LONG-TERM EVOLUTION OF PLANET-INDUCED VORTICES IN PROTOPLANETARY DISKS

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Abstract

Recent observational evidence suggests that large-scale vortices exist in protoplanetary disks. These vortices can be excited when there is a strong gradient in the disk radial density profile. Due to the significant density variations and the corresponding angular velocity adjustments, the gap edge can typically excite the Rossby wave instability (RWI). The evolution of RWI will try to smooth out the density variation, the continuous accretion from material at large radii in the disk provides a driving effect on the RWI.

1. INTRODUCTION

The new Atacama Large Millimeter/Submillimeter Array (ALMA), although still at an early stage of configuration, provides unprecedented resolution and sensitivity in the (sub)millimeter wavelength range. Recent high-fidelity ALMA images of transitional disks around stars (Isella et al. 2013), HD 142527 (Casassus et al. 2013), Oph IRS 48 (van der Marel et al. 2013), and HD 135344B (Ataiee et al. 2013) have revealed high contrast dust asymmetries in the outer regions of the disk. These features are observed in dozens of circumstellar disks (Forrest et al. 2004; Andrews et al. 2011; Espaillat et al. 2010; Kraus et al. 2013; Rosenberg et al. 2013; Dodson-Robinson & Salyk 2011; Zhu et al. 2011; Kraus & Israel 2012; Dobinson et al. 2013; Ruge et al. 2013). When a planet becomes massive enough, it carves out a deep gap around its orbit. Due to its significant density variations and the corresponding angular velocity adjustments, the gap edge can typically excite the RWI (e.g., Li et al. 2005), leading to the formation of vortices. Further nonlinear development of the RWI can lead to the formation of a ”banana-shaped” asymmetric density enhancement (e.g., Li et al. 2005) or one large vortex (e.g., Lin & Papaloizou 2011; Lin 2012, 2014). One important condition for exciting RWI by a planet is that the disk viscosity needs to be sufficiently low, as it has been empirically studied by various groups (e.g., de Val-Borro et al. 2007; Li et al. 2009; Yu et al. 2010; Lin & Papaloizou 2011). This scenario has been proposed to explain the ALMA observation of Oph IRS 48 (van der Marel et al. 2013) as well as the disk gap/hole (Ataiee et al. 2013).

These vortices are potentially very important because they can efficiently trap dust particles (e.g., Barge & Sommeria 1995; Chavanis 2000; Johansen et al. 2004; Inaba & Barge 2006; Rice et al. 2006; Meheut et al. 2012b; Pinilla et al. 2012; Zhu et al. 2012; Birnstiel et al. 2013; Lyra & Lin 2013), which in turn can produce asymmetric features in disk dust emission and help promote potential planet formation. Even though many previous studies have shown the generation of strong vortices in the disk, their long-term evolution, especially their survival time under different disk conditions, has been left unaddressed. Though the
exact lifetime of these vortices and/or asymmetric features is difficult to pin down observationally, the general expectation is that they need to survive up to $\sim$disk lifetime at tens of AU distances.

In this Letter, we present high-resolution, long-term two-dimensional simulations of disk–planet interactions that span $>10^4$ orbits at the location of the vortex and we have explored the effects of several key disk/planet parameters on the vortex lifetime, including planet mass, disk viscosity, and disk temperature. In Section 2, we present the detailed setup of our numerical simulations. We summarize our main results in Section 3, and discuss the implication of our results in Section 4.

2. NUMERICAL SETUP

In our study, the protoplanetary disks are assumed to be geometrically thin so that the hydrodynamical equations can be reduced to two-dimensional Navier–Stokes equations by considering vertically integrated quantities. We adopt an isothermal equation of state $P = c_s^2 \Sigma$ where $P$ is the vertically integrated pressure, $\Sigma$ is the surface density, and $c_s$ is sound speed. Simulations are carried out using our code LA-COMPASS (Los Alamos Computational AStrophysics Suite).

