^8 M_{\odot}$ binary, with mass ratio $q = M_2/M_1 = 0.05$ and accretion rate $M/M_{\text{Edd}} = 0.25$ (assuming a radiative efficiency of 10 per cent). The secondary is located at the radius $r_s = 230 R_\odot$ ($R_\odot \equiv G M_{\odot}/c^2$), creating a cavity inside 470$R_\odot$. We assume in all of our models that the BHs are non-spinning, and adopt a viscosity parameter $\alpha = 0.1$. For the other less important parameters, we use the same fiducial parameters as KHL12, except we set $f_2 = 3/8$ to be consistent with our assumption of vertically uniform dissipation. The dashed curve shows, for comparison, $T_{\text{eff}}(r)$ for a disc around a single BH with the same mass. Most importantly, this figure shows that outside the cavity, the circumbinary disc is hotter (by a factor of $\sim 2$; see also Lodato et al. 2009) than the corresponding single-BH disc, but still not nearly as hot as the innermost regions of this single-BH disc.

![Temperature profiles for a circumbinary disc around a $10^8 M_{\odot}$ binary (solid) and for a thin disc around a single $10^8 M_{\odot}$ BH (dashed).](https://academic.oup.com/mnrasl/article-abstract/443/1/L64/1053281/1053281)
thermodynamic equilibrium (NLTE) effects may cause an emission edge instead.

To model the emission from the disc, we use the RT code TLUSTY (Hubeny & Lanz 1995). This code self-consistently solves the equations of vertical hydrostatic equilibrium, energy balance, RT, and the full NLTE statistical equilibrium equations for all species that are present in the disc. Contributions from all bound–free and free–free transitions at all frequencies of interest are included, while bound–bound transitions are assumed to be in detailed balance.

We model H as a nine-level atom and He as a four-level atom. Electron scattering, including Comptonization, is also included. We assume that the disc is composed of H and He (at their solar ratio). Metals are not included, but would make little difference to continuum spectra for $10^4 \lesssim T_{\text{eff}} \lesssim 10^5$ K. For any given annulus, we calculate the vertical structure by specifying the vertical gravity $g_z$, disc surface density $\Sigma$, and the total energy dissipation rate $T_{\text{eff}}$. Spectra are insensitive to the surface density (provided the disc remains optically thick) and, for computational convenience, we fix $\Sigma = 2 \times 10^2$ g cm$^{-2}$ throughout this Letter. Thus, specifying the radial profile $T_{\text{eff}}(r)$ and vertical gravity $g_z(r)$ fully determines the spectrum emerging from the disc annulus at radius $r$. $g_z(r)$ is approximated to be linear in $z$ and proportional to the square of the local Keplerian angular frequency, $q_z \equiv \Omega^2$. The composite spectrum may be computed by summing over all annuli.

Although we have assumed that flux is radiatively transmitted through the disc, most of our model annuli have convectively unstable zones. Models with small density inversions (density increasing outwards) also occur. These solutions are unstable. Finally, we assume that tidal and viscous torques dissipate energy locally, and uniformly in height (i.e. equal dissipation per unit column mass). The vertical energy distribution is poorly understood, and real discs may be advective, or the energy may be carried away by density waves (Dong, Rafikov & Stone 2011; Duffell & MacFadyen 2012).

3 RESULTS: EDGES IN DISC SPECTRA

In this section, we show examples of composite circumbinary disc spectra, and compare these to the simpler black- and greybody models, as well as to the corresponding single-BH disc spectra.

In the left-hand panel of Fig. 2, the solid (dashed) curves show composite disc spectra corresponding to the circumbinary (single-BH) disc in Fig. 1. Realistically, the disc may extend to 2000$R_g$, where it would become gravitationally unstable, according to the Toomre criterion. However, due to practical issues with convergence, we were only able to get models within $\sim 40R_g$ of the inner disc edge, and we only integrate the emission from this region.

However, the excluded region is cooler than the inner edge of the disc and its emission should not mask the Lyman edge.

