224. Strings, snakes and pearls

I WILL START this essay with the opening words of the review by Zucker et al. (2023): *'Most of what we know about the formation of stars, and essentially everything we know about the formation of planets, comes from observations of our solar neighbourhood within 2 kpc of the Sun. Before 2018, accurate distance measurements... were few and far between. Since 2018, data from the Gaia mission are revealing previously unseen and often unexpected 3D distributions of gas, dust, and young stars in the solar neighbourhood.'*

In my previous five essays, I summarised our latest knowledge of the structure and evolution of nearby open clusters and associations as revealed by Gaia's astrometry and photometry. Here, I will look at some new – and unexpected – structures associated with star formation in the solar neighbourhood, including those described in the discovery papers as 'strings', 'snakes', and 'pearls'.

IT IS PERHAPS useful to recall the definition of open clusters and associations by Lada & Lada (1991): groups of stars of the same physical type whose surface density significantly exceeds that of similar field stars.

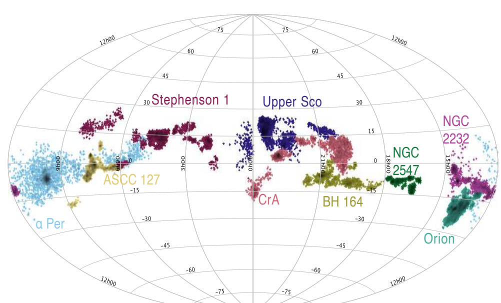
They then considered *clusters* to be physically related groups of 10 or more stars whose stellar density, of around $1 M_\odot\ \mathrm{pc}^{-3}$, would render it stable against tidal disruption by the Galaxy, as well as by passing interstellar clouds. *Associations* are loose groups of 10 or more physically related stars whose space density is considerably below the tidal stability limit. At least some 'moving groups' are the remnants of such structures. Today, we might be less strict on membership numbers, and we know that clusters progressively 'dissolve' as a result of gas dispersal, as well as internal and external disruptive processes. But these definitions serve as a guide.

KNOWLEDGE OF THE 3D distribution of young stars, as well as the gas and dust from which they form, is essential for modelling the many processes that determine star formation, such as gravity, turbulence and magnetic fields (e.g. Hartmann et al., 2001; Kennicutt & Evans, 2012; Evans et al., 2014; Heyer & Dame, 2015).

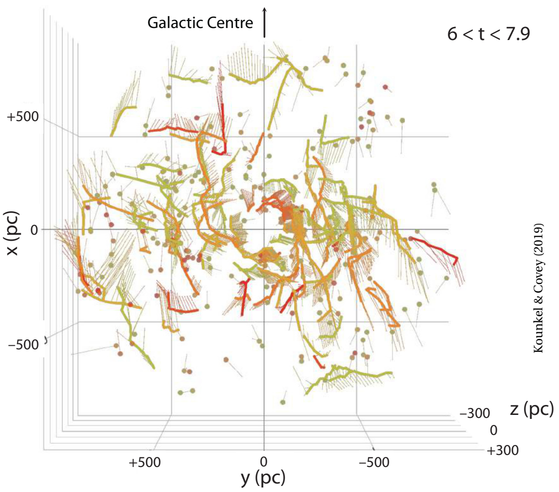
MAPPING OF THE local distribution of gas and dust has been greatly advanced using Gaia astrometry to derive the distances and 3D structures of molecular clouds and local star-forming regions, a topic which I detailed in essay 192. In the present context, I will only emphasise the point that the gas in giant molecular clouds, such as Orion, is often found in the form of extended filaments (e.g. Bally et al., 1987; Hacar et al., 2018; Kounkel et al., 2018; Zucker et al., 2021).

Of Gaia's new open cluster discoveries, a particular curiosity is Meingast–1 (Meingast et al., 2019), aka the Pisces–Eridanus stream (Röser & Schilbach, 2020; Ratzenböck et al., 2020), a massive elongated co-moving population at a distance of only 100 pc. This extends 120° on the sky, viz. several hundred pc in length. Identified in velocity space, it was 'hiding' amongst hundreds of thousands of unrelated field stars. It is held to be a dissolving open cluster, with an age similar to that of the Pleiades, around 120 Myr (Curtis et al., 2019; Arancibia et al., 2020; Hawkins et al., 2020), and with at least one planetary system so far identified (Newton et al., 2021).

