223. Associations – an update

WHAT ARE 'associations', and how do they differ from open clusters? What was the state of knowledge pre-Gaia, and what has Gaia contributed to the census of nearby associations? And what do we now know about their formation, dynamics, and dispersal?

I presented some early results on associations based on Gaia DR2 in essay 18 (in early 2021). Let me recall that, in contrast to the higher stellar density and gravitationally bound open clusters, *associations* were originally defined by Lada & Lada (1991) as looser groups of some 10 or more physically related stars, often of large spatial extent. In the case of OB associations, they are characterised by their overdensity of O and B stars (there are also, for example, T-associations comprising T Tauri stars). High masses and luminosities imply that the stars are young and short lived, and so implicitly associated with sites of recent star formation. They are unbound, and survive as recognisable groups only for a short time, 25–50 Myr... although somewhat longer with Gaia!

A number of OB associations within 150 pc of the Sun have long been known (with early work by Kapteyn, 1914; Rasmuson, 1921; Pannekoek, 1929; Blaauw, 1946), including Scorpius–Centaurus (with subgroups including Lower Centaurus Crux and Upper Scorpius), Taurus–Auriga, Hercules–Lyra, and Tucana–Horologium. Their large extent on the sky has traditionally prevented accurate kinematic membership determination for any but the brightest stars. Many studies were already made with the Hipparcos data, which provided a major improvement in their kinematic detection.

EARLY IDEAS OF 'monolithic formation' posited that associations were expanding from their origins as gravitationally bound clusters. Gaia DR1/DR2 results showed that, instead, many probably formed in a highly sub-structured state with multiple small-scale star formation events rather than a single, monolithic burst.

Such a conclusion was suggested based on the Gaia DR1 data for the Sco–Cen OB association by Wright & Mamajek (2018), and in a much larger (12 000 OB stars) Gaia DR2-based study by Ward et al. (2020).

MY STARTING POINT in this essay is the general picture already reached in 2021: that the Gaia results are far more consistent with a scale-free, hierarchical picture of star formation, in which stars are formed across a continuous density distribution throughout molecular clouds, rather than exclusively within clusters, and in which OB associations are formed *in situ* as relatively large-scale and gravitationally-unbound structures (e.g. Ward & Kruijssen, 2018).

Before continuing with the subsequent studies, let me stress that the subject of associations, the advances being made by Gaia, and the inferences being made in more theoretical studies of star formation, is a very substantial field, for which I refer to some recent reviews for the broader context and many more details (Krumholz et al., 2019; Wright, 2020; Cantat-Gaudin, 2022; Wright et al., 2023; Zucker et al., 2023; Quintana, 2024).

THE GAIA DATA, using parallaxes, proper motions, radial velocities and photometry, has enabled the improved membership and characterisation of all known associations, and the discovery of many others.

Studies extended out to around 150 pc with DR1 (Gagné et al., 2018a; 2018b; 2019), to several hundreds of parsecs with DR2, including associations in Orion, Perseus, Taurus, and Sco–Cen (Zari et al., 2018; Kounkel & Covey, 2019; Dickson-Vandervelde et al., 2021; Kerr et al., 2021; McBride et al., 2021; Teixeira et al., 2021), and to beyond 1 kpc with EDR3/DR3 (Zari et al., 2021; Moranta et al., 2022; Pang et al., 2022; Prisinzano et al., 2022; Kerr et al., 2023; Luhman, 2023).

One recurring theme that emerges from these studies is their spatial complexity. For example, the massive star-forming regions within 600–700 pc, such as Orion, Sco–Cen, and Vela, trace a complex three-dimensional pattern (Prisinzano et al., 2022). Most young stars are not organised into distinct spiral arms (Zari et al., 2021). And cluster analyses points to structural connections between often-separated populations, such as between the Orion Complex and Perseus OB2, and between the subregions of Vela (Kerr et al., 2023).

The nearest and most well-studied association is Scorpius–Centaurus (Sco–Cen, aka Sco OB2), and subgroups including Lower Centaurus Crux and Upper Scorpius. At 130 pc, and extending over 2000 sq. deg., Hipparcos identified over 400 members (de Zeeuw et al., 1999). Gaia allows a more rigorous membership, and the detection of lower-mass stars, and has brought the latest census to around 15 000 (Goldman et al., 2018; Luhman et al., 2018; Röser et al., 2018; Wright & Mamajek, 2018; Damiani et al., 2019; Luhman & Esplin, 2020; Squicciarini et al., 2021; Luhman, 2022; Briceño-Morales & Chanamé, 2023; Ratzenböck et al., 2023a; 2023b; Žerjal et al., 2023; Bobylev & Bajkova, 2024).

