Substructure in protoplanetary discs: a signpost of planet formation?

ESO Cosmic Duologue 5 - Interview

29 June 2020

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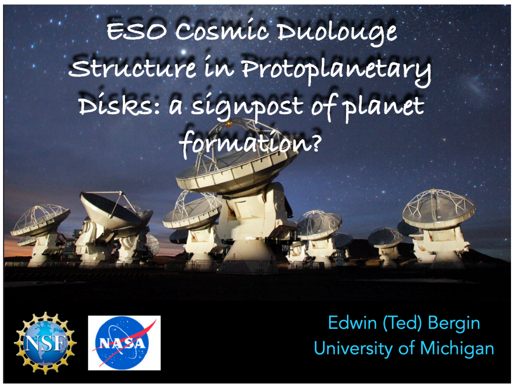
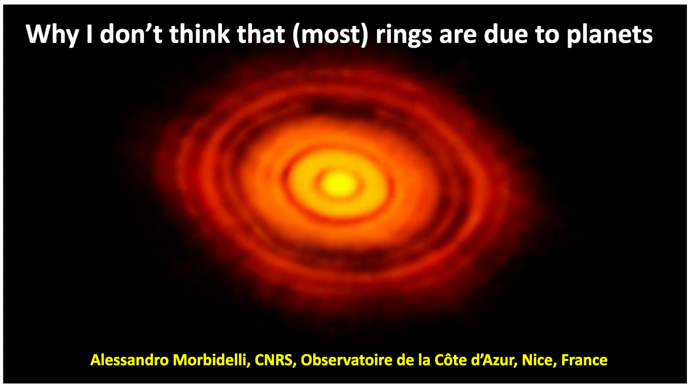
On Monday 29 June, 2020, the fifth ESO Cosmic Duologue took place. It consisted in a discussion between *Edwin Bergin* (University of Michigan, USA) and *Alessandro Morbidelli* (OCA, Nice, France) and chaired by *Stefano Facchini* (ESO), about substructures in protoplanetary discs. Further information on this event, including a copy of the slides, the link to the video of the duologue, as well as to some background material, is available at *https://www.eso.org/sci/meetings/2020/Cosmic-Duologues/duologue5.html*.

As a follow-up to this successful event, we have asked our two speakers to answer in more details some of the questions raised during the event. This is provided below, where the answers are identified by the initials of the speaker.





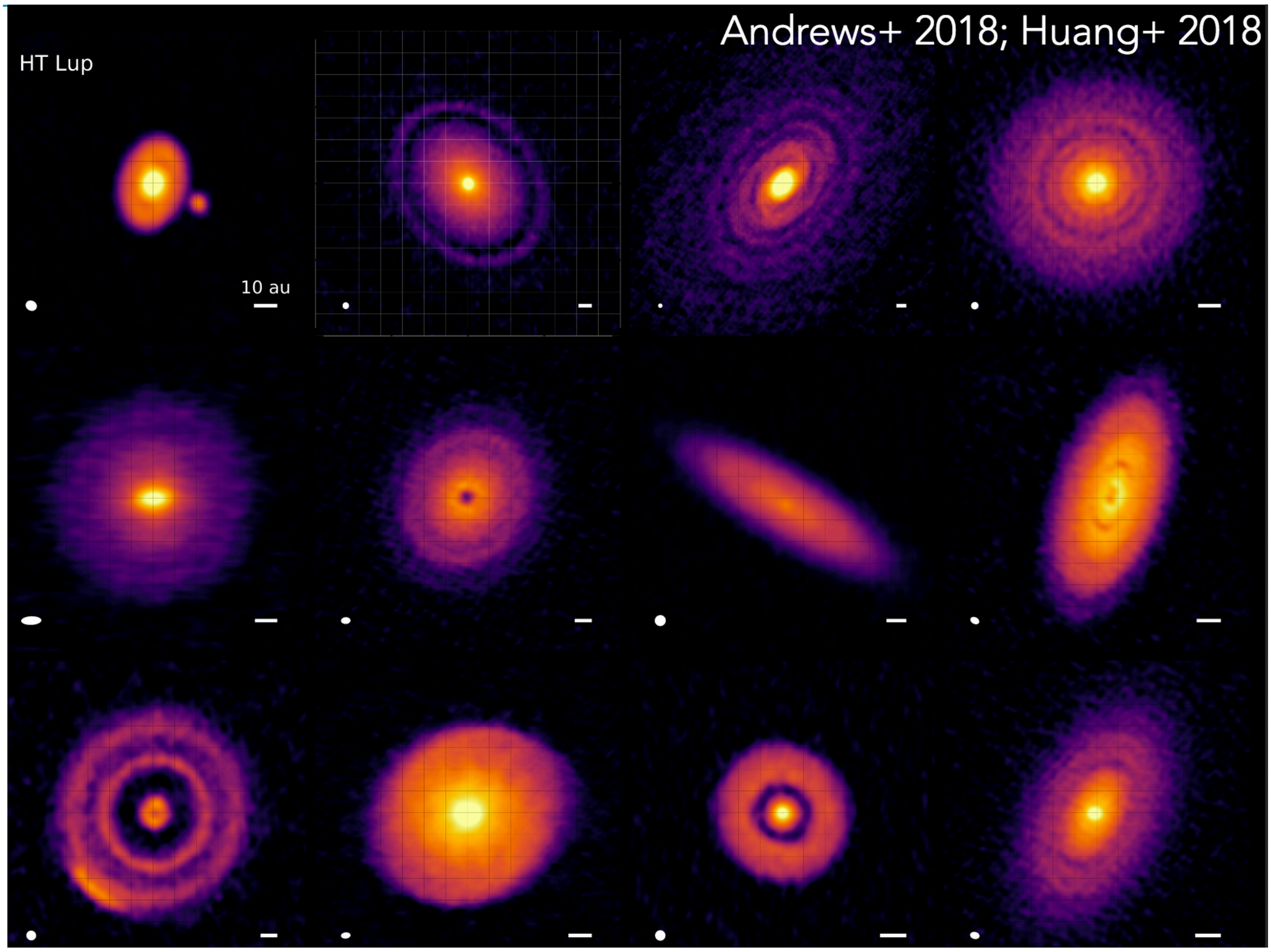
1. Is a planet able to create multiple gaps and rings in a disc and if yes, why?

