EXOR OUTBURSTS FROM DISK AMPLIFICATION OF STELLAR MAGNETIC CYCLES

PHILIP J. ARMITAGE\textsuperscript{1,2}
\textsuperscript{1} JILA, University of Colorado and NIST, 440 UCB, Boulder, CO 80309-0440, USA; pja@jila.colorado.edu
\textsuperscript{2} Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder, CO, USA

Received 2016 June 20; revised 2016 November 28; accepted 2016 November 29; published 2016 December 12

\textbf{ABSTRACT}

EXor outbursts—moderate-amplitude disk accretion events observed in Class I and Class II protostellar sources—have timescales and amplitudes that are consistent with the viscous accumulation and release of gas in the inner disk near the dead zone boundary. We suggest that outbursts are indirectly triggered by stellar dynamo cycles, via poloidal magnetic flux that diffuses radially outward through the disk. Interior to the dead zone the strength of the net field modulates the efficiency of angular momentum transport by the magnetorotational instability. In the dead zone changes in the polarity of the net field may lead to stronger outbursts because of the dominant role of the Hall effect in this region of the disk. At the level of simple estimates we show that changes to kG-strength stellar fields could stimulate disk outbursts on 0.1 au scales, though this optimistic conclusion depends upon the uncertain efficiency of net flux transport through the inner disk. The model predicts a close association between observational tracers of stellar magnetic activity and EXor events.

\textit{Key words:} accretion, accretion disks – instabilities – planets and satellites: formation – protoplanetary disks

1. INTRODUCTION

EXor outbursts are repetitive moderate-amplitude accretion events observed in Class I and Class II protostellar sources (Herbig 1989). The prototypical source, EX Lupi, is a 0.6 $M_\odot$ M star with a moderate-mass disk and a quiescent luminosity of 0.7 $L_\odot$. Outbursts in EXors have durations of the order of a year, recurrence timescales of a few years, and amplitudes that can be as large as $\Delta V \approx 5$ mag (Audard et al. 2014).

The origin of EXor outbursts is something of a mystery. They resemble anaemic versions of FU Orionis outbursts (Hartmann & Kenyon 1996), which can be modeled as eruptive accretion disk phenomena localized to the inner au of the system (Zhu et al. 2009a). Indeed, with improving statistics on episodic accretion in pre-main-sequence stars it has been suggested that FUors and EXors may be limiting cases of a continuum of events that occur with a range of amplitudes in both Class I and Class II systems (Audard et al. 2014). Any observational kinship between FUors and EXors, however, sits uneasily with theoretical models for these phenomena. Hartmann & Kenyon (1996) noted that a continuous range of outbursts would be consistent with thermal instability models (Bell & Lin 1994), but this conclusion probably does not carry forward to more recent models for FU Orionis outbursts that involve a limit cycle in which the inner disk alternates between a cold “dead zone” (Gammie 1996) and a rapidly accreting hot state, whose onset is triggered by gravitational instability (Armitage et al. 2001; Martin & Lubow 2011). Time-dependent calculations of such a grave-magno limit cycle can broadly match observations (Zhu et al. 2009b; Bae et al. 2014). It is unlikely that the same model could be scaled down for EXors, whose lower-mass disks and modest outbursts disfavor any role for gravitational instability. The same is true of an alternate class of models that links FU Orionis events to gravitational instability in the outer disk (Vorobyov & Basu 2005). Models that invoke Roche lobe overflow from close-in planets have more potential to produce phenomenology that spans FUor and EXor-class events (Nayakshin & Lodato 2012), but are less studied.

We propose that EXor outbursts in the inner disk are externally triggered by changes in the strength and polarity of the stellar magnetic field. Young stars—including EXors (Hamaguchi et al. 2012)—are frequently magnetically active (Bouvier et al. 2007), and cyclic accretion could occur as a consequence of either a time-variable torque on the inner disk (Armitage 1995; Clarke et al. 1995), or from instability of a trapped disk whose inner edge is near corotation (D’Angelo & Spruit 2010). D’Angelo & Spruit (2012) developed an explicit model for EXors based on the latter idea. In addition to this direct influence differential rotation between the star and the inner disk inflates and ultimately opens up a fraction of the stellar field lines (Lynden-Bell & Boily 1994; Agapitou & Papaloizou 2000). Outward diffusion of this stellar flux can modulate the net flux threading the inner disk and dead zone. Under ideal magnetohydrodynamic (MHD) conditions, a weak net flux acts to stimulate accretion occurring as a consequence of the magnetorotational instability (Hawley et al. 1995). Slightly further out, in the dead zone, the Hall effect (Warde 1999; Balbus & Terquem 2001) is the most important non-ideal MHD process (for reviews, see Armitage 2011; Turner et al. 2014). Simulations show that the efficiency of angular momentum transport in the Hall-dominated regime differs dramatically depending upon whether the net field is aligned or anti-aligned to the rotation axis (Bai 2014; Lesur et al. 2014; Simon et al. 2015). We therefore suggest that EXor outbursts occur due to the MHD response of the inner disk to the changing strength and polarity of a stellar-derived net magnetic field.

