Quasi-Periodic Eruptions: Unstable Mass Transfer from a Main-Sequence Star

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Quasi-Periodic Eruptions: Unstable Mass Transfer from a Main-Sequence Star

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Quasi-periodic eruptions (QPEs) are enigmatic high amplitude bursts of X-ray radiation with a recurrence period of a few to several hours, recently discovered near the central supermassive black holes (SMBHs) of a few distant galaxies [1–3]. The periodic flares are naturally explained by a star on an eccentric orbit, shedding mass at each pericenter passage, resulting in a highly-modulated accretion luminosity. The energetics of each eruption indicate accretion of roughly $10^{-7}\,\mathrm{M}_{\odot}$ and therefore an apparent evolution time of ~ 5000 years for a solar mass donor. Assuming stable mass transfer driven by the emission of gravitational waves, the mass-losing object must be a dense stellar object (white dwarf or Helium star) on a highly eccentric ($e \gtrsim 0.95$) orbit [4, 5]. However, these objects are rare since emission of gravitational waves tends to circularize orbits. This lead to the suggestion of more complicated scenarios involving two interacting stars on coplanar, counter-rotating orbits [6], or star-disk collisions [7]. Here we argue that QPEs are produced by a main-sequence star orbiting a SMBH on a mildly eccentric orbit ($e \approx 0.1$). By relaxing the assumption of stable mass transfer, we break the equality between the gravitational wave timescale and the apparent evolution timescale, and therefore infer almost circular orbits which are more frequent. The unstable mass transfer implies that the observed QPEs will evolve within the next ~ 10 years - they will significantly brighten, and then cease to flare. This timescale is

much shorter than the apparent lifetime, allowing for observational test of our predictions. Indeed, archival data of one QPE system shows that it was dimmer two decades ago [2]. We show that a combination of two body scattering and gravitational wave emission around SMBHs produces roughly $10^{-6}\,\mathrm{yr}^{-1}\,\mathrm{gal}^{-1}$ stars on orbits that generate QPEs. Given our calculated lifetime of ~ 10 years, we obtain an abundance of order 10^{-5} gal^{-1}, consistent with the eROSITA blind QPE search [3].

1 Main

The QPE flares' soft X-ray spectrum is similar to the emission expected from the radiatively-efficient accretion of material onto a $10^5 - 10^7\,\mathrm{M}_\odot$ SMBH (e.g., [4, 6]). Given their periodic behavior, QPEs are naturally explained by a star on an eccentric orbit, marginally stripped by tidal forces at every pericenter passage. Their hours-day period dictates a semimajor axis of about ~ 1 AU. In stable mass transfer, the system evolves over the timescale of the angular momentum loss mechanism - the emission of gravitational waves. Since the orbital evolution time is a strong function of the orbit's closest approach to the SMBH, the apparent evolution time of ~ 5000 years implies a pericenter distance of roughly 0.05 AU (e.g., [4, 5]). For the star to shed mass only around pericenter, it must have a high mean density of $\sim\ 10^4\,\mathrm{gr\,cm}^{-3}$, i.e., it cannot be a main sequence star [4, 5] However, as we show later, the observed abundance of QPEs is challenging to explain by these models - the most common objects are low mass main sequence stars, while Helium stars or white dwarfs are less abundant. Furthermore, gravitational wave emission tends to circularize orbits and highly eccentric orbits are rare. Other explanations, such as [6] and [7] resorted to more complicated scenarios with additional degrees of freedom. [6] suggested that the flares arise from interaction between two counter-rotating main-sequence stars on circular orbits near the tidal radius, shedding excess mass at each conjunction between the stars. [7] proposed that collisions between an orbiting star and a pre-existing accretion disk are generating the observed QPE flares.

In light of these shortcomings, we suggest a simple model that explains the periodicities, energetics, and rate of the observed QPEs. We begin with a brief description of the dynamical environments in which QPEs are formed, and continue to describe their salient features and our predictions regarding their long term evolution. Most galaxies harbor a supermassive black hole at their nuclei, with a mass $M_\bullet$ of about $10^5 - 10^9\,\mathrm{M}_\odot$, and a gravitational radius $R_g \approx GM_\bullet/c^2$, extending to $\sim 10^5 - 10^9\,\mathrm{km}$ [8]. The central SMBH is embedded in the center of a dense cluster of stars, containing millions of stars within a volume of just a few cubic light-years [9]. The high number density of stars close to the SMBH implies that their orbits evolve by gravitational two-body scatterings on timescales shorter than the age of the universe (e.g., [10]).

