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Spirals and Rings in Accretion Discs

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1. What we see

- Recent improvements in telescope resolution have revealed an **abundance of substructure in the circumstellar discs** around young stars.
- A combination of **gravitational instability and ice-lines** may be the **cause** of **spirals and rings** respectively in the same discs.
- Rings in these discs could help to explain the radial drift problem hindering current theories of planet formation.

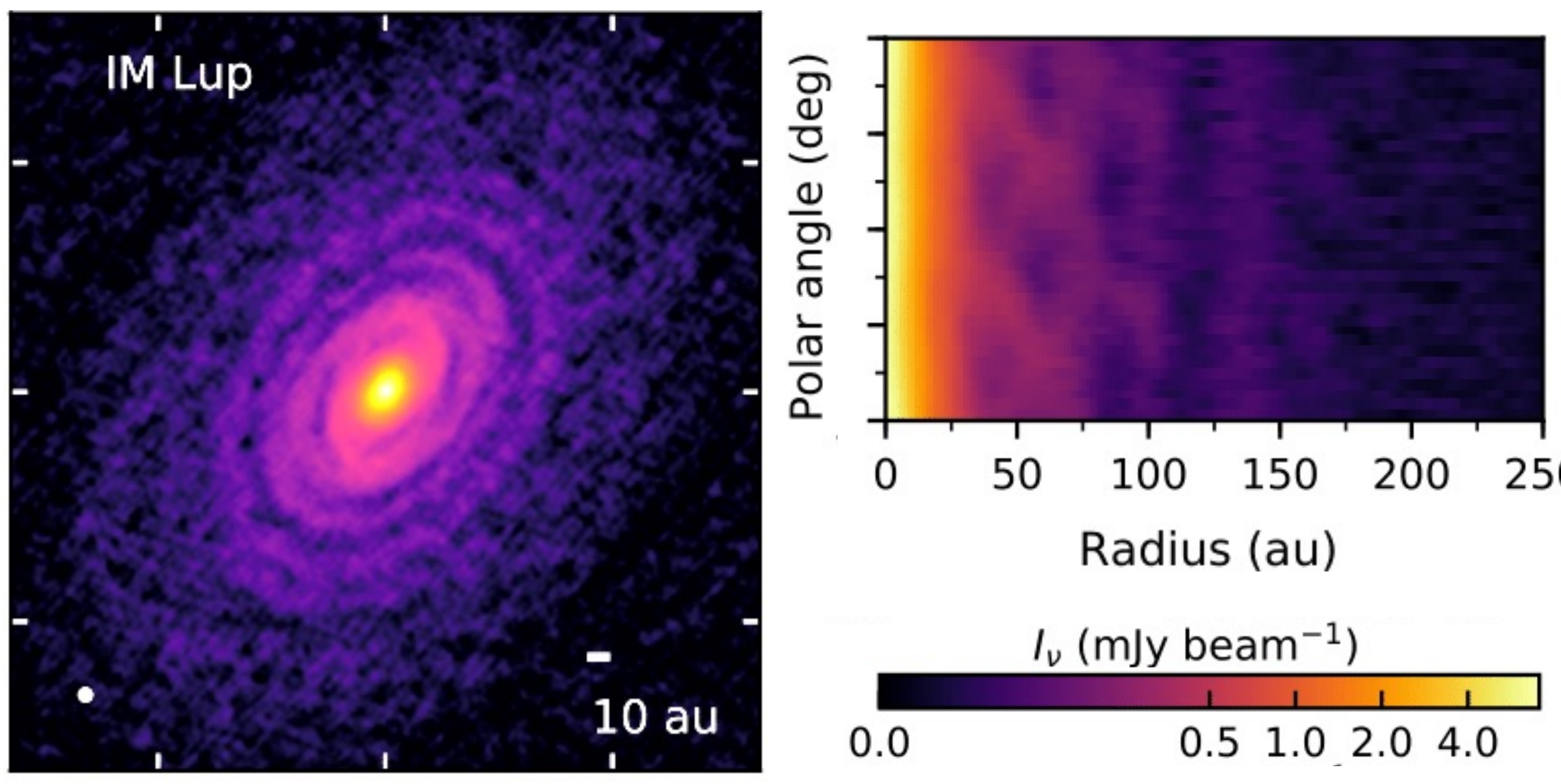

Fig. 1: mm continuum emission image showing spirals and rings in the IM Lup disc (left) and deprojected equivalent (right). The vertical lines indicate rings and diagonal lines indicate spiral arms in the deprojected plot [1].