2. DISK AMPLIFICATION OF STELLAR MAGNETIC ACTIVITY CYCLES

We assume that a net vertical magnetic field, derived from the stellar field, threads the inner part of the Keplerian accretion disk. At radii just outside the magnetosphere, the disk is conductive enough to behave as an ideal MHD fluid (this requires that the alkali metals are thermally ionized; Gammie 1996), while further out in the dead zone non-ideal MHD effects are dominant. In both regimes, the effect of the net
vertical field on accretion is conventionally parameterized by the mid-plane ratio of gas to magnetic pressure:

$$\beta_z \equiv \frac{P_{\text{gas}}}{B_z^2/(8\pi)}.$$  \hfill (1)

We make use of the results of shearing-box simulations in which the $B_z$ entering into the above equation is the initial field threading the local domain (e.g., Simon et al. 2015; Salvesen et al. 2016), and hence define $\beta_z$ using the gas pressure in the disk and only the external magnetic field derived from the star. Under ideal MHD conditions it is well-established that a net accretion rate into the star and its disk is likely to open up stellar magnetic fields may be multiply threaded in its magnetosphere, which may act to protect the star from significant magnetic field numerical simulations suggest that the magnetorotational instability (Balbus & Hawley 1998) yields $\alpha \approx 0.01 - 0.02$ (Davis et al. 2010; Simon et al. 2012). A net field then enhances the stress of the disk outside the magnetosphere and only the external magnetic field is an outwardly diffusing disk rather than a direct extrapolation of the stellar dipole. Second, the naive estimate for $r_{\text{crit}}$ above lies close to the inner edge of the dead zone (namely $0.1\text{ au}$ in the original model of Gammie 1996). A dynamically significant $\beta_z$ that extends into the dead zone opens up a stronger path to instability because in the Hall-dominated inner disk not just the strength but also the polarity of the net field has a decisive impact on accretion (Bai 2014; Lesur et al. 2014; Simon et al. 2015).

To estimate the disk field, we assume that differential rotation opens up stellar field that threads the disk beyond the magnetospheric radius $r_{\text{m}}$. With a dipole approximation, the open magnetic flux that is available to diffuse through the disk is

$$\Phi_{\text{open}} = 2\pi B_0 \frac{r_{\text{m}}^3}{r_{\text{m}}}.$$  \hfill (5)

The detailed distribution of open flux in the inner disk will be time-dependent and complex, but is generically expected to have a flatter distribution than a simple extrapolation of the stellar dipole. The principle dependence is on the ratio of the effective velocities for the advection and diffusion of magnetic flux, $v_{\text{adv}}$, and $v_{\text{diff}}$ (Lubow et al. 1994). Guilet & Ogilvie (2014; see also Okuzumi et al. 2014) find approximate steady-state solutions for the disk field:

$$B_z \propto r^{-n},$$  \hfill (6)

with power-law slopes

$$n = 0 \quad v_{\text{adv}}/v_{\text{diff}} \ll 1,$$

$$n = 1 \quad v_{\text{adv}}/v_{\text{diff}} \sim 1,$$

$$n = 2 \quad v_{\text{adv}}/v_{\text{diff}} \gg 1.$$  \hfill (7)

The appropriate values for the transport coefficients (and hence the ratio $v_{\text{adv}}/v_{\text{diff}}$) in protoplanetary disks are not fully determined, but the general theoretical preference is for $v_{\text{adv}}/v_{\text{diff}} \lesssim 1$ (Lubow et al. 1994). Leaving $n$ as a free parameter, we assume that after a reversal the open flux follows a power law out to some distance $r$, with no flux at larger radii. The disk