The TLUSTY binary spectrum (in black) shows a prominent break at the Lyman limit (3.28 $\times 10^{15}$ Hz), which is not present in the black- or greybody disc models (shown in blue and red, respectively). Overall, the blackbody model overpredicts the flux at both low and high frequencies, but underpredicts it immediately below the Lyman limit. The greybody model does a better job at frequencies below the Lyman limit, but overpredicts the flux more significantly at higher frequencies.

In contrast to the binary-BH spectrum, the single-BH spectrum has no sharp absorption edge at the Lyman limit (although there is a weak kink). This is because, as shown in Fig. 1, the innermost region of the single-BH disc is much hotter than the inner edge of the binary disc. Specifically, the binary disc has a maximum $T_{\text{eff}}$ of 11 000, whereas, the single-BH disc is considerably hotter, with a maximum $T_{\text{eff}}$ of 80 000 K (we have chosen a somewhat high $M/M_{\text{Edd}}$ so that inner edge of the circumbinary disc is above $10^5$ K). However, we have verified that there is no Lyman edge in the single-BH case for $M/M_{\text{Edd}} \sim 0.11$. For a spinning BH, the inner edge is expected to be closer to the BH horizon (following the innermost stable circular orbit), which would further increase the maximum temperature in the single-BH case. However, winds may limit the maximum $T_{\text{eff}}$ in single-BH discs to 50 000 K (Laor & Davis 2014).

In the right-hand panel of Fig. 2, we show another set of illustrative disc spectra, with the same parameters as in the left-hand panel, except for a lower mass ($M_{\text{tot}} = 4 \times 10^7 M_\odot$). In this case, the binary disc is hotter ($T_{\text{eff}} = 17 000$ K at the inner edge) and the Lyman edge feature is correspondingly weaker. The single-BH model looks similar to the one shown in the left.

3.1 Binary parameter space with edges

We now discuss under what conditions binary discs are likely to have prominent Lyman edges.

If the inner edge of the disc falls below a particular threshold temperature, the composite disc spectrum will have a prominent Lyman absorption edge. An example of a spectrum close to the threshold temperature is the one shown in the right-hand panel of Fig. 2: if the disc were much hotter, the Lyman edge feature would be wiped out. The precise threshold will depend on the vertical gravity and other parameters. Physically, the vertical gravity sets the scaleheight, which determines the vertical density. The density, in turn, determines the ionization state, which then affects the opacity difference between the two sides of the Lyman limit.

To establish a quantitative criterion for the threshold $T_{\text{eff}}$, we find the maximum effective temperature such that there is at least an order of magnitude drop in the flux at the Lyman limit (for different gravity parameters). We then establish the following fitting formula between the threshold temperature as a function of the square of the local Keplerian angular frequency, $q_z \equiv \Omega^2$:  

$$\log \left( \frac{T_{\text{thres}}}{17 000 \text{ K}} \right) = 0.06 \log \left( \frac{q_z}{10^{-12} \text{ s}^{-2}} \right).$$

This is accurate to $\sim 1$ per cent$^1$ in the range $10^{-12} \text{ s}^{-2} \lesssim q_z \lesssim 10^{-9} \text{ s}^{-2}$. At higher $q_z$, the threshold temperature increases less steeply with $q_z$. However, $q_z > 10^{-9} \text{ s}^{-2}$ lies outside our parameter space of interest. At lower $q_z$, we were unable to construct models

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$^1$ Assuming $\Sigma = 2 \times 10^2$ g cm$^{-2}$. In the optically thick limit, changes in $\Sigma$ may affect the threshold by $\sim 5$ per cent.
at the threshold, and simply extrapolated this fit. \( q_e = 10^{-12} \) s\(^{-2}\) at 160 \( R_g \), for a 10\(^7\) M\(_\odot\) BH. Note that the spectrum in the right-hand panel of Fig. 2 would not satisfy our conservative criterion. We also impose a low-temperature threshold of 10\(^8\) K, below which metal absorption becomes important and possibly causes metal edges to appear in the spectrum. Comparing the maximum disc temperature to the fitting formula above, we identify regions in binary parameter space which are cool enough to have Lyman edges.\(^2\) In Fig. 3, we show the ranges of masses and separations for which a prominent Lyman edge is produced, for two different accretion rates and mass ratios. The corresponding ranges of orbital periods, and time-scale over which the edge would be visible, may be calculated (to within a factor of a few) by the following fitting formulas:

\[
t_{\text{ed}} \simeq 0.04-0.09 \text{ yr} \left( \frac{M}{M_{\text{Edd}}} \right)^{1/4} \left( \frac{q}{1000} \right)^{1/10}.
\]

\[
t_{\nu} \simeq 10^{4} \text{ yr} \left( \frac{M}{M_{\text{Edd}}} \right)^{-1/2} \left( \frac{M}{10^7 \text{M}_\odot} \right)^{1/3} \left( \frac{q}{1000} \right)^{3/4}.
\]

