On the Evolution of the Snow Line in Protoplanetary Discs

Rebecca G. Martin and Mario Livio

Space Telescope Science Institute,
3700 San Martin Drive, Baltimore, MD 21218, USA

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Abstract

We model the evolution of the snow line in a protoplanetary disc. If the magneto-rotational instability (MRI) drives turbulence throughout the disc, there is a unique snow line outside of which the disc is icy. The snow line moves closer to the star as the infall accretion rate drops. Because the snow line moves inside the radius of the Earth's orbit, the formation of our water-devoid planet is difficult with this model. However, protoplanetary discs are not likely to be sufficiently ionised to be fully turbulent. A dead zone at the mid-plane slows the flow of material through the disc and a steady state cannot be achieved. We therefore model the evolution of the snow line also in a time-dependent disc with a dead zone. As the mass is accumulating, the outer parts of the dead zone become self gravitating, heat the massive disc and thus the outer snow line does not come inside the radius of the Earth's orbit, contrary to the fully turbulent disc model. There is a second, inner icy region, within the dead zone, that moves inwards of the Earth's orbit after a time of about 10^6 yr. With this model there is sufficient time and mass in the disc for the Earth to form from water-devoid planetesimals at a radius of 1 AU. Furthermore, the additional inner icy region predicted by this model may allow for the formation of giant planets close to their host star without the need for much migration.

Keywords: accretion, accretion discs – protoplanetary discs – stars: pre-main-sequence – planets and satellites: formation – Earth

1 Introduction

Bodies in our solar system show a distribution of water abundance. The innermost terrestrial planets contain little water compared with the outer planets. Planet formation is thought to occur from planetesimals that formed in the solar nebula. Within the solar nebula, ice forms beyond a radius from the central star known as the snow line, $R_{\rm snow}$. This is thought to play an important role in the composition of forming planets. The solid mass density outside the snow line is much higher because of water ice condensation. In fact, for a solar composition, water ice abundance is as high as silicate and iron (e.g. Pollack et al. 1994). Observations of the asteroid belt, located between Mars and Jupiter, suggest that the snow line is currently located within this region. The outer asteroids are icy C-class objects (e.g. Abe et al. 2000; Morbidelli et al. 2000) whereas the inner asteroid belt is largely devoid of water. This implies that when planetesimal formation occurred the snow line was located at around $R_{\rm snow} = 2.7\,{\rm AU}$ from the Sun.

The snow line occurs at a temperature, $T_{\rm snow}$, that is in the range of 145 K (Podolak & Zucker 2004) to 170 K (Hayashi 1981), depending on the partial pressure of nebular water vapour. Its distance from the star is usually calculated in a fully turbulent steady state accretion disc (e.g. Sasselov & Lecar 2000; Lecar et al. 2006; Kennedy et al. 2006; Kennedy & Kenyon 2008). The magneto-rotational instability (MRI) is thought to drive the turbulence in the disc (Balbus & Hawley 1991) and thus transport angular momentum outwards allowing accretion on to the central star (e.g. Fromang & Nelson 2006). Recent calculations have used a detailed disc structure and include a stellar radiation flux and viscous dissipation of the gas as the main heating sources. The disc is assumed to be in a quasi-steady state as the infall accretion rate decreases in time (e.g. Ida & Lin 2005; Garaud & Lin 2007; Min et al. 2011). Davis (2005) found that the radius of the snow line reaches a minimum of about 0.6 AU, inside the current orbit of the Earth and this was confirmed by Garaud & Lin (2007). They find that the snow line migrates inwards as the accretion rate drops (down to an accretion rate of around $\dot{M} = 10^{-10}\,\mathrm{M_\odot\,yr^{-1}}$) because the viscous dissipation decreases. However, as the accretion rate drops below $10^{-10}\,\mathrm{M_\odot\,yr^{-1}}$, the snow line migrates outwards again as the disc becomes optically thin and the temperature rises.