The planet is taken to reside on a fixed circular orbit at radius $r_p$ with Keplerian orbital frequency $\Omega_p$. We adopt dimensionless units in which the unit of length is $r_p$ and the unit of time is $1/\Omega_p$. In dimensionless units, the disk is modeled between $0.2 \leq r \leq 6.48$ with the planet at $r = 1$. We consider two mass ratios of the planet to the central star $\mu = M_p/M_* = 0.001$ and 0.005, corresponding to a 1 $M_J$ planet and a 5 $M_J$ planet given a 1 $M_\odot$ central star. Planet mass is ramped up to its final value in the first 10 orbits. A smoothing length $r_s = 0.6 r_p$ is applied to the gravitational potential of the planet. We choose a power-law profile for both initial disk surface density and disk temperature of the form $\Sigma \propto r^{-1}$, $c_s \propto r^{-0.5}$. The disk aspect ratio given by $h/r = c_s/(\Omega r)$ is nearly independent of $r$ (hereafter we will use $h$ to stand for the dimensionless disk temperature). The initial disk mass is about 1 $M_J$. The dimensionless kinematic viscosity $\nu$ (normalized by $r_p^2 \Omega_p$) is taken to be spatially constant and ranges from $\nu = 10^{-8}$ to $\nu = 10^{-5}$. The Shakura–Sunyaev viscosity is related to $\nu$ by $\alpha = \nu/(\Omega h^2)$. All the simulations have a resolution of $(n_\phi \times n_r) = 3072 \times 3072$. The smallest Hill radius $r_H = 0.07$ is thus resolved by 35 cells. We employ fixed value condition at boundaries. The initial disk surface density is completely smooth without an initial gap. Our simulations typically last for $>10^3$ orbits (at $r = 1$).

3. RESULTS

Figure 1 shows the disk surface density evolution for two different planet masses. For a 1 $M_J$ planet, a gap in the disk can be developed quickly and the edges of the gap become unstable, giving rise to vortices that quickly merge into a single vortex. This type of behavior is quite general for all massive planet cases we have studied. This vortex can last for slightly more than 10$^3$ orbits (Figure 1(c)), then it finally disappears (when azimuthal density variation across the vortex falls below $\sim 10\%$).

For a 5 $M_J$ planet (Figures 1(d)–(f)), a single vortex remains robust at 5000 orbits and persists even after 10$^4$ orbits in Figure 1(f). We see that after increasing the planet mass by a factor of five, the vortex lifetime becomes almost 10 times longer for the same disk conditions. We expect the vortex survival time to increase with planet mass because a more massive planet is able to clear a deeper gap. The planet creates and maintains a sharper density jump at the gap edge that drives a stronger RWI. The vortex induced by the more massive planet covers a larger azimuthal range (see Figures 1(b) and (e)).

Runs presented in Figure 2 all have the same planet mass $M_p = 5 M_J$, but different disk temperatures, $c_s/\Omega|_{r=1} = h$. Both cases have vortex lifetime only on the order of a few thousands of orbits. Together with Figures 1(d)–(f), $h = 0.06$ seems to be the optimal disk temperature for the purpose of disk vortex survival time. In that case, the vortex lifetime is $\sim 13,000$
orbits. We see that disk temperature has a very interesting nonmonotonic effect on the disk vortex lifetime. Either a higher or lower disk temperature results in more rapid vortex damping.

Figure 2. Similar to Figure 1 except we now fix $M_p = 5 M_J$ and vary disk temperatures ($c_s/(r \Omega) = h = 0.05, 0.07$). Again, both runs employ disk viscosity $\nu = 1 \times 10^{-7} r^2 \Omega$. Together with Figures 1(d)-(f), we see the vortex lifetime is not monotonic with the disk temperature.

(A color version of this figure is available in the online journal.)

