Circumstellar disks do erase the effects of stellar flybys on planetary systems

F. Marzari and G. Picogna

Dipartimento di Fisica, University of Padova, Via Marzolo 8, 35131 Padova, Italy
 e-mail: Francesco.Marzari@pd.infn.it

Received 25 September 2012 / Accepted 3 December 2012

ABSTRACT

Context. Most stars form in embedded clusters. Stellar flybys may affect the orbital architecture of the systems by exciting the eccentricity and causing dynamical instability.

Aims. Since, incidentally, the timescale on which a cluster loses its gaseous component and begins to disperse is comparable to the circumstellar disk's lifetime, we expect that closer and more perturbing stellar flybys occur when the planets are still embedded in their birth disk. We investigate the effects of the disk on the dynamics of planets after the stellar encounter to test whether it can damp the eccentricity and return the planetary system to a nonexcited state.

Methods. We used the hydrodynamical code FARGO to study the disk+planet(s) system during and after the stellar encounter in the context of evolved disk models whose superficial density is 10 times lower than that of the minimum mass solar nebula.

Results. The numerical simulations show that the planet's eccentricity, excited during a close stellar flyby, is damped on a short timescale (~ 10 Kyr) in spite of the disk's low initial density and subsequent tidal truncation. This damping is also effective for a system of 3 giant planets, and the effects of the dynamical instability induced by the passing star are quickly absorbed.

Conclusions. If the circumstellar disk is still present around the star during a stellar flyby, a planet (or a planetary system) is returned to a nonexcited state on a short timescale. This does not mean that stellar encounters do not affect the evolution of planets, but they do it in a subtle way with a short period of agitated dynamical evolution. At the end of it, the system resumes a quiet evolution and the planetary orbits are circularized by the interaction with the disk.

Key words. planets and satellites: dynamical evolution and stability – planet-disk interactions – methods: numerical

1. Introduction

It is widely believed that most stars form in embedded clusters on a timescale of about 1 Myr (Hillenbrand 1997; Palla & Stahler 2000). About 80% of stars within 1 kiloparsec of the Sun are actually found in clusters with a population exceeding 100 members (Porrás et al. 2003). During the early stages of cluster evolution, stellar encounters are believed to significantly affect the formation and subsequent dynamical evolution of planetary systems around stars belonging to the structure. According to Malmberg et al. (2011, 2007), Malmberg & Davies (2009), and Zakamska & Tremaine (2004), scattering interactions with other stars in their birth cluster may excite the eccentricity of planets populating the outer parts of the system. This dynamical mechanism might contribute to explaining why eccentric orbits occur relatively commonly in extrasolar planetary systems. In the case of multiple-planet systems, the eccentricity perturbations due to a stellar flyby can leave the planetary system in an unstable state. On timescales ranging from a few million to billion years an unstable planetary system may undergo a phase of planet-planet scattering leading to the ejection of one or more planets from the system (Weidenschilling & Marzari 1996; Rasio & Ford 1996).

Stellar flybys are more frequent and statistically close in the early stages of a cluster evolution when the structure is more compact. When, after a few times the crossing time (Allen et al. 2007), a cluster loses its gaseous component, a substantial amount of unbinding occurs (Adams 2000) and it disperses. The gas removal occurs within about 3–5 Myr from the formation of the cluster and, according to Allen et al. (2007), Fall et al. (2009), Chandar et al. (2010), and Dukes & Krumholz (2012),

after about 10 Myr, 90% of stars born in clusters have dispersed into the field. We then expect that most of the close stellar encounters causing significant changes to the orbital elements of the planets occur when the planets are still embedded in circumstellar disks. Even if gas disk lifetimes are not well constrained observationally, they are assumed to be shorter than 10 Myr (Pascucci et al. 2006), possibly in the range between 3–6 Myr as suggested by Haisch et al. (2001). It is then reasonable to assume that, statistically, most of the close stellar passages occur when the planets are still embedded in disks. The effects of stellar encounters must be modeled by considering the system planet+disk rather than isolated planets.