Interior to $r_{\text{crit}}$, the response of the disk depends upon how the timescale for variations in the net flux compares to the viscous timescale. Rapid changes to the flux would modulate the local $M$ at approximately constant $\Sigma$, while slow changes would lead to order unity variations in the surface density and mass of the inner disk (once it had attained a new steady state). The amount of mass involved is $\Delta m \sim \pi r_{\text{crit}}^2 \Sigma (r_{\text{crit}}) \sim (1/3) \sqrt{GM_\ast \alpha^{-1} M r_{\text{m}}^{1/2} \beta_z^{-2}}$. Adopting the same fiducial parameters as in Equation (4), we find $\Delta m \sim 4 \times 10^{-6} M_\odot$. This is comparable to the amount of mass accreted during some EXor outbursts. Audard et al. (2010), for example, estimated an accretion rate during an outburst of $10^{-6} M_\odot \text{ yr}^{-1}$ for the EXor V1118 Orionis.

The above estimate suggests that changes to the stellar magnetic field, acting indirectly via its influence on the accretion stress in the inner disk, could potentially modulate the accretion rate at levels comparable to those required to explain EXor events. We now proceed to consider two additional complications. First, differential rotation between the star and its disk is likely to open up field lines, such that the relevant net field is an outwardly diffusing disk field rather than a direct extrapolation of the stellar dipole. Second, the naive estimate for $r_{\text{crit}}$ above lies close to the inner edge of the dead zone (namely $0.1\text{ au}$ in the original model of Gammie 1996). A dynamically significant $\beta_z$ that extends into the dead zone opens up a stronger path to instability because in the Hall-dominated inner disk not just the strength but also the polarity of the net field has a decisive impact on accretion (Bai 2014; Lesur et al. 2014; Simon et al. 2015).

To estimate the disk field, we assume that differential rotation opens up stellar field that threads the disk beyond the magnetospheric radius $r_{\text{m}}$. With a dipole approximation, the open magnetic flux that is available to diffuse through the disk is

$$\Phi_{\text{open}} = 2\pi B_0 \frac{r_{\text{m}}^3}{r_{\text{m}}}.$$  \hfill (5)

The detailed distribution of open flux in the inner disk will be time-dependent and complex, but is generically expected to have a flatter distribution than a simple extrapolation of the stellar dipole. The principle dependence is on the ratio of the effective velocities for the advection and diffusion of magnetic flux, $v_{\text{adv}}$, and $v_{\text{diff}}$ (Lubow et al. 1994). Guilet & Ogilvie (2014; see also Okuzumi et al. 2014) find approximate steady-state solutions for the disk field:

$$B_z \propto r^{-n},$$  \hfill (6)

with power-law slopes

$$n = 0 \quad v_{\text{adv}}/v_{\text{diff}} \ll 1,$$

$$n = 1 \quad v_{\text{adv}}/v_{\text{diff}} \sim 1,$$

$$n = 2 \quad v_{\text{adv}}/v_{\text{diff}} \gg 1.$$  \hfill (7)

The appropriate values for the transport coefficients (and hence the ratio $v_{\text{adv}}/v_{\text{diff}}$) in protoplanetary disks are not fully determined, but the general theoretical preference is for $v_{\text{adv}}/v_{\text{diff}} \lesssim 1$ (Lubow et al. 1994). Leaving $n$ as a free parameter, we assume that after a reversal the open flux follows a power law out to some distance $r$, with no flux at larger radii. The disk
field at $r$ is then (for $n \neq 2$)

$$B_{\zeta,\text{disk}} \simeq (2 - n)B_n \frac{r^3}{r_m} r^{-2}. \quad (8)$$

Combining this with the expression for the radial dependence of the disk pressure (Equation (3)), we find

$$\beta_\zeta = \frac{8}{3\sqrt{2\pi}} \frac{GM_*}{(2 - n)^2} B_n \frac{r_m}{r_n} r \sqrt{M \alpha^{-1} c_s^{-1} r}, \quad (9)$$

where $c_s$ and $\alpha$ are to be evaluated at radius $r$. Numerically,

$$\beta_\zeta = \frac{5.6 \times 10^4}{(2 - n)^2} \left( \frac{M_*}{M_\odot} \right)^2 \left( \frac{B_n}{1.5 \text{ kG}} \right)^{-2} \left( \frac{r_n}{10 \text{ au}} \right)^{-4} \times \left( \frac{r_m}{r_n} \right)^2 \left( \frac{\dot{M}}{10^{-8} M_\odot \text{ yr}^{-1}} \right) \left( \frac{\alpha}{10^{-2}} \right)^{-1}$$

$$\times \left( \frac{c_s}{2 \text{ km s}^{-1}} \right)^{-1} \left( \frac{r}{0.1 \text{ au}} \right). \quad (10)$$

