Pulsed Disc Accretion Driven by Hot Jupiters

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1 INTRODUCTION

The detection of planets around young stars offers a direct way of testing theories of planet formation and migration. Observations of such planets remain difficult because of the strong stellar activity of their parent (T Tauri) stars, and the presence of an optically-thick disc, which can cause additional variabilities. In this context, the young \( (∼2 \text{ Myr}) \) system CI Tau is of particular interest. Recently, Johns-Krull et al. (2016) reported radial velocity detection of a short-period companion to the star. With a projected mass of \( \frac{M_p}{\sin I} \approx 8M_J \) and a period of 9 days, it represents a rare example of young hot Jupiters co-existing with protoplanetary discs. Moreover, the radial velocity data from Johns-Krull et al. (2016) suggests a non-zero eccentricity for this object. Further measurements by Flagg et al. (2019) gave a planetary eccentricity of \( 0.25 \pm 0.16 \), and a mass of \( 11.6^{+2.9}_{-2.7} M_J \). In addition Biddle et al. (2018) reported photometric variability of the star with a 9 day period, while also recovering a 6.0 day signal, presumably corresponding to the stellar rotation. The authors suggested that although the planetary companion is likely not transiting, it can still cause photometric variability by driving pulsed accretion of disc material onto the star. This is the scenario that we will examine in this paper.

The origin of the significant eccentricity of CI Tau b could be found in planet-disc interactions. A large body of hydrodynamical simulations have explored the possibility of eccentricity excitation of planets embedded discs (see, e.g., Papaloizou et al. 2001; D’Angelo et al. 2006; Rice et al. 2008). More recently, long-term simulations by Rosotti et al. (2017) and Ragusa et al. (2018), especially tailored for the CI Tau system, have found that the growth of planetary eccentricity is indeed possible, albeit on time-scales longer than what was previously suggested. On the theoretical side, it has long been argued that disc-planet interactions can result in a growth of eccentricity under the action of Lindblad resonances (Goldreich & Tremaine 1980; Goldreich & Sari 2003; Ogilvie & Lubow 2003; Teyssandier & Ogilvie 2016). In particular, the linear analysis of Teyssandier & Ogilvie (2016) showed that Lindblad resonances can overcome the damping effect of corotation resonances and viscosity, and allow for the growth of eccentricity of both the disc and the planet. One important numerical result of planet-disc interactions that remains poorly understood is the fact that planets on circular orbits seem to only excite eccentricity in the disc when the planet-to-star mass ratio exceeds \( ∼ 0.003 \) (see, e.g. Kley & Dirksen 2006; Regály et al. 2010; Teyssandier & Ogilvie 2017; Muley et al. 2019).

The photometric variability observed by Biddle et al. (2018) can also find its origin in planet-disc interactions. The variability of mass accretion in the presence of a companion can strongly differs from that of a disc around a single star. In the case of circumbinary accretion, both numerical simulations (e.g., MacFadyen & Milosavljević 2008; D’Orazio et al. 2013; Muñoz & Lai 2016; Miranda et al. 2017; Muñoz et al. 2019)
and observations (e.g., Jensen et al. 2007; Muzerolle et al. 2013; Bary & Petersen 2014; Tofflemire et al. 2017; Biddle et al. 2018) show that accretion is variable on time-scales comparable with the binary orbital period. One interesting finding is that while circular binaries (with mass ratio of order unity) lead to a pulsed accretion at 5 times the binary period \( T_b \), eccentric binaries lead to pulsed accretion with a dominant period of \( T_b \) (Múnoz & Lai 2016; Muñoz et al. 2019). Because observations suggest that the companion to CI Tau is on an eccentric orbit, it is necessary to address the issue of pulsed accretion driven by eccentric short-period planets. In this paper we explore, by mean of hydrodynamical simulations, the accretion of disc material onto a star in the presence of an eccentric planetary companion.