AM: Yes, under some conditions. Gap opening is due to angular momentum transfer from the planet to the disc. This happens where a spiral density wave launched by the planet shocks and different waves (primary, secondary, tertiary…) will shock at different locations (Zhu et al. 2015; Bae et al. 2017). The secondary gaps are less deep than the primary gap. They tend to disappear with increasing disc's viscosity and planet migration. Their existence also depends on the disc's equation of state. In isothermal discs they form easily, but in discs with slow cooling they don't form because the spiral density wave is strongly damped in this case (Miranda and Rafikov, 2020).

EAB: I noted that the 3D simulations in Bae et al. 2017 also illustrate that a single planet can create multiple gaps verifying some aspects of what is observed in 2D simulations.

2. Are there indication that there is a reservoir of material at large distance from the star to explain formation of planets where we see rings and gaps?

AM: In general the mass observed in T-Tauri discs is too small to form planets (Manara et al., 2018). The current rings don't contain enough dust mass to form planets larger than about an Earth mass within the disc's lifetime (Morbidelli, 2020). But planets may have formed in principle at earlier disc stages, when the mass was larger (Class-0, Class-1).

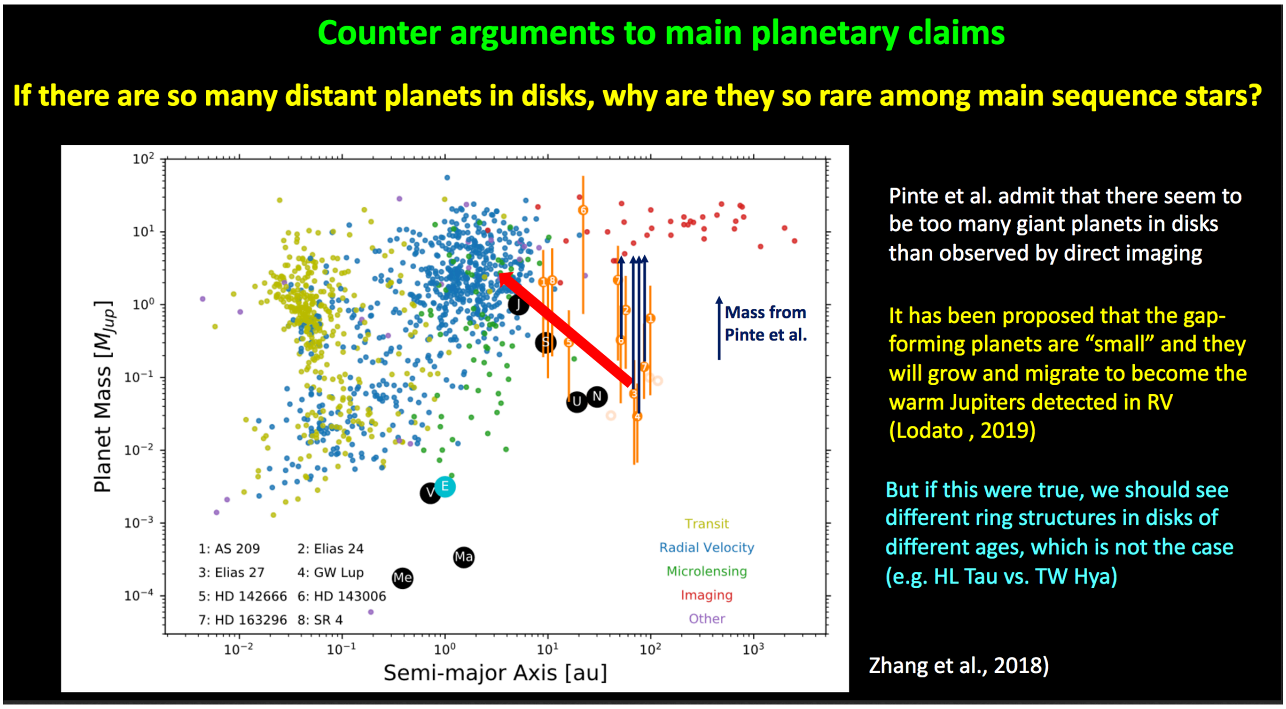


EAB: It is clear that the mass of solids is not enough to account for the observed planetary population that exists (Manara et al. 2018). However, solids that grow to many centimeters in size are untraced by our observational facilities. Thus, there could be additional hidden solid mass – which must