In effect, most numerical modeling of the effects of stellar encounters on planetary systems in clusters are based on pure N -body simulations where the effects of circumstellar disks are neglected (Malmberg et al. 2011, 2007; Malmberg & Davies 2009; Zakamska & Tremaine 2004). However, as suggested by the near coincidence between the cluster lifetime and that of circumstellar disks, this assumption may not be fully justified. Close stellar flybys are frequent in the initial stages of cluster evolution when the disks are still interacting with the embedded planets. We concentrate in this paper on the effects of close stellar encounters on planets still embedded in their birth disk. Fragner & Nelson (2009) have shown that stellar flybys significantly altering the orbital parameters of planets are also expected to affect the disk structure. Via hydrodynamical simulations they find that stellar encounters with distances less than three times the disk radius r_d can cause a significant shrinkage of the disk. They concentrated on the effects of the modification of the disk structure on planet growth and migration, suggesting that giant

planets in systems involved in stellar encounters during their early evolution should have higher masses and larger semimajor axes. We focus instead on the damping effects of the disk on the eccentricity of a planet after which a stellar encounter significantly excited it. For this reason we resort to hydrodynamical modeling to simultaneously compute the disk and planet evolution during and after the stellar flyby. Our goal is to test whether the tidal interaction of the planet(s) with the disk, even truncated after the encounter, is able to damp the planet eccentricity excited after the flyby. The damping might also prevent the onset of gravitational instability in multi-planet systems at later times. We consider an evolved disk with a density significantly lower than the minimum mass solar nebula since planet growth is supposed to have already occurred.

The paper is organized as follows. In Sect. 2 we describe the numerical algorithm used to model the disk and planet evolution during and after a hyperbolic close encounter with another star. Section 3 is devoted to single-planet evolution after a stellar flyby, while in Sect. 4 we explore the evolution of three planet systems. In Sect. 5 we discuss the results of our numerical simulations and their implications for the statistical distribution of the planet orbital elements.

2. The numerical model

We used the numerical code FARGO (Masset 2000) to model the time evolution of a planet embedded in a two-dimensional circumstellar disk surrounding a solar type star ($M = 1 M_{\odot}$). The reliability of FARGO, without additional special numerical resolution requirements, has been recently confirmed by Kley et al. (2012). The code solves the hydrodynamical equations on a polar grid, and it uses an upwind transport scheme along with a harmonic, second-order slope limiter (van Leer 1977). We focused on evolved disks since we assumed that planets have already formed or are in their final growth stage. At this stage, along with viscous diffusion, the disk is also dispersed by photoevaporation produced by photons emitted by the central star and, possibly, by nearby stars. For this reason we adopt a low initial disk's surface density, which allowed us to neglect the effects of disk self-gravity. For the same reason we can work under the assumption that the disk is locally isothermal so that the temperature only depends on r and H/r is a constant. The initial density profile is $\Sigma = \Sigma_0 r^{-1/2}$ where Σ_0 is the 2D density at 1 AU from the star and was set to 100 g/cm^2 , a value significantly lower than that of the minimum mass solar nebula, which is at least ten times higher, while for the aspect ratio H/r we chose 0.05. A constant shear kinematic viscosity, $\nu = 10^{-5}$ in code units (mass unit is $1 M_{\odot}$, G is equal to 1, while the length unit is set to 1 AU), is adopted in all simulations. The disk ranges initially from 0.5 to 30 AU, and the density is smoothly reduced to a floor value of 1×10^{-9} (in code units) beyond 30 AU. The computational domain extends to 50 AU and is discretized in 864×240 grid zones, in r and θ . An outflow boundary condition is adopted at both the grid's inner and outer edges. No mass can flow back into the system once it has escaped. The secondary star ($M = 1 M_{\odot}$) is started on a hyperbolic orbit having a minimum impact parameter q fixed at the beginning of the simulation, larger than the outer border of the grid. It is initially located at a distance of 800 AU from the star with the planetary system and the relative velocity at infinity is set to 1 km s^{-1} , a typical value in clusters.