Stars are occasionally perturbed through two body scatterings onto a nearly radial trajectory that passes within the tidal radius, $r_{\rm tidal} \approx R_\star(M_\bullet/M_\star)^{1/3} \approx 1\,\mathrm{AU}$ - where tidal forces exerted by the SMBH exceed the self gravity of a star of mass $M_\star$ and radius $R_\star$. The victim star is then torn apart, with roughly half of its mass falling back towards the black hole producing a bright transient known as a tidal disruption event (TDE) [11, 12]. TDEs occur roughly once every $\mathcal{R}_{\rm TDE}^{-1} \approx GM_\bullet/\sigma^3 \approx 10^4\,\mathrm{M}_{\bullet,7}^{0.3}\,\mathrm{yr}$, where σ is the velocity dispersion of stars in the galactic bulge

[9, 13]. Here we consider a complementary process that leads to the consumption of stars on nearly circular orbits by the black hole, known as "stellar extreme mass-ratio inspirals (EMRIs)" [14, 15]. These inspirals can occur for stars that find themselves on sufficiently tight eccentric orbits, that evolve primarily due to gravitational wave emission, rather than stochastic two-body scattering. At a rate of $\mathcal{R}_{\rm Stellar-EMRI} \approx \mathcal{R}_{\rm TDE}(R_g/r_{\rm tidal})^2 \approx 10^{-6} M_{\bullet,7}^{1.0}$ yr^{-1} stars of sufficiently small initial semi-major axis, are perturbed to tight eccentric orbits, that rapidly circularize and inspiral towards the central black hole through the emission of gravitational waves [13]. The star then approaches the tidal radius on a nearly circular, grazing orbit, shedding mass at every pericenter passage (figure 1).

The residual orbital eccentricity at the onset of mass transfer depends on the orbit's initial pericenter when gravitational waves took over two body scatterings. Very circular inspirals with $e \ll 1$ are unlikely because these would originate from stars with initially small semi-major axis, which are rare. Very eccentric inspirals with $1 - e \ll 1$ are also rare, because they originate from stars with initial pericenter very close to $r_{\rm tidal}$, requiring fine tuning. The full eccentricity distribution is derived in the Methods section. We adopt a fiducial value of $e = 0.1$, which is close to the peak of the distribution. We note that our results are quite insensitive to the specific value of e we use, as long as it is not very small or very close to 1.

If mass lost by the star is rapidly accreted onto the black hole, a highly variable accretion luminosity is produced, modulated at the orbital period. We argue that such mass-transferring stellar EMRIs can produce flares with properties similar to those of the observed QPEs. Stellar