have grown to larger sizes during the earlier phases as noted by Morbidelli. For the gas, it is harder. These systems are accreting with rates that require a reservoir of material that is commensurate with their age (Rosotti et al. 2017). Mass measurements from Hydrogen Deuteride imply relatively high gas masses (Bergin et al. 2013, McClure et al. 2016, Kama et al. 2020) in a handful of systems. What is not certain is the distribution of the mass inside the system and on the evolution of the gas surface density as a function of both position and time. In general, this is a challenge, but it points to interesting avenues of research for the coming decade.

3. Pebble accretion may be hard to achieve at large distance from the star, but we know there is some dust at large distance, so can we imagine that this dust can be dumped closer in and lead to the creation of planets?

AM: Certainly! Planet formation is an issue only at large distances from the central star. But this is where we see the gaps. This is why there is debate on whether the observed gaps can be due (in majority) to planets.

EAB: If the discs are more massive during early stages then gravitational instability could provide a method to create planets at large distances. However, we also are compiling strong evidence for dust drift. For example, in TW Hya the gaseous disc extends to ~200 au but the dust disc is truncated well within 100 au. Thus, the dust from the outer 100 au disc was deposited somewhere in the inner 100 au – this clearly has implications for planet formation.



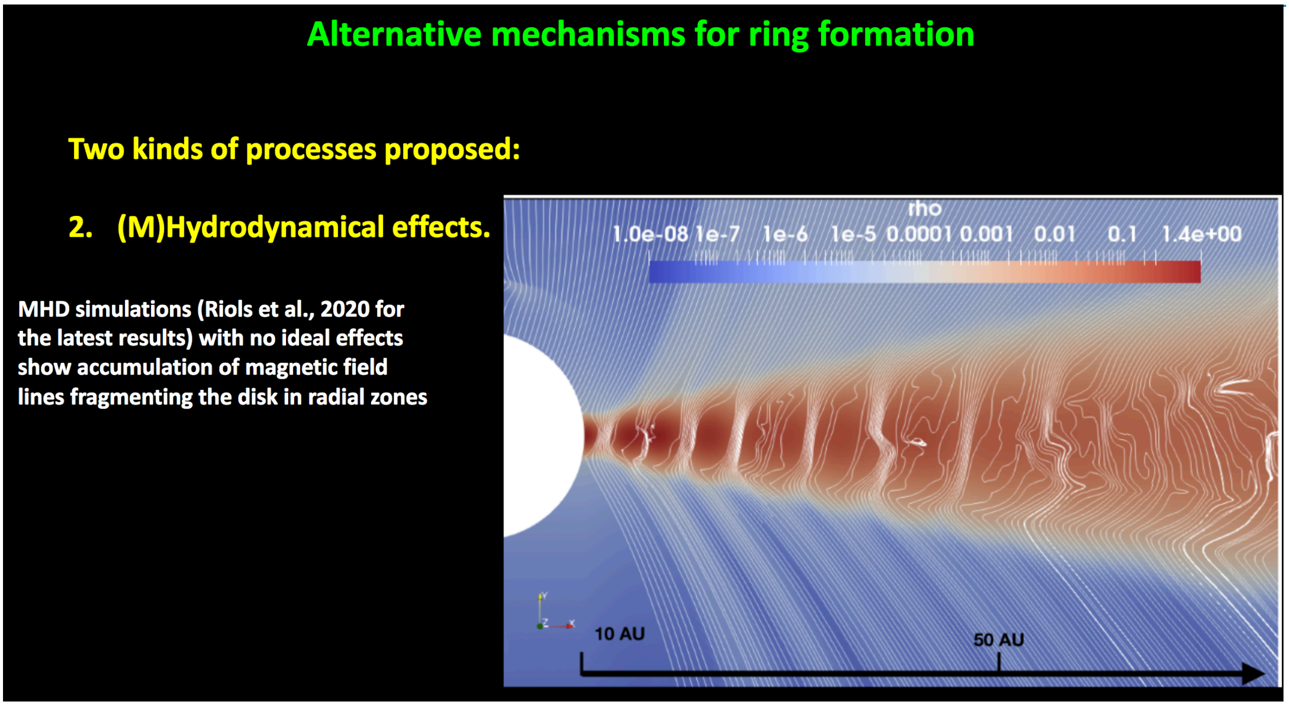
4. Is there a way to distinguish between gaps created by magnetic fields and those created by a planet?

