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From stars and disks to planets: Reconstructing the formation of Solar Systems

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Abstract

Young stellar clusters are the laboratories to explore our understanding of how stars and their planets form and interact with their environment. Putting together clusters with different ages, we can witness the time evolution that brings us from the less evolved objects, to the precursors of our Solar System, tracking the processes for a large number of sources to investigate the underlying physics and statistics. Nevertheless, although young clusters are typically attributed a representative age and disk fraction and treated as a single entity, we are increasingly finding that this is often not the case: clusters are by far more diverse, and their substructures betray a variety of star formation histories, which are connected to the initial conditions of the protoplanetary disks and their final outcome as planets.
The way disks gets converted into planetary systems is also not smooth nor follows a single line. The interplay of different processes, together with the different initial conditions of disks, is expected to lead to various evolutionary pathways that may explain the diversity of extrasolar planetary systems. Finally, the planet-disk-star connection, where matter transport is driven through the disk and channelled onto the star, affects both planets sizes and locations as well as the properties of the stars.
Here, I review the observational results and existing challenges in the field of star and planet formation, and how we can use an increasing body of data, with wavelength-, spatial- and time-resolution, to probe further into the evolution of young stars and disks.

1 Introduction

Star and planet formation are two sides of the same problem: how to enable the collapse of a fragment of molecular cloud while conserving angular momentum, which bring us though the formation of a protoplanetary disk. The latest stages of star and planet formation involve the dispersal of the disk leaving behind a young star surrounded by planets.

In this summary, I focus on the observational progress done to study these later stages of star and planet formation, investigating the limitations of the historical approach and identifying new routes to derive observational constraints and boundaries that can aid future observational strategies and supply the constraints required for modelling.

2 Finding and measuring protoplanetary disks

From an observational point of view, understanding star and planet formation in advanced phases has two main challenges. First, measuring the timescales requires putting together information on different regions and objects to draw significant constraints and to visualise the process. Second, the properties of the systems need to be measured with enough detail, which includes determining star and disk properties over the entire range covered by planetary systems: from those forming in the outskirts of the disk, which may be susceptible of direct imaging, to those growing inside the disk up to very close to the star, which are often only indirectly detected [1, 2]. Obtaining very detailed information on particular systems is nowadays feasible (e.g. using GRAVITY or SPHERE; [3, 4]), although this may not be able to track objects representative of the whole class but rather those bright enough to be observed in great detail. Looking at clusters as sites where a large number of systems can be found provides a complementary approach with stronger statistical constraints, even if individual systems are not mapped in as much detail (e.g. [5, 6, 7, 8, 9, 10]).

Indirect measurements of disks take advantage from the differences in temperature and chemistry at the various distances from the star (e.g., [1, 2]), which means that even if a source remains unresolved, data from X-ray to millimetre wavelengths tracks different locations within the system. This indirect resolution can be enhanced by using variability, which adds a temporal dimension to the observations, allowing us to both capture dynamical processes as well as to pinpoint the locations where different processes occur. While essentially all young stars are variable *by definition* [11], the timescales of the variations are key to determine the spatial location of the phenomena that originate them [12]. *"Using time to map space"* is the only available tool to reach tiny scales from the stellar radius up to the inner planet region, unveiling accretion processes, stellar activity, and the way stars are connected to their disks (e.g. [13, 14, 16, 15, 17, 18]). Time-resolved spectroscopy can further probe these innermost regions by adding velocities to the time variability [68, 20, 21, 22].

Systems ages (see also Section 4) and disk masses are also key to put constraints on planet formation. Determining disk masses is tracer- and model-dependent, so different methods produce very different results [1, 2]. Accretion feeds forming planets [23], but whether we are able to capture it properly using standard proxies [24, 25] may also depend on whether what we observe is a direct measurement or a correlation [26], fueling mismatches, especially in intermediate-mass stars, between ages, disk masses, and accretion rates [1].

3 Understanding young star clusters

Clusters have been always considered as very good sites to study the properties of stars and their disks, since they contain large numbers of sources, located at approximately the same distance, and having the same age, metallicity and similar formation history. Comparing stars in clusters has been a routine exercise since long and has provided much of our existing timescale knowledge [5, 6, 7, 8]. Nevertheless, differences between clusters suggestive of environmental effects or initial conditions are often observed (e.g. [9, 27]), as well as differences for various types of stars (e.g. binaries, [28]). Furthermore, different star formation histories and ages within clusters have been since long suspected, based on the diversity of evolutionary stages (e.g. [29, 30, 6, 31, 32, 33, 34, 35]) as well as radial velocities (e.g. [36]).