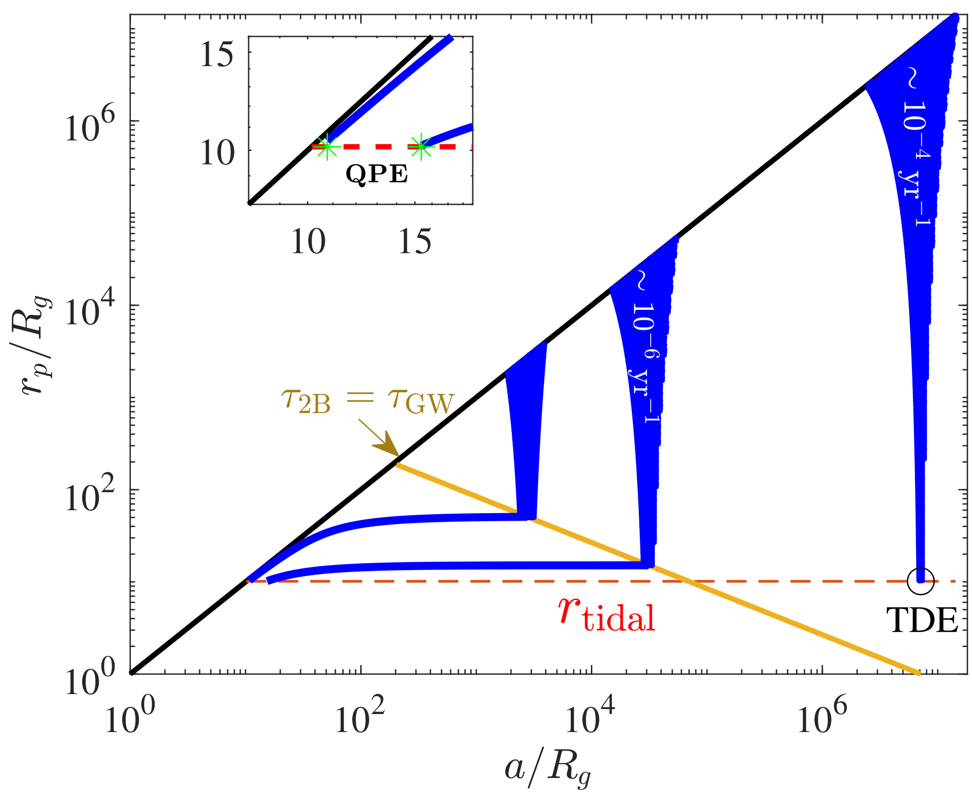

Figure 1: Schematic phase space describing dynamical processes occurring around SMBHs in galactic nuclei - the formation of tidal disruption events (TDEs) and quasi-periodic eruptions (QPEs). The vertical axis is the orbital pericenter distance (closely related to the orbital angular momentum), and the horizontal axis is the orbital semi-major axis (related to the orbital energy). The diagonal black solid line corresponds to circular orbits, and the dashed horizontal red line is the tidal radius, where tidal forces exerted by the central supermassive black hole exceed the self gravity of a sun-like star. TDEs are generated as a result of diffusion in angular momentum of stars orbiting the black hole at the radius of influence, due to two-body encounters (the right blue funnel). QPEs are generated primarily by stars on smaller initial radii, with $r_h(R_g/r_{\rm tidal})^2$. These stars are stochastically driven to low angular momentum, until circularization through gravitational wave emission becomes dominant (where the blue funnel crosses the yellow line). The star's orbit shrinks until it begins to shed mass onto the black hole (represented by the stars in the inset).

EMRIs orbit the black hole on a nearly circular orbit of radius $r_{\rm tidal}$, and have an orbital period $P \approx \sqrt{R_\star^3/GM_\star}$, that depends only on the mean stellar density. Assuming a standard main-sequence stellar structure, the stellar mass and orbital periods are related by $M_\star = 0.94\,M_\odot\,P_{10}^{1.4}$ where $P_{10} = P/10\,\rm h$. Currently known QPEs have a recurrence period in the range $P = 2.4 - 18.5\,\rm h$, corresponding to stellar masses in the range $0.1 - 2.2\,\rm M_\odot$ - which comprises the majority of stellar objects in the galactic center.

The observed period-averaged QPE luminosity of roughly $\langle L \rangle \approx 10^{41} - 10^{42}\,\rm erg\,s^{-1}$ can be explained by an average accretion rate $\left\langle \dot{M}_\star \right\rangle = \langle L \rangle / \eta c^2 \approx 10^{-4}\,\rm M_\odot\,yr^{-1}$ onto the SMBH, where $\eta \approx 0.1$ is the accretion radiative efficiency. This corresponds to an apparent mass-loss timescale, $\tau_{\rm app} = M_\star / \left\langle \dot{M}_\star \right\rangle \approx 5300\,\rm yr$. The mass loss rate is a sensitive function of the extent to which the orbit penetrates the tidal radius at pericenter [15]: $\xi = (r_{\rm tidal} - r_p)/r_{\rm tidal}$, with $\left\langle \dot{M}_\star \right\rangle \approx (M_\star/P)\xi^4$. Using the observed luminosities, we evaluate $\tau_{\rm app}$ and conclude $\xi = (P/\tau_{\rm app})^{0.25} \approx 10^{-2}$.

