A reduced orbital period for the supermassive black hole binary candidate in the quasar PG 1302-102?

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ABSTRACT

Graham et al. (2015) have detected a 5.2 year periodic optical variability of the quasar PG 1302-102 at redshift $z = 0.3$, which they interpret as the redshifted orbital period $(1 + z)t_{\text{bin}}$ of a putative supermassive black hole binary (SMBHB). Here we consider the implications of a $3 - 8$ times shorter orbital period, suggested by hydrodynamical simulations of circumbinary discs (CBDs) with nearly equal–mass SMBHBs ($q \equiv M_2/M_1 \gtrsim 0.3$). With the corresponding 2 – 4 times tighter binary separation, PG 1302 would be undergoing gravitational wave-dominated inspiral, and serve as a proof that the BHs can be fueled and produce bright emission even in this late stage of the merger. The expected fraction of binaries with the shorter $t_{\text{bin}}$, among bright quasars, would be reduced by 1-2 orders of magnitude, compared to the 5.2 year period, in better agreement with the rarity of candidates reported by Graham et al. (2015, hereafter G15). Finally, shorter periods would imply higher binary speeds, possibly imprinting periodicity on the light curves from relativistic beaming, as well as measurable relativistic effects on the Fe K$\alpha$ line. The CBD model predicts additional periodic variability on timescales of $t_{\text{bin}}$ and $\approx 0.5t_{\text{bin}}$, as well as periodic variation of broad line widths and offsets relative to the narrow lines, which are consistent with the observations. Future observations will be able to test these predictions and hence the binary+CBD hypothesis for PG 1302.

1 INTRODUCTION

Graham et al. (2015) hereafter G15 recently reported strong optical variability of the quasar PG 1302-102, with an observed period of $t_{\text{obs}} = 5.2 \pm 0.2$ years. G15 attribute the variability to the orbital motion of a super-massive black hole binary (SMBHB). Broad emission lines in the spectrum of PG 1302 imply a binary mass in the range $M = 10^{8.3 - 9.4}\,M_\odot$. Assuming that the binary’s orbital period $t_{\text{bin}}$ equals the rest–frame optical variability period $t_{\text{opt}}$, G15 derive a fiducial binary separation $a \approx (0.0084 \pm 0.0003)\,pc$ for $M = 10^{8.5}\,M_\odot$, where $R_S = 2GM/c^2$ is the Schwarzschild radius. Hydrodynamical simulations of a binary BH embedded in a gaseous accretion disc predict that, depending on the binary mass ratio and the physical parameters of the disc, the strongest periodicity in the accretion rate onto the BHs may correspond to the motion of gas farther out in the disc, at a few times the binary separation, producing optical variability at several (~3-8) times the binary orbital period. In this Letter, we discuss this expectation, and show that a reduced binary period, in the case of PG 1302, would have several important implications. Follow up spectroscopy and photometric monitoring can determine the true binary period.

The rich variability structure of the mass accretion rates seen in simulations can be roughly divided into four distinct categories, based on the binary mass ratio $q \equiv M_2/M_1$. For $q \lesssim 0.05$, the disc is steady and the BH accretion rate displays no strong variability (D’Orazio et al. 2013; Farris et al. 2014). For $q \gtrsim 3$, the disc is steady and the BH accretion rate displays no strong variability (D’Orazio et al. 2013; Farris et al. 2014). D’Orazio et al. in prep.). For $0.05 \lesssim q \lesssim 0.3$, the accretion rate varies periodically on the timescale $t_{\text{bin}}$, with additional periodicity at $\approx 0.5t_{\text{bin}}$. Binaries with $0.3 \lesssim q \lesssim 0.8$ clear a lopsided central cavity in the disc, causing variability on three timescales. The dominant period, $(3 - 8)t_{\text{bin}}$, is that of an over-dense lump, orbiting at the ridge of the cavity, with additional periodicities at $t_{\text{bin}}$ and $\approx 0.5t_{\text{bin}}$ (MacFadyen & Milosavljevic 2008; Shi et al. 2012; Noble et al. 2012; Roedig et al. 2012; D’Orazio et al. 2013; Farris et al. 2014). The dominant period depends on the size of the cavity, and thus on disc parameters, such as temperature and viscosity. Finally, equal-mass ($q = 1$) binaries display variability at the longer lump period and at $\approx 0.5t_{\text{bin}}$.

