The vertical structure of planet-induced gaps in protoplanetary discs

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ABSTRACT

Giant planets embedded in circumstellar discs are expected to open gaps in these discs. We examine the vertical structure of the gap edges. We find that the planet excites spiral arms with significant (Mach number of a half) vertical motion of the gas, and discuss the implications of these motions. In particular, the spiral arms will make the edge appear ‘puffed up’ relative to the bulk of the disc. Infrared observations (sensitive to dust) would be dominated by the light from the thick inner edge of the disc. Submillimetre observations (sensitive to gas velocities) would appear to be hot in ‘turbulent’ motions (actually the ordered motion caused by the passage of the spiral arms), but cold in chemistry. Resolved submillimetre maps of circumstellar discs might even be able to detect the spiral arms directly.

Key words: planetary systems: protoplanetary discs.

1 INTRODUCTION

Recently, Calvet et al. (2005) and D’Alessio et al. (2005) identified three young stars (CoKu Tau 4, GM Aur and DM Tau) where the circumstellar disc appears to have an inner hole. These observations were performed with the Spitzer Space Telescope. CoKu Tau 4 shows no evidence of continued accretion, while GM Aur and DM Tau are still accreting. GM Aur even shows some evidence for an optically thin disc in the innermost portions of the hole. These systems are often referred to as ‘transition discs’. It has been suggested that these holes were cleared by a planet (Quillen et al. 2004; Varni`ere, Quillen & Frank 2004; Varni`ere et al. 2006).

In this paper we shall discuss the three-dimensional (3D) structure of gaps created in discs by embedded planets, and the possible observational consequences. This is important, since Spitzer cannot image these systems directly; we are obliged to analyse spectral energy distributions (SEDs). A key problem in interpreting Spitzer measurements is our lack of knowledge about the dust and gas dynamics close to a planet-induced disc gap. In particular, the disc edges appear to have \(h/r \approx 0.1\), which is too large for simple [two-dimensional (2D)] thin disc models to be wholly appropriate.

Despite these limitations, Rice et al. (2006) have already demonstrated (using 2D calculations) the interesting possibility of a ‘dust filter’ acting close to the edge. This could be a way of permitting GM Aur and DM Tau to continue to accrete (cf. Lubow & D’Angelo 2006), while still retaining their disc holes. Several authors (Paardekooper & Mellema 2004; Fouche et al. 2007; Maddison, Fouche & Gonzalez 2007) have noted that a gap might open in the dust, before the gas disc shows similar behaviour. This is due to the dust disc having zero pressure. Vertical settling of the dust within the disc (D’Alessio et al. 2006) will also be relevant. If any cross-gap flow is primarily from the upper layers of the disc, then it will naturally be depleted in dust.

Most previous numerical work on protoplanet-forming discs has been performed in 2D (see de Val-Borro et al. 2006, for a selection of codes which have been used to study the problem), due to the large computational cost of 3D calculations. Most previous work in 3D has concentrated on migration (e.g. Kley, D’Angelo & Henning 2001; D’Angelo, Henning & Kley 2002), and the flow in the circumplanetary region (Klahr & Kley 2006). Bate et al. (2003) studied migration rates of planets in 3D discs, finding that 3D considerations slowed type I migration rates (as predicted by Tanaka, Takeuchi & Ward 2002). Paardekooper & Mellema (2006) studied the effect of including radiative transfer in their 3D code, concluding that the pressure gradients induced could reverse type I migration. These studies have illustrated that 2D calculations are poor approximations to the true flow in the vicinity of the planet. Of course, for calculations of the global effect of lower mass planets on a disc, the 2D approximation is more than adequate (and we shall see an aspect of this in our results below). In this paper, we shall demonstrate important effects in the gap edges which are only seen in 3D calculations.

Boley, Durisen & Pickett (2005) and Boley & Durisen (2006) studied the vertical structure of shocks in self-gravitating discs, without an embedded protoplanet. They particularly examined the behaviour of the gas before and after the shock jump. Depending on the nature of the equation of state and the degree to which self-gravity was important, they found that the disc might compress or expand vertically after passing a shock. They find that a breaking wave could be excited on the surface layers of the disc, which has the potential to mix the disc radially. In this paper, we discuss the effect of the spiral arms raised by an embedded planet.

