18. The origin of OB associations

All stars are believed to have been born in dense molecular gas clouds. Clusters and associations appear to have formed within their massive dense cores.

What is the difference between clusters and associations? Did all stars form in clusters, some of which spread out to form looser associations and moving groups, before 'dissolving' completely? Gaia has added some very significant new insight to these questions.

But first we will need some definitions. Lada & Lada (1991) defined open clusters and associations as groups of stars of the same physical type whose surface density significantly exceeds that of the field for stars of the same physical type.

They 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 stellar space density is considerably below the tidal stability limit. Moving groups are, loosely, the remnants of such structures.

A typical cluster contain a few tens to several thousands stars within a typical radius of 1–10 pc. Constituent stars progressively dissolve back into the field over time through a variety of mechanisms, notably gravitational perturbations from the disk or passing interstellar gas clouds, and supplemented by cluster ejection through gravitational encounters within the cluster. Typical lifetimes are of order 100 Myr, with the least tightly bound surviving for only a few million years, and the richest for as much as a billion years.

In practice, OB associations are characterised by low stellar densities and a large spatial extent, and survive as a recognisable group only for a short time, of order 25 Myr. They are made recognisable not necessarily by their general overdensity with respect to field stars, but by their overdensity of luminous O and B stars.

Their large masses and high luminosities imply that the constituent stars are young and short lived, and are therefore associated with sites of recent star formation.

From the theoretical side, the 'monolithic formation scenario' holds that most (if not all) stars form in gravitationally-bound clusters. In this picture, the gravitationally-unbound OB associations found in the solar neighbourhood and beyond must have been significantly more compact at the time of their formation, and must have subsequently expanded into the configurations we see today. The process suggested to initiate expansion was the expulsion of residual gas from embedded clusters through stellar feedback.

Over the past few years, this view of monolithic formation has seemed somewhat in contradiction to observations of present-day star formation, which appears to proceed over a wide range of environments, including both large-scale hierarchical structures and isolated young stellar objects.

THere are a couple of dozen clusters, moving groups, and OB associations within about 150 pc of the Sun. Associations include those of Scorpius–Centaurus (with subgroups including Lower Centaurus Crux and Upper Scorpius), Taurus–Auriga, and Hercules–Lyra. And with the exception of the more distant α UMa (Dubhe) and η UMa (Alkaid), all the stars in the Plough/Big Dipper constellation are part of the Ursa Major association. OB associations have also been found in the Large Magellanic Cloud and the Andromeda Galaxy.

The large extent of nearby OB associations on the sky has traditionally prevented accurate kinematic membership determination for any but the brightest stars.

Many studies of OB associations were made with the Hipparcos data, with one of the most extensive being by de Zeeuw et al. (1999). They made a comprehensive census of the stellar content of OB associations within 1 kpc from the Sun, based on 9150 Hipparcos candidate members. It was part of a long-term project to study the formation, structure, and evolution of nearby young stellar groups. Hipparcos provided a major improvement in the kinematic detection of these structures, resulting in improved astrometric members for 12 young stellar associations out to a distance of 650 pc.

THE SCIENTIFIC CASE for Gaia, back in 2000, included the goal of detecting and studying associations to much larger distances. For those nearer than 2000 pc, reliable member selection should be possible down to the lowest stellar masses. This would include objects that are still on their way to the main sequence, amongst them objects bright in X-rays.

The first studies of OB associations using the early Gaia data already suggested disagreement with the monolithic formation scenario, in which associations must be expanding from their early origins as gravitationally bound clusters. The problem was that none of the associations exhibited any significant evidence of an expanding velocity field. Indeed, their bulk kinematic properties were far more consistent with randomised velocity fields than expanding ones.

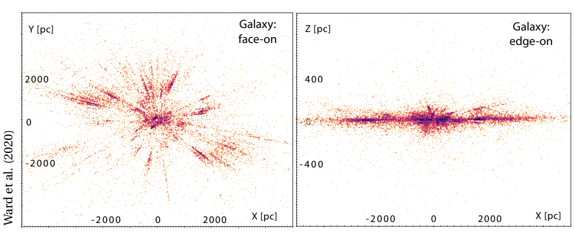
Specifically the kinematics of 18 nearby OB associations using the first Gaia data release found little evidence for systematic expansion (Melnik & Dambis, 2017). The same was true for 18 other associations (Ward et al., 2018), while Wright & Mamajek (2018) used Gaia DR1 to show that the Sco–Cen OB association was most likely formed in a highly sub-structured state with multiple small-scale star formation events rather than a single, monolithic burst of star formation.

A subsequent study of 28 associations with DR2 found that the majority of associations are not undergoing expansion (Melnik & Dambis, 2020). In a possible counter-example, Cantat-Gaudin et al. (2019) found that, while the Vela OB2 association *is* expanding, the Gaia data suggests that this expansion began before the stars in Vela OB2 were formed, and therefore probably the result of a supernova-driven shock.

A MUCH LARGER study was carried out with the Gaia DR2 data by Ward et al. (2020), and the numbers of associations, and numbers of objects available for study in each, are worth emphasising.

Their starting point was the Galactic OB star catalogue, GALOBSTARS, containing some 16 000 OB-star candidates. Further selection according to Gaia colours resulted in a set of 11 844 OB stars from DR2.

In the resulting distribution of the selected OB stars out to 3000–4000 pc from the Sun, shown below, the apparent elongation of the associations in the radial direction is primarily due to the present uncertainty in distance of those stars.

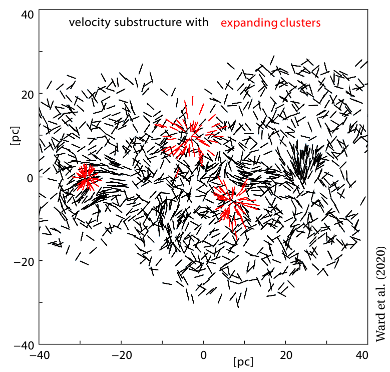


Use of a cluster-finding algorithm resulted in the discovery of 109 OB associations out to about 3000 pc. With typically 10–50 OB stars in each of these, they then searched for additional, lower mass members from the wider DR2 catalogue. This resulted in a typical total of about 6000 stars in each association.

The main part of their analysis then involved determining the key kinematic properties of these associations, such as their velocity dispersions. They could then quantify the extent to which they are undergoing expansion in excess of what could be expected from a random velocity distribution.

They concluded that a simple monolithic cluster that subsequently underwent gas-expulsion driven expansion can be firmly ruled out as an origin of the associations. But their kinematic properties are also found to be inconsistent with purely random velocity fields.

Only with a combination of small-scale localised expansion events, shown here in red, along with positional substructure and a randomised but sub-structured velocity field were they able to reproduce the kinematic properties of these OB associations.



Velocity maps based on a Gaia-observed OB association

THE GAIA DATA convincingly rule out simple models in which Galactic OB associations are formed from the expansion of previously compact clusters. They also contradict the picture that most stars form in clusters, of which a large fraction is subsequently unbound by gas expulsion-driven expansion.

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.

While localised expansion of individual substructures within associations does appear to be an important component of their kinematic properties, this expansion is not the primary driver of their large-scale structural evolution.