This paper is organized as follows: We detail the problem setup and numerical methods in Section 2, and introduce some necessary diagnostic tools in Section 3. We present results relevant for CI Tau in Section 4, and explore a larger parameter space in Section 5. Finally we discuss the implications of our results and conclude in Section 6.

## 2 PROBLEM SETUP AND NUMERICAL METHODS

The problem of interest consists of a viscous hydrodynamical accretion disc around a star (mass \( M_* \)), which is also orbited by a short-period giant planet (mass \( M_p \)). We denote \( q \) the planet-to-star mass ratio, and \( a_p \), \( \Omega_p \), \( T_p \) and \( e_p \) the semi-major axis, Keplerian mean motion, orbital period and eccentricity of the planet, respectively. The disc radial extend goes from \( r_{in} \) to \( r_{out} \).

We assume that the disc is locally isothermal with a pressure scale height \( H \), and a constant aspect ratio \( h = H/r \). Our fiducial setup uses \( h = 0.05 \). The relation between the vertically-integrated pressure \( p \) and surface density \( \Sigma \) is therefore \( p = \Sigma c_s^2 \), where \( c_s = H \Omega \) is the sound speed, and \( \Omega \) the Keplerian frequency. We parametrize the kinematics viscosity through the \( \alpha \)-prescription, i.e., \( \nu = \alpha c_s H \); we use \( \alpha = 0.1 \) throughout the paper. The code units are chosen such that \( G(M_* + M_p) = a_p = \Omega_p = 1 \). Unless mentioned otherwise, we set \( r_{in}/a_p = 0.65 \) and \( r_{out}/a_p = 10 \).

Our initial and boundary conditions are similar to those of Miranda et al. (2017). The initial disc surface density is initially set to be:

\[
\Sigma(r) = \Sigma_0 \left( \frac{r}{a_p} \right)^{-\frac{3}{2}} \exp \left( -\frac{r}{r_{edge}} \right)^{-2}.
\]

The exponential factor creates a cavity, speeding up the process of the cavity opening by the planet, and therefore allowing for a quicker relaxation. We chose \( r_{edge} = 2a_p \).

The initial radial fluid velocity is

\[
u_r = \frac{3}{2} \frac{\nu}{r} \left[ 1 - \left( \frac{r}{r_{in}} \right)^{1/2} \right]^{-1},
\]

while the azimuthal velocity is

\[\nu_\phi = r \Omega.\]

The initial orbital frequency \( \Omega \) is set by the balance between the pressure force and gravity, including the quadrupole force from the planet:

\[
\Omega^2(r) = \Omega_0^2 \left[ 1 + \frac{3}{4} \frac{q}{1 + q^2} \left( 1 + \frac{3}{2} \frac{r}{a_p} \right)^{-2} \right] + \frac{1}{r^2} \frac{dP}{dr}.
\]

At the inner edge, we use the same “diode” boundary condition as Miranda et al. (2017), which allows mass to leave the domain at the inner edge, but prevents it from re-entering. This is done by applying a zero-gradient condition \( \partial u_r / \partial r = 0 \) on \( u_r \) whenever it is negative, but a reflective condition on \( u_r \) when it is positive. Zero-gradient conditions are imposed on \( \Sigma \) and \( u_\phi \). These boundary conditions mimic the loss of mass at the inner edge as the gas is accreted onto the star at the magnetospheric radius.

At the outer disc edge, we assume that mass is injected into the domain at a constant rate \( M_0 \). We apply a wave-killing zone that extend from \( (r_{out} - 1) \) to \( r_{out} \) (see, e.g., de Val-Borro et al. 2006). In this zone, all fluid quantities (generically denoted by \( X \)) are relaxed towards their initial value \( X_0 \) via:

\[
\frac{dX}{dr} = -\frac{X - X_0}{t_{damp}} R(r).
\]

Here \( t_{damp} \) is a damping time-scale, which we take to be the orbital period at the outer edge, and \( R \) is a quadratic function that increase from 0 at \( (r_{out} - 1) \) to 1 at \( r_{out} \). In code units, we chose \( \Sigma_0 = 1 \), and therefore we have \( M_0 = 3\pi a h^2 \).