Here we consider the identification of the observed variability of PG 1302 with the long, cavity-wall period, and introduce the parameter $\chi \equiv t_{\text{opt}}/t_{\text{bin}}$, denoting the ratio, $3 \lesssim \chi \lesssim 8$, of the observed rest-frame period and the true binary period. The binary separation is then

$$a \approx (94 \pm 3)R_S \left(\frac{\chi}{5}\right)^{-2/3} \left(\frac{M}{10^{8.5}\,M_\odot}\right)^{1/3},$$

or $(0.0029 \pm 0.0001)\,pc$ for the fiducial choices of $\chi$ and $M$.

In the rest of this Letter, we first (\S 2) explore several implications of a reduction in the binary’s orbital period, including the nature of PG 1302’s orbital decay and its ability to produce electromagnetic (EM) radiation (\S 3), the expected binary fraction of quasars (\S 4), and the detectability of gravitational waves (GWs)
timescale dominating, is observed for \(0.3 \lesssim q \lesssim 0.8\). The location of the highest-frequency peak is closer to \(0.5t_{\text{bin}}\) near the low end of this range \((q \sim 0.3)\), and also has a weak dependence on disc parameters. The bottom panels, for \(q = 0.1\), show no orbiting lump and exhibit accretion rate periodicity only at \(t_{\text{bin}}\) and \(0.5t_{\text{bin}}\). This behaviour is found in the range \(0.05 \lesssim q \lesssim 0.3\).

Farris et al. (2014) have shown that for unequal-mass binaries, accretion occurs preferentially onto the secondary BH, with the ratio of accretion rates as skewed as \(M_2/M_1 \approx 10 - 20\) in the range \(0.02 \lesssim q \lesssim 0.1\). Over long timescales, this would drive the binary to more equal masses, suggesting that mass ratios of \(0.3 \lesssim q \lesssim 0.8\) may be common. Near-equal mass binaries are also preferred in cosmological models of the population of merging SMBHs (Volonteri et al. 2003). This motivates us to examine the possibility that the apparent 5.2 year period in PG 1302 is the (redshifted) lump period, and assess the implications.

### 2.1 Binary-Disc Decoupling

A shorter orbital period would place the binary at a later stage of its orbital decay. A critical point during the orbital decay is the decoupling of the binary from the CBD, and it is important to know whether the binary is past this point. Decoupling occurs when the binary’s orbital decay becomes dominated by gravitational radiation reaction, and outpaces the viscous inflow of the CBD (Milosavljević & Phinney 2005). We use simple 1D models of the binary + disc system (Haman et al. 2009) hereafter HKM09) to calculate the separation \(r_{\text{GW}}\) at which decoupling occurs for a circular binary with mass ratio \(q = 0.3\). We assume an \(\alpha\)-viscosity \(\nu = \alpha P_{\text{gas}}(\dot{M})^{-1}\), with gas pressure \(P_{\text{gas}}\), density \(\rho\), disc angular velocity \(\Omega\), and \(\alpha \approx 0.1\). All other disc parameters are assumed to have the fiducial values given in HKM09. In Fig. 6, we plot the ratio \(a/r_{\text{GW}}\) as a function of the total binary mass, with the binary separation from Eq. (1), for the range of masses in G15, and for three values of \(\chi\) covering the range suggested by the hydrodynamical simulations.