One or more planets are considered and their orbits are affected by the disk, the mutual gravitational attraction if more than one planet is present, the gravitational force of the central star, and that of the passing star. To properly model the

Fig. 1. Evolution of the eccentricity of a Jupiter size planet during and after a close stellar encounter in a pure three-body problem (no disk). The initial mean anomaly M of the planet is sampled with a step of 30° starting from 0° . The eccentricity step Δe depends on the initial value of M which changes the geometrical configuration of the 3 bodies at the stellar encounter.

strong gravitational interactions between the passing star and the planets, the numerical integrator computing the planet orbits (a 5th order Runge Kutta in FARGO) has been updated with a variable stepsize.

The orbital changes of the planet orbit caused by the stellar flyby significantly depend on the approach configuration. In Fig. 1 we show the outcome of pure three-body numerical integrations (the disk is neglected) showing the eccentricity evolution of the planet for different initial values of its mean anomaly M sampled from 0° to 360° with a constant interval of 30° (the second star trajectory is kept fixed). Since the initial orbit of the planet is circular, this is the only relevant angle in determining the relative position of stars and planet when the flyby occurs. The jump in eccentricity Δe due to the stellar flyby perturbations significantly depends on M and ranges approximately from about 0.13 to 0.27. Since our goal is to show that the disk is able to damp the eccentricity pumped up during stellar encounters, in our full model stars-planet-disk we always look for initial conditions leading to the largest Δe . However, the outcome shown in Fig. 1 give us only an indication of the eccentricity variation but cannot guide us in looking for the initial value of M to set in the input file of FARGO to get the maximum Δe . This because the evolution of the planet embedded in the disk is different from a pure three-body problem. The interaction with the disk causes migration in the time interval from the beginning of the simulation and the occurrence of the stellar encounter and this leads to a different geometrical configuration at the encounter. For this reason, in each model we perform four test runs where we sample the initial value of M of the planet and we continue the model with the largest Δe , the most perturbing configuration. We cannot perform an accurate sampling, like the one shown in Fig. 1, using the complete model that includes the stars, the planet(s), and the disk since it would be too much time consuming.

The FARGO code is two-dimensional (2D), so our modeling covers those cases where the trajectory of the incoming star is not very inclined with respect to the planet's orbit. A full three-dimensional (3D) approach would be able to cover a wider range of situations where the inclination of the passing star is large. In this case we expect not only a significant warping of the disk but also a step in the inclination of the planet in addition to that in

eccentricity. However, once the warping of the disk is damped after the stellar encounter, the inclination of the disk relative to the new disk plane might be quickly damped as shown in Marzari & Nelson (2009), Bitsch & Kley (2011), and Cresswell et al. (2007). As a consequence, we expect that also in an inclined configuration the final outcome would be a damping of both the eccentricity and inclination forced by the stellar flyby and then an almost complete cancellation of the flyby effects on the planetary system in terms of eccentricity and inclination excitation. We plan to perform in the future 3D simulations to explore the detailed evolution of the system when a significant inclination is assumed for the star's trajectory, but it would be a more difficult task due to still very time-consuming performance of 3D codes.

It is interesting that in their paper Cresswell et al. (2007) compared the damping rate of eccentric Neptune size planet in 2D and 3D models in denser disks and then less evolved than those we study in this paper. They conclude that for high initial eccentricities of the planet orbit ($e > 0.1$) there is a discrepancy in the eccentricity damping rate of about 20% possibly due to the potential softening applied in 2D simulations. Their scenario is different from ours since they have an almost stationary disk perturbed only by the planet while our disk is strongly affected by the stellar flyby. However, this indicates that 3D simulation would confirm our results concerning the eccentricity damping of the planetary system after the stellar encounter, even if at a different rate. This is not a potential problem since the timescale of the eccentricity damping is shorter than the lifetime of the leftover disk in our scenario.