The fully turbulent steady state model predicts a minimum snow line radius within the Earth's orbit. If planetesimals formed during this time, the Earth would have formed from icy bodies. This appears to be contradictory with the current water content on Earth that is very low at around 0.023% by weight (Lewis 2004). For comparison, the outer solar system planets have a mass fraction of water of greater than 40%. The terrestrial planets in our solar system are thought to have formed from water-devoid planetesimals. Hence the planetesimals must have formed either before the snow line moved inward or after the snow line moved outward past the Earth's orbit. Oka et al. (2011) included ice opacity as well as the silicate opacity and find similar results to Garaud & Lin (2007). They find that there is a deficit of solid mass at the later times and formation of water-devoid planetesimals is impossible. It is improbable for the planetesimals to form before the snow line moves inwards because the timescale involved is very short. Machida & Abe (2010) investigated the possibility that the Earth formed from sublimating icy planetesimals after the snow line moved outwards. However, the extremely low observed water content on Earth appears to be an unlikely outcome, because of the competition between sublimation and collision of the planetesimals. In this paper we attempt to address the inconsistency between the theoretical models for the snow line evolution and the observations of the solar system.

Protoplanetary discs may have a region of low turbulence at the disc mid-plane. The MRI drives turbulence but may be suppressed by a low ionisation fraction (Gammie 1996; Gammie & Menou 1998). The inner parts of the disc are hot enough to be thermally ionised but farther away from the central star, cosmic rays are the dominant source of ionisation and these can only penetrate the surface layers. The mid-plane layer, the dead zone, has no turbulence. A variation of the turbulence with height from the mid-plane has been considered in some previous snow line models (e.g. Kretke & Lin 2007). However, the mid-plane layer had a sufficiently large viscosity that a steady disc was still achieved. Kretke & Lin (2010) consider the vertical structure of a layered disc and find that the location of the snow line is a little more ambiguous with the vertical stratification. The upper layers of the disc have a cooler temperature and so the snow line is closer to the star in the surfaces than at the mid-plane. For an accretion rate of $10^{-8}\,\mathrm{M_\odot\,yr^{-1}}$ they predict a snow line radius of around 1 AU. This is similar to that found by Garaud & Lin (2007) and Oka et al. (2011) for the fully turbulent disc model.

If there is no turbulence within the dead zone, the disc cannot be in a steady state and it is this possibility that we consider here. Material accumulates in the dead zone which can then become gravitationally unstable. While the infall accretion rate is high, this can lead to the gravo-magneto disc instability. The disc spends the majority of the time with a dead zone in a quiescent state with a low accretion rate on to the star. However, the extra turbulence driven by the gravitational instability in the dead zone increases the disc temperature until the MRI is triggered. This causes a large accretion outburst on to the star that is thought to explain FU Orionis outbursts (Armitage et al. 2001; Zhu et al. 2010; Martin & Lubow 2011). At later times, when the infall accretion rate drops, there is not sufficient material in the disc for the gravo-magneto instability to operate but a dead zone may still be present (Martin et al. 2012a). Given this rather different (from a steady-state disc) configuration and behaviour, in this paper, we consider the evolution of the snow line in a time dependent disc model that includes a dead zone.

2 Protoplanetary Disc Model

The material in an accretion disc orbits the central mass, M, with a Keplerian velocity at radius R with angular velocity $\Omega = \sqrt{GM/R^3}$ (Lynden-Bell & Pringle 1974; Pringle 1981). We use a one dimensional layered disc model described in Martin & Lubow (2011) and further developed in Martin et al. (2012a) to evolve the total surface density, $\Sigma(R,t)$ and mid-plane temperature, $T_\mathrm{c}(R,t)$. We take a solar mass star, $M = 1\,\mathrm{M_\odot}$, with a disc that extends from a radius of $R = 5\,\mathrm{R_\odot}$ up to $R = 40\,\mathrm{AU}$. Turbulence is driven by the MRI in some regions of the disc and we parametrise this viscosity with a Shakura & Sunyaev (1973) α parameter that we take to be 0.01 (e.g. Brandenburg et al. 1995) although there is still some uncertainty in this value (e.g. King et al. 2007). The disc consists of a turbulent surface layer of surface density, Σ_m and