2. Aims

I. Find when/if ice-lines cause the viscous instability.
II. Hydrodynamically simulate our ice-line model in gravitationally unstable discs.

3. Ice-lines (Rings)

- **Ice-lines** are the positions where **volatiles transition** from **gas to solid**.
- Freezing causes a sudden **increase in surface density of solids** beyond the ice-line resulting in a **large increase in opacity** across the ice-line.
- A sufficiently sharp change in opacity can result in a **negative diffusion coefficient** for disc material. This is the **viscous instability** [2].
- Our simple opacity prescription lowers the opacity inside the ice-line by a constant factor κ_{drop}.

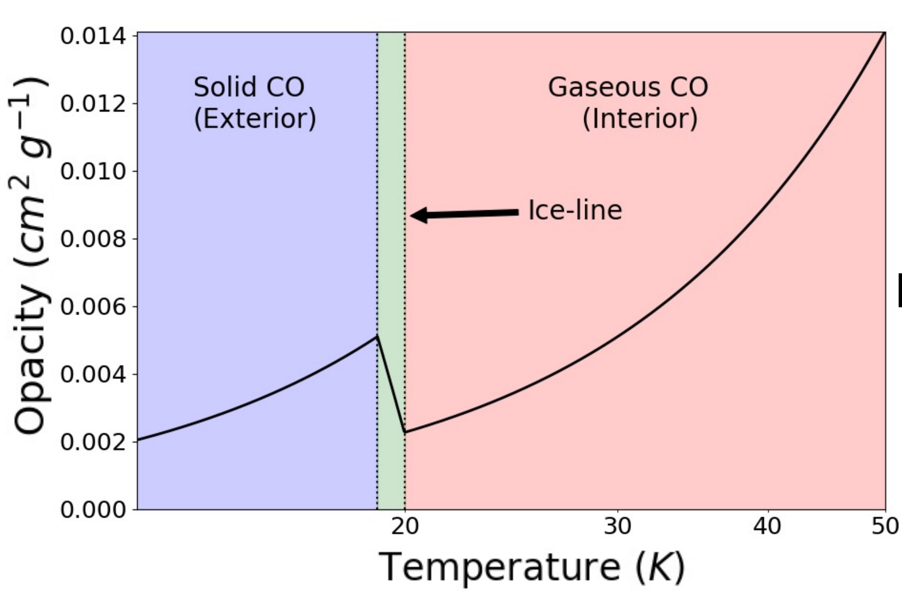

Fig. 2: A plot of opacity interior, exterior and inside the ice-line using our opacity prescription. Notice the sudden increase In opacity exterior to the ice-line.

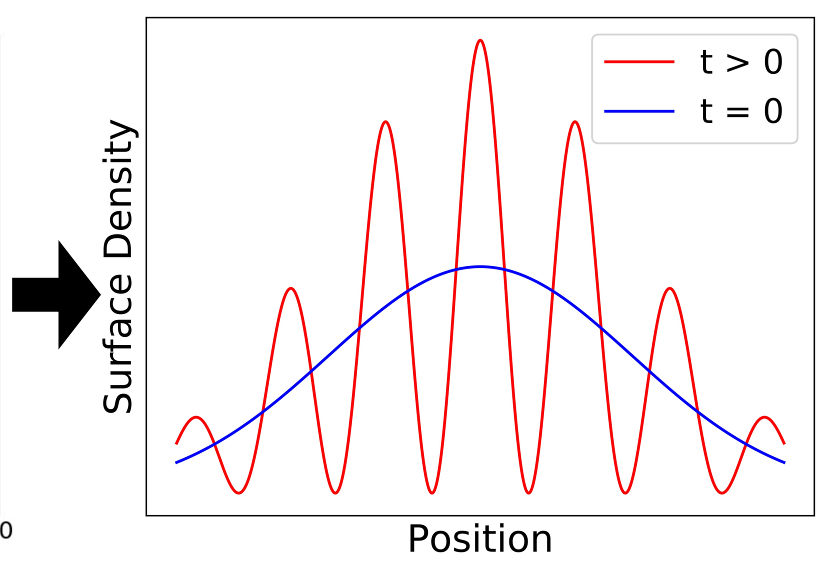

Fig. 3: Sketch illustrating the evolution of surface density under a negative diffusion constant. The red bumps could be the cause of observed rings.

4. Gravitational Instability (Spirals)

- **Self-gravity can cause fragmentation** in the disc whereby material collapses to form giant planets and stars.
- If the **cooling time is high** enough then pressure and shear resists fragmentation to **form** a quasi-stable state of trailing **gas spiral arms.**
- The degree of **gravitational instability** is **encoded** by the **Toomre** $\boldsymbol{Q}$ parameter [3].