3. Case A: a single planet orbiting at 18 AU from the star

We first consider a planet with a mass equal to $M_p = 30 M_\oplus$, a super-Earth or the core of a giant planet, initially on a circular orbit ($e = 0$) around the star with semimajor axis $a = 18$ AU. Such a large semimajor axis is adopted to cover the extreme cases where the planet is located close to the outer border of the disk after the stellar flyby and might be less affected by the disk force. When the planet is fully embedded in the disk, it is expected that the damping is faster and efficient. The minimum approach distance during the stellar encounter q is set to 70 AU. This is a close encounter configuration that has strong effects on both the disk and planet orbit. In fact, when the passing star approaches the system, a significant amount of mass is stripped away from the disk. At the same time, the orbital elements of the planet are changed on a short timescale. A sudden jump occurs in both eccentricity and semimajor axis, as predicted by Malmberg et al. (2011, 2007), Malmberg & Davies (2009), and Zakamska & Tremaine (2004).

In Fig. 2 we show the evolution of the disk during the stellar flyby. More than half of the initial mass $M_{d0} = 0.008 M_\odot$ is lost, and the disk is left with $M_d = 0.003 M_\odot$. Just after the encounter the disk is shrunk to about 12 AU, and it relaxes to 14 AU with time (assuming that its border is marked by a density of $10^{-5.5}$, which is the lowest density of the disk at the truncation radius and before the stellar encounter). The elliptical internal low-density region around the central star has been observed in a number of previous numerical studies of isothermal disks in binaries (Kley et al. 2008; Marzari et al. 2009, 2012). It is related to the formation of strong spiral density waves that propagate all over the disk and cause a flow of mass through the inner border of the disk down to the star surface. It disappears at later times due to the continuing viscous evolution of the disk.

Fig. 2. Contours of the gas density (in normalized units) when the passing star is at 800 AU before the pericenter passage (*top panel*), 150 AU and 10 000 AU after the pericenter (*middle and bottom panels*, respectively).

Fig. 3. Evolution of the eccentricity and semimajor axis of a light planet ($M_p = 30 M_\oplus$) in a circumstellar disk during and after a close stellar encounter. The eccentricity is damped on a short timescale and normal migration is resumed.

In spite of the strong mass depletion, the disk is still able to interact with the planet and circularize its orbit. This behavior is illustrated in Fig. 3. The planet eccentricity is excited to about 0.2 and the semimajor axis jumps down to 17.5 AU during the interaction with the passing star. However, the subsequent interactions between the disk and the planet damps the eccentricity on a short timescale (less than 10^4 yr) and, at the same time, the planet resumes its type I migration inwards. It is clear from this example that, if excited by stellar encounters, planets on inner orbits will return to circular orbits on an even shorter timescale since the gas density increases closer to the star.

A second simulation was performed with a Jupiter-size planet $M_p = 1 M_J$ and with the same configuration for the disk and the passing star. To make the model more precise, we should have run the code without the passing star and with the planet on a fixed orbit to give it the time to carve a gap in the disk at its location prior to the stellar flyby. However, as also shown by [Fragner & Nelson \(2009\)](#), a close stellar encounter strongly perturbs the disk, destroying any previous structure present in it. A pre-existing planetary gap would be fully erased by the tidal perturbations of the passing star.

As in the case of the light planet, after the initial step due to the passing star perturbations, the eccentricity of the Jupiter-size planet is damped on a short timescale as shown in Fig. 4. Just after the stellar encounter, the planet is left on an eccentric orbit, and without a gap. It has a fast inward migration that halts when its eccentricity is damped to almost zero. At that time, it

Fig. 4. Same as in Fig. 3 but for a more massive planet ($M_p = 1 M_J$). Even in this case the eccentricity is damped and type II migration resumed.

has carved a new gap around its orbit, and it resumes its regular type II migration. Even in this case the stellar encounter does not leave the system with a planet on an eccentric orbit, but it eventually causes a period of rapid inward migration after destroying the gap that the planet developed prior the encounter. But, after about 10^4 yr, the system has absorbed most, if not all, the perturbing effects of the stellar encounter. The disk may still bear some eccentricity, but the viscous evolution will bring it back to a circular state. When this happens, the system will have erased all records of the close stellar passage.