Previous theoretical studies (see Ward & Hahn 2000, and references therein) have usually assumed that the disc is 2D. However,
some study has been made of the vertical structure of waves in accretion discs. Lubow & Pringle (1993) studied the propagation of axisymmetric waves in accretion discs, which was later re-examined numerically by Bate et al. (2002). However, the perturbation produced by a planet is strongly non-axisymmetric. Lubow & Ogilvie (1998) studied the linear response of a 3D polytropic disc to non-axisymmetric perturbations, finding that the waves would damp within a few scaleheights of the perturber. The polytropic structure of their discs also caused ‘wave channelling’, where the waves launched at resonances were refracted towards the surface of the discs. Tanaka et al. (2002) developed a 3D perturbation theory for the torque exerted on a planet embedded in a disc, finding that 3D effects reduced the migration rate. However, they had to assume that the disc was isothermal in the radial direction, as well as the vertical. Zhang & Lai (2008) were able to relax the last assumption, but still concentrated on the torques produced in a linear calculation.

In this paper, we discuss our numerical method in Section 2. We present our results in Section 3, and discuss their consequences in Section 4. Our conclusions are presented in Section 5.

2 NUMERICAL SET-UP

In this section, we shall describe the code we used in our numerical experiments. Full 3D models of circumstellar discs are extremely challenging, requiring over an order of magnitude more computing power than 2D models of comparable resolution.

Our code is based on the FLASH code of Fryxell et al. (2000), an adaptive mesh refinement (AMR) code based around a piecewise parabolic method (PPM) hydrodynamics solver.1 We made several modifications to the code, to adapt it for these experiments. First, we added physical viscosity to the code. We implemented all components of the viscous stress tensor, but the calculations shown here are a number of different criteria for determining whether a planet’s orbit of $R \equiv r^2 \Omega/v = 10^5$ and $10^4$, respectively. There are a number of different criteria for determining whether a planet should open a gap. First is the tidal criterion of Lin & Papaloizou (1993):

$$q > 3(h/r)^3.$$  \hfill (2)

This is obtained by comparing the size of the Hill sphere, $r_H \equiv r/(q/3)^{1/3}$, which is the volume over which the planet’s gravity dominates, to the thickness of the disc. More commonly used is the viscous condition

$$q > 40R^{-1}.$$  \hfill (3)
Table 1. Predictions of gap opening according to different criteria. The criteria are explained in the text. Each entry lists three values, for the zero, low and high viscosity cases, respectively. An 'n' indicates that no gap should form; a 'g' indicates that a gap is expected.

| Criterion       | 1 $M_J$ | 2 $M_J$ |
|-----------------|---------|---------|
| Tidal           | ggg     | ggg     |
| Viscous         | ggn     | ggn     |
| Combined        | gnn     | ggn     |

as discussed by Bryden et al. (1999). Crida, Morbidelli & Masset (2006) combined these two conditions into a single one:

$$\frac{3}{4} \frac{h}{r_H} + \frac{50}{qR} \leq 1.$$  

In Table 1 we show the gap-opening predictions for each criteria, listed by planet mass and disc viscosity. There is significant uncertainty, underlined by the fact that the definition of a gap is somewhat arbitrary (see Hosseinbor et al. 2007).

We shall study the state of the disc after 100 orbits. Although a steady state is never reached (see e.g. Varnière et al. 2006; Edgar 2007), the condition of the disc after 100 orbits is generally accepted as being representative (de Val-Borro et al. 2006). Each orbit requires approximately 300 h of CPU time on NCSA’s (National Center for Supercomputing Applications) Mercury cluster.

3.1 Jupiter-mass planet

We will now discuss the results we obtained from a Jupiter-mass ($q = 10^{-3}$) planet embedded in the zero, low and high viscosity discs. In Fig. 1, we show the surface density of the disc after 100 orbits. Note that although the total surface density of our disc is 1000 g cm$^{-2}$, we are only computing the portion of the disc with $z > 0$. Hence the initial surface density was only 500 g cm$^{-2}$ in the computational volume. The behaviour we see is expected (see e.g. the comparisons of de Val-Borro et al. 2006). The zero viscosity case has lots of fine structure and a very clean gap. The low viscosity case has a clean gap, but most of the fine structure has been suppressed, while the gap in the high viscosity case has been suppressed (although we can still see a substantial depression in the surface density).