Requiring stars at the same distance for a meaningful comparison is now less critical thanks to Gaia [37], which provides parallaxes for most young sources in the solar neibourhood as long as they are bright enough at optical wavelengths. Nevertheless, what Gaia has also reveals is that clusters are by far less monolithic than previously expected. Even a region as well-known as Taurus, used as a template for other young clusters, happens not to be at the classical *Taurus' distance* [38]. The differences in formation history and stellar populations are further exposed by Gaia [39, 40, 41, 42, 43], which is also showing us that cluster members may not even be so *clustered* around the *classical cluster* location [44, 42].

4 Joining the dots: Reconstructing disk evolution

The historical perspective to reconstruct disk evolution, including that of our Solar System, has involved connecting systems with different ages, and comparing them. This works well under the assumption that all disks start up in a similar way and evolve along the same pathway. It also requires a good knowledge of the system ages.

Even without considering the potential spread in ages within the same cluster, ages of young stars can be tricky in extreme (see [45, 46, 47, 48] for a start). Moreover, the assumption that all disks need to evolve in the same way may be challenged by the diversity of initial conditions and disk properties [49, 50, 51]. To make matters even more complex, if star formation in clusters may be multi-episodic, so can disk formation, to the point that if late infall is common, it may mean that some stars have different ages than their disks - or, at least, than parts of their disks [52, 53, 54, 55]. Extreme misalignments in disks have been long observed [56, 57], and may betray disks that were not formed in a single step.

Scatter due to initial conditions and stellar mass is known since long [58], and thus *connecting the dots* to derive e.g. accretion evolution requires similar sources to be cross-matched. Selecting by mass is relatively easy (even if determining the spectral type of heavily veiled objects is subject to uncertainty), but finding out which objects are precursors of which ones is far from immediate [59]. Observed trends suggest that accretion rates decrease over time in a way consistent with viscous evolution [58] combined with photoevaporation [60], but the fact that at older ages there are only very few surviving disks [5, 6, 8, 9] means that we risk comparing pretty much every object at a young age, with the rare oddballs that survived in the most aged clusters.

Very old, accreting systems have to be regarded with care, since rather than being *Peter Pan disks* [61] they may better follow the example of *Dorian Gray* and not be as young-looking upon deeper scrutiny of their *secrets* (or their mass reservoirs, or the features in their spectral energy distribution [68]). One should distrust a star that appears to have been accreting strongly for a long time, since it is likely not going to be well-represented by most isochrone models [63] and thus, if we really trust its accretion rate, we may not be able to put so much trust on its age. To minimise those risks, the ages of regions need to be carefully considered, and surveys need to ensure completeness (or, at least, good upper limits) to include all disks, not only those that are easy to detect. The faint, nearly dissipated disks are likely those that dominate at later stages [64].

5 Conclusions and outlook

Once upon a time, disks with gaps were expected to be in rapid transition, even though often, spectral energy distributions suggested that radial discontinuities (including holes, gaps, and diversity of flaring, dust grains, and composition,[65]) appeared to be very common [66, 67, 68]. Nowadays, ALMA is confirming that signs of evolution in the shape of rings and gaps are ubiquitous (e.g., [69, 4]) and are thus not a signature of imminent disk demise. Deeper and broader observations start converging, bringing together the clusters-vs-details perspectives in disk studies [4], encouragingly starting to look similar to the results of cluster simulations [70]. This also confirms suspected differences based on environment [9, 27], so not all disks start equal as there is a variety of initial conditions due to cloud properties as well as interactions (e.g. in crowded regions).

