186. Moving groups and traceback ages

YOUNG LOCAL ASSOCIATIONS and moving groups are small nearby aggregates of typically a few dozen stars, assumed to have been born within the same molecular cloud, and therefore at the same time and place, with similar initial chemical composition, and sharing a common global space motion. Their uniform initial properties underpins their importance for studies of star formation and their subsequent evolution (e.g. de Zeeuw et al., 1999; Jayawardhana, 2000).

Their age is key in modelling the early stages of star and planet formation, and various methods based on stellar evolution models can be used for their estimation, most notably based on theoretical isochrones or models of lithium depletion.

An independent method, yielding what are referred to as dynamical or traceback ages, makes use of their expanding space motions. Assuming that the stars were formed at a time when the association was most spatially concentrated, tracing back their space motions can establish their birth epoch. In most cases, this yields ages broadly consistent with those from stellar evolution models, but not always precisely so.

In practice, dynamical traceback models have variously employed linear trajectories, epicyclic approximations, or orbit integration within a specified Galactic potential. One crucial limitation has been knowledge of the stars' space motions, due to uncertainties in their distances, proper motions, and radial velocities (e.g. Ortega et al., 2002; Song et al., 2003; Ortega et al., 2004).

Today, traceback studies of several moving groups are making use of the Gaia astrometry and radial velocities. I will start with the important case of β Pictoris.

ONE OF THE NEAREST, richest and today most intensively studied of these nearby associations or moving groups, β Pic was discovered through the identification of two companions to the A star β Pic by Barrado y Navascués et al. (1999). Subsequent identification of other co-moving stars has led to several hundred possible members known today (Zuckerman et al., 2001; Torres et al., 2006; Malo et al., 2013; Binks & Jeffries, 2016).

AT A DISTANCE of only 40 pc, some members host disks (Kalas & Jewitt, 1995; Kalas et al., 2004); exoplanets (Lagrange et al., 2010; Lagrange et al., 2019; Chauvin et al., 2012), and exocomets (Kiefer et al., 2014).

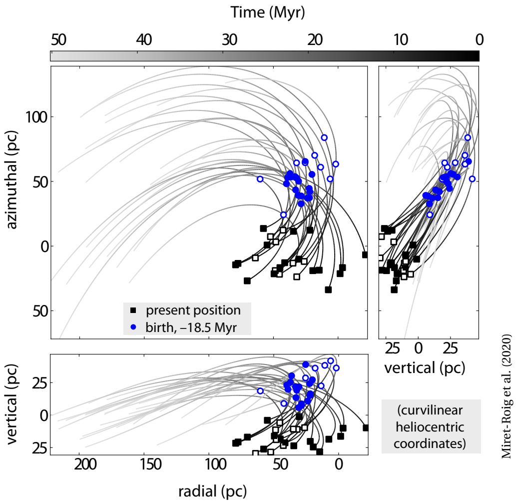
Of some two dozen ages for the β Pic moving group tabulated by Miret-Roig et al. (2020, their Table 6), pre-Gaia estimates have centred around 20 Myr (e.g. Mamajek & Bell, 2014), but with Li depletion estimates as high as 25 ± 3 Myr (Messina et al., 2016), and more uncertain dynamical traceback ages ranging from 11.5 Myr (Ortega et al., 2002) to 31 ± 21 Myr (Makarov, 2007).

Gaia astrometry has now been used to refine group membership, based on DR2 (Ujjwal et al., 2020), and subsequently DR3 (Lee et al., 2024). The latter resulted in 106 single and resolved companions, and 47 unresolved binaries, but still with a wide model-dependent age range: 23 ± 8 Myr from Dartmouth magnetic models fit to the lithium depletion boundary, 33 ± 10 Myr fit to the Gaia M_G versus $B_P - R_P$ colour–magnitude diagram, and 11 ± 4 Myr as best fit to the 2MASS–Gaia M_{K_S} versus $B_P - R_P$ colour–magnitude diagram.

BUT I WILL focus here on the association's Gaia-based dynamical traceback age. Miret-Roig et al. (2020) used DR2 astrometry, supplemented by new ground-based as well as Gaia-determined radial velocities, to determine the accurate space motions for their selected 26 *bona fide* members.