In Fig. 2 we plot the vertical Mach number, $M_z = v_z/c_s$ in the disc for slices with $z = r_H/4$ and $z = r_H$. Unsurprisingly, there are strong motions close to the planet. However, we also see vertical motions associated with the spiral arms seen in Fig. 1. These motions are relatively strong (up to $M_z \approx 0.5$), and reach well into the gap edge (although they do not propagate as far as the spiral arms in the density field). The strength of these motions does not appear to be affected by the viscosity, with a similar structure appearing for the zero, low and high viscosity cases. This is not especially surprising, since viscous effects take several orbits to become apparent, whereas the planet stirs each part of the disc every orbit. Furthermore, we only apply the $r$-$\phi$ component of the viscous stress tensor, so the vertical motion can only be affected indirectly.

Averaging the motion around an orbit, we find that the mean velocity is zero, indicating that the vertical motions are waves. Given their location, we conclude that these vertical motions are the 3D aspect of the spiral arms generated by the planet. The gas contracts and expands vertically as it passes through the spiral arms. However, this 3D structure is only apparent close to be planet, as the vertical motions rapidly fade at larger radial distances. The damping of the waves is expected from the work of Lubow & Ogilvie (1998), who predicted that the waves driven by a Jupiter-mass planet would damp after propagating a distance equal to a few scaleheights (recall that for a planet at the threshold of opening a gap, the Hill sphere and disc scaleheight are comparable). We also estimate a lower limit on the planet mass which can excite vertical motions. The waves must be excited within the planet’s Hill sphere, where the planet’s gravity dominates over that of the star (and hence provides an extra vertical gravity component to drive the wave). However, a stationary perturber cannot excite waves in a subsonic flow (Landau & Lifshitz 1959; Goodman & Rafikov 2001), which implies a minimum orbital separation from the planet for wave excitation. Applying the shearing sheet approximation, this leads to the condition that

$$r_H > \frac{2}{3} h.$$  

Figure 1. Surface density after 100 orbits for a $q = 10^{-3}$ planet in the zero (top), low (middle) and high (bottom) viscosity cases. The scale is linear, and ranges between 0 and 1000 g cm$^{-2}$. Note that since we only model the disc for $z > 0$, the unperturbed surface density is 500 g cm$^{-2}$.
Figure 2. Mach number of the vertical velocity on planes with $z = rH/4$ (left) and $rH$ (right) for a $q = 10^{-3}$ planet in the zero (top), low (middle) and high (bottom) viscosity cases. These are snapshots taken after 100 orbits. The scale ranges from $M_z = -1$ (black) to 1 (white).

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the buffer zone damping time (see de Val-Borro et al. 2006) had to be reduced to half an orbit, to suppress wave reflection.

We start with Fig. 3, which shows the surface density in the disc after approximately 100 orbits of the planet. This can be compared to Fig. 1. We see that a substantial gap has appeared in all cases, although there is some material visible in the gap for the high viscosity case. In the zero viscosity case, we can see a density enhancement moving along the gap edge. When viscosity is present, it appears that formation of this enhancement is suppressed. As in the case of Fig. 1, the surface density plots are much as expected.

Fig. 4 shows the strength of the gap edge $M_t$ on planes with $z = r_H/4$ and $z = r_H$, and may be directly compared to Fig. 2. The $M_t$ arms are more prominent, particularly on the $z = r_H$ surface. However, the velocities reached are not substantially greater and the radial propagation of the velocity field does not appear to be greater. We conclude that increasing the planet’s mass increases the vertical domain over which the planet can drive vertical motions, but does not substantially increase their maximum strength or radial domain.

The vertical domain of the vertical oscillations expands because the driving is stronger. Doubling the mass of the planet will double its gravitational field, increasing the vertical distance over which driving is effective. However, the extent of the driving in the orbital plane is still limited by the size of the Hill sphere. Since $r_H \propto q^{1/3}$, we should not expect a $2 M_J$ planet to excite vertical oscillations over a substantially larger radial domain than a $1 M_J$ planet.