We note that the apparent evolution timescale $\tau_{\rm app}$ is several orders of magnitude shorter than the gravitational wave inspiral time of a solar mass main-sequence star orbiting an SMBH at $r_{\rm tidal}$, $\tau_{\rm GW} \approx 5 \times 10^5\,M_{\bullet,7}^{-2/3}\,\rm yr$ (e.g., [15]). This suggests that the system cannot be undergoing a stable mass transfer driven by GW emission, as that would imply $\tau_{\rm app} \approx \tau_{\rm GW}$. We conclude that the system is currently undergoing an *unstable* mass transfer, where the stellar response to mass loss causes the star to expand, therefore ξ to increase, further accelerating the mass loss, in a runaway process.

Our inference of unstable mass transfer has strong consequences on the estimate of the system's remaining lifetime. Significant increase in the accretion rate would occur once the mass of the star changes by only a small fraction ξ, rather than by order unity as is in the case of stable mass transfer. Thus, the evolution time is approximately $\tau_L \approx \xi\tau_{\rm app} \approx 10\,P_{10}^{1.3}\,L_{42}^{-0.7}\,{\rm yr}$. We therefore predict that over the next few years, the known QPEs will continue to brighten, doubling their luminosity within about a decade. These systems will eventually cease to brighten, once they will approach the Eddington luminosity, $L_{\rm Edd} \approx 10^{45}\,M_{\bullet,7}\;{\rm erg\,s^{-1}}$, at which point radiation pressure regulates the black hole's accretion rate, and the variable mass transfer will no longer modulate the emitted radiation.

We emphasize the following hierarchy between the relevant timescales - the star's dynamical time is comparable to the orbital period P. The system brightens over a timescale τ_L corresponding to $\xi^{-3} \approx 10^6$ orbits. The apparent timescale, $\tau_{\rm app}$ overestimates the actual evolution time by a factor $\xi^{-1} \approx 100$. Finally, the apparent timescale is shorter than $\tau_{\rm GW}$ by several orders of magnitude.

The QPE system RX J1301.9+2747 was identified in 2019 with the XMM-Newton X-ray satellite [2]. Archival observations show that this object was flaring already in the year 2000, with a similar recurrence time of $\sim 4.5\,{\rm hr}$. The observations also indicate that the source has brightened by a factor of $\sim 1.5-3$ in the two decades that separate the observations [2]. These observations support our prediction that QPEs typically brighten on a decade timescale.

Given the stellar-EMRI production rate of $\sim 10^{-6}\,{\rm yr^{-1}\,gal^{-1}}$, we estimate an abundance of roughly $10^{-5}\,L_{42}^{-0.7}$ QPEs with luminosity of order L per galaxy, at any given time. The eROSITA survey covered a volume containing roughly 2×10^5 galaxies hosting an SMBH with $M_\bullet \approx 10^7\,M_\odot$ [3, 6]. The discovery of 2 QPE systems within this volume is therefore in agreement with our theoretical rate estimate.

Even though the lifetime of brighter systems is shorter, they could be seen to further distances. Hence, in a flux limited survey, bright systems would dominate the number of detections. The exact luminosity upper cutoff is unclear - and is possibly related to the Eddington luminosity of the SMBH. The observed luminosities of the current systems are about two orders of magnitude smaller than the SMBH Eddington limit [3, 6].

Finally, using the $M - \sigma$ relation, we can scale these rates to galaxies with any SMBH mass. We find that the occurrence rate scales as $\propto M_\bullet^{0.73}$. However, for SMBHs more massive than a fraction of the Hill's mass, matter expelled from the star at each pericenter passage would not circularize outside the innermost stable circular orbit (at $1 - 9$ time R_g, depending on the black hole's spin) and is unlikely to produce QPE flares. We therefore expect that SMBHs close to this limiting mass of $\sim 5 \times 10^6\,M_\odot$, to be the most fertile environments for QPEs. This is roughly consistent with the estimated mass of SMBHs for the known QPE systems, in the range $10^5 - 10^{6.5}\,\mathrm{M}_\odot$ [16]. Note that this argument also implies that QPEs with periods of less than $\sim 2\,\mathrm{hr}$ are less likely to occur, as those would imply an orbit too close to the black hole.