Interpreting the observed variability in PG 1302 with \(t_{\text{bin}}\), may be justified for \(q \lesssim 0.3\), it is unclear whether or not the binary had entered the GW dominated regime and decoupled from the disc. The binary would still be coupled to the disc for \(M < 10^8 M_\odot\) (the range inferred from the broad lines by G15), but GW-driven and decoupled if \(M > 10^8 M_\odot\). However, for the shorter binary periods \(3 \lesssim \chi \lesssim 8\), justified for \(0.3 \lesssim q \lesssim 0.8\), we find that the inferred smaller binary separation would place the binary well past decoupling. For \(q > 0.3\) and \(\alpha < 0.1\), the binary in PG 1302 is plunged even deeper into the GW–dominated regime.

Because the binary outpaces the viscous inflow of the disc, it has been argued that the post-decoupling BHs may be “starved” and thus dim (Milosavljević & Phinney 2005; Shapiro 2010; Tanaka & Menou 2010). Recent simulations (Noble et al. 2012; Farris et al. 2015) show that high levels of accretion can persist well past the decoupling phase, delivering gas to the binary efficiently until much closer to coalescence. These simulations also exhibit the lopsided cavity which generates the \(\chi t_{\text{bin}}\) variability considered here. Identification of the variability in PG 1302 with the cavity wall lump period would constitute the (to our knowledge, first-ever) detection of a SMBHB which is undergoing GW dominated inspiral, yet producing bright emission, near the Eddington limit.

\[ \text{Note that in the precessing binary model for OJ287} \]

Lehto & Valtonen (1996a, b), the orbital period is 12.2 yr, the primary is very massive \((\sim 1.8 \times 10^{10} M_\odot)\), but the secondary is light \((\sim 1.4 \times 10^5 M_\odot)\).
2.2 Binary Fraction among Quasars

A shorter binary orbit also reduces the expected number of detectable SMBHBs in quasars, because gas driven binaries are expected to spend less time at smaller separations. A simple estimate of the fraction of quasars that would harbour binaries with an orbital period $t_{\text{bin}}$, can be obtained from the residence time $t_{\text{res}} = a/\dot{a}$ at each separation $a$, and the lifetime of bright ($L/Q/\dot{L}_{\text{rad}} \gtrsim 0.3$) quasars, $t_Q \sim 10^8$ years [Martin 2004]. Assuming that a fraction $f_{\text{bin}}$ of all quasars are triggered by coalescing SMBHBs (e.g. [Hopkins et al. 2007] and references therein), it follows that among bright quasars, the fraction with orbital period $t_{\text{bin}}$ is $f_{\text{bin}} \approx f_{\text{bin}} f_{\text{duty}}$, where $f_{\text{duty}} = t_{\text{res}}(t_{\text{bin}})/Q$ is the fraction of the bright quasar phase that a typical binary quasar spends at the orbital period $t_{\text{orb}}$.

We use the binary+disc models of HKM09 to predict the residence times of binaries. Prior to decoupling, $t_{\text{res}}$ is determined by the binary’s interaction with the gas disc. For the masses and separations relevant for PG 1302, the disc would be radiation pressure dominated, yielding a relatively shallow power-law dependence $t_{\text{res}} \propto t_{\text{bin}}^{\alpha}$ with $0.5 \lesssim \alpha \lesssim 1.5$. These scalings depend on the poorly understood physical model of the disc and its coupling to the binary. Past decoupling, the residence time is precisely known, since it is determined by the strength of GWs. The dependence is much steeper, $t_{\text{res}} \propto t_{\text{bin}}^{-\beta} \propto \lambda^{-3/3}$. For reference, a binary with $M = 10^{5.5} M_\odot$ and $t_{\text{bin}} = 4$ yr would be in the disc-driven stage and would have $t_{\text{res}} \approx 10^8$ yr, yielding a large $f_{\text{duty}} \approx 10^{-2}$.