3.3 Low-mass planet

In addition to the two sets of runs described above, we performed a set of runs with a $0.1 M_J$ planet. As predicted, this planet did not open a gap, but merely caused a depression in the surface density. Furthermore, we did not find a substantial vertical motions being driven, in contrast to those shown in Figs 2 and 4. This is consistent with the arguments about the planet’s Hill sphere presented above and equation (5). The Hill sphere of a $0.1 M_J$ planet does not reach into the region where Keplerian shear makes the flow supersonic.

4 DISCUSSION

In Section 3 we presented an analysis of the vertical velocity structure induced by a Jupiter-mass planet embedded in a circumstellar disc. Significant vertical motions were induced in the spiral arms raised by the planet, with vertical Mach numbers up to $\approx 0.5$. We shall now discuss the possible observable consequences.

4.1 Thickness of the gap edge

Vertical motions induced by the spiral arms have the potential to alter the appearance of the gap edge in a number of ways. Since the gap edge is likely to be the first feature which will be imaged directly, it is important to understand these.

First, if the inner disc is depleted (not in our current calculations, but recall systems such as CoKu Tau/4, DM Tau and GM Aur), then stellar radiation will directly strike the gap edge, and heat it. This would increase the scaleheight, but only modestly since $h \propto c_s \propto \sqrt{T}$. The edge of the gap would also appear to be very bright, due to its large directly illuminated surface area. A more significant increase may come from the density variations in the spiral arms themselves. Across the spiral arm, densities vary by a factor of a few. However, since the density distribution in a vertically isothermal disc is a Gaussian, the scaleheight only depends on the log of this. We might expect the spiral arms (if not resolved) to increase the apparent scaleheight by $\approx h$. We note that Wolf et al. (2002) made simulated observations of a similar situation, and found that the spiral arms were difficult to see. However, their work appears to have been based on a 2D hydrodynamic code, which would suppress the strong vertical motions we found.

Since instruments such as Spitzer observe the dust (and not the gas), it is important to consider the effect of the coupling between the gas and dust. The strong vertical motions imply that gas streamlines move up and down about half the scaleheight. Dust coupled to gas would also move up and down by the same distance. The strong vertical streaming motions imply that there are larger velocity gradients present than expected from a stratified or sedimented disc. We expect these streaming motions to affect dust sedimentation, as compared with a standard turbulent disc.

Dullemond & Dominik (2004b) showed that dust sedimentation can have a significant effect on the SED of a circumstellar disc.
Our numerical experiments make use of a much denser gas disc than Dullemond and Dominik – see particularly their equation (19). Their disc is depleted by a factor of roughly 30, as compared with ours. This strengthens the coupling between the dust and gas in our runs, in turn increasing the time required for dust to settle to the mid-plane. Consequently, we would not expect our disc to sediment at all. Paardekooper & Mellema (2004) made use of a disc depleted by a similar amount, in their work showing decoupling between the gas and dust discs. They also followed grains of size 1 mm, which are observable to instruments such as the Submillimeter Array (SMA) and Atacama Large Millimeter Array (ALMA), but less easily detectable by Spitzer.

At later times, the disc would be depleted and we would expect sedimentation along the lines of the theory developed by Dullemond & Dominik (2004b). The planet could well affect the settling in this case. The vertical stirring caused by the spiral arms occurs on the synodic time-scale, and causes vertical motions of roughly half a scaleheight. The synodic time-scale is given by \( \Omega_{\text{syn}} \equiv \Omega - \Omega_p \), and varies with position in the disc. However, we are interested in particles close to the gap edge, which invariably lies close to the \( m = 2 \) Lindblad resonances, making synodic period about twice the orbital period. Schräpler & Henning (2004) discuss the modelling of turbulent diffusion of dust in great detail, obtaining similar results to Dullemond & Dominik (2004b). They note that a key assumption is that the turbulent time-scale is very different from the global evolution time-scale of the fluid. Turbulent eddies last for approximately an orbital time-scale, while the global time-scale for an undisturbed disc is its viscous time-scale (and hence many times larger). In the depleted disc, the planetary perturbations are on a time-scale comparable to the orbital time-scale, and so this approximation fails. The range of possibilities is broad. At one extreme, the streaming motion past the planet might compress all eddies equally, meaning that there would be no effect on the dust sedimentation. At the other, consideration of the speeds and length scales involved suggest that the effective diffusion coefficient could be orders of magnitude greater, strongly suppressing sedimentation. Further study is required to determine the effect of a planet on dust close to a gap edge in a depleted disc. Specifically, dust particles should be included as a separate component, and evolved concurrently with the gas flow.