2 Discussion

QPEs are only quasi-periodic, with a typical scatter in the flare timing of order $\delta t/P \approx 0.1$. One possible origin of this quasi-periodicity may be stellar oscillations. The strong tidal forces exerted on the star can naturally excite different modes of stellar oscillations. Low order radial modes result in periodic changes in the mean stellar density, and as a result - in $r_{\rm tidal}$. If the stellar oscillations are not in phase with the orbital motion, the peak of mass transfer may occur slightly before or after pericenter. The resulting flares will therefore occur quasi-periodically, with a scatter that depends on the stellar density fluctuations and on the (average) tidal radius penetration, ξ.

The accretion of a total mass $\delta M_\star$ onto the black hole is capable of producing a total of $N_{\rm ph} \approx \eta(\delta M_\star/m_e)\alpha^{-2} \approx 10^{63}\,(\delta M_\star/{\rm M}_\odot)$ hydrogen-ionizing photons, where m_e and α are the electron mass and the fine structure constant. The known QPE systems have shed about $\delta M_\star = \xi M_\star \approx 10^{-2}\,{\rm M}_\odot$, which could have ionized a total of $\sim 10^5\,M_\odot$ in neutral hydrogen. The elapsed time since the onset of mass transfer is roughly $\Delta t \approx \tau_{\rm GW}(P/\tau_{\rm GW})^{0.25} \approx 3500\,{\rm yr}$, implying a maximal extent of $\sim 1\,{\rm kpc}$ of the ionized region. Whether or not the QPE emission can sustain a narrow-line region depends on the recombination rate of the ionized gas. If the recombination rate is low enough, our model could explain the recently identified narrow-line regions in the QPE host galaxies [16].

In our calculation of the QPE production rate we made several simplifying assumptions regarding galactic nuclei dynamics. In particular, we assumed that all stars engulfing the SMBH are of equal mass. More massive objects (i.e., stellar black holes) tend to sink towards the SMBH due to mass segregation. The concentration of stellar black holes in small radii will tend to scatter low-mass main-sequence stars away from the SMBH, altering the QPE production rate from the value we find here (Linial & Sari, in prep.).

3 Methods

Tidal radius and stellar orbit. We define the tidal radius, $r_{\rm tidal}$, as the distance of the star from the black hole at the moment at which mass transfer first occurs. This is also the distance at which the star first fills its Roche lobe[1], and it is given by

$$r_p \approx r_{\rm tidal} = \alpha_{\rm RL} R_\star \left(M_\bullet/M_\star\right)^{1/3} \ , \tag{1}$$

where $\alpha_{\rm RL} \approx 2$ is an order unity prefactor that may weakly depend on e. The orbital semi-major axis $a = r_p/(1-e)$, corresponds to an orbital period

$$P = 2\pi \sqrt{\frac{a^3}{GM_\bullet}} = 2\pi \alpha_{\rm RL}^{3/2} (1-e)^{-3/2} \tau_{\rm dyn} \ , \tag{2}$$

showcasing the fact that at the Roche limit, the pericenter passage time is similar to the star's dynamical timescale, $\tau_{\rm dyn} = \sqrt{R_\star^3/GM_\star}$.

Low-mass ($0.08 M_\odot \lesssim M_\star \lesssim M_\odot$) main-sequence stars are characterized by the following approximate mass-radius relation

$$R_\star = R_\odot \left(\frac{M_\star}{M_\odot}\right)^{0.8} \ , \tag{3}$$

[1]The Roche potential formalism is defined for circular orbits, and here we adopt a generalized definition for eccentric orbits. At pericenter, the Roche lobe is analogous to that of an object orbiting the black hole on a circular orbit with $r = r_p$.

and for a given QPE period P, that stellar mass is (equation 2)

$$M_\star(P) = 0.94\, M_\odot \left(\frac{P}{10\,\mathrm{hr}}\right)^{1.4} , \tag{4}$$

where we used $\alpha_{\rm RL} = 2.17$ and $e = 0.1$.