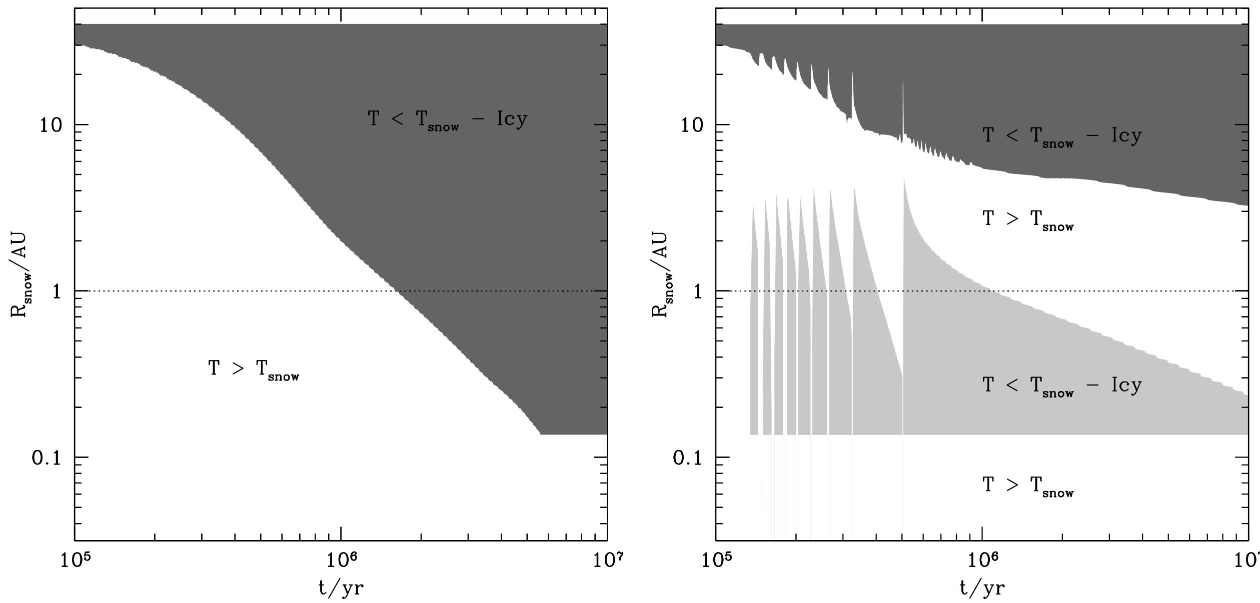

Figure 1: The evolution of the icy regions of a protoplanetary disc around a solar mass star. Left: A fully turbulent disc ($Re_{\rm M,crit} = 0$). Right: A disc with a dead zone determined by a critical magnetic Reynolds number of $Re_{\rm M,crit} = 5 \times 10^4$. Time begins at $t = 10^5\,$yr. The shaded areas show the icy regions of the disc. Where a dead zone exists there is an inner icy region (pale shaded areas) as well as the outer icy region (dark shaded areas). In the innermost parts of the disc, the radiation flux from the central star heats the disc above the snow line temperature, $T_{\rm snow}$. The dotted line shows the current radius of the Earth's orbit.

temperature $T_{\rm m}$. Where it exists, the dead zone has surface density $\Sigma_{\rm g} = \Sigma - \Sigma_{\rm m}$. The extent of the dead zone in the disc is determined by a critical magnetic Reynolds number, $Re_{\rm M,crit}(R, z)$. We use the analytical approximations for the surface density in the turbulent layer given in equations 26 and 27 of Martin et al. (2012b). The innermost parts of the disc are externally heated by a flux of radiation from the central star (see also Chiang & Goldreich 1997). We take the temperature of the star $T_{\rm star} = 3000\,{\rm K}$ and its radius to be $R_{\rm star} = 2\,{\rm R}_\odot$.

We consider a model for the collapse of a molecular cloud on to the disc (Armitage et al. 2001; Martin et al. 2012a). Initially the accretion rate is $2 \times 10^{-5}\,{\rm M}_\odot\,{\rm yr}^{-1}$ and this decays exponentially on a timescale of $10^5\,$yr. Material is added to the disc at a radius of 35 AU. The dead zone can become self gravitating when the Toomre parameter (Toomre 1964) is sufficiently small, $Q < 2$. We approximate the radius of the snow line to be where the temperature of the disc is $T_{\rm snow} = 170\,{\rm K}$. The disc models of Lecar et al. (2006) suggest that this is a good approximation for varying disc mass and opacity.