It may be time to rethink the way to connect the different evolutionary paths between themselves, with targeted observations that include large number of all types of sources, spatially-resolved observations. This includes observing *boring* sources and those that are very weak (including non-detections), for meaningful limits. Full cluster coverage (including the outskirts) is also a requirement to track the diversity in environment and evolutionary paths. Finally, moving from multi-wavelength through time-resolved data for increasing number of objects and over increased periods of time (and, when dealing with variability, as time goes by so does our spatial range for indirect resolution increases) is an opportunity to investigate what cannot be directly resolved. Rather than a linear story, evolving disks are a bit of a case of *choosing your own adventure*, where the initial conditions and environment affect the outcomes and likely as well, the planetary systems. Knowing all the limits (in depth, in number of sources, in detectability) is needed before jumping to conclusions. And, for observers, the adventure to follow is ours.

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References

[1] Sicilia-Aguilar, A., Banzatti, A., Carmona, A., et al. 2016, PASA, 33, e059

[2] Miotello, A., Kamp, I., Birnstiel, T., et al. 2023, Protostars and Planets VII, 534, 501

[3] GRAVITY Collaboration, Ganci, V., Labadie, L., et al. 2021, A&A, 655, A112

[4] Garufi, A., Ginski, C., van Holstein, R. G., et al. 2024, A&A, 685, A53

[5] Haisch, K. E., Lada, E. A., & Lada, C. J. 2001, ApJl, 553, L153

[6] Sicilia-Aguilar, A., Hartmann, L., Calvet, N., et al. 2006, ApJ, 638, 897

[7] Hernández, J., Calvet, N., Briceño, C., et al. 2007, ApJ, 671, 1784

[8] Fedele, D., van den Ancker, M. E., Henning, T., et al. 2010, A&A, 510, A72

[9] Fang, M., van Boekel, R., Bouwman, J., et al. 2013, A&A, 549, A15

[10] Pfalzner, S. & Dincer, F. 2024, ApJ, 963, 122

[11] Joy, A. H. 1945, ApJ, 102, 168

[12] Fischer, W., Hillenbrand, L., Herczeg, G., et al. 2023, Protostars and Planets VII, 534, 355

[13] Dupree, A. K., Brickhouse, N. S., Cranmer, S. R., et al. 2012, ApJ, 750, 73

[14] Cody, A. M., Stauffer, J., Baglin, A., et al. 2014, AJ, 147, 82

[15] Froebrich, D., Scholz, A., Campbell-White, J., et al. 2024, MNRAS, 529, 1283

[16] Froebrich, D., Scholz, A., Eislöffel, J., et al. 2020, MNRAS, 497, 4602

[17] Herbert, C., Froebrich, D., & Scholz, A. 2023, MNRAS, 520, 5433

[18] Sicilia-Aguilar, A., Kahar, R. S., Pelayo-Baldárrago, M. E., et al. 2024, MNRAS, 532, 2108

[19] Sicilia-Aguilar, A., Fang, M., Roccatagliata, V., et al. 2015, A&A, 580, A82

[20] Campbell-White, J., Sicilia-Aguilar, A., Manara, C. F., et al. 2021, MNRAS, 507, 3331

[21] Sicilia-Aguilar, A., Campbell-White, J., Roccatagliata, V., et al. 2023, MNRAS, 526, 4885

[22] Armeni, A., Stelzer, B., Frasca, A., et al. 2024, A&A, 690, A225

[23] Matsumura, S., Brasser, R., & Ida, S. 2021, A&A, 650, A116

[24] Fang, M., van Boekel, R., Wang, W., et al. 2009, A&A, 504, 461

[25] Alcalá, J. M., Manara, C. F., Natta, A., et al. 2017, A&A, 600, A20

[26] Mendigutía, I., Oudmaijer, R. D., Rigliaco, E., et al. 2015, MNRAS, 452, 2837

[27] Sicilia-Aguilar, A., Henning, T., Linz, H., et al. 2013, A&A, 551, A34

[28] Bouwman, J., Lawson, W. A., Dominik, C., et al. 2006, ApJl, 653, L57

[29] Sugitani, K., Tamura, M., & Ogura, K. 1995, ApJL, 455, L39

[30] Reach, W. T., Rho, J., Young, E., et al. 2004, ApJs, 154, 385

[31] Getman, K. V., Feigelson, E. D., Garmire, G., et al. 2007, ApJ, 654, 316

[32] Getman, K. V., Feigelson, E. D., Sicilia-Aguilar, A., et al. 2012, MNRAS, 426, 2917

