A possible close supermassive black-hole binary in a quasar with optical periodicity

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Quasars have long been known to be variable sources at all wavelengths. Their optical variability is stochastic and can be due to a variety of physical mechanisms; it is also well-described statistically in terms of a damped random walk model. The recent availability of large collections of astronomical time series of flux measurements (light curves) offers new data sets for a systematic exploration of quasar variability. Here we report the detection of a strong, smooth periodic signal in the optical variability of the quasar PG 1302−102 with a mean observed period of 1.884 ± 88 days. It was identified in a search for periodic variability in a data set of light curves for 247,000 known, spectroscopically confirmed quasars with a temporal baseline of about 9 years. Although the interpretation of this phenomenon is still uncertain, the most plausible mechanisms involve a binary system of two supermassive black holes with a subparsec separation. Such systems are an expected consequence of galaxy mergers and can provide important constraints on models of galaxy formation and evolution.

Subparsec supermassive black-hole (SMBH) binary systems are not resolvable except possibly with long baseline radio interferometry. An alternative approach to their detection is through a modulated variability—caused by, for example, perturbations in their accretion disks or precession of relativistic jets, if they are present (Fig. 1). The best known candidate, OJ 287, has shown a pair of outburst peaks every 12.2 years. The recent availability of archival monitoring data available back to May 1993, giving a total coverage of 4.1 cycles. These data are consistent with the behaviour seen in the past nine years of CRTS data, particularly with stochastic photometric variation imposed on a periodic signal. Further simulations show that the detection is statistically significant, with an observed signal 40 times the scatter from the mean.

As PG 1302−102 is bright and nearby, it has featured in a number of studies of quasars and their host galaxies. The radio and optical structures of the source is noted to be unusual. Hubble Space Telescope (HST) imaging shows the quasar resides in a luminous elliptical host, as typical for radio-loud quasars. There are also two companion galaxies that lie at projected distances of 3 and 6 kpc. Several features in radio observations of the Sloan Digital Sky Survey but is associated with bright infrared and X-ray sources. It is also a very bright (720 mJy at 4.86 GHz), core-dominated flat spectrum radio source. Its optical/near-infrared spectrum (Fig. 3) shows broad emission lines (Hβ, Hα, Paβ, Paα) with an inferred mass of log(M/M☉) = 8.3−9.4 and the object appears to be radiating at or close to its theoretical Eddington limit (log(𝐿/𝐿 Erot) = 0).

The light curve for the quasar is well-fitted by a sinusoid with an orbital period of 1.884 ± 88 days (corresponding to a rest-frame period of 1,474 ± 69 days) and an amplitude of ~0.14 mag. CRTS data (covering ~1.8 cycles; that is, May 2005 to the present day) are augmented by archival monitoring data available back to May 1993, giving a total coverage of 4.1 cycles.

Figure 1 | The parameter space of SMBH binary pairs. The expected orbital periods for SMBH close binary pairs at the specified separations as a function of total black-hole mass. The solid upper line for each separation indicates ~5 track and the solid lower line a z = 0.05 track, while the two internal dotted lines show z = 1.0 (lower) and z = 2.0 (upper) tracks, respectively. The hatched region indicates the range over which CRTS has temporal coverage of 1.5 cycles or more of a periodic signal. The pink shaded region shows the region of detection for the best CRTS candidate given the range of virial black-hole masses reported in the literature. Also shown (solid black star) is the location of the best known SMBH binary candidate, OJ 287.

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images of PG 1302−102, such as the small radio core and sharp bends in the radio structure very close to the central source, correspond with features seen in the optical19. An interpretation is that the host galaxy is a fairly old merger, but that there might be more recent activity, with the radio source just turning on and possible radio jets just emerging from the host galaxy. There may also be some indication of relativistic beaming connected with a jet. It should be noted that OJ 287 also exhibits a similar radio and optical morphology20.