Figure 3. Similar to Figure 1, except that we fix the planet mass as $5 M_J$ and disk temperature $c_s/(r \Omega) = h = 0.06$ but vary disk viscosities ($\nu = 10^{-5}, 10^{-6}, 10^{-8} r^2 \Omega$). Together with Figures 1(d)-(f), we see the vortex lifetime is not monotonic with disk viscosity.

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A similar effect can also be seen in Figure 3 where we show runs with three additional disk viscosities ($\nu = 10^{-5}, 10^{-6}, 10^{-8}$). Note that our code has numerical viscosity on the order of $10^{-9}$ or less. For $\nu = 1 \times 10^{-5}$ (first row),
the disk is barely able to form a discernible non-axisymmetric feature even though there seems to be a clean gap. Any vortex disturbance gets damped out in a very short time (a few hundreds of orbits). For $\nu = 1 \times 10^{-6}$ (second row), the vortex evolution is very similar to that for $\nu = 1 \times 10^{-7}$ (Figures 1(d)–(f)), except that vortex lifetime is almost 10 times shorter. One would expect an even longer vortex lifetime for an even smaller viscosity because damping should decrease with smaller viscosity. Surprisingly, in the case of $\nu = 1 \times 10^{-9}$ (third row), vortex lasts for significantly shorter time than in the case of $\nu = 1 \times 10^{-7}$. Therefore disk viscosity affects vortex lifetime also in a non-monotonic way. A viscosity value $\nu = 1 \times 10^{-7}$ seems to be optimal for vortex survival with $M_p = 5 M_J$ and $h = 0.06$. Vortex suppression at large disk viscosity has been found before (de Val-Borro et al. 2007; Li et al. 2009; Lin & Papaloizou 2011; Isella et al. 2013; Ataiee et al. 2013), but previous studies have only considered $\nu > 1 \times 10^{-7}$ and concluded the effect is monotonic. If the viscosity is above some threshold ($\sim 10^{-5}$ in our runs), vortex formation can also be completely suppressed. The dependence of vortex lifetime on viscosity and temperature is summarized in Figure 4, which includes more cases than we presented in Figures 1 and 2. We will give a tentative explanation for this behavior in Section 4.

We now consider the evolution of vortex in more detail. The upper part of Figure 5 shows the evolution of $\zeta(r, \phi)$ and $\Sigma(r, \phi)$, where $\zeta = (\nabla \times \mathbf{v})_z/\Sigma$ is the PV. The vortex appears as a localized region of low PV (Figures 5(a)–(c)) because the surface density is higher in those regions. To ease comparison, we have shifted the plots azimuthally so that the vortex is at the center in each panel (panels (a)–(c) and (d)–(f)). Due to the large velocity perturbation and very low surface density, the PV within the gap region $(r-r_p)/h < 10$ is much higher than in other regions of the disk. We set an upper cutoff on our color scale in order to make the vortex more clearly visible. The lower part of Figure 5 shows the azimuthal density variation or the averaged azimuthal potential vorticity variation within 10H (scale height) wide band around the vortex drops below 10%. The dashed lines are rough interpolations.

(A color version of this figure is available in the online journal.)

4. DISCUSSION AND SUMMARY

We have considered the interaction of gaseous protoplanetary disks with high mass planets that are in circular orbits with orbital frequency $\Omega_p$ and radius $r_p$ from a central star. We have sampled the parameter space of different planet masses, different disk viscosities, and different disk temperatures and investigated how these parameters affect the lifetimes of disk vortices. We find that higher planet mass generally leads to longer vortex lifetimes, given the same disk viscosity and temperature. This result occurs because a more massive planet carves out a cleaner gap and promotes a stronger RWI at the gap edge. Both disk viscosities, and different disk temperatures and investigated how these parameters affect the lifetimes of disk vortices. We find that even lower viscosity (e.g., $\nu > 1 \times 10^{-7}$) actually results in shortened vortex lifetimes. Instead, we speculate that the vortex is damped by shocks. Several competing effects are at play which jointly determine the evolution and lifetime of the vortex. For lower viscosity or lower temperature, on one hand, a
Figure 5. Top: color contours of disk potential vorticity and surface density distributions at different times for the run with planet mass \( M_p = 5 M_J \), viscosity \( \nu = 10^{-7} r_p^2 \Omega_p \), and dimensionless disk temperature \( c_s/(r \Omega) = h = 0.06 \). Time is in units of the planet orbital period. \( \phi_0 \) is the azimuthal coordinate of vortex center. Bottom: azimuthally averaged disk potential vorticity and surface density profiles for the same times as the upper plots. (A color version of this figure is available in the online journal.)