AM: Possibly. There may be differences in the flow of the gas near the gap. But both the theoretical knowledge and the observational capabilities are not yet at the level to be able to tell the difference.

EAB: Right now the observational side is only beginning to explore the question of what can be done with the kinematics. Our dream is to use multiple tracers to probe the gas kinematics at successively deeper layers in the disc using for example ^{12}CO tracing the upper surface and ^{13}CO which traces the deep surface. Thus, we can aim to have constraints on the velocity field along with the density structure as traced by the mm-dust emission and $C^{18}O$. However, today we don't have the full data products that are obtained for this goal in mind. This will happen in the coming few years and we will then see what can be probed via observations. Concurrently, dynamicists need to work closely with observers (something which is happening; see, e.g., Liu with Isella and Bae with Teague) to provide simulations in a manner that matches the limitations of resolution and the molecular probe being used.

5. Would the ionisation fraction in the mid-plane be sufficient for material to be influenced by the magnetic field?

AM: In modern MHD simulations showing the formation of rings (e.g., Bethune et al. 2017; Riols et al. 2020), no ionisation is assumed on the midplane. Ionisation is assumed to occur only in the surface layer of the disc where FUV radiation can penetrate, typically above 3.5 pressure scale heights. All non-ideal MHD effects are taken into account (Ohmic resistivity, ambipolar diffusion, Hall effect). The critical parameter that governs the effects is $\beta=2\rho c_s^2/B_z^2$, where ρ is the density of the gas, c_s is the sound speed and B_z is the vertical component of the magnetic field. β is an a-dimensional number. Gaps and rings appear for β in the range 10^3-10^5. Thus, a weak magnetic field is sufficient.



6. Do the statistics from the "kinks" and gaps fit with the exoplanet statistics? If not, why is it so?

AM: First, kinks and gaps give different statistics. Kinks have been found for only 8 gaps in 18 discs (Pinte et al. 2020). The masses of the planets deduced from kinks are much larger than those deduced from gaps. The planets deduced from kinks can be directly compared to giant planets observed by direct imaging. They seem to be too numerous compared to directly imaged planets, but large uncertainties exist (Pinte et al. 2020). If the planets are as small as deduced by gaps widths, then they may just be the precursors of the warm Jupiters, that are found around ~10% of main-sequence stars at distances of 1-5 au (Lodato et al. 2019). This is because planets should migrate towards the central star as they grow. Also, in this case they seem to be too numerous, but just by a factor 2-3.

EAB: The Lodato paper and Fernandes et al. (2019) summarize the state of the field today quite nicely. We also need to understand why Uranus and Neptune exist in our solar system and some of the planets inferred by ALMA could be precursors to these types of planets. Better statistics from, e.g., the Nancy Grace Roman Telescope, on this distant exo-planet population, if present, will help. We also need to push our capabilities on the kinematic side to see if we can detect planets less massive than say 1 Jupiter Mass with ALMA (Pinte et al. 2018, 2020; Teague et al. 2018).

7. Can non-axisymmetric structures help distinguish between planets and other gap-opening mechanisms?

AM: Non-axysimmetric structures are indeed the best indicators for a perturbation localized in azimuth. Hence a planet is a natural candidate in these cases.

References

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