PG 1302−102 was spectroscopically monitored over a six-month period in 199021 and showed no detectable (greater than 5–10%) change in any component of its spectrum over that time. This lack of variation is not inconsistent with the ~60 month period that we have identified. A SMBH binary may also exhibit double-peak broad line profiles in its spectrum for a small window of separation between the pair22 (although disk emission from an accretion disk around a single source may also produce the same effect23). At closer distances, the two black holes dynamically affect the broad-line region clouds as a single complex entity producing single-peaked spectral lines with asymmetric line profiles. The Balmer and Paschen series spectral lines in PG 1302−102 do not show a double peak profile but are consistently asymmetric (Fig. 4). In particular, a small bump on the red wing of Hβ has been reported24, implying a velocity shift of the order of 200 km s$^{-1}$ between the narrow and broad components of Hβ. One proposed explanation for this is a binary system.

**Figure 2** | The composite light curve for PG 1302−102 over a period of 7,338 days (~20 years).
The light curve combines data from two CRTS telescopes (CSS and MLS) with historical data from the LINEAR and ASAS surveys, and the literature15,16 (see Methods for details). The error bars represent one standard deviation errors on the photometry values. The red dashed line indicates a sinusoid with period 1,884 days and amplitude 0.14 mag. The uncertainty in the measured period is 88 days. Note that this does not reflect the expected shape of the periodic waveform, which will depend on the physical properties of the system. MJD, modified Julian day.

**Figure 3** | The composite spectrum for PG 1302−102. This combines an archival GALEX spectrum (ultraviolet) with optical/near-infrared spectra taken with the Keck and Palomar 200 inch telescopes in April and June 2014. $F_\lambda$, flux density. The prominent emission lines are indicated. The median flux errors are $5.6 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ for the GALEX data ($\lambda < 0.3$ μm), $4.5 \times 10^{-16}$ and $7.6 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$, respectively, for the blue (0.3 μm $< \lambda < 0.5$ μm) and red (0.5 μm $< \lambda < 0.9$ μm) optical spectra from Palomar, and $4.6 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ for the Keck near-infrared ($\lambda > 0.9$ μm) spectrum.

**Figure 4** | The profiles of the Balmer and Paschen series lines of PG 1302−102. The data have been modelled with a multi-component line fitting technique (see Methods for details). a, b, Balmer Hβ (a) and Hα (b) have been fitted using a narrow component (dashed blue line) and a broad Gaussian (solid orange line). The dashed green line shows the linear continuum component, and the total fitted profile is shown as a solid red line. Hβ requires a single Gaussian offset from the narrow component but Hα requires two components—a central Gaussian plus a red wing. c, d, The Paschen lines (Paβ (c) and Paα (d)) also show a consistent small asymmetry on the red side.
The physical interpretation of the periodicity is uncertain, although its sinuousidal nature suggests that it is kinematic in origin: we consider three possibilities here. (1) The optical flux could be the superposition of thermal emission from the accretion disk and a non-thermal contribution from a precessing jet, and such a model can fit the observed data (see Methods). The expected precession period with a single SMBH is about $10^{24} - 10^{25}$ years, much longer than the observed period. Thus, a binary SMBH origin for the jet precession is more plausible. In this latter case, the jet could precess for two reasons: either as a result of inner disk precession due to the tidal interaction of an inclined secondary SMBH, or because of the precession of a circumbinary disk warped by the SMBH binary. (2) Another possibility is a temporary hotspot in the inner region of an accretion disk, but this leads to implausible single SMBH mass estimates of $\log(M/M_\odot) = 11.4 - 12.2$, depending on the degree of rotation of the SMBH (the largest reported SMBH masses are of the order of $\log(M/M_\odot) \approx 10$). However, with a SMBH binary, periodic mass accretion rates can give rise to an overdense lump in the inner circumbinary accretion disk. The spectral energy distribution of a circumbinary disk also has a steeper power law and so accretion variations will have a more noticeable effect at shorter wavelengths. (3) Yet another possibility is a warped disk eclipsing part of the continuum as it precesses, although SMBH binaries are proposed as a possible cause for such warped disks. We note as well that light curves for objects known to exhibit these phenomena do not resemble that of PG 1302−102 (see Extended Data).

If PG 1302−102 were to be described as a binary SMBH pair with a total virial mass of $\log(M/M_\odot) = 8.5$, the observed period gives an upper-limit separation of $\sim 0.01$ pc between the pair. This would mean that the system has evolved well into the “final phases” scale. The expectation is that both SMBH systems will spend the majority of their lifetime at such separations (0.01–1 pc), in an intermediate phase of evolution between scattering any stars in the nuclear region and gravitational radiation dominance.