Mass transfer and Roche lobe overflow. The mass transfer rate from the star towards the black hole is sensitive to the extent to which the star overfills its Roche lobe at pericenter. We define the normalized Roche lobe overfilling parameter as

$$\xi \equiv \frac{R_\star - R_{\rm RL}}{R_\star} , \tag{5}$$

where $R_{\rm RL} = \alpha_{\rm RL}^{-1} r_p (M_\star/M_\bullet)^{1/3}$ is the Roche lobe radius, defined locally at pericenter. Assuming a polytropic stellar structure, the flow through the inner Lagrange point L1 can be approximated as (e.g. [15])

$$\dot{M}_{\star,p} \approx \frac{M_\star}{\tau_{\rm dyn}} \xi^{n+3/2} , \tag{6}$$

where n is the polytropic index, accurate up to an order-unity coefficient. The above expression is valid in the limit $\xi \ll 1$. If additionally, $\xi \ll e$, mass transfer is significantly modulated along the orbit, limited to an "active" duty cycle around pericenter, given by

$$\frac{\Delta t}{P} = \xi^{1/2} \sqrt{\frac{(1-e)^3}{2\pi^2 e}} , \tag{7}$$

Put together, the *orbit averaged* mass transfer rate is roughly

$$\left\langle \dot{M}_\star \right\rangle = \frac{1}{P} \int_0^P \dot{M}_\star(t)\, dt = \alpha_{\rm M} e^{-1/2} \frac{M_\star}{P} \xi^{n+2} , \tag{8}$$

where $\alpha_{\rm M}$ is a dimensionless prefactor, which we approximate as $\alpha_{\rm M} \approx 9.1$ for $n = 3/2$ and $\alpha_{\rm M} \approx 1.8$ for $n = 3$.

Unstable mass transfer can explain the observations. Assuming that the QPE luminosity traces the accretion rate towards the black hole, we can write

$$\left\langle \dot{M}_\star \right\rangle = \frac{\langle L \rangle}{\eta c^2}\,, \tag{9}$$

where $\langle L \rangle$ is the orbit averaged QPE luminosity, and $\eta \approx 0.1$ is the accretion radiative efficiency. Since the stellar mass is constrained from the observed QPE periodicity (equation 4), we obtain an apparent mass-loss timescale

$$\tau_{\rm app} = \frac{M_\star}{\left\langle \dot{M}_\star \right\rangle} \approx \frac{\eta M_\star c^2}{\langle L \rangle} \approx 5300\ P_{10}^{1.4}\, \langle L \rangle_{42}^{-1}\ \text{yr}\,, \tag{10}$$

and an estimate of the Roche lobe overfilling parameter (equation 8)

$$\xi = \left(\frac{P e^{1/2}}{\alpha_{\rm M} \tau_{\rm app}} \right)^{1/(n+2)} \approx 6 \times 10^{-3}\ \frac{e^{1/7}}{(1-e)^{0.6}} P_9^{-0.11}\, \langle L \rangle_{42}^{0.29}\ , \tag{11}$$

specialized for the case $n = 3/2$.

The apparent evolution timescale $\tau_{\rm app}$ is several orders of magnitude shorter than the gravitational wave inspiral timescale for a $\sim 1{\rm M}_\odot$ main-sequence star orbiting an SMBH with $\sim 10^6\,{\rm M}_\odot$ ($\tau_{\rm GW} \approx 10^5 - 10^7$ yr, e.g., [15]). This suggests that the system cannot be undergoing a stable mass transfer driven by GW emission, as that would imply $\tau_{\rm app} \approx \tau_{\rm GW}$. We conclude that the system is currently undergoing an *unstable* mass transfer.

Eccentricity distribution. Circularization due to the emission of gravitational waves begins once the pericenter distance of a star with an initial semi-major axis $a_i \gg (R_g^2 r_h)^{1/3}$ approaches $r_{p,i} \approx R_g (a_i/r_h)^{-1/2}$, where $r_h \approx GM_\bullet/\sigma^2$ is the SMBH's radius of influence. The initial eccentricity at this phase is very close to 1, with $1 - e_i \approx (R_g^2 r_h / a_i^3)^{1/2} \ll 1$. As the orbit continues to dissipate, the pericenter eventually approaches $r_{\rm tidal}$. Following [17] we can infer the eccentricity at the onset of mass transfer, e, as a function of the initial semi-major axis a_i