The expected $f_{\text{bin}}$ can be compared with the number of periodic candidates uncovered in CRTS [Drake et al. 2009; Djorgovski et al. 2010; Mahabal et al. 2011]. There are $\approx 114, 000$ quasars in the CRTS sample with luminosity higher than PG 1302, $\approx 6$ of which are SMBHB candidates with period $t_{\text{obs}} \lesssim 5$ yr (Graham, private communication), amounting to an observed fraction of $f_{\text{obs}} = 5 \times 10^{-5}$. Fig. 3 illustrates combinations of $M$, $\chi$, and $f_{\text{bin}}$, for which we expect 1 (light gray regions) or 10 (dark gray) candidates in the CRTS quasar sample with periods $\lesssim 5$ year.

Each shaded region is bounded by the assumed fraction of quasars related to SMBHBs at all. $f_{\text{bin}} = 0.01$ (left) to $f_{\text{bin}} = 1$ (right).

If the observed period of PG 1302 is assumed to be the binary orbital period ($\chi = 1$), then the rarity of the binary candidates in CRTS require $f_{\text{bin}} < 0.06 (< 0.19)$ at $q = 0.3$ ($q = 1.0$), even at the most extreme mass of $M = 10^{5.5} M_\odot$. Taking the G15 fiducial mass of $M = 10^{5.5} M_\odot$, these fractions must be as low as $f_{\text{bin}} < 0.004$ at $q = 0.3$ and $f_{\text{bin}} < 0.006$ for $q = 1.0$. These low values would be surprising, as a large fraction of quasars are commonly believed to be triggered by mergers. This association is based on various pieces of observational evidence, as well as on the success of merger-based quasar population models to reproduce many properties of the observed quasar population (e.g. [Kauffmann & Hachnelt 2000]). If, instead, the observed period of PG 1302 is due to the $3 - 8$ times longer lump-periodicity, then the SMBHB fraction and the inferred binary mass of PG 1302-12 come into wider agreement with the expectation that $f_{\text{bin}} = O(1)$, e.g. allowing $f_{\text{bin}} \sim 0.3$ with $q = 0.3$ and $M = 10^{5.5} M_\odot$.

2.3 Detectability of Gravitational Waves

A reduced orbital period increases the frequency and amplitude of gravitational waves (GWs) emitted by a binary, and it is interesting to ask whether PG 1302 may be detectable by present or future pulsar timing arrays (PTAs). The GW frequency, $f_{\text{GW}} = 2\chi^{-1} f_{\text{bin}} \approx 61 (\chi/5) \text{nHz}$, places the binary in the range of PTA sensitivity (e.g. [Hobbs et al. 2010]). We calculate a SNR for the PG 1302 binary assuming optimistic binary parameters $M = 10^{5.4} M_\odot$, $q = 0.5$, and $t_{\text{bin}} = 1.884 \times 10^5$ days. The GW induced timing residual (for simplicity, adopting the sky and polarization averaged values) is $\delta t_{\text{GW}} = h/(2\pi f_{\text{GW}}) \approx 3.3 (\chi/5)^{1/6} \text{ns}$, while for $f_{\text{GW}} \gtrsim 10 \text{nHz}$, the timing residual noise is nearly constant in frequency. Using noise curves of currently operating PTAs, the SNR for GW detection of the PG 1302 binary is $\approx 0.006 (\chi/5)^{1/6}$ for NANOGrav (Fig. 12 in [Arzoumanian et al. 2014]) or $\approx 0.014 (\chi/5)^{1/6}$ for the PPTA (black curve in Fig. 9 of [Zhu et al. 2014]). The reduced binary period increases the SNR, but this increase is unfortunately modest. Future detectors, such as the international pulsar timing array (iPTA; [Manchester & IPTA 2013]), as well as inclusion of the square kilometre array (SKA; [Dewdney et al. 2009]) in the PTA telescope networks will improve the SNR by about an order of magnitude, but PG 1302 will remain a factor of $\sim 10$ below detection.