In summary, several effects should lead to apparent thickening of edges of discs near planets. Direct stellar radiation raises the temperature in the gap edge by a factor of a few. However, the disc scaleheight only depends on square root of temperature so the increase in scaleheight is only modest. Density variations caused by spiral arms lead to raising of \( \tau = 1 \) surface. The density contrasts...
in spiral arms are a factor of a few but the variation in scaleheight depends on the natural log of this, so the apparent edge will be raised by a scaleheight or so. The vertical motions themselves will make some portion of the disc edge appear higher – perhaps by as much as half a scaleheight. However, since the vertical motions are waves, other portions of the disc edge will be depressed by a similar amount. Whether this extra thickening (or thinning) is observable will therefore depend on the viewing angle and orbital phase of the planet. In an azimuthally averaged SEDs, this will probably be completely suppressed (or at least not unambiguously identifiable). In a depleted disc, the planet may also suppress sedimentation of dust towards the mid-plane. Unfortunately, we cannot estimate the extent of this effect at present since the time-scales involved invalidate the mean field approach of Schräpler & Henning (2004). Combined, these effects can make the inner edge of the gap appear significantly thicker than the bulk of the disc. We note that D’Alessio et al. (2005) calculated an aspect ratio of \( h/r = 0.1 \) for the edge of CoKu Tau/4’s disc, which seems quite large for a disc 11 au from a 0.5 \( M_\odot \) star.

It is possible that the thick disc edge will cast a shadow over the outer disc, causing it to cool and become geometrically thinner (see Dullemond & Dominik 2004a, for a discussion of self-shadowing in the context of Herbig Ae/Be stars). The light observed from such a disc would be completely dominated by the bright inner edge of the gap induced by the planet.

### 4.2 Detection of the velocity field

Almost all extrasolar planets have been discovered by the radial velocity (RV) method. Although its success is unquestioned, the RV method suffers from two strong biases. First, it is most sensitive to massive planets in close orbits. Secondly, it can only be used on old stars (\( t > 1 \) Gyr), or surface activity will wipe out the small signal from a companion. We would greatly deepen our understanding of planet formation, if we could catch planet formation in progress. New instruments, primarily ALMA, offer this possibility. Wolf et al. (2002) and Wolf & D’Angelo (2005) have already argued that the ‘accretion hotspot’ of an embedded protoplanet will be detectable in ALMA images. We shall now discuss the prospects of using ALMA’s high velocity resolution to detect the spiral arms raised by a protoplanet.

Dartois, Dutrey & Guilloteau (2003) examined the structure of DM Tau’s outer (\( r > 50 \) au) accretion disc in several CO lines. They found that the velocity dispersion in the disc mid-plane was higher than that towards the surface. This implies that the turbulence is greater in the mid-plane, even though they found that the disc surface was warmer than the mid-plane. A natural explanation for this would be spiral arms stirring up the mid-plane. A planet is unlikely so far out in the disc, but gravitational instability would be quite likely.

Even with its 0.05-arcsec resolution, the beam of ALMA will still be approximately 5 au across at the nearest star-forming clouds (located approximately 100 pc away from us). This means that any effects of a planet in a 5-au orbit are highly unlikely to be visible. Accordingly, we have rescaled our results to place the planet on a 10-au orbit. We computed the line of sight velocity for every grid cell in our computational domain, and projected this on to the sky. We then traced rays through the projected density structure, evaluating the integral

\[
\Sigma_{\text{los}} = \int_{-\infty}^{\infty} \rho \, dl.
\]

We assumed that ALMA would observe the velocity in the grid cell where \( \Sigma_{\text{los}} = 1 \). Although this is not necessarily the surface ALMA would see, it serves as a useful initial estimate.