Note that for a given \( M/M_{\text{Edd}} \) and \( q \), there is a maximum total mass for the edge which is set by our low-temperature threshold:

\[
\left( \frac{M}{10^7 \text{M}_\odot} \right) \lesssim 50 \left( \frac{M}{M_{\text{Edd}}} \right)^{3/5} \left( \frac{q}{1000} \right)^{-3/5}.
\]

### 4 MINI-DISCs

In mini-discs, we would not expect any central cavity to be completely empty. As first discussed in the smoothed-particle hydrodynamics simulations of Artymowicz & Lubow (1996) and confirmed by several recent works (Hayasaki, Mineshige & Sudou 2007; MacFadyen & Milosavljević 2008; Cuadra et al. 2009; Roedig et al. 2012; Shi et al. 2012; D'Oraio, Haiman & MacFadyen 2013; Farris et al. 2014; Gold et al. 2014), gas leaks into the cavity through non-axisymmetric streams. These streams can feed `mini-discs` around each individual BH, at rates set by the viscous time-scale of each mini-disc. The recent simulations suggest that accretion rates inside the cavity may be comparable to those on to a single BH.

\(^2\) Using the hottest annulus, as opposed to full composite spectra, is a good proxy to identify the presence/absence of the Lyman edge.

The emission from hot mini-discs may mask the Lyman edge feature. To illustrate this, we calculate spectra for the discs shown in fig. 8b of Farris et al. 2014 (reproduced here as the left-hand panel of Fig. 4). This figure shows a time-averaged surface density profile for a \( q = 0.43 \) binary. The simulation is scale-free, so the masses, separation, and accretion rate are arbitrary. We adopt an \( M_{\text{eff}} = 5 \times 10^7 \text{M}_\odot \) and separation \( r_s = 460R_g \). For \( q = 0.43 \), the masses of the primary and secondary are then 3.5 \( \times 10^7 \) and 1.5 \( \times 10^7 \) \text{M}_\odot, and the system is on the verge of the GW inspiral stage.

To model the spectrum of the circumbinary disc, we use \( T_{\text{eff}}(r) \) from an axisymmetric KHL12 circumbinary disc model with inner radius at 460\( R_g \) (even though the simulated disc is in fact lopsided; note that the simulations are isothermal and do not predict \( T_{\text{eff}} \)). To obtain the \( T_{\text{eff}} \) profile, we set \( M/M_{\text{Edd}} = 0.1 \). We likewise model the circumsecondary disc as a standard thick disc around a non-spinning BH (with truncation radius of 400 \( R_g \), where \( R_g \) is defined in terms of just the secondary mass. This is roughly consistent with the size of the circumsecondary disc in Fig. 4). Fig. 4 shows spectra of the circumbinary and circumsecondary discs, assuming that 50 (purple), 10 (blue), and 5 per cent (red) of the external \( M \) fuels the secondary. For the 5 per cent case, the Lyman edge is still prominent. However, it is greatly reduced for 10 per cent, and for 50 per cent it is completely obscured. Thus, if more than a few per cent of the \( M \) in the circumbinary disc leaks into the cavity and fuels a radiatively efficient, hot accretion flow, the Lyman edge can be obscured. As discussed above, Farris et al. (2014) find circumsecondary accretion rates comparable to the rate on to a single BH, which would favour the >50 per cent case. There should also be some emission from the circumprimary disc, which we have not included.