The latter reduces the efficiency of GWs, but increases the impact of a gas disc; as a result, the OJ287 binary is gas-driven, well before decoupling. 2 Since the expected $f_{\text{obs}}(M, t_{\text{bin}})$ declines steeply with increasing $M$ and decreasing $t_{\text{bin}}$, it is a good proxy for the fraction of quasars with period $t_{\text{bin}}$, or less, and BH mass $M$ or higher (or equivalently luminosity $L$ or higher, further assuming a monotonic relation between $L$ and $M$).
3 TESTING THE BINARY BH SCENARIO FOR PG 1302

3.1 Broad Line Variability and Asymmetry

Jackson et al. (1992) hereafter J92 report a bump on the red side of PG 1302’s Hβ emission line, and infer a ~ (150 ± 50) km s⁻¹ offset between the broad and narrow line components of Hβ. This is much shorter than the orbital velocity of the (secondary) BH, $v₂ = 14,500 (1.5/[1 + q])(M/10^8 M_☉)(1/3) (5/1)^{1/3}$ km s⁻¹, requiring either that the broad line region is unrelated to the minidisks, or that the minidisks are seen nearly face on.

We posit that the broadened emission is due to recombination in the orbiting circumbinary gas and consider the role of a lopsided cavity (Fig. 1) on generating the observed offset and width of Hβ broad lines. We compute the offset as the emission–weighted line–of–sight velocity,

$$V₀ = \int_0^{2\pi} \int_{r_{in}}^{r_{out}} \rho v_{los} r dr dφ \int_0^{2\pi} \int_{r_{in}}^{r_{out}} \rho r dr dφ$$

and the line–width as the weighted r.m.s. line–of–sight velocity

$$\left( \frac{Γ}{2\sqrt{2\ln 2}} \right)^2 = \int_0^{2\pi} \int_{r_{in}}^{r_{out}} \rho (v_{los} - V₀)^2 r dr dφ \int_0^{2\pi} \int_{r_{in}}^{r_{out}} \rho r dr dφ$$

over an annulus with radii ($r_{in}, r_{out}$) in a $q = 0.5$ simulation (see Fig. 1). Note that $Γ$ reflects the orbital speed of the emitting gas, while non–zero offsets $V₀$ are generated only by deviations from axisymmetry. We use the simulated surface density $Σ$ and azimuthal velocity $vφ$ to compute the disc scale height $H = r_c / vφ$ (assuming vertical hydrostatic equilibrium), volume density $ρ = Σ / H$, and line of sight velocity $v_{los} = v_{los} \cos φ$. All l.o.s. velocities are multiplied by an additional factor of $\sin i$, where $i$ is the inclination angle, measured from face–on.

We calculate $V₀$ and $Γ$ ten times per orbit for 20 orbits choosing the annulus ($r_{in}, r_{out}$) = $(2a, 6a)$ where $a$ is the binary separation. Fig. 3 displays the variations of $V₀$ and $Γ$ with time. The line centroid varies asymmetrically about zero,

$$V₀ = (-5 \pm 19) \ km/s \ \left( \frac{M}{10^8 M_☉} \right)^{1/2} \ \left( \frac{a}{94 R_☉} \right)^{1/2} \ \left[ \frac{\sin i}{\sin(14.2°)} \right]$$

while the full width at half maximum (FWHM) fluctuates periodically by ±5 per cent, following the lump’s orbital time,

$$Γ = (4.450 \pm 214) \ km/s \ \left( \frac{M}{10^8 M_☉} \right)^{1/2} \ \left( \frac{a}{94 R_☉} \right)^{1/2} \ \left[ \frac{\sin i}{\sin(14.2°)} \right]$$

Here $i = 14.2°$ is chosen to match the observed Hβ FWHM. If the broadening and offset are both generated by orbital motion in a lopsided CBD, then they must require consistent inclinations. The observed ratio of the Hβ line width and offset is $\sim 29.7 ± 10$. Dividing the average FWHM $Γ$ by the maximum deviation of the line offset $V₀^{dev}$, we find $Γ/V₀^{dev} \sim 22.6$. Varying the boundaries of the annulus associated with the broad line region, this ratio ranges from 18.0 for ($r_{in}, r_{out}$) = $(3a, 5a)$ to 25.0 for ($r_{in}, r_{out}$) = $(a, 8a)$, in remarkable agreement with the observations.