Further observations could test the different interpretations mentioned above, particularly reverberation mapping to measure the behaviour of emission line response to continuum variations, which is expected to be different for different explanations. Continued monitoring by CRTS and other synoptic surveys will track future cycles, and historical photometric data from photographic plate collections may provide more data for previous ones. With decadal baselines, the predicted change in the system may be detectable. Future spectroscopic observations could also test whether the line asymmetries vary on binary orbital timescales. Multiwavelength observations should provide more information about the innermost regions of the quasar and the nature of the jet. The relationship between PG 1302−102 and its two nearby companions may also furnish insight into the merger history of this source, and may also provide further information about the innermost regions of the quasar.

Received 25 July; accepted 5 December 2014.

Published online 7 January 2015.

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Acknowledgements This work was supported in part by NSF grants AST-0909182, IIS-1118031 and AST-1313422. We thank J. S. Stuart, MIT Lincoln Laboratory, for assistance with the LINEAR data. We also thank the staff of the Keck and Palomar Observatories for their help with observations, and the CRTS team. Some of the data presented here were obtained at the W.M. Keck Observatory, which is operated as a partnership among the California Institute of Technology, the University of California and NASA. The observatory was made possible by the financial support of the W.M. Keck Foundation. The work of D.S. was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

Author Contributions M.J.G. performed the analysis and wrote the paper. S.G.D. is the PI of the CRTS survey and obtained the Keck spectrum. E.G. obtained and reduced the near-infrared data and provided the Balmer and Paschen line fits. D.S. reduced the Keck data. A.I.D. is the co-PI of the CRTS survey and provided the CRTS data. S.L. and E.C. are the PIs of the CSS survey. All authors contributed to the text.

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We add a Gaussian deviate normalized by the photometric error associated with the magnitude to be replaced at each time \( t \) to incorporate measurement uncertainties into the mock light curves. For each light curve, we set \( bt \) to its median value and use the rest frame DRW fitting functions:

\[
\log f = A + B \log \left( \frac{\Delta \beta}{40000} \right) + C(M + 23) + D \log \left( \frac{M + 10}{10^M} \right)
\]

where \((A, B, C, D) = (-0.51, -0.479, 0.113, 0.18)\) for \( r,F_\text{PG} \), \( \tau = 0.7/2 \), and \((A, B, C, D) = (2.4, 0.17, 0.03, 0.21)\) for \( r,F_\text{PG} \). The absolute magnitude of the quasar and \( \Delta \beta \) is the rest-frame wavelength of the filter. The mass of the black hole is either the measured virial mass or is drawn from a Gaussian distribution:

\[
p(\log M_{\text{BH}} | M) = \frac{1}{\sqrt{2\pi \sigma^2}} \exp \left( -\frac{1}{2\sigma^2} \left( \log M_{\text{BH}} - \mu \right)^2 \right)
\]

where \( \mu = 2.0 - 0.27M \) and \( \sigma = 0.58 + 0.01M \).

**Statistical significance.** To assess the statistical significance of the detection of PG 1302–102, we generated 1,000 simulated light curves as above. From these we determined the mean weighted light curve power spectrum as a function of time and frequency and its variance. The dominant signal in the observed WWZ spectrum of PG 1302–102 is then seen to be \( 40 \) times above the corresponding mean DRW value in terms of the expected standard deviation.

We have also performed a periodicity analysis of the light curve of PG 1302–102 using the generalized Lomb-Scargle method which shows a statistically significant peak at the same period identified by the wavelet and autocorrelation analyses. The false alarm probability is \( < 10^{-15} \) and the 3-\( \sigma \) level is \( P(\sigma) = 0.335 \) and the observed peak is at \( P(\sigma) = 0.818 \).