5. Finding the viscous instability

- Using **semi-analytical methods** we solved the disc equations for a constant mass accretion rate and a constant $Q = Q_0$.
- We **searched** the parameter space **for the viscous instability** in the CO ice-line around a solar mass star.

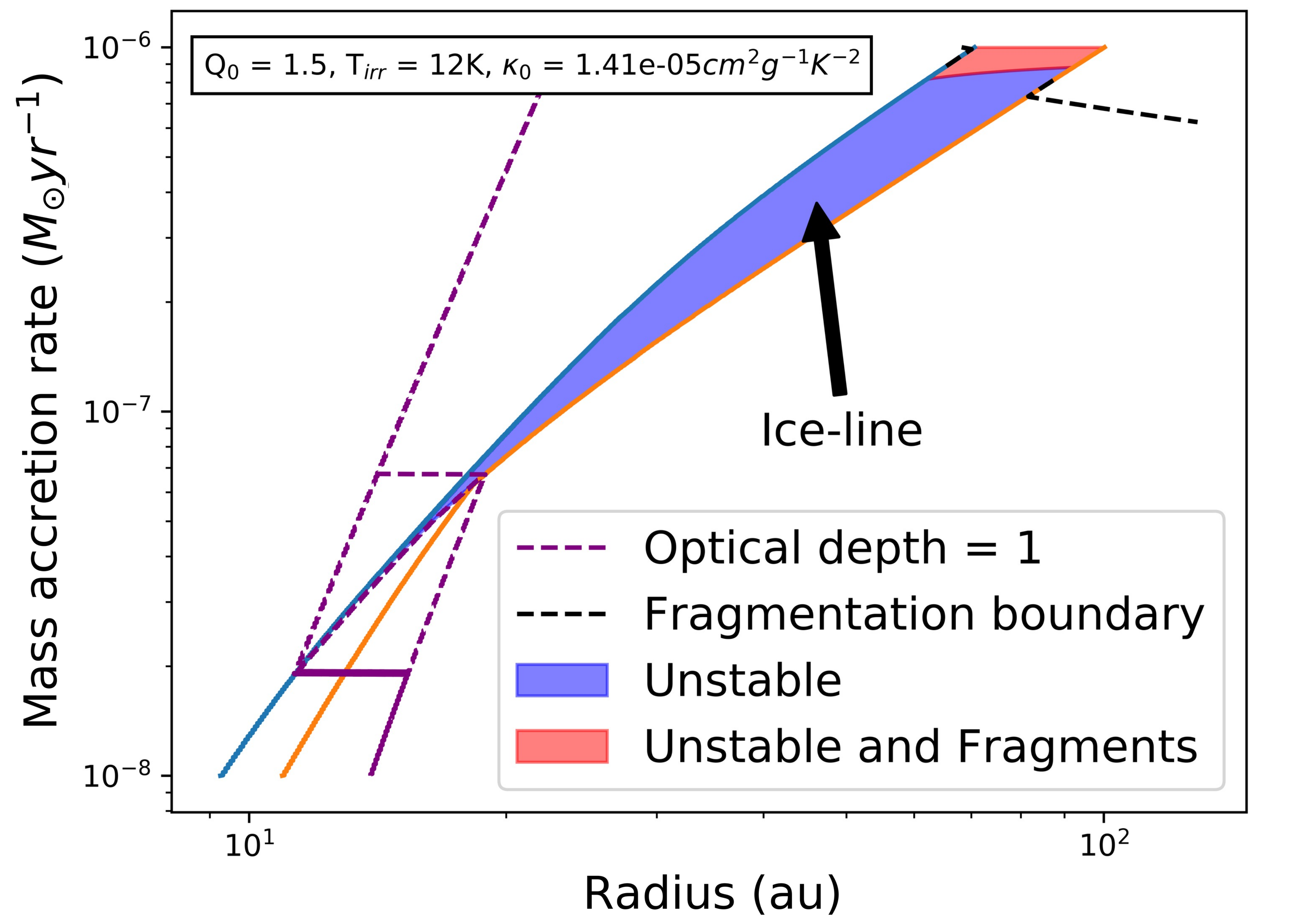

Fig. 4: A region of parameter space indicating the CO ice-line along with stable and unstable regions. Notice the disc fragments at higher mass accretion rates and radii in the top right.

- We **observe** a region of **viscous instability within the ice-line**.
- The region of instability which does not fragment is a **promising candidate for the rings** we observe.
- $1 \leq Q_0 \leq 2$ indicates spirals should also be present [4]; this provides strong **motivation** to perform hydrodynamic simulations.