We find that $Γ$ varies by up to ~ 10 per cent over a cycle. Since these fluctuations arise from the lump’s varying position along the cavity wall, they correlate with long-term variations in the BH accretion rate. In the right panel of Fig. 3, we plot the accretion rate onto the BHs, together with the $Γ$ variations. The phase lag between line–width maximum and accretion maximum derives from the time between lump passage near the BHs, and the lump–enhanced accretion in the mini-disk. The phase difference is therefore independent of the observer’s viewing angle. This is not true for the amplitude and shape of the FWHM variations, and the relative phase of $V₀(t)$, which all depend on viewing angle. Furthermore the line width variation amplitude can change by a factor of 2 – 3 depending on disc parameters. A full study of the CBD broad lines, which examines line shape over a range of disc parameters and viewing angles, is warranted in a future study.

The above prediction for broad line variation is not inconsistent with known spectra of PG 1302. A five–month observing campaign by J92 track Hβ emission lines for ~ 0.08 cycles of PG 1302’s 5.2 yr period. We predict a < 2 per cent change in $Γ$ over this time, which is undetectable, given the ~ 5 per cent measurement uncertainties. With the ±88 day uncertainty in the measured 5.2-yr period, the J92 measurements are 0.1-0.5 cycles later in relative phase than the spectrum in G15. The latter is taken near a luminosity maximum; identifying this with the accretion rate maximum, it should roughly coincide with a maximum $Γ$ in our model; the J92 $Γ$ would then be predicted to be ~ 2 – 10 percent narrower. This is consistent with an Hβ FWHM reported by J92 (3900 ± 195 km s⁻¹) with a 6 per cent narrower mean than the G15 measurement (4450 ± 150 km s⁻¹).

The behaviour of the broad lines indicated in Fig. 3 derives from the existence of a cavity-wall lump, requiring $3 \lesssim \chi \lesssim 8$, and identifying the broad line region with the corresponding inner annuli of the CBD. Observation of such line variability, matched to luminosity variability, would provide evidence for the CBD model and identification of the CBD cavity wall period.

3.2 Relativistic Effects

Beaming. In the lumpy CBD model, the shorter binary period translates to a higher secondary period (by $\chi^{1/3}$). The bright optical continuum emission is naturally attributable to the mini-disks, and one may ask whether additional variability, at the true orbital period, could arise from relativistic beaming. The relativistic beaming factor is $Γ = \left[1 - v/c \cos θ \right]^{-2}$, where $Γ$ is the Lorentz factor of a source moving with velocity $v$. We estimate the spectral index $α = 1.1$ from an average over the continuum in the V band (G15). Requiring consistency with $\S 3.1$, we use the maximum binary mass and minimum mass ratio ($q = 0.3$) to put an upper limit on the secondary’s l.o.s. velocity. We find that this maximum velocity imprint a 0.07 mag amplitude modulation on the PG 1302 light curve. PG 1302’s periodogram does not show a significant secondary peak with sub-5.2 yr periods; noise modelling suggests that such second peaks would be detectable only at amplitudes of

Figure 4. Predicted variations of the centroid $V₀$ (left) and FWHM $Γ$ (right) of an emission line emanating from the inner annuli of a circumbinary disc. The total accretion rate onto both black holes is over-plotted in the right panel in arbitrary units (orange). Dark black lines are smoothed versions of the light gray simulation data.