The simulations are carried out on a grid centred on the centre of mass of the star-planet system. The planet is kept on a fixed eccentric orbit with \( a_p = 1 \). A fluid element with coordinates \((r, \phi)\) feels the total potential \( \Phi \) given by

\[
\Phi(r, \phi) = -\frac{GM_0}{r^2 + r_0^2 - 2rr_0 \cos(\phi - \phi_0)}^{1/2} - \frac{GM_p}{r^2 + r_0^2 - 2rr_0 \cos(\phi - \phi_p) + \epsilon^2}^{1/2},
\]

where \((r_0, \phi_0)\) and \((r_p, \phi_p)\) are the coordinates of the star and planet, and \( \epsilon \) is a smoothing length. We take \( \epsilon = 0.6H \). The star and planet do not feel the potential from the disc, and we compute their positions at each timestep by solving Kepler’s equation, following the method outlined in Murray & Dermott (1999).

Finally, we follow Kley (1999) and allow mass to accrete onto the planet. At each time-step \( \Delta t \), the gas density inside the Roche lobe of the planet (radius \( a_p(q/3)^{1/3} \)) is reduced by a factor \((1 - 0.5Q_\alpha \Delta t)\). Note that the “accreted” mass is not added to the mass of the planet, but simply removed from the domain. Finally, the mass of the planet is smoothly increased from 0 to \( M_p \) over the first 10\( \Delta t \) of the simulation.

We use the PLUTO code (Mignone et al. 2012), with a two-dimensional cylindrical grid. We use the \texttt{hll} solver with a linear reconstruction method and a second-order Runge-Kutta time-integration scheme. Our fiducial grid has a resolution of 384 x 886 in radius and azimuth, respectively. As we use a logarithmic grid in radius, this resolution ensures nearby cells with a constant aspect ratio across the computation domain. Additional runs carried out at a higher resolution show no significant differences in accretion variabilities at the inner disc edge compared to the ones carried out at our fiducial resolution (see Teyssandier & Ogilvie).
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3 DIAGNOSTIC TOOLS

The goal of this paper is to determine the accretion variability at the inner edge of the disc in the presence of a massive planetary companion. It is important to ensure that the disc has reached a quasi-steady state (independent of the initial conditions). To this end, we first need to insure viscous relaxation of the inner disc region. The viscous time-scale at radius \( r \) is \( \tau_r = (4/9) h^2 (r^2/\nu) \). Thus after a time \( t \), the disc is viscously relaxed up to a radius \( r_{\text{relax}} \) given by

\[
r_{\text{relax}}(t) = \left( \frac{9}{4} \alpha h^2 \Omega_p t \right)^{2/3} a_p.
\]

With \( \alpha = 0.1 \) and \( h = 0.05 \), after 4000 orbits, the disc is viscously relaxed up to \( r \sim 6 a_p \), which is adequate for the purpose of this study.

Secondly, pulsed accretion onto the star is driven by eccentric motion. It is therefore important to insure that the disc’s eccentricity has reached a quasi-steady state. The simulations of Kley & Dirksen (2006) and Teyssandier & Ogilvie (2017) have shown that for mass ratios of \( q \geq 0.003 \), the outer disc would develop a significant eccentricity, which will eventually saturate. A useful quantity to measure eccentricity growth and saturation is the radial kinetic energy:

\[
K_r = \int_{r_{\text{in}}}^{r_{\text{out}}} \int_0^{2\pi} \frac{1}{2} \Sigma u_r^2 \, d\phi \, dr.
\]

Figure 1 shows an example of the time evolution of the radial kinetic energy \( K_r \) and the accretion rate at the disc inner edge. The latter is computed from

\[
M(r, t) = -\int_0^{2\pi} r \Sigma u_r \, d\phi.
\]

In practice we use a sampling of 20 measurements of the accretion rate per orbit of the planet. We see that after 4000 orbits, neither \( K_r \) nor \( M \) show long-term variation, and the system has reached quasi-steady state. Of course, variabilities of \( K_r \) and \( M \) on orbital timescales still exist, and we study these variabilities in the following sections. Note that although the simulations have reached a quasi-steady state, the time-averaged accretion rate at the inner edge is not equal to the mass supply rate at the outer edge, \( M_0 \). This is because some of the mass is “accreted” onto the planet and removed from the computational domain.