6. Do rings form?

- We **implemented** our **ice-line** opacity prescription **into** the **FARGO hydrodynamical code.**
- The results of these simulations will **confirm** whether **viscous instability could explain ring formation** in spiralled discs.

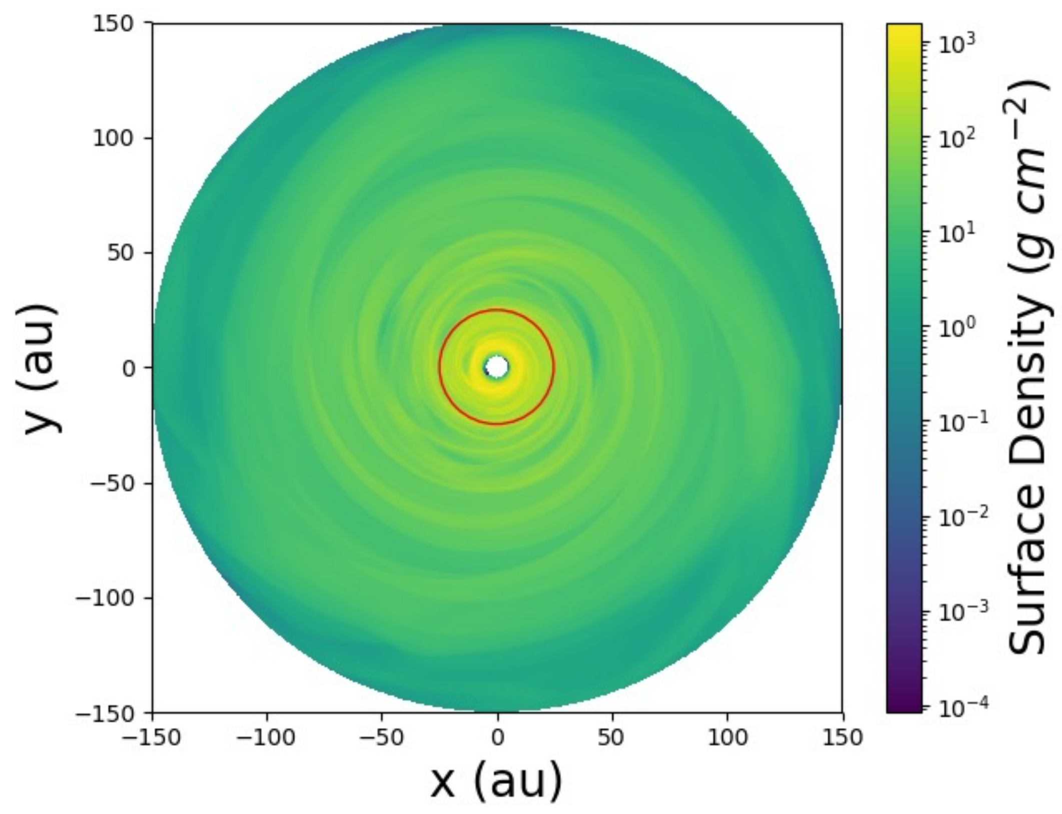

Fig. 5: FARGO simulation of gas surface density after 22,000 yrs. The red ring indicates the estimated location of the Ice-line.

7. Conclusion

- We find a **sharp change in opacity** across the CO ice-line produces **viscous instability** for a variety of mass accretion rates and Q values (see Figure 4). Many of **these $\boldsymbol{Q}$ values suggest spirals** will also be present.

8. Future Work

- Hydrodynamical **simulations** will be performed **to confirm** the presence of **rings and spirals** in discs exhibiting viscous and gravitational instability. Thus, providing an **explanation for** the substructures seen in **Figure 1.**
- Future work could self-consistently derive the opacity law within the snowline, **improving upon our simple prescription.**

[1] Huang et al. 2018. The disk substructures at high angular resolution project (DSHARP). III. Spiral structures in the millimeter continuum of the Elias 27, IM Lup, and WaOph 6 disks. *The Astrophysical Journal Letters*, *869*(2), p.L43.
[2] Pringle, J.E., 1981. Accretion discs in astrophysics. *Annual review of astronomy and astrophysics*, *19*(1), pp.137-160.
[3] Toomre, A., 1964. On the gravitational stability of a disk of stars. The Astrophysical Journal, 139, pp.1217-1238.
[4] Dong, R., Hall, C., Rice, K. and Chiang, E., 2015. Spiral arms in gravitationally unstable protoplanetary disks as imaged in scattered light. The Astrophysical Journal Letters, 812(2), p.L32.