This estimate is derived assuming a steady-state disk. To apply it to the dead zone, we need to know how the mid-plane pressure there differs from that in the adjacent thermally ionized region. One possibility is that $\alpha$ at the inner edge of the dead zone is very low, in which case gas could accumulate in a high-pressure region that would render the dead zone very low, in which case gas could accumulate. One possibility is that pressure there differs from that in the adjacent thermally ionized region. One possibility is that pressure there differs from that in the adjacent thermally ionized region.

Adopting as the criterion for Hall effect physics to impact accretion at the inner edge of the dead zone that $\beta_\zeta \lesssim 10^5$, Equation (10) suggests that it is possible (but not guaranteed) for residual stellar fields diffusing through the disk to play a role. The factors that favor a role for stellar fields are lower disk accretion rates, strong stellar magnetic fields, and a larger fraction of the stellar flux available to diffuse through the disk. Exactly where the inner edge of the dead zone lies will also be critically important. The radius where the disk temperature first falls below the thermal ionization threshold of 800–1000 K (Gammie 1996; Desch & Turner 2015) is dependent on the degree of viscous heating. A purely passive disk model (Chiang & Goldreich 1997) attains temperatures of $10^5$ K only well inside 0.1 au. Models that include viscous heating (typically following an $\alpha$-prescription formalism and assuming standard dust opacity) push the critical radius out to $r \simeq 0.3$ au (Bell et al. 1997). Intermediate values would result if dead zone heating is strongly concentrated toward low optical depths near the disk surface.

Figure 1 illustrates how stellar dynamo cycles could trigger accretion outbursts via the polarity dependence of Hall MHD. Low-rate accretion occurs when the net disk field threading the inner edge of the dead zone, derived from the stellar field, is anti-aligned to the disk rotation ($\Omega \cdot \mathbf{B} < 0$). High-rate accretion is triggered when the stellar magnetic field flips and aligned net field ($\Omega \cdot \mathbf{B} > 0$) diffuses outward into the dead zone region. As noted above, the reversal in net field polarity could plausibly alter the efficiency of angular momentum transport by an order of magnitude, or more. We caution, however, that the impact of the Hall effect on disk accretion depends on details of the disk chemistry, and simulations relevant to the inner edge of the dead zone at radii interior to 1 au have not been reported.

In addition to the field being strong enough, two additional conditions need to be met for stellar magnetic cycles to trigger dead zone EXor outbursts. First, changes in the stellar field need to be communicated to the dead zone region on a timescale of, at most, a few years, to match observational constraints on outburst recurrence times (Audard et al. 2014). Second, the viscous timescale in the outburst state needs to match observations.
To estimate the timescale for communication of stellar field changes to the dead zone, we apply the transport theory developed by Lubow et al. (1994), which is based on assuming that a purely poloidal force-free field threads a thin turbulent disk. In this limit diffusion of the net field occurs on a timescale that is shorter by a factor of $\sim (h/r)$ than radial advection by the accretion flow (implying, in this scenario, that net field liberated from the magnetosphere escapes radially outward). This results in an estimate:

$$t_{\text{diff}} \sim \frac{1}{\alpha \Omega} \left(\frac{h}{r}\right)^{-1}$$

$$\sim 2.4 \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{c_s}{2 \text{ km s}^{-1}}\right)^{-1} \left(\frac{r}{0.1 \text{ au}}\right) \text{years.} \quad (11)$$

We adopt a higher value of $\alpha$ here because the field is diffusing through the inner disk, described by ideal MHD, where the net field enhances transport independent of field polarity (Hawley et al. 1995).

This estimate is crude and it ignores important physical effects. The complex and time-dependent interaction between the stellar magnetosphere and the disk (Romanova et al. 2008; Blinova et al. 2016) will affect net flux transport in the inner disk. Both MHD and force-free simulations show that open field is rapidly dispersed from the vicinity of the magnetosphere (Romanova et al. 2009; Parfrey et al. 2016). Outward transport at a rate substantially faster than that implied by the Lubow et al. (1994) model would reduce the field strength threading the dead zone and limit the influence of the Hall effect on accretion. Working in the opposite direction, the effect of the vertical disk structure on the transport coefficients can enhance (inward) advection with the mean flow (Lovelace et al. 2009). Finally, the discontinuity in disk properties at the location of the dead zone may also impact transport, perhaps particularly in the case where the inner part of the dead zone is largely laminar. None of these effects are easy to quantify. We note, however, that an outburst with an accreted mass of $10^{-6} M_\odot$ requires a surface density change of only $\Delta \Sigma \sim 300$ g cm$^{-2}$ over 0.1 au scales. It seems possible that enough field could diffuse to 0.1 au on $\sim$yr timescales to cause such a perturbation.