In Fig. 1 we show the evolution of the snow line in two model discs, one that is fully turbulent (or equivalently $Re_{\rm M,crit} = 0$) and one that has a dead zone determined by a critical magnetic Reynolds number of $Re_{\rm M,crit} = 5 \times 10^4$. The fully turbulent model shows a monotonic decrease of the snow line radius in time so that at late times the snow line is within the radius of the Earth's orbit at 1 AU. We do not obtain the increase of the snow line radius at smaller accretion rates shown by Oka et al. (2011) because there is sufficient mass in the disc that the model remains optically thick at the radius where the snow line occurs. For example, at a time of $2 \times 10^6\,$yr, the infall accretion rate on to the disc has dropped to less than $10^{-13}\,{\rm M}_\odot\,{\rm yr}^{-1}$ but the accretion on to the star is $6 \times 10^{-9}\,{\rm M}_\odot\,{\rm yr}^{-1}$. The disc does not remain in a quasi-steady state as the accretion rate decreases as assumed in previous models.

For the model with $Re_{\rm M,crit} = 5 \times 10^4\,$yr, initially there is no dead zone and the disc evolution proceeds as for the case with $Re_{\rm M,crit} = 0$. As the infall accretion rate drops, the disc cools and a dead zone forms in the protoplanetary disc. The inner parts of the disc remain hot because they are heated by the radiation from the central star. Within the dead zone, an icy region exists. The outer parts of the dead zone become self gravitating and this drives a small amount of turbulence that heats the disc above the snow line temperature

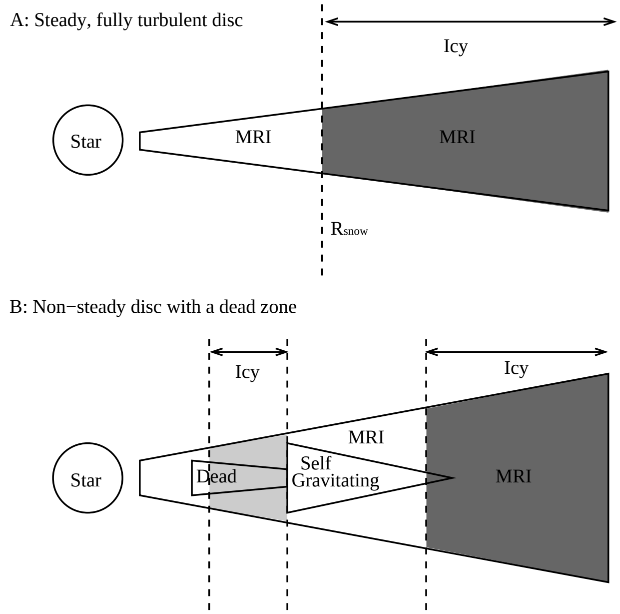

Figure 2: Sketches of the disc structure for the two models. Figure A represents a steady disc that is fully turbulent. The temperature decreases monotonically with radius and only the outer regions of the disc are icy. Figure B represents a disc with a dead zone. The outer parts of the dead zone are self-gravitating, more massive and thus have a higher temperature.. There are two icy regions in this model. The outer icy region is farther out than that predicted by the fully turbulent model. The inner icy region exists within the dead zone.The shaded regions correspond to the inner (pale shaded) and outer (dark shaded) icy regions as described in Fig. 1.

(see the sketch of the two disc models in Fig. 2). The very brief periods of time during which there is no inner icy region are when the disc is in outburst. Self gravity heats the disc sufficiently to trigger the MRI within the dead zone. The temperature of the disc increases significantly and there is an FU Orionis type outburst where the accretion rate on to the star increases by several orders of magnitude (see Martin et al. 2012a).

As with the fully turbulent disc, the outermost parts of the disc are cool and icy. At late times the outer icy region reaches a minimum radius of about 3.1 AU, roughly consistent with current observations. In our solar system, the Earth and other terrestrial planets likely formed after the inner icy region passed inside their radius because they are water devoid. This means that the Earth must have formed after a time of about 10^6 yr. At this time, there is little infall accretion on to the disc but there is a significant amount of mass in the disc, a total of about $0.3\,\mathrm{M}_\odot$. The surface density at $R = 1\,\mathrm{AU}$ is high at $7.5 \times 10^4\,\mathrm{g\,cm^{-2}}$. This is in agreement with the standard minimum mass solar nebular at this radius of about $1.7 \times 10^3\,\mathrm{g\,cm^{-2}}$ (Hayashi 1981). It is comparable to the model of Desch (2007) based on the 'Nice' model of planet formation that predicts a surface density of $5 \times 10^4\,\mathrm{g\,cm^{-2}}$ at the radius of the Earth's orbit. At this time there was still sufficient mass in the disc for planetesimal and Earth mass planet formation from the water-devoid disc.