Amongst these, within Lower Centaurus Crux, Goldman et al. (2018) reported *'... the revelation of a large moving group containing more than 1800 intermediate- and low-mass young stellar objects and brown dwarfs that escaped identification until Gaia DR2'.*

Also from Gaia DR2, Damiani et al. (2019) identified 11 000 pre-main-sequence members, while Žerjal et al. (2023) identified eight kinematically distinct components consisting of 8185 stars distributed in dense and diffuse groups, each with an independently fit kinematic age. From EDR3, Luhman (2022) estimated that the complex contains 10 000 members with masses $\gtrsim 0.01 M_\odot$. With DR3, Ratzenböck et al. (2023b) found more than 13 000 young co-moving objects (19% of substellar mass), organised into 37 co-moving groupings.

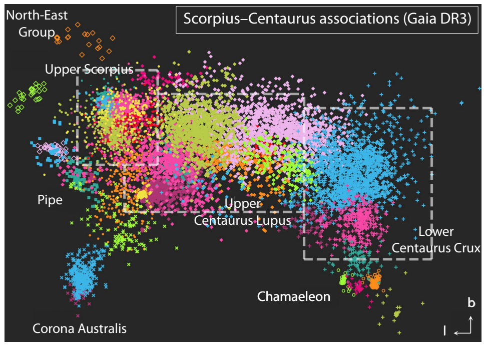
Squicciarini et al. (2021) concluded that star formation in Sco–Cen lasted more than 10 Myr, proceeding in small groups that, after a few Myr, dissolve in the field of the older population but continue to retain memory of their initial structure. A detailed star-formation chronology is given by Ratzenböck et al. (2023a).

Of more general applicability, Buckner et al. (2024) ran simulations of the detectability and reliability of these associations based on Gaia DR3.

Melnik & Dambis (2021) estimated the contribution of binary systems to the velocity dispersion inside OB-associations derived from the Gaia DR2 proper motions. The maximum contribution to the velocity dispersion is given by binaries with orbital period around 5.9 yr.

Whether associations are expanding or not is linked to the underlying star-formation processes. During the early phases, radiation from hot stars and supernovae can rapidly strip residual gas, although not necessarily resulting in the association's rapid dispersal (e.g. Kruijssen, 2012; Kruijssen et al., 2012).

Equipped with the individual space motions from Gaia, it appears that many associations *are* expanding, some albeit only slowly (Mel'nik & Dambis, 2017; Ward & Kruijssen, 2018; Kuhn et al., 2019; Melnik & Dambis, 2020; Ward et al., 2020), although others are not (Kounkel et al., 2018; Wright & Mamajek, 2018).



Ratzenböck et al. (2023)

In their wide-ranging review, Krumholz et al. (2019) opened their abstract as follows: *'Star clusters stand at the intersection of much of modern astrophysics: the interstellar medium, gravitational dynamics, stellar evolution, and cosmology'.* They summarise the present understanding of the formation, evolution, and eventual disruption of star clusters so authoritatively and lucidly, that I will quote verbatim from their abstract.

"The current literature suggests a picture of this life cycle with several phases:
• clusters form in hierarchically-structured, accreting molecular clouds that convert gas into stars at a low rate per dynamical time until feedback disperses the gas;
• the densest parts of the hierarchy resist gas removal long enough to reach high star formation efficiency, becoming dynamically-relaxed and well-mixed. These remain bound after gas removal;
• in the 100 Myr after gas removal, clusters disperse moderately fast, through a combination of mass loss and tidal shocks by dense molecular structures in the star-forming environment;
• after ~100 Myr, clusters lose mass via two-body relaxation and shocks by giant molecular clouds, processes that preferentially affect low-mass clusters and cause a turnover in the cluster mass function to appear on 1–10 Gyr timescales;
• after dispersal, some clusters remain coherent and detectable in chemical or action space for multiple Galactic orbits."

For those still struggling to understand the big picture, Krumholz et al. (2019) perhaps provide some comfort. For despite this broad and broadly satisfying picture, star clusters, which cover a huge range of mass, size, and density scales, *'remain mysterious'. 'Conceivably'*, they continue, *'all stars formed in groups, clusters, or hierarchies, although, for this to be true, most clusters must have dissolved into the Galactic background soon after formation. However, our understanding of when, how, and why stars cluster remains primitive'.*

Gaia is contributing significantly to their understanding, and I will finish with a quote from Wright (2020): *'It is clear now that OB associations have considerably more substructure than once envisioned, both spatially, kinematically and temporally. These changes have implications for the star formation process, the formation and evolution of planetary systems, and the build-up of stellar populations across galaxies.'*