4. Case B: three planets orbiting the star

Stellar encounters are important for multiplanet systems since they could trigger a phase of dynamical instability followed by the ejection of one or more planets and significant changes in the orbital architecture. If the eccentricity of the outer planet is excited by a passing star, Hill's stability might be destroyed, leading to a phase of planet-planet scattering at later times ([Malmberg et al. 2011, 2007](#); [Malmberg & Davies 2009](#); [Zakamska & Tremaine 2004](#)). A high eccentricity is actually the first step in developing of a chaotic behavior.

We explore here the case of a system made of three Jupiter size planets embedded in an evolved disk and migrating towards the star. We preferred a three-planet system rather than a two-planet one for its higher dynamical complexity and stronger tendency to develop crossing orbits ([Chatterjee et al. 2008](#)). [Marzari et al. \(2010\)](#) have already studied a system of three giant planets embedded in a circumstellar disk, and they show that the

Fig. 5. Evolution of a 3-planet system ($M_{p1} = M_{p2} = M_{p3} = 1 M_J$) during and after the stellar encounter. Even in this case the eccentricity is damped in less than 10 Kyr.

migration leads the planets into different evolutionary paths, either mutual resonance trapping or planet-planet scattering. The choice between the two dynamical paths depends on the masses of the planets and on the disk physical properties. In this paper we investigate whether the stellar flyby is always leading to planet-planet scattering with final eccentric orbits that can be observed or if, again, the influence of the disk is able to damp the eccentricity of the planets and erase any memory of the chaotic phase.

In Fig. 5 we illustrate the evolution of a three-planet system with the planets initially on circular orbits with semimajor axis 5, 10, 18 AU, respectively. The eccentricity of all planets are excited during the stellar encounter. The outer planet shows a sudden step when the passing star reaches the pericenter, and the other two planets are strongly perturbed, at subsequent times, both by the eccentricity of the outer planet and by the strong eccentricity developed by the disk. The inner planet is the most affected by the turmoil of the stellar encounter, and its eccentricity is slowly pumped up to almost 0.4. However, the disk is slowly circularized and the subsequent disk-planet interactions damp the eccentricities of all the planets. After about 10^4 yr, the system has completely erased the effects of the stellar encounter, and all the three planets migrate towards the star at a slow rate trapped in a mutual 2:1 resonant configuration. Their further evolution would be no different from what is observed in a single star that has not undergone a stellar encounter even if a longer integration would be needed to figure out if the resonant capture is stable or not. However, this is beyond the scope of this

Fig. 6. Same as in Fig. 5 but for a system initially more compact ($a_1 = 4$ AU, $a_2 = 8$ AU and $a_3 = 12$ AU). The eccentricity is damped and only the forced component due to mutual gravitational interactions between the planets is left.

paper which focuses on showing that the disk is able to erase the effects of stellar encounters.

A second more compact system was modeled where the planets are closer to each other. The inner one has a semimajor axis of 4 AU, the middle one of 8 AU, and the outer of 12 AU. The stellar hyperbolic trajectory is kept the same. Even in this case we observe a consistent eccentricity excitation for all three planets. In Fig. 6 we show the orbital element evolution of the system before and after the close stellar passage. A close encounter occurs between the two outer planets, but even in this case on the long term the disk damping takes over, and the eccentricity is slowly reduced after about 10 Kyr from the stellar encounter. The system returns to a quiet evolution with the planetary eccentricities reduced to pre-encounter values with an additional forced component due to the mutual secular perturbations. The planets keep migrating inside within a common gap as shown in Fig. 7. The two inner planets are trapped in a 2:1 resonance, while the outermost planet is drifting at almost the same speed as the resonant pair. This does not mean that the stellar encounter did not affect the evolution of the system since the semimajor axes possibly evolved faster during the period of high eccentricity. However, at the end of the excited period, the eccentricities are damped, and simply by looking at the values of the semimajor axes, it is not possible to guess the occurrence of the stellar encounter. This same behavior was observed in other simulations where the initial orbital elements had different initial orbital angles.