Potentially the hardest constraint to match is on the expected timescale of the events. If we assume that the $\sim$5 magnitude increase in brightness during an EXor event points to roughly a 2 orders of magnitude increase in accretion rate, the disk sound speed at the onset of outburst might rise by a modest factor (very approximately we expect $c_s \propto M^{-1/8}$). The nominal viscous time $t_v = r^2/v$ is then

$$t_v \sim \sqrt{GM_\odot \alpha^{-1} c_s^{-2} r^{1/2}}$$

$$\sim 28 \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{c_s}{4 \text{ km s}^{-1}}\right)^{-2} \left(\frac{r}{0.1 \text{ au}}\right)^{1/2} \text{years.} \quad (12)$$

In practice, the evolution of disk structures containing sharp initial gradients occurs on a small fraction of the nominal viscous time (see, e.g., the Green’s function solution for a narrow ring; Pringle 1981), so the above estimate is likely marginally consistent with EXor durations of the order of a year. Generically, if both FUors and EXors originate from disk instabilities associated with the dead zone, we expect FUors to be longer-lived events, consistent with observations, as the inner edge of the dead zone is further out at higher accretion rates.

3. DISCUSSION

We have argued that EXor outbursts could be triggered by stellar dynamo cycles, via a mechanism that involves diffusion of stellar magnetic flux through the inner disk into the Hall-dominated dead zone. There are obvious uncertainties. In the region of the disk governed by ideal MHD, we have ignored the possibility that net flux threading the inner disk launches a disk wind (Bai & Stone 2013) and neglected the known complexities of disk–magnetosphere interactions (Romanova et al. 2009; Parfrey et al. 2016). In the dead zone, we have motivated our arguments using simulations that are strictly appropriate only at larger radii, and although the physics underlying the Hall-mediated bimodality in accretion stress is well-established (Wardle 1999; Bai 2014; Lesur et al. 2014; Simon et al. 2015), our conclusions are quite dependent on the location of the inner edge of the dead zone. More broadly, of course, it is not known whether EXors hosts exhibit the requisite dynamo activity.

Observationally, an association between EXors and stellar magnetic activity is an obvious possibility given the timescales, recurrences, and approximately periodic nature of the outbursts. Irrespective of the details, the model predicts that EXor events ought to correlate with indicators of stellar magnetic activity (with a lag reflecting the propagation timescale of magnetic field through the disk), and might be preferentially seen toward those stars with the strongest magnetic activity.

In the broader context of eruptive protostellar phenomena, some recent observational studies advocate a scenario in which FUors and EXors are members of a continuum of outbursting systems (Audard et al. 2014). Such a scenario appears consistent with a theoretical model in which FUors and EXors both arise from modulation of inner disk accretion related to instabilities that occur near the inner edge of the dead zone at 0.1–1 au scales. What may distinguish EXors and FUors is the nature of the trigger, with EXors being externally triggered by changes in the stellar magnetic field, whereas FUors are internally triggered by the onset of gravitational instability (Armitage et al. 2001).

I thank the referee for an insightful report, and acknowledge support from NASA through grants NNX13A158G and NNX16AB42G, and from the NSF through grant AST 1310321.