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\( \geq 0.07 \text{mag, } \sim \text{half of the 5.2-yr modulation (Charisi et al. in prep., see the next section). Irrespective of the broad line model, } a \sim 0.14 \text{ mag detection threshold allows us to place an upper limit on the inclination angle of a binary with a luminous circum-secondary mini-disc. For } M = 10^{9.4} M_\odot, \chi = 8, \text{ and } q = 0.3, \text{ we find that binary must be } i < 31^\circ \text{ from face on. In a model where broad lines do not originate from the CBD, it is possible for the entire 0.14 mag variability amplitude of PG 1302 to be explained purely by relativistic beaming of a binary on a 5.2 year period. }

**Iron K\textsubscript{o} lines.** Because the binary separation can be reduced below \( \lesssim 100 R_\odot \), FeK\textsubscript{o} lines generated at such small separations can have characteristic binary-related features, such as “missing wings” (due to the central cavity), or “see-saw oscillations” of the red and blue wings (due to Doppler-shifting of the emission from mini-discs) (McKernan et al. 2013). These may be detectable with the upcoming Astro-H mission (Takahashi et al. 2014).

### 3.3 Orbital Timescale Variability

The binary+CBD model discussed above generically predicts multiple periodic variations. If the observed period of PG 1302 is the true binary period, then its periodogram could contain lower-frequency, higher-amplitude, and also higher-frequency, lower-amplitude peaks. These could be revealed in future data, combined with more sophisticated search algorithms for periodicity (e.g. VanderPlas & Ivezic 2015 and references therein). It will be helpful with more sophisticated search algorithms for periodicity (e.g. Van der Plas & Ivezic 2015) and proving that gas can follow the binary past the central cavity), or “see-saw oscillations” of the red and blue characteristic binary-related features, such as “missing wings” (due to Doppler-shifting of the emission from mini-discs). (McKernan et al. 2013). These may be detectable with the upcoming Astro-H mission (Takahashi et al. 2014).

No significant peaks were detected, and an upper limit of \( \delta m > 0.07 – 14 \text{ mag (depending on frequency) was derived for the amplitude of additional modulations.}

### 4 CONCLUSIONS

For binaries with mass ratio in the range \( 0.3 \leq q \leq 0.8 \), hydrodynamical simulations of circumbinary discs predict periodic luminosity variations at \( 3 \sim 8 \) times the binary orbital period, due to a dense lump in the CBD (Fig 4). If the periodic variability observed in quasar PG 1302 is identified with this lump period, rather than the orbital period of a putative SMBHB, a \( 2 \sim 4 \) times smaller binary separation is inferred. This would place the PG 1302 binary securely in the GW-driven regime, making it the first EM detection of such a system, and proving that gas can follow the binary past decoupling. This is encouraging for the possibility of locating EM counterparts of GW sources. Because binaries spend less time at smaller separations, a shorter \( t_{\text{orb}} \) is in better agreement with the small number of SMBHB candidates reported by G15. The higher orbital velocity of the binary increases the effects of relativistic beaming, causing optical variability at the orbital period, and also on inferred broad line widths.

The binary+CBD model can be tested as it predicts variability at multiple, well-defined frequencies which depend on binary mass ratio and disc parameters. Since a recent search (Charisi et al. in prep.) did not reveal secondary variability in the optical light-curve of PG 1302, follow up observations are required. Finally, associating the broad line region with the inner annuli of a lumpy CBD, we find that the FWHM of the lines can vary periodically by \( \pm 5 \) per cent, in phase with the continuum variability; we also predict a much smaller shift of the broad line centroids. These predictions are consistent with existing observations of the width and offset of the H\textsubscript{β} broad line. Follow-up spectra, sampling PG 1302’s apparent 5.2 yr period, could test this interpretation of the broad line region and aid in identifying the nature of PG 1302’s variability.

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