4 RESULTS FOR \( q = 0.01 \)

To illustrate the accretion onto the inner edge, we begin with a fiducial example with \( q = 0.01 \), and varying the planet eccentricity. This setup is similar to the observed properties of the candidate planet around CI Tau. A snapshot of the disc surface density after several thousand orbits is shown in Figure 2, where the planet is at pericentre, for two different planet eccentricities: \( e_p = 0 \) and \( e_p = 0.2 \). The main morphological difference is that the eccentric planet carves out a large eccentric cavity, which does not appear when the planet is on a circular orbit.

This feature appears even more clearly in Figure 3, where we show azimuthally averaged profiles for the disc eccentricity, surface density, argument of pericentre and angular momentum deficit (AMD). These quantities were calculated using azimuthally averaged components of the eccentricity vector of each grid cells, following Teyssandier & Ogilvie (2017). In the case where \( e_p = 0 \), the outer disc \( r > a_p \) is not eccentric; the inner disc appears to have some residual eccentricity, but since it is depleted in material, its effect is negligible (as can be seen from the fact that the AMD is nearly zero everywhere in the disc). For higher planet eccentricities, the outer disc becomes clearly eccentric, and the cavity becomes larger. The outer part of the disc also precesses nearly-rigidly.

The accretion rate at the inner edge, and the corresponding periodogram are shown in Figure 4 for various planet eccentricities. As the planet eccentricity increases, the modulated accretion rate becomes more pronounced, with a period that matches the planet’s orbital period. This is confirmed when taking the Lomb-Scargle periodogram of the time-varying accretion rate. The periodogram clearly shows a main peak at the planet’s orbital frequency. The amplitude of the accretion rate modulation increases with eccentricity for the range of eccentricities we consider, as shown in Figure 5.

In Figure 6 and 7 we show the accretion flow morphology for the circular and \( e_p = 0.2 \) cases, at different phases of
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Figure 2. Disc surface density (zoomed-in to the inner part of the disc) for a planet-to-star mass ratio of \( q = 0.01 \) and two different planet eccentricities, \( e_p = 0 \) (left) and \( e_p = 0.2 \) (right). In the right panel, the planet is at the pericentre.

Figure 3. Azimuthally averaged radial profiles for disc eccentricity, surface density, argument of pericentre, and angular momentum deficit for different planet eccentricities.

the planet’s orbital trajectory. The circular case exhibits a constant flow morphology at all phases, thus a flat accretion curve in Figure 4. However, when the planet is eccentric, the accretion rate clearly varies as the planet goes over its orbit. The two bottom panels of Figure 7 show the two episodes of maximum accretion observed in Figure 4: A first burst occurs when the planet enters a region of higher density and launches material inwards, closely followed by a second burst as the planet approaches the pericentre.

From this set of simulations, the following picture emerges: when eccentric, the giant planet drives a pulsed accretion onto the star, with a period matching the orbital period of the planet; the amplitude of the pulsation depends on the eccentricity. It is worth pointing out that in several previous works, planets on fixed circular orbits with \( q = 0.01 \) were able to excite eccentricity in the outer disc (see Kley & Dirksen 2006; Regály et al. 2010; Teyssandier & Ogilvie 2017; Muley et al. 2019), a feature not observed in our simulations. This is likely caused by the high viscosity used in our simulations, which results in a strong eccentricity damping. Only when the planet is eccentric can it force some eccentricity in the disc and overcome viscous damping.