**Theoretical predictions.** Simple disk models for circumbinary gas and the binary-disk interaction have been used\(^{11,10} \) to consider the number of SMBH binaries expected in a variety of surveys, assuming that such objects are present in the final gravitational-wave-dominated phase of coalescence (this equates to separations less than \(-0.01 \) pc for a \( 10^8 \text{M}_\odot \) SMBH binary). This approach has been combined\(^{12} \) with merger tree assembly models to similarly predict the number of expected SMBH binaries at wider separations where spectral line shifts may be seen (this equates to separations greater than \(-0.2 \) pc for a \( 10^8 \text{M}_\odot \) SMBH binary). The latter shows that in a sample of 10,000 quasars at \( z < 0.7 \), there should be \( \sim 10 \) objects and this number increases by a factor of \(-5-10 \) for \( z < 1 \). We note, however, that these theoretical arguments are still subject to considerable uncertainties; for example, if the final parsec problem cannot be resolved then there will not be any binaries in the \(-0.01 \) pc regime.

Assuming a limiting magnitude of \( V = 20 \), a detectable range of orbital periods from 20–300 weeks (spanning both GW- and gas-dominated regimes), a survey sky coverage of 24\( \pi \), and a redshift range of 0.5–4.5, we would expect 450 SMBH binaries following these approaches. Our finding of 20 candidates from a sample of 240,000 quasars is therefore conservative. 89,000 quasars in our sample also have virial black-hole mass estimates\(^{23} \) (%3% at \( z > 2 \)) and if we assumed that each of these was a SMBH binary with a separation of \( 0.01 \) pc then the CRTS temporal baseline is sufficient to detect 1.5 cycles or more in 63% of them (including 55% of the \( z > 2 \) population). Our search is therefore sensitive to a large fraction of the close SMBH binary population.

We note that our approach assumes that periodicity associated with SMBH binaries manifests in a Keplerian form. If there is a larger set of non-Keplerian periodic SMBH binaries, either flaring, such as OJ 287, or not, then the 20 objects we have identified may be a small sample of the total close binary SMBH population.

**Archival data.** \( \text{LINEAR data} \). These were calibrated with pre-release photometry from Pan-STARRS using the \( g,r,i,j \) bandpasses. Comparison stars with instrumental magnitudes (ccd\text{mag}) between 14 and 17 were selected within 0.1" of PG 1302–102 in LINEAR images. \( g-i \) colours were used to compute an \( r-b \) correction so that a calibration star with \( g-i = 0 \) has an instrumental magnitude, ccd\text{mag} = \( r \) for each frame were then derived from these stars. The reported bandpasses for the calibrated magnitudes is therefore approximately \( r \).

**Magnitude errors are computed by SExtractor, with typical r.m.s. errors between \(-0.1 \).**

\( \text{ASAS data.} \) The nominal limiting magnitude for ASAS\( ^{13} \text{S} \) is \( I = 13 \) and so PG 1302–102 is very close to the detection threshold. The low signal-to-noise ratio for such an object is the primary cause of the large degree of scatter seen in ASAS data for this source.

**Historic data.** Such data for PG 1302 from previous quasar monitoring campaigns is available in the literature\(^{14,16} \). To put all data on the same photometric scale, offsets were applied to account for differences in the photometric systems used. Region of temporal overlap between a pair of data sets were used to derive offsets so that both data had the same median value. Where no temporal overlap exists, the phased light curve was used to determine the median offset.

Earlier individual photometric observations also exist of PG 1302–102 but the observational errors on these are typically \( \sim 0.1 \) mag and so it is difficult to determine...
whether they agree with the extrapolated behaviour. They also tend to be in dif-
ferent passbands which requires colour terms to convert to the V-passband to which
CRTS is calibrated. However, colour terms for quasars are known to vary (“bluer
when brighter”) so a constant value cannot be assumed (the quoted (B – V) values
for PG 1302-02 have a range of at least 0.2 mag), which introduces an additional
error to the transformed magnitude. Such historical data are thus of limited utility.

**Spectroscopic data.** An optical spectrum was obtained using the Double-
graph on the Hale 200-inch telescope at Palomar Observatory on UT 2014 April
22. We obtained two 250 s exposures in cloudy conditions using the 1.0′′ wide slit,
the 5.500 Å dichroic, the 600 Å mm⁻¹ grating on the blue arm (λ blaze = 4000 Å),
and the 316 Å mm⁻¹ grating on the red arm (λ blaze = 7500 Å).