They used a specific axisymmetric (bulge/disk/halo) Galaxy potential to integrate the equations of motion, propagated backward in time to –50 Myr. They defined the dynamical age as the time at which the members of the association were most concentrated in space.

Their orbital projections in the Galaxy (actually in curvilinear heliocentric coordinates, centred on the Sun's position, and rotating around the Galactic centre) are shown below, colour-coded according to this backward time. Black squares are the present positions, with blue circles representing positions at the inferred birth epoch, $t = -18.5$ Myr. They also identified a particular concentration of 17 'core' stars, shown as filled symbols.



They found a dynamical traceback age of $18.5^{+2.0}_{-2.4}$ Myr, broadly consistent with the most robust estimates from isochrone or lithium depletion models, and a size (defined by the trace covariance matrix) of 7 pc at birth. And they concluded that, with Gaia, the observational uncertainties no longer dominate the uncertainties in the age, although it does remain sensitive to the definition and selection of association members. Further DR2-based studies were made by Crundall et al. (2019).

A subsequent study based on Gaia DR3 by Couture et al. (2023) concluded that the radial velocities include biases, due to gravitational redshift and convective blueshift, of order 0.6 km s^{-1}. Their chosen sample of 25 stars (out of their full sample of 76 members) then yields a corrected age of 20.4 ± 2.5 Myr.

Let me briefly mention some of the other Gaia-based studies that are being made on nearby associations. Some have been focussed on refining association membership, some on improved isochrone ages, and others on estimating dynamical traceback ages.

At around 400 pc, the Orion star-forming region is of complex morphology, with multiple stellar populations, and star formation having taken place over an extended period of some 10 Myr. It is too distant for precise parallax or proper motion estimates by Hipparcos, such that much of its structure and dynamics has remained uncertain. Studies have been reported using Gaia DR2 (Kounkel et al., 2018), and EDR3 (Swiggum et al., 2021), the latter providing evidence for radial expansion of two of its stellar groups from a common centre.

Other Gaia-based membership and traceback studies have been reported for 32 Ori (Luhman, 2022), TW Hya (Luhman, 2023), Upper Scorpius (Squicciarini et al., 2021), Ophiuchus (Miret-Roig et al., 2022), Cepheus Far North (Klutsch et al., 2020; Kerr et al., 2022a), and Fornax–Horologium (Kerr et al., 2022b).

Interesting insights into the star-formation process are emerging from detailed consideration of these expansion velocities. Kuhn et al. (2019) used Gaia DR2 data for a sample of 28 clusters and associations with ages from 1–5 Myr, to show that at least 75% are expanding, but with rotation detected in only one. Typical expansion velocities are on the order of 0.5 km s^{-1}, with a positive radial gradient in expansion velocity in some.

Systems still embedded in molecular clouds are less likely to be expanding than those that are partially or fully revealed. In star-forming regions containing multiple clusters or sub-clusters, they found no evidence that the groups are coalescing, implying that hierarchical cluster assembly, if it occurs, must happen rapidly during the embedded stage.

In related work, a variation of the dynamical traceback age based on the association's 'evaporation age', is also being advanced by Gaia (Pelkonen et al., 2024).

Developing these ideas, and based on a comparison of recent dynamical traceback and isochrone ages, Miret-Roig et al. (2024) showed that there is a systematic difference between the two, with the traceback ages consistently younger than the isochrone ages by an average of 5.5 ± 1.1 Myr. They concluded that the discrepancy arises because the two methods have a different time origin: if the star cluster is gravitationally bound before the dispersion of the parent gas cloud, the zero-point of the expansion time scale is a few Myr after that of the colour–magnitude diagram method.

In other words, the dynamical traceback 'clock' starts when a stellar cluster or association begins to expand after expelling most of the gas, whereas the isochronal 'clock' starts earlier when most stars form; for example, when most of the material in the envelope has collapsed onto the disk, and the central protostar becomes observable at infrared wavelengths (e.g. Wuchterl & Tscharnuter, 2003). As a result, the age difference between the two methods is providing important clues about the cluster formation and gas dispersal processes.

In particular, the age difference appears to represent an observational measurement of the duration of the embedded phase, and the timescale of gas dissipation.