5 EXPLORING THE PARAMETER SPACE

5.1 Planet mass

Although our study was motivated by the photometric variability observed in CI Tau, it is useful to consider other planet masses. We therefore carry out simulations for planet-to-star mass ratios ranging from \( q = 0.001 \) to \( q = 0.01 \).

In Figure 8 we show the accretion rate evolution and periodogram for a planet with eccentricity \( e_p = 0.2 \) and various planet-to-star mass ratios. For \( q = 0.001 \), the accretion rate at the inner disc edge does not exhibit significant variations compared to the larger mass ratio cases. Interestingly, for \( q = 0.002 \), large-amplitude variability at twice the planet’s orbital frequency appears. As the planet mass increases, the two pulses per orbit gradually merge, and pulsed accretion at the planet’s orbital frequency occurs. To illustrate this further, we plot in Figure 9 the peak-to-trough amplitude of the accretion rate time series shown in Figure 8, with additional data points to resolve the transition around \( q = 0.002 \). We have also added a point for \( q = 0.008 \), where the accretion rate variation amplitude has the largest amplitude of all our simulations. This is possibly because as the planet becomes too massive, it starts accreting more mass than it
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Last 10 planetary orbits

Figure 4. Top: Accretion rate at the inner disc radius over the last 10 planetary orbits of the simulations, for $q = 0.01$ and different planetary eccentricities. For comparison, the grey dashed curved shows the radial position of the planet over time. Bottom: the corresponding periodogram. The amplitudes of the periodograms are normalized so that the amplitude of the largest signal ($e_p = 0.2$) is 1, and all the other ones are scaled by the squared amplitude of the accretion rates. They are arbitrarily offset from each others for clarity.

5.2 Separation between the planet’s orbit and the disc’s inner edge

We now examine the effect of placing the planet further away from the inner edge. We consider the case of $q = 0.004$ and $e_p = 0.2$. In addition to our fiducial run with $r_{in}/a_p = 0.65$, we have carried out two simulations with $r_{in}/a_p = 0.35$ and $r_{in}/a_p = 0.5$. Figure 10 shows snapshots of the disc surface density after several thousand orbits for the three cases. Because of the high viscosity, the planet does not open a clear gap, and a lot of material is able to accrete onto the inner disc edge. The corresponding periodograms show a transition from pulsed accretion at the planet’s orbital frequency (when the planet is close to the edge) to twice its orbital frequency (when the planet is far for the edge). Interestingly, the variation amplitude is smaller for $r_{in}/a_p = 0.5$ than for $r_{in}/a_p = 0.35$ and 0.65.

In order to understand why the $r_{in}/a_p = 0.35$ case is dominated by the variability component at twice the planet’s orbital frequency, it is useful to consider time evolution of the Fourier components of the surface density, integrated over the inner parts of the disc (between $r_{in}$ and $a_p$):

$$
\tilde{\Sigma}_m(t) = \frac{1}{2\pi(a_p - r_{in})} \int_{r_{in}}^{a_p} \int_{0}^{2\pi} \Sigma(r, \phi, t) e^{-im\phi} d\phi dr.
$$

In Figure 12 we plot $\tilde{\Sigma}_m$ for $m = 1, 2 & 3$, showing that the $m = 2$ component indeed dominates the inner disc. We speculate that this mode is dominant for $r_{in}/a_p = 0.35$ because it corresponds to the density wave launched at the 3:1
Figure 6. Streamlines overplotted on top of the surface density, for a planet-to-star mass ratio of $q = 0.01$ and planet eccentricity $e_p = 0$. We show four different snapshots taken over a single orbit of the planet, at different orbital phases of the planet. The position of the planet is highlighted by the white circle. The planet is at pericentre at $\phi = 0$, and at apocentre at $\phi = \pi$. The corresponding $\dot{M}$ at the inner disc edge is indicated on top of each panel. In this case, the planet on a circular orbit does not cause any time variation of the accretion rate at the inner disc edge.