$$g(e) = \frac{r_{\rm tidal}}{r_{p,i}} = \left(\frac{a_i}{r_h (R_s/r_{\rm tidal})^2}\right)^2 , \tag{12}$$

where

$$g(e) = \frac{2e^{12/19}}{1+e}\left[\frac{304 + 121e^2}{455}\right]^{870/2299} , \tag{13}$$

where we approximated $e_i \approx 1$. Since $\mathcal{R}_{\rm QPE} \propto a$, the eccentricity's probability density is given by $p(e) = 2g(e)g'(e)$, plotted in figure 2. $p(e)$ peaks at around $e_\star = 0.081$ and vanishes as $e^{5/9}$ as $e \to 0$. Very circular QPEs with $e \ll 1$ are unlikely because these would originate from stars with initially small semi-major axis, whose scattering rate is reduced ($\mathcal{R}_{\rm QPE} \propto a$). Very eccentric QPEs with $1 - e \ll 1$ are also rare, because they originate from stars with $r_{p,i}$ very close to $r_{\rm tidal}$ when gravitational waves take over two-body scatterings, requiring fine tuning. In our calculations we used $e = 0.1$ as our fiducial eccentricity value. Residual eccentricity of $e = 0.1$ corresponds to stars whose pericenter was $r_{p,i} = r_{\rm tidal}/g(e_\star) \approx 3.1 \times r_{\rm tidal}$ when gravitational waves become the dominant evolutionary channel.

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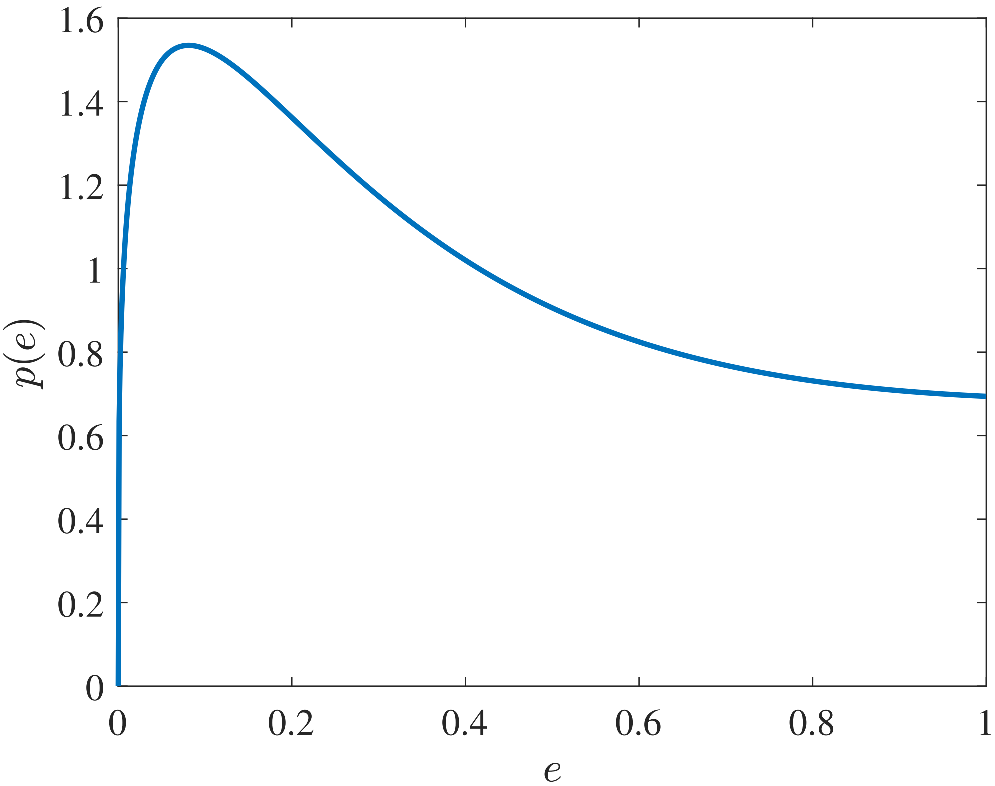

Figure 2: The probability density of the orbital eccentricity at the onset of mass transfer, for systems that circularize due to gravitational wave emission.

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