EVEN MORE CURIOUS are the nearby discoveries reported by Kounkel & Covey (2019). From Gaia DR2, they identified 1901 distinct groups within 1 kpc, together comprising 288 370 stars. Many of these groups appear to be filamentary structures that they refer to as 'strings', oriented parallel to the Galactic plane, and with some spanning hundreds of pc in length. One of the largest, α Per, seen here in light blue, extends over 120°.



Kounkel & Covey (2019)



THE ANALYSIS by Kounkel & Covey (2019) found that these nearby 'strings', shown above, appear to be coherent both spatially and kinematically, and roughly parallel to the Galactic plane. Each can be characterised with a single isochrone, spanning ages of $10^7 - 10^9$ yr, albeit with a possible scatter of few Myr. The youngest strings (< 100 Myr) are the most prominent, and are orthogonal to the Local Arm. The older features appear to be remnants of other arm-like structures that cannot be presently traced by dust and gas.

Most lack a central cluster, implying that their filamentary nature is primordial, rather than the result of, say, tidal stripping. The velocity dispersion increases with age, and suggests a timescale for dynamical heating of ∼300 Myr. This timescale is also consistent with the age at which the string population begins to decline, while the population in more compact groups continues to rise. This all suggests that various dynamical processes are disrupting the more weakly bound string populations, leaving only individual clusters to be identified at later times.

Kounkel et al. (2020) extended this search to a distance of 3 kpc, and compiled a catalogue (referred to as Theia; Kounkel et al., 2022) of 8292 separate low-density filamentary or streams, comprised of hundreds to thousands of stars and spanning hundreds of pc.

OTHER YOUNG and highly elongated stellar structures in the solar neighbourhood have been reported. In the area of the Vela OB2 association, stellar bridges extending over a few hundred parsecs and connecting several known clusters suggest a star-formation episode in a filamentary giant molecular cloud about 35 Myr ago (Beccari et al., 2018; Tian, 2020; Wang et al., 2022).

Jerabkova et al. (2019) identified a 17 Myr old and 90 pc long stellar relic filament in the Orion star-forming region, too young to have been entirely shaped by tidal forces, and also attributed to a filamentary remnant.

Beccari et al. (2020) detected a 260 pc-long structure linking two previously known clusters, BBJ 1 and NGC 2547. Tian (2020) identified a young (30–40 Myr) stream, 200 pc long and 80 pc wide, comprising several thousand stars, which they referred to as a 'snake'.

Somewhat distinct from these filaments are the stellar 'pearls': distinct clusters that follow similar Galactic orbits, and identified as overdensities in action-angle space (Coronado et al., 2022). While these are not, it seems, coeval systems originating from the same molecular gas cloud, their existence points to recent star formation which is strongly clustered along an orbit.

AN UNAMBIGUOUS picture of how these filamentary structures arise and evolve remains unclear. GALAH-based studies of the chemical abundances of five of the large stellar strings do suggest that they are, in general, chemically homogeneous (Manea et al., 2022).

In a follow-up study of Theia 456, a low-density thin-disk stream extending nearly 200 pc and 20° across the sky, Andrews et al. (2022) supplemented Gaia astrometry with spectroscopic metallicities from LAMOST, and rotation periods from ZTF and TESS photometry. They reported strong evidence that the members have a common age (175 Myr), a common dynamical origin, and were formed from chemically homogeneous pre-stellar material, with [Fe/H] = –0.07 dex.

However, Zucker et al. (2022) suggest that the large radial velocity dispersions of some filaments, averaging ∼16 km s^{-1} as found with Gaia DR3, would imply that their reported ages are significantly larger than the inferred dispersal times. The chemical homogeneity may also not be conclusive, together perhaps calling into question their true physical association.

GAIA IS REVEALING considerable and largely unexpected complexity in the various physical and kinematical structures in these young star-forming regions. While they can be roughly broken down into smaller components of varying densities that may evolve separately over time, many appear to be formed from the same parental cloud complex.

And while Kounkel & Covey (2019) used the term 'group' to embrace gravitationally bound clusters, associations, and co-moving groups, they emphasised that the question of nomenclature, and whether there is indeed a conceptual difference between them, needs to be revisited in the future.

I WILL FINISH with another quote from Zucker et al. (2023), to which I refer for a more substantial review: *'This new 3D view of our solar neighbourhood in the age of Gaia shows that star-forming regions once thought to be isolated are often connected on kpc scales, causing us to reconsider models for the arrangement of gas and young stars in galaxies.'*