Figure 7. Same as Figure 6, but with a planetary eccentricity of $e_p = 0.2$. In this case, the morphology of the flow and the accretion rate at the disc inner edge vary over the planet’s orbit.
inner Lindblad resonance, which is an $m = 2$ mode excited at $r_{\text{in}}/a_p = 0.48$ (Papaloizou et al. 2001).

This feature may have important observational consequences, as it suggests that observing pulsed accretion alone is not enough to deduce the orbital period of the planet. It is necessary to break this degeneracy by other means, for instance using radial velocity measurements as was done for CI Tau.

5.3 Planet inside the cavity

So far we have considered the case where the planet’s orbit lies outside the inner disc edge, i.e. $a_p(1 - e_p) > r_{\text{in}}$. This is consistent with the observed stellar rotation period (6 days) for CI Tau if we assume that the inner disc is truncated at the corotation radius. Indeed, if $r_{\text{in}}$ is determined by magnetosphere truncation, then the disc rotation rate at $r_{\text{in}}$ is expected to be close to the stellar rotation rate (e.g., Lai 2014).

However, it is possible that the inner disc radius of CI Tau is larger than the corotation radius. Indeed modelling of the CI Tau disc by McClure et al. (2013) has suggested an inner disc edge at 0.12 au, which would put CI Tau b inside the inner cavity of the disc. More generally, it is useful to consider the case of a planet orbiting inside the inner edge of the disc: such a case may occur at the end-stage of disc migration, as disc torques may push the planet slightly inwards of the disc inner truncation radius.

We therefore ran additional simulations with $a_p(1 + e_p) < r_{\text{in}}$. The numerical setup is the same, the only difference being that the planet is no longer in the computational domain. We still observed the pulsed accretion phenomenon. The accretion rate time series and the corresponding periodograms look similar to the case where the planet orbits inside the inner cavity of the disc. More generally, it is useful to consider the case of a planet orbiting inside the inner edge of the disc: such a case may occur at the end-stage of disc migration, as disc torques may push the planet slightly inwards of the disc inner truncation radius.

We therefore ran additional simulations with $a_p(1 + e_p) < r_{\text{in}}$. The numerical setup is the same, the only difference being that the planet is no longer in the computational domain. We still observed the pulsed accretion phenomenon. The accretion rate time series and the corresponding periodograms look similar to the case where the planet orbits inside the inner cavity of the disc. Since these plots are similar to Fig. 4, we simply summarize our findings in Table 1, which lists the ratio $M_{\text{max}}/M_{\text{min}}$ (similar to what is plotted in Figures 5 and 9), as well as the dominant frequency of the pulsed accretion. We see that larger mass planets lead to larger amplitude pulsed accretion (for $q = 0.001$, the amplitude of the pulse
is almost zero, regardless of whether the planet is eccentric or not. For planets on circular orbits we did not observe any pulsed accretion. In almost all cases where pulsed accretion is observed, the dominant frequency of the pulsation is the planet’s orbital frequency. The only exception is the case $q = 0.001$, $r_{in}/a_p = 1.5$ and $e_p = 0.2$, where two peaks of equal amplitude are observed at $\Omega_p$ and $2\Omega_p$, although in this case the amplitude of variation in the accretion rate is very small.

6 SUMMARY AND DISCUSSION

In this paper we have used hydrodynamical simulations to study the accretion variabilities at the inner edge of a protoplanetary disc in the presence of a hot Jupiter. This is
 motivated by the recent observations of the T-Tauri star CI Tau with a young hot Jupiter candidate. We have shown that a giant planetary companion (planet-to-star mass ratio of \( \sim 0.005 \)) on an eccentric orbit can drive pulsed accretion onto the star with a period matching the orbital period of the planet, in agreement with the observation. We have also found that an equally massive but circular planet would not produce such a large-amplitude pulsed accretion. This suggests that the giant planet around CI Tau is indeed eccentric.