[33] Barentsen, G., Vink, J. S., Drew, J. E., et al. 2011, MNRAS, 415, 103

[34] Sicilia-Aguilar, A., Roccatagliata, V., Getman, K., et al. 2014, A&A, 562, A131

[35] Niederhofer, F., Hilker, M., Bastian, N., et al. 2016, A&A, 592, A47

[36] Fűrész, G., Hartmann, L. W., Szentgyorgyi, A. H., et al. 2006, ApJ, 648, 1090

[37] Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1

[38] Roccatagliata, V., Franciosini, E., Sacco, G. G., et al. 2020, A&A, 638, A85

[39] Yalyalieva, L., Carraro, G., Vazquez, R., et al. 2020, MNRAS, 495, 1349

[40] van Terwisga, S. E., van Dishoeck, E. F., Mann, R. K., et al. 2020, A&A, 640, A27

[41] Teixeira, P. S., Alves, J., Sicilia-Aguilar, A., et al. 2021, MNRAS, 504, L17

[42] Pelayo-Baldárrago, M. E., Sicilia-Aguilar, A., Fang, M., et al. 2023, A&A, 669, A22

[43] Bonilla-Barroso, A., Ballesteros-Paredes, J., Hernández, J., et al. 2024, MNRAS, 529, 3925

[44] Mendigutía, I., Solano, E., Vioque, M., et al. 2022, A&A, 664, A66

[45] Hartmann, L. 2003, ApJ, 585, 398

[46] Mayne, N. J., Naylor, T., Littlefair, S. P., et al. 2007, MNRAS, 375, 1220

[47] Hillenbrand, L. A. 2008, Physica Scripta Volume T, 130, 014024

[48] Naylor, T. 2009, MNRAS, 399, 432

[49] Sicilia-Aguilar, A., Kim, J. S., Sobolev, A., et al. 2013, A&A, 559, A3

[50] Lau, T. C. H., Drażkowska, J., Stammler, S. M., et al. 2022, A&A, 668, A170

[51] Lau, T. C. H., Birnstiel, T., Drażkowska, J., et al. 2024, A&A, 688, A22

[52] Ginski, C., Facchini, S., Huang, J., et al. 2021, ApJl, 908, L25

[53] Pelkonen, V.-M., Padoan, P., Haugbølle, T., et al. 2021, MNRAS, 504, 1219

[54] Kuffmeier, M., Jensen, S. S., & Haugbølle, T. 2023, European Physical Journal Plus, 138, 272

[55] Kuffmeier, M., Pineda, J. E., Segura-Cox, D., et al. 2024, A&A, 690, A297

[56] Roccatagliata, V., Ratzka, T., Henning, T., et al. 2011, A&A 534, A33

[57] Pinilla, P., Benisty, M., de Boer, J., et al. 2018, ApJ, 868, 85

[58] Hartmann, L., Calvet, N., Gullbring, E., et al. 1998, ApJ, 495, 385

[59] Sicilia-Aguilar, A., Henning, T., & Hartmann, L. W. 2010, ApJ, 710, 597

[60] Alexander, R. D., Clarke, C. J., & Pringle, J. E. 2006, MNRAS, 369, 229

[61] Silverberg, S. M., Wisniewski, J. P., Kuchner, M. J., et al. 2020, ApJ, 890, 106

[62] Sicilia-Aguilar, A., Roccatagliata, V., Getman, K., et al. 2015, A&A, 573, A19

[63] Spezzi, L., de Marchi, G., Panagia, N., et al. 2012, MNRAS 421, 78

[64] Roccatagliata, V., Sicilia-Aguilar, A., Kim, M., et al. 2024, A, 682, A63

[65] Espaillat, C., Ingleby, L., Hernández, J., et al. 2012, ApJ, 747, 103.

[66] Sicilia-Aguilar, A., Henning, T., Juhász, A., et al. 2008, ApJ, 687, 1145

[67] Sicilia-Aguilar, A., Henning, T., Dullemond, C. P., et al. 2011, ApJ, 742, 39.

[68] Sicilia-Aguilar, A., Roccatagliata, V., Getman, K., et al. 2015, A&A, 573, A19

[69] Andrews, S. M., Huang, J., Pérez, L. M., et al. 2018, ApJl, 869, L41

[70] Bate, M. R. 2018, MNRAS, 475, 5618