In Figs 5 and 6, we show two simulated position–velocity plots, based on a Jupiter-mass planet in the low viscosity disc. The plots differ only in the beam track. The disc was inclined at 45° to the line of sight, and we average the velocities over a 5-au beam. The planet was on the ‘far’ side of the disc, in approximately the 2 o’clock position. The beam track of Fig. 5 (the ‘near’ side of the disc) does not pass over the planet, while that of Fig. 6 does. Note that there is a clear difference in velocity structure between the ‘near’ and ‘far’ tracks, indicating that we can easily identify which side of the disc we are inspecting.

Of greater interest is the fact that the planet is detectable in the right-hand panel of Fig. 6, as the extra contours around \( x = 10 \) au and \( y = 6 \) km s\(^{-1}\). This is slightly outside the planet’s actual location (after projecting on to the sky), indicating that the detection is of the spiral arm raised by the planet. Of course, real observations will be noisy, and the detection in Fig. 6 is only in one contour. Furthermore, our approach of using the \( \Sigma_{\text{los}} = 1 \) surface to construct our velocity field is crude. Real observations will have to select

![Figure 5. Simulated ALMA observation of a Jupiter-mass planet in a 10-au orbit. The orbital plane is inclined at 45° to the line of sight, and the planet is located approximately at the 2 o’clock position. The line of sight velocity is shown in the left-hand panel, along with the beam track (which does not pass over the planet). The circle placed on beam track indicates the 5 au size of the ALMA beam. In the right-hand panel, we show the position–velocity plot produced along the track.](https://academic.oup.com/mnras/article-abstract/387/1/387/1000734)
particular molecular transitions, based on the temperature structure of the disc. Optically thin lines will convolve velocities from many positions along the line of sight.

The vertical motions we have discovered might even make a planet detectable in a face-on disc, even if it is poorly resolved. In this case, the vertical motions induced by the (unresolved) spiral arms might well be (mis-)interpreted as turbulent motions. According to $\alpha$-disc theory, the turbulent velocity is $v_{\text{turb}} \approx \alpha v_c$. If the disc were assumed to have a ‘normal’ value of $\alpha \approx 10^{-3}$, then the sound speed in the disc would be overestimated by a factor of $M_f/\alpha^{1/2} \approx 10$, implying that the temperature would be overestimated by a factor of roughly 3. At this point, we would only have a disc with an unreasonably large aspect ratio. However, the temperature of the disc might be independently computable from observations of disc chemistry. If these observations suggested a more reasonable temperature, then one might conclude that a planet was stirring the disc, causing the mismatch between the ‘turbulent’ temperature (in reality, the spiral arm stirring) and the chemical temperature. Instruments such as the SMA are already making detailed observations of circumstellar discs (e.g. Qi et al. 2004, 2006), and analysis of these systems may well find anomalies which can be explained by the presence of a planet.

Despite the caveats raised above, we have demonstrated the tantalizing possibility of detecting a young planet embedded in its nascent disc. Such a detection would greatly extend our understanding of the planet formation process. Observational considerations have restricted all previous planet searches to old systems, where the disc has long since vanished.

5 CONCLUSIONS

In this paper, we have presented the results of 3D numerical experiments of disc–planet interactions. We have concentrated on the case of 1 and 2 $M_f$ planets. Our computations have shown strong vertical stirring of disc material by the planet. This stirring has a number of potentially observable consequences.

The gap edge is likely to appear relatively thick for a number of reasons. Direct illumination from the star will warm the gap edge, slightly increasing the scaleheight. Density enhancements in the spiral arms might also be interpreted as a larger scaleheight in an unresolved image. Combined, these effects will make the region close to the planet appear ‘puffed up’ relative to the disc. We argue that this strengthens the case for a planetary cause of the hole seen in CoKu Tau/4, since the disc edge is not only sharp, but also quite thick.

We have also examined the possibility of detecting the velocity structure produced by the planet using the latest generation of telescope, such as ALMA. Rescaling the orbit of our planet to 10 au, we believe that the presence of a planet is just detectable. Even if the disc were unresolved, the effects of a planet might still be detectable. A high ‘turbulent’ temperature in a disc with a cold ‘chemistry’ temperature would suggest the presence of a planet.