Fig. 7. Disk density distribution in cylindrical coordinates after the stellar flyby. The three planets are migrating inside, and they have carved a partial gap. The two inner planets are in a 2:1 mean motion resonance.

As shown in Marzari et al. (2010), a wide variety of outcomes are possible after the chaotic scattering phase ranging from orbital exchange, planet merging, and scattering of a planet in a hyperbolic orbit. Of course in 2D models like those shown in Marzari et al. (2010) and presented here, the probability of planet merging is significantly increased over a more realistic 3D model, since the 2D cross section for impact is significantly larger than for the 3D one. However, this is a possibility that needs to be taken into account. In the case of three planet systems perturbed by a stellar flyby we expect that the statistical distribution of all possible outcomes is different from the unperturbed case. In particular, the occurrence of planet-planet scattering as shown in Fig. 6 may occur more frequently than the unperturbed case due to the large perturbations in the planet orbits induced by the stellar encounter. However, a deep exploration of the parameter space is required, and this appears to be a really complicated task due to the large number of free parameters, such as the masses of the planets, their initial orbits, and the disk parameters. Undertaking this task would bring out the real influence of stellar flybys on the planet architecture of systems embedded in clusters, not in terms of eccentricity excitation but in the semimajor axis and mass distribution of the planets. Unfortunately, the required amount of CPU time even for a 2D statistical exploration appears out of reach for the moment.

5. Resolution

To validate our results and demonstrate that the damping of eccentricity after a stellar flyby is a robust result and that it does not depend on the grid resolution used in FARGO, we performed two additional simulations for the case of a single massive planet shown in Fig. 4, which represents our standard model. The first is a lower resolution run with a grid size of 432×120 , while the second is a high-resolution run with a 1152×320 grid. The outcome of these two additional models are shown in Fig. 8, where they are compared to the standard resolution model. The three runs confirm that the eccentricity damping occurs independently of the resolution used in the code. However, there are differences in the eccentricity evolution, which are mostly related to the configuration of the planet at the stellar encounter. As shown in Fig. 1,

Fig. 8. Eccentricity evolution of a single massive planet for 3 different grid resolutions: 432×120 , 864×240 and 1152×320 , respectively. The parameters are the same as used in the model shown in Fig. 4.

the eccentricity jump depends on the position of the planet in its orbit, i.e. on its mean anomaly M , when the stellar passes close to the planet. If a different resolution is used, prior to the stellar encounter the evolution of the semimajor axis due to the interaction with the disk will be slightly different, and the value of M at the stellar encounter will differ in the three runs. This leads to an avalanche effect that affects the peak eccentricity at the stellar flyby, the subsequent planet migration and the damping rate. However, Fig. 8 confirms that erasing the stellar flyby effects is a robust effect, and the resolution does not alter the morphology of the long-term evolution of the system, which tends towards the circularization of the planet orbit.

6. Discussion and conclusions

We have shown that circumstellar disks are able to absorb the effects of close stellar encounters on planetary systems orbiting stars in clusters. The orbital eccentricity of planets is excited during the stellar passage, but the disk damps it back to low values on a short timescale on the order of 10 Kyr. This damping is very efficient since in our simulations we consider evolved disks with a density at least ten times lower than the MMSN. This assumption is dictated by the fact that planets take time to form, and in the meantime the disk is slowly dissipating by viscous evolution and photo-evaporation.

The relevance of disk eccentricity damping may be significant since stellar flybys are expected to be more frequent and closer in the early stages of a stellar cluster lifetime. As a matter of fact, the timescale on which a cluster loses its gaseous component and begins to disperse is comparable to the circumstellar disk lifetime. Statistically, a large fraction of close stellar encounters are expected to occur while the circumstellar disk is still present and able to damp the eccentricity induced by the stellar flyby.