On UT 2014 May 26, we obtained additional spectroscopy of PG 1302 – 102 using
the Low Resolution Imaging Spectrometer (LRIS) on the Keck I telescope. We
obtained two 300 s exposures in non-photometric conditions, using the 1.5′′ slit,
the 5.600 Å dichroic, the 600 Å mm⁻¹ grism on the blue arm (λ blaze = 4000 Å),
and the 400 Å mm⁻¹ grating on the red arm (λ blaze = 8500 Å).

These set-ups provided moderate resolution spectra across the entire optical win-
dow, 3100 Å to 1 μm. The data from both telescopes were reduced using standard
procedures and calibrated using observations of standard stars obtained on the
same (non-photometric) nights.

**Near-infrared.** We obtained a near-infrared spectrum of PKS 1302 – 102 with the
TripleSpec instrument on the Hale 200-inch telescope at Palomar Observatory on
UT 2014 April 15. Conditions were clear and the seeing was ~1 arcsec. The source
was observed at an airmass of 1.3890 and was observed for four 300 s-exposures in
an ABBA dither pattern for a total of 20 min of on-source exposure. A spectrum of
Paschen lines in the near-infrared 45. To determine the full-


defined by the angles φθ (between the jet axis and the line of sight) and θhook (the
(position angle in the plane of the sky):

\[
\sin^2 \phi = (\sin \Omega \cos \theta_r + \cos \Omega \sin \phi \sin \theta_{hook})^2 + (\sin \Omega \cos \phi \sin \theta_r + \cos \Omega \sin \phi \cos \theta_{hook})^2
\]

Assuming a constant Lorentz factor γ for the relativistic bulk motion of the jet,
\( \gamma = (1 - \beta^2)^{-1/2} \), the Doppler factor is given by: \( \delta = \gamma^2 - (1 - \beta \cos \phi)^{-1} \). Modelling
the light curve in this way, we get best-fit parameters of: \( \gamma = 5.4 \pm 0.1, \Omega = 0.5 \pm
0.1, \phi = 0.5 \pm 0.2, \) and \( \theta_{hook} = 0.6 \pm 1.4 \) (assuming \( \gamma = 1.66 \).
A number of radio-loud quasars have been reported59–60 as showing periodic
variability in their radio light curves. While a SMBH binary could explain this,
a more likely explanation is shock interaction with a helical jet or precession of a jet.

However, the optical light curves of these objects (see Extended Data Fig. 1) do not
show the distinctive behaviour seen in that of PG 1302 – 102 suggesting that a dif-
ferent physical mechanism is in play. We note as well that of the 20 objects in
our full sample showing optical periodicity, only 3 are associated with a radio
source. Warped accretion disks. These have been observed in a handful of AGN61–64
and the suggestion here is that as a warp precesses, it could obscure a small amount
of continuum emission which would then appear quite regular. Again there is no indi-
cation of any periodic behaviour in the CRTS light curves available for known objects
with warped disks (see Extended Data Fig. 2) similar to that seen in PG 1302 – 102.
PG 1302 – 102 shows a 14% variation in flux, which would suggest that the size
of the warp in the disk is quite large. This would also be an orientation-dependent
phenomenon and as the source is a blazar, its accretion disk should be oriented
close to face-on to us and so any obscuring feature should be limited in effect. We
also note that many stellar systems with warped accretion disks are resolvable
binary systems.

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Extended Data Figure 1 | The optical light curves of quasars showing radio periodicity. Shown are the CRTS light curves for 11 quasars reported\textsuperscript{49,50} to show periodicity in their radio emission. Each light curve has been normalized to zero mean and individual curves are offset by a constant of 1.5 mag from each other. The data are split across two panels for ease of viewing. Error bars shown are standard 1σ photometric errors. The CRTS light curve of PG 1302−102 (solid black stars) is also shown for comparison.
Extended Data Figure 2 | The optical light curves of quasars with warped accretion disks. Shown are the CRTS light curves for 6 quasars reported\textsuperscript{52–55} to have warped accretion disks. Each light curve has been normalized to zero mean and individual curves are offset by a constant of 0.5 mag from each other. Error bars shown are standard 1σ photometric errors. The CRTS light curve of PG1302–102 (solid black stars) is also shown for comparison.