There are a number of avenues for further work, which we are actively pursuing. First, we are expanding our library of models, testing planets of different mass, in discs of varying viscosity and aspect ratio. We have demonstrated that planet-induced velocity structures should be detectable, but we are not yet in a position to interpret real observations. Compiling a library of models will provide us with the tools necessary to interpret future observations in detail. Our simulated observations are somewhat crude, since they take no account of disc chemistry (which directly affects which molecules are available for observation; freeze-out of CO could be a problem). We will refine our models in the future, computing the disc temperature and chemistry in more detail and comparing these to the temperature profile assumed by FLASH.

We have shown how planets embedded in circumstellar discs create significant features in the vertical structure of those discs. These structures were not visible in earlier 2D computations. The vertical features created are likely to have detectable consequences, raising the exciting possibility of catching planets as they form.

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APPENDIX A: EFFECT OF THE EQUATION OF STATE

All the numerical experiments presented above used an adiabatic gas with $\gamma = 1.1$ in the Riemann solver. However, we imposed a temperature structure, and did not evolve the energy equation. This is not entirely self-consistent. To check the effect of this inconsistency on our results, we reran the low viscosity case for a Jupiter-mass planet, with $\gamma = 1.01$.

In Fig. A1, we show the effect of this change on the value of $M_2$ on slices with $z = r_H/4$ (top) and $r_H$ (bottom). Apart from the value of $\gamma$, the numerical experiment used to produce this figure was identical to that of the middle row of Fig. 2. We see that similar behaviour occurs in the disc with a $\gamma = 1.01$ gas.

Ideally, one should solve the energy equation in the disc (e.g. D’Angelo, Henning & Kley 2003), perhaps even considering radiative transfer (shown to have a significant effect on low-mass planets by Paardekooper & Mellema 2008). However, this test reassures us that the vertical motions induced by the planet are real, and not merely artefacts of the numerical method.

APPENDIX B: ADDING COMPONENTS OF THE VISCOUS STRESS TENSOR

As noted in Section 2, the runs presented above only used the $r-\phi$ component of the viscous stress tensor. We made this decision because the true nature of viscosity in accretion discs is not known, and we simply wished to include a term which would cause

![Figure A1](https://example.com/figureA1)

**Figure A1.** The effect of the choice of $\gamma$ on the Mach number of the vertical velocity on planes with $z = r_H/4$ (top) and $r_H$ (bottom) for a $q = 10^{-3}$ planet in the low viscosity disc. The scale ranges from $M_2 = -1$ (black) to 1 (white). The numerical experiment producing this figure was identical to that of the middle row of Fig. 2, except this figure uses $\gamma = 1.01$ in the Riemann solver.
Figure B1. The effect of including all components of the viscous stress tensor on the Mach number of the vertical velocity on planes with $z = r_H/4$ (top) and $r_H$ (bottom) for a $q = 10^{-3}$ planet in the low viscosity disc. The scale ranges from $M_z = -1$ (black) to 1 (white). The numerical experiment producing this figure was identical to that of the middle row of Fig. 2, except this figure includes the extra viscous terms.

APPENDIX C: EFFECT OF RESOLUTION

As noted in Section 3, our resolution (particularly the vertical resolution) in the innermost portions of the disc is not especially good.

Figure C1. The effect of doubling the grid resolution on the Mach number of the vertical velocity on planes with $z = r_H/4$ (top) and $r_H$ (bottom) for a $q = 10^{-3}$ planet in the low viscosity disc. The scale ranges from $M_z = -1$ (black) to 1 (white). This is a continuation of the numerical experiment which produced the middle row of Fig. 2, with the resolution doubled.

This is a result of necessity: global 3D numerical experiments are extremely computationally expensive. However, it is important to verify that numerical results are not purely artefacts of resolution. Accordingly, we instructed FLASH to continue the run with Jupiter in a low viscosity disc, but with the resolution doubled. Fig. C1 shows the result of this continuation.

We can see that the structure in $M_z$ is retained. However, the noise in the inner portions of the disc has been substantially suppressed (albeit not eradicated), especially in the $z = r_H$ plane. The peaks in $M_z$ appear to be slightly smaller in Fig. C1, indicating that our runs at standard resolution might be slightly underresolving the vertical stirring. This said, the structures seen are very similar.