More generally, we have systematically investigated how the accretion variabilities depend on the planet mass, orbital semi-major axis and eccentricity. For the typical disc parameters adopted in this paper (aspect ratio \( H/r \sim 0.05 \) and viscosity \( \alpha = 0.1 \)), we find the following trends:

1. An eccentric planet can drive large-amplitude pulsed accretion onto the central star, with the dominant variability frequency given by one or two times the planet’s orbital frequency \( \Omega_p \). The variability amplitude generally increases with the planet’s eccentricity. A circular giant planet produces a small or negligible accretion variability (see Figs. 4-5).

2. More massive planets tend to drive accretion variability with large amplitudes, although the dependence may not be strictly monotonic (see Figs. 8-9).

3. The accretion variability depends in a non-trivial way on the planet’s semi-major axis relative to the inner disc radius (Sections 5.2 and 5.3). For a given planetary mass and eccentricity, the dominant variability frequency may change from \( \Omega_p \) to \( 2\Omega_p \) and the amplitude may change non-monotonically as \( r_{\text{in}}/a_p \) changes (see Fig. 11).

We emphasize that some of our more quantitative results (such as the non-monotonic trends) must be considered tentative. An important limitation of the work reported here is that our simulations only covered the region outside the inner disc truncation radius \( r_{\text{in}} \). We used an inflow “diode” boundary condition at \( r = r_{\text{in}} \) (see Section 2), and this boundary condition cannot be justified rigorously without actually simulating the flow inside \( r_{\text{in}} \). A real protoplanetary disc is likely truncated by the magnetic field of the central star. So an “authentic” numerical study of the accretion variability induced by a planet would involve full 3D MHD simulations of magnetosphere accretion, a complicated task that is beyond the scope of the paper (see Lai 2014; Romanova et al. 2014, for a review). In any case, the long-term simulations required to attain “quasi-steady” results, as well as the coverage of a large parameter space, as we have attempted in this paper using viscous hydrodynamics, would be difficult to replicate in full MHD simulations. Overall, despite the caveats of the simulations reported in this paper, we believe that our general results and trends are valid, at least qualitatively (see Miranda et al. 2017; Muñoz et al. 2019, for a similar problem of circumbinary accretion). These results can serve as a guide for ongoing observations of young hot Jupiters in protoplanetary discs and for future more sophisticated numerical simulations.

Table 1. Results of simulations for a planet inside the disc’s inner edge. For each planet-to-star mass ratio \( q \), separation between planet and disc inner edge \( r_{\text{in}}/a_p \), and planet eccentricity \( e_p \), we give the peak-to-trough amplitude of the accretion rate at the inner edge \( M_{\text{max}}/M_{\text{min}} \), and the dominant frequency of the pulsed accretion (in units of the planet’s orbital frequency).

| \( q \) | \( r_{\text{in}}/a_p \) | \( e_p \) | \( M_{\text{max}}/M_{\text{min}} \) | Dominant frequency (\( \Omega_p \)) |
|---|---|---|---|---|
| 0.010 | 1.35 | 0.2 | 3.68 | 1 |
| 0.010 | 1.50 | 0.2 | 2.34 | 1 |
| 0.010 | 1.65 | 0.2 | 2.39 | 1 |
| 0.004 | 1.35 | 0.2 | 1.40 | 1 |
| 0.004 | 1.50 | 0.2 | 1.40 | 1 |
| 0.004 | 1.65 | 0.2 | 1.39 | 1 |
| 0.001 | 1.35 | 0.2 | 1.13 | 1 |
| 0.001 | 1.50 | 0.2 | 1.06 | 1–2 |
| 0.001 | 1.65 | 0.2 | 1.06 | 1 |
| 0.001 | 1.35 | 0.0 | 1.00 | – |
| 0.001 | 1.50 | 0.0 | 1.00 | – |
| 0.001 | 1.65 | 0.0 | 1.00 | – |

Figure 12. Time evolution of the first three Fourier components of the inner disc surface density for the case of \( r_{\text{in}}/a_p = 0.35 \) shown in Figure 10.

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