3 Discussion

Our simplified model clearly contains a number of uncertainties. Note that because we took the upper value for T_{snow}, our results show the upper limit of the extent of the icy regions. Also, we have assumed, as did previous researchers, that the radius of the snow line in the gas disc is equivalent to the radius of the snow line of the planetesimal disc (e.g. Oka et al. 2011). However, once the planetesimals grow large enough, they may decouple from the gas disc, and follow quasi-circular orbits. If they were to move over the snow line, then they would sublimate or condense at the water-ice evaporation front (Stevenson & Lunine 1988). The process of sublimation can occur on a short timescale (e.g. Sack & Baragiola 1993, Brown & Bolina 2007) but condensation is less well understood. Marseille & Cazaux (2011) find there is an extended region beyond the snow line where both icy and bare grains coexist, for a radial distance of about 0.4 au. This should be investigated further in future work with a disc model that tracks the evolution of the water. While Ciesla & Cuzzi (2006) investigated this phenomenon in a fully turbulent disc, such calculations should be extended to a disc that contains a dead zone.

There are other unknown parameters in the model such as the value of the critical magnetic Reynolds number (e.g. Fleming et al. 2000), and the viscosity parameter α. Martin et al. (2012a) showed that in order to reproduce FU Orionis outbursts, $Re_{\rm M,crit}$ must be a few 10^4. There is also some uncertainty about whether the surface density in the turbulent surface layer is determined by Ohmic resistivity (as we have assumed) or if ambipolar diffusion or the Hall effect could play an important role (e.g. Perez-Becker & Chiang 2011; Bai & Stone 2011). On this last point, however, Wardle & Salmeron (2011) find the Ohmic resistivity term provides an average value for the active layer surface density for a range of vertical magnetic fields. We should also note that there appears to be some inconsistency between the accretion rates predicted by these dead zone models and observed T Tauri rates. The work presented here is not intended to be a comprehensive study of the evolution of the snow line. Rather, the purpose is to show that the formation a dead zone in a protoplanetary disc *can* keep the outer snow line farther away from the central star. Thus, a model that includes a dead zone can provide a solution to the problem that the Earth must form from water-devoid planetesimals that may not be present at 1 AU in a fully turbulent disc model. This should be investigated further in future work with more detailed numerical simulations once some of the current issues have been resolved.

On a more speculative note, the inner icy region, not predicted by the turbulent disc model, could allow for the formation of icy planets or gas giants in the inner regions of exo-solar systems. For example, at a time of 6×10^5 yr there is a mass of $6.7\,\mathrm{M_J}$ in the inner icy region of the disc. The cores of giant planets are usually assumed to form in the cool region beyond the outer snow line. For example, hot Jupiters are giant planets that are very close to their central star. They are thought to have migrated through the disc to their current position (e.g. Masset & Papaloizou 2003). However, with the proposed disc model (including a dead zone) it is possible that they could form much closer to the star, and closer to their observed locations. The newly formed core would not migrate inwards very fast because it would be within a dead zone (e.g. Matsumura & Pudritz 2007) and the dead zone extends closer to the star than the icy region (see Fig. 2). It is possible that the inner icy region could exist for around 10^7 yr leaving perhaps sufficient time for giant planet core formation. However, we note that in order to form icy planetesimals we need not only a low temperature, but also water vapour to be present. For example, if the cold gas is dry, then icy planetesimals will neither form, nor will ice be added to pre-existing planetesimals. The speculative possibility of the formation of hot Jupiters at their current location needs further investigation.

4 Conclusions

We have computed the evolution of the icy regions of a protoplanetary disc that contains a dead zone. The disc evolves from times of high infall accretion through FU Orionis outbursts to late times when the infall accretion rate is negligible and planetesimals are thought to form. In a fully turbulent disc, the unique snow line passes inside the radius of the Earth's orbit causing problems for the formation of our water-devoid planet Earth. However, when a dead zone forms in the disc, it prevents mass flow through the disc and the outer regions become self-gravitating. The turbulence driven by self-gravity increases the temperature of the outer parts of the dead zone and thus the outer icy region is much farther from the star as shown in the sketches in Fig. 2. Our model also predicts an inner icy region during early times of disc evolution, while a dead zone is present. This moves inside the radius of the Earth's orbit after a time of around 10^6 yr. The outer icy region exists at all times but has a minimum radius of around 3.1 AU, allowing for the formation of our water-devoid planet at its current radius.