higher mass planet is able to create a sharper gap edge and thus form stronger disk vortices. However, they also enhance spiral shocks that act to damp the vortex. For high viscosity or high temperature, shocks produced by the planet are weaker but the planet cannot create a sharp edge. Consequently, in this regime the planet either does not induce vortex formation at all or only excites a weak vortex which damps quickly. Therefore, intermediate values for disk viscosity and temperature provide the longest lived vortices that nearly balance the driving with damping of disk vortex.

Our findings can be compared with several recent observations. The longest vortex lifetime we find is \( \sim 10^4 \) orbits for \( M_p = 5 M_J, \nu = 1 \times 10^{-7} r_p^2 \Omega_p \), and \( h = 0.06 r_p \). The vortex is located at \( r = 2 r_p \). For the other sets of parameters that we have tried, the vortex lifetime spans from 0 to a few \( \times 10^3 \) orbits. To explain relatively large disk gaps with dust emission asymmetries (Casassus et al. 2013; Fukagawa et al. 2013), the planet needs to be located far from the central star. For a slightly smaller hole as seen in Oph IRS 48, if we take the planet to be located at a radius of 20 AU, then the vortex
reduces to a few $\times 10^3$ orbits that can be realized for a broader range of disk parameters. Due to the resolution of current ALMA configuration, all of the dust asymmetries are found to be far from the central star. With the most extended ALMA configuration, future observations will be able to resolve disk feature on scales closer to the central star. Ongoing exoplanet surveys (Brandt et al. 2014) could also shed light on the direct detection of forming massive planets in disks with these asymmetry features.

At a large orbital radius (~50 AU), the very low disk viscosity value ($v = 10^{-7} r_0^2 \Omega_p$ or $\alpha = 10^{-4}$ at $r = 2$ where the vortex is located) for vortex longevity implies that this region does not evolve viscously over the disk lifetime. Such a low viscosity requires some explanation. In the T Tauri phase, the observationally inferred accretion rates onto the central star suggest that $\alpha \sim 10^{-2}$ (Hartmann 1998). At that level of turbulence, we do not expect that vortices can form.

The magnetorotational instability (MRI) is a likely source of turbulence in the outer regions of a protoplanetary disk (Balbus & Hawley 1991). MRI typically results in an $\alpha$ value $\gtrsim 0.01$ that is again too high to permit the development of a vortex. On the other hand, the efficiency of MRI is weakened considerably in certain regions of protostellar disks due to nonideal MHD effects that result from the low levels of ionization (e.g., Bai & Stone 2011). Recent simulations by Zhu & Stone (2014) indicate that sufficiently low levels of $\alpha$ and long vortex lifetimes can be achieved through the nonideal effects of ambipolar diffusion. The reconciliation of the low viscosity requirements of vortex generation with the high viscosity requirement of accretion is unclear, possibly involving alternate accretion mechanisms.

The results presented here represent some preliminary steps toward understanding the joint evolution of planet, disk accretion, vortices, and dust asymmetries in the outer parts of the protoplanetary disk. Dust–gas interaction, disk self-gravity, more sophisticated viscosity profile, three-dimensional structure could all affect disk vortex evolution to some extent. We plan to address these issues in future studies.

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