Our results do not imply that stellar flybys do not affect the evolution of planetary systems in clusters. However, they may do it in a more subtle way if the circumstellar disk is still present. The eccentricity is quickly damped, but the evolution of the system, in particular planet migration, is faster when the eccentricity is excited and the disk may also temporarily enhance the eccentricity excitation, as shown in the case of three planet systems. Even close encounters can occur, but after the period of dynamical excitation, the disk damps the eccentricity, the system returns to a quiet state, and it resumes normal migration

speed. By inspecting the dynamical properties and architecture of planetary systems around stars that were members of clusters, it would be difficult “a posteriori” to distinguish between systems whose evolution was influenced by stellar flybys and those that were not. The influence of stellar flybys will be detectable only on a statistical basis as shown by the modeling of [Fragner & Nelson \(2009\)](#). Many parameters are indeed affecting the behavior of the disk+planet system during the stellar flyby, and they include the initial disk density profile and the architecture of the planetary system. A large number of simulations are required to statistically assess the contribution of stellar flybys to the evolution of planetary systems in clusters.

Our modeling is based on a 2D code, so the results apply to scenarios where the passing star has a small inclination with respect to that of the planet’s orbit. In the future we plan to perform full 3D simulations to test the effect of an inclined stellar flyby on the planetary system embedded in the disk both on the eccentricity and inclination of the planet.

References

- Adams, F. C. 2000, *ApJ*, 542, 964
- Allen, L., Megeath, S. T., Gutermuth, R., et al. 2007, *Protostars and Planets V*, 361
- Bitsch, B., & Kley, W. 2011, *A&A*, 530, A41
- Chandar, R., Fall, S. M., & Whitmore, B. C. 2010, *ApJ*, 711, 1263
- Chatterjee, S., Ford, E. B., Matsumura, S., & Rasio, F. A. 2008, *ApJ*, 686, 580
- Cresswell, P., Dirksen, G., Kley, W., & Nelson, R. P. 2007, *A&A*, 473, 329
- Dukes, D., & Krumholz, M. R. 2012, *ApJ*, 754, 56
- Fall, S. M., Chandar, R., & Whitmore, B. C. 2009, *ApJ*, 704, 453
- Fragner, M. M., & Nelson, R. P. 2009, *A&A*, 505, 873
- Haisch, Jr., K. E., Lada, E. A., & Lada, C. J. 2001, *ApJ*, 553, L153
- Hillenbrand, L. A. 1997, *AJ*, 113, 1733
- Kley, W., Papaloizou, J. C. B., & Ogilvie, G. I. 2008, *A&A*, 487, 671
- Kley, W., Müller, T. W. A., Kolb, S. M., Benítez-Llambay, P., & Masset, F. 2012, *A&A*, 546, A99
- Malmberg, D., & Davies, M. B. 2009, *MNRAS*, 394, L26
- Malmberg, D., Davies, M. B., & Heggie, D. C. 2011, *MNRAS*, 411, 859
- Malmberg, D., de Angeli, F., Davies, M. B., et al. 2007, *MNRAS*, 378, 1207
- Marzari, F., & Nelson, A. F. 2009, *ApJ*, 705, 1575
- Marzari, F., Scholl, H., Thébault, P., & Baruteau, C. 2009, *A&A*, 508, 1493
- Marzari, F., Baruteau, C., & Scholl, H. 2010, *A&A*, 514, L4
- Marzari, F., Baruteau, C., Scholl, H., & Thebault, P. 2012, *A&A*, 539, A98
- Masset, F. S. 2000, in *Disks, Planetesimals, and Planets*, eds. G. Garzón, C. Eiroa, D. de Winter, & T. J. Mahoney, *ASP Conf. Ser.*, 219, 75
- Palla, F., & Stahler, S. W. 2000, *ApJ*, 540, 255
- Pascucci, I., Gorti, U., Hollenbach, D., et al. 2006, *ApJ*, 651, 1177
- Porras, A., Christopher, M., Allen, L., et al. 2003, *AJ*, 126, 1916
- Rasio, F. A., & Ford, E. B. 1996, *Science*, 274, 954
- van Leer, B. 1977, *J. Comput. Phys.*, 23, 276
- Weidenschilling, S. J., & Marzari, F. 1996, *Nature*, 384, 619
- Zakamska, N. L., & Tremaine, S. 2004, *AJ*, 128, 869