The key point of the present work is that the inclusion of a dead zone in time-dependent protoplanetary disc models can significantly change the evolution of the snow line. We have shown that it could resolve the apparent contradiction of the formation of the Earth from water-devoid planetesimals and it also introduces the possibility for icy planet formation close to the central star.

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References

Abe Y., Ohtani E., Okuchi T., Righter K., Draker M., 2000, Origin of the Earth and moon, eds Canup R. M., Righter K., Tuscon, University of Arizona Press, 413
Armitage P. J., Livio M., Pringle J. E., 2001, MNRAS, 324, 705
Bai X., Stone J. M., 2011, ApJ, 736, 144
Balbus S. A., Hawley J. F., 1991, ApJ, 376, 214
Brandenburg A., Nordland A., Stein R. F., Torkelsson U., 1995, ApJ, 446, 741
Brown W. A., Bolina A. S., 2007, MNRAS, 374, 1006
Chiang E. I., Goldreich P., 1997, ApJ, 490, 376
Ciesla F. J., Cuzzi J. N., 2006, Icarus, 181, 178
Davis S. S., 2005, ApJ, 620, 994
Desch S. J., 2007, ApJ, 671, 878
Fleming T. P., Stone J. M., Hawley J. F., 2000, ApJ, 530, 464
Fromang S., Nelson R. P., 2006, A&A, 457, 343
Gammie C. F., 1996, ApJ, 457, 355
Gammie C. F., Menou K., 1998, ApJ, 492, 75
Garaud P., Lin D. N. C., 2007, ApJ, 654, 606
Hayashi C., 1981, Prog. Theor. Phys. Suppl., 70, 35
Ida S., Lin D. N. C., 2005, ApJ, 626, 1045
Kennedy G. M., Kenyon S. J., Bromley B. C., 2006, ApJ, 650, L139
Kennedy G. M., Kenyon S. J., 2008, ApJ, 673, 502
King A. R., Pringle J. E., Livio M., 2007, MNRAS, 376, 1740
Kretke K. A., Lin D. N. C., 2007, ApJ, 664, 55
Kretke K. A., Lin D. N. C., 2010, ApJ, 721, 1585
Lecar M., Podolak M., Sasselov D., Chiang E., 2006, ApJ, 640, 1115
Lewis J. S., 2004, Physics and Chemistry of the Solar System, San Diego, CA, Elsevier Academic Press, 550
Lynden-Bell D., Pringle J. E., 1974, MNRAS, 168, 60
Machida R., Abe Y., 2010, ApJ, 716, 1252
Marseille M. G., Cazaux S., 2011, A&A, 532,60
Martin R. G., Lubow S. H., 2011, ApJ, 740, L6
Martin R. G., Lubow S. H., Livio M., Pringle J. E., 2012a, MNRAS, 423, 2718
Martin R. G., Lubow S. H., Livio M., Pringle J. E., 2012b, MNRAS, 420, 3139
Masset F. S., Papaloizou J. C. B., 2003, ApJ, 588, 494
Matsumura S., Pudritz R. E., 2007, ApJ, 660,1609
Min M., Dullemond C. P., Kama M., Dominik C., 2011, Icarus, 212, 416
Morbidelli A., Chambers J., Lunine J. I., Petit J. M., Robert F., Valsecchi G. B., Cyr K. E., 2000, Meteoritics Planet Sci., 35, 1309
Oka A., Nakamoto T., Ida S., 2011, ApJ, 738, 141
Perez-Becker D., Chiang E., 2011, ApJ, 727, 2
Podolak M., Zucker S., 2004, Meteortics & Planetary Science, 39, 1859
Pollack J. B., Hollenbach D., Beckwith S., et al., 1994, ApJ, 421, 615
Pringle J. E., 1981, ARA&A, 19, 137
Sack N. J., Baragiola R. A., 1993, Phys. Rev. B, 48, 9973
Sasselov D. D., Lecar M., 2000, ApJ, 528, 995
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Stevenson D. J., Lunine J. I., 1988, Icarus, 75, 146
Gammie C. F., Balbus S. A., 1996, ApJ, 463, 656
Toomre A., 1964, ApJ, 139, 1217
Wardle M., Salmeron S., 2012, MNRAS, 422, 2737
Zhu Z., Hartmann L., Gammie C., 2010, ApJ, 713, 1143