REFERENCES

Agapitou, V., & Papaloizou, J. C. B. 2000, MNras, 317, 273
Armitage, P. J. 1995, MNras, 274, 1242
Armitage, P. J. 2011, ARA&A, 49, 195
Armitage, P. J., Livio, M., & Pringle, J. E. 2001, MNras, 324, 705
Audard, M., Ábrahám, P., Dunham, M. M., et al. 2014, in Protostars and Planets VI, ed. H. Beuther et al. (Tucson, AZ: Univ. Arizona Press, Tucson), 387
Audard, M., Stringfellow, G. S., Güdel, M., et al. 2010, A&A, 511, A63
Bae, J., Hartmann, L., Zhu, Z., & Nelson, R. P. 2014, ApJ, 795, 61
Bai, X.-N. 2014, ApJ, 791, 137
Bai, X.-N., & Stone, J. M. 2013, ApJ, 769, 76
Balbus, S. A., & Hawley, J. F. 1998, RvMP, 70, 1
Balbus, S. A., & Terquem, C. 2001, ApJ, 552, 235
Bell, K. R., Cassen, P. M., Klahr, H. H., & Henning, T. 1997, ApJ, 486, 372
Bell, K. R., & Lin, D. N. C. 1994, ApJ, 427, 987
Blinova, A. A., Romanova, M. M., & Lovelace, R. V. E. 2016, *MNRAS*, 459, 2354
Bouvier, J., Alencar, S. H. P., Harries, T. J., Johns-Krull, C. M., & Romanova, M. M. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press, Tucson), 479
Chiang, E. I., & Goldreich, P. 1997, *ApJ*, 490, 368
Clarke, C. J., Armitage, P. J., Smith, K. W., & Pringle, J. E. 1995, *MNRAS*, 273, 639
D’Angelo, C. R., & Spruit, H. C. 2010, *MNRAS*, 406, 1208
D’Angelo, C. R., & Spruit, H. C. 2012, *MNRAS*, 420, 416
Davis, S. W., Stone, J. M., & Pessah, M. E. 2010, *ApJ*, 713, 52
Desch, S. J., & Turner, N. J. 2015, *ApJ*, 811, 156
Gammie, C. F. 1996, *ApJ*, 457, 355
Gole, D., Simon, J. B., Lubow, S. H., & Armitage, P. J. 2016, *ApJ*, 826, 18
Guilet, J., & Ogilvie, G. I. 2014, *MNRAS*, 441, 852
Hamaguchi, K., Grosso, N., Kastner, J. H., et al. 2012, *ApJ*, 754, 32
Hartmann, L., & Kenyon, S. J. 1996, *ARA&A*, 34, 207
Hawley, J. F., Gammie, C. F., & Balbus, S. A. 1995, *ApJ*, 440, 742
Hayashi, C. 1981, *PThPS*, 70, 35
Herbig, G. H. 1989, in European Southern Observatory Conf. and Workshop Proc, 33, ed. B. Reipurth (Garching: ESO), 233
Lesur, G., Kunz, M. W., & Fromang, S. 2014, *A&A*, 566, A56
Lovelace, R. V. E., Rothstein, D. M., & Bisnovatyi-Kogan, G. S. 2009, *ApJ*, 701, 885
Lubow, S. H., Papaloizou, J. C. B., & Pringle, J. E. 1994, *MNRAS*, 267, 235
Lynden-Bell, D., & Boily, C. 1994, *MNRAS*, 267, 146
Martin, R. G., & Lubow, S. H. 2011, *ApJL*, 740, L6
Nayakshin, S., & Lodato, G. 2012, *MNRAS*, 426, 70
Okuzumi, S., Takeuchi, T., & Muto, T. 2014, *ApJ*, 785, 127
Parfrey, K., Spitkovsky, A., & Beloborodov, A. M. 2016, *MNRAS*, submitted (arXiv:1608.04159)
Pringle, J. E. 1981, *ARA&A*, 19, 137
Romanova, M. M., Kulkarni, A. K., & Lovelace, R. V. E. 2008, *ApJL*, 673, L171
Romanova, M. M., Ustyugova, G. V., Koldoba, A. V., & Lovelace, R. V. E. 2009, *MNRAS*, 399, 1802
Salvesen, G., Simon, J. B., Armitage, P. J., & Begelman, M. C. 2016, *MNRAS*, 457, 857
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Simon, J. B., Beckwith, K., & Armitage, P. J. 2012, *MNRAS*, 422, 2685
Simon, J. B., Lesur, G., Kunz, M. W., & Armitage, P. J. 2015, *MNRAS*, 454, 1117
Turner, N. J., Fromang, S., Gammie, C., et al. 2014, in Protostars and Planets VI, ed. H. Beuther et al. (Tucson, AZ: Univ. Arizona Press, Tucson), 411
Vorobyov, E. I., & Basu, S. 2005, *ApJL*, 633, L137
Warde, M. 1999, *MNRAS*, 307, 849
Zhu, Z., Espaillat, C., Hinkle, K., et al. 2009a, *ApJL*, 694, L64
Zhu, Z., Hartmann, L., & Gammie, C. 2009b, *ApJ*, 694, 1045