However, there are two reasons why Lyman edges could remain detectable, even with efficient fuelling of the individual BHs. First, most of the gas entering the cavity may fuel the secondary (rather than the primary) BH. This could then lead to a radiatively inefficient, super-Eddington accretion flow, rather than a thin mini-disc; such discs have much fainter fluxes in the UV (see e.g. Kawaguchi 2003). Secondly, the fuelling of the individual BHs may be intermittent. The simulations listed in the preceding paragraphs show that the rate at which the gas enters the cavity fluctuates strongly, tracking the binary’s orbital period. Whether the BHs can accept this fuel depends on the viscous time-scale in their vicinity. There is some evidence from 3D magnetohydrodynamic simulations that the effective \( a \) may strongly increase inside the cavity (Noble et al. 2012; Shi et al. 2012; Gold et al. 2014). The streams from the circumbinary disc would then rapidly accrete on to the individual BHs, and mini-discs would either not form or would be intermittent.
The relevant time-scale would be the viscous time of the mini-disc, which should generally extend to the tidal truncation radius as long as the specific angular momentum of the accreting streams exceeds that at the ISCO (Roedig et al. 2014). Ultimately, the prominence of the Lyman edge features is tied to the nature of the mini-discs, and requires a better understanding of these flows.

5 SUMMARY AND CONCLUSIONS

In this Letter, we have proposed that spectral edges, in particular at the Lyman limit, may be characteristic signatures of a circumbinary disc. Our conclusions can be summarized as follows.

(i) If binary torques clear a cavity in the circumbinary disc, the disc spectrum may exhibit a sharp drop at the Lyman limit. This is because the hottest region (i.e. the inner edge) of the disc is cool enough to have neutral H, absorbing nearly all flux bluewards of the Lyman limit. This occurs below a critical $T_{\text{crit}}$ which generally lies in the range $\sim 10000-20000$ K, depending on vertical gravity and other parameters. At lower temperatures, absorption from metals (i.e. C) may cause spectral edges redwards of the Lyman limit.

(ii) Observationally, AGN spectra only show Lyman edges due to absorption by intervening neutral gas (see Antonucci, Kinney & Ford 1989). The inner regions of a single-BH AGN disc are hotter than for binaries (Fig. 1), and can mask any edge produced in the outer disc, leaving only a small ‘kink’ (Fig. 2). Such kinks are not seen observationally, and understanding what would smear them (e.g. general relativistic effects or winds) is an open theoretical problem. For an overview of the Lyman edge problem in AGN spectral modelling, see e.g. Kolykhalov & Sunyaev (1984) and Koratkar & Blaes (1999).

(iii) Neutral H in the binary’s host galaxy, unrelated to the nuclear accretion disc itself, could cause a Lyman edge (as seen in a few AGNs). However, in the case of the disc, one could look for rotational broadening of the edge due to orbital motions in the disc, with velocities of the order of $10^3$ km s$^{-1}$. This may cause an $\approx 10$ percent smearing on the edge.

(iv) A portion of the binary parameter space could have a truncated circumbinary disc, with $T_{\text{crit}}$ in the critical range for a prominent Lyman edge (Fig. 3). This parameter space partially overlaps with the expected typical parameters for individually resolvable PTA sources. These are very massive binaries, with $10^4 M_\odot \lesssim M \lesssim 10^6 M_\odot$, and separations ranging from tens to thousands of $R_g$, and mass ratios peaking at $q \sim 1$ but with a long tail to lower values (Sesana et al. 2012).

(v) Efficient fuelling of the BHs inside the central cavity could mask the Lyman edge feature in the circumbinary disc spectrum. For example, persistent emission from hot mini-discs (see Farris et al. 2014) would obscure the Lyman edge. However, if the accretion flows on to the individual BHs are radiatively inefficient and/or intermittent (Tanaka 2013), the Lyman edge could remain visible, or appear periodically on the time-scale of the binary’s orbit (which could be weeks to years; Haiman et al. 2009b).

(vi) The proposed Lyman edge signature could be used in combination with other proposed EM signatures to refine the search for SMBHBs. We have conducted a preliminary search for the Lyman edge feature in X-ray-weak quasars discussed in Brandt, Laor & Wills (2000). In particular, we looked at $\text{FUSE}$ and $\text{IUE}$ spectra for the 10 objects in their table 2, but found no sign of any Lyman edge feature.

If detected in an AGN, a prominent Lyman edge would tighten the case for the presence of a compact binary BH.