192. The structure of molecular clouds

ON THE subject of the structure of Galactic molecular clouds, Dharmawardena et al. (2023) wrote *'Great progress has been made in this field with the arrival of the Gaia mission'*. I will give some background, explain why their 3D structure is relevant, and illustrate how Gaia is contributing. I should also mention that my previous essay, on extinction, is closely tied to this present topic.

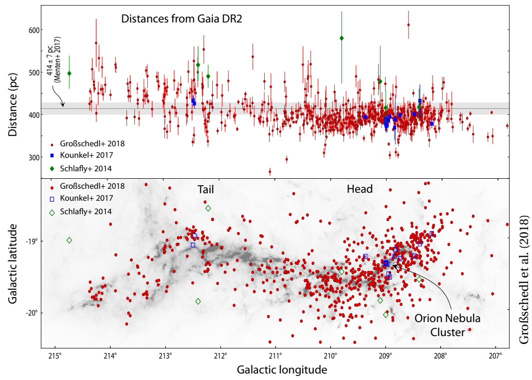
MOLECULAR CLOUDS are regions of the interstellar medium dense enough (10–30 cm^{-3}) to form molecular gas. This results in 'dark nebulae' that obscure light from background stars, and in whose densest regions star formation can occur. *Giant* molecular clouds (GMC) extend to 10–200 pc, and masses $10^4 - 10^7 M_\odot$.

Maps of the Galaxy in CO, a constituent more easily detectable than the dominant H_2, show that such molecular gas is largely confined to the mid-plane of the Galaxy, with a scale height ~50–60 pc. Since ultraviolet photons from associated star formation transform molecular material back to the atomic state, their close association with spiral arms in turn suggests that molecular clouds form and dissociate on a timescale ≲10 Myr.

Parallaxes for relatively nearby stars make it possible to derive cloud distances and even their 3D structures, important in understanding how processes such as turbulence and magnetic fields affect star formation within them (e.g. Hartmann et al., 2001; Kennicutt & Evans, 2012; Evans et al., 2014; Heyer & Dame, 2015).

THE PRINCIPLES underlying Gaia's contributions can be seen in the GMC archetype, Orion A, the most active local star-forming region, from which many key observables, including star-formation rates and history, multiplicity, initial mass function, and protoplanetary disk populations, have been derived. Estimates of cloud mass, physical size, and star formation all depend critically on accurate distance measurements.

The Orion Nebula Cluster, the richest cluster at the northern end of Orion A, lies at ~400 pc. Pre-Gaia observations, while suggesting a distance gradient across the cloud (Schlafly et al., 2014; Kounkel et al., 2017), could say little about its shape or 3D structure.



The Gaia DR2 parallaxes for a number of Young Stellar Objects (YSO), with ages ≲ 3 Myr, can now be used as tracers of the cloud's 3D shape (Großschedl et al., 2018; Kounkel et al., 2018). Großschedl et al. (2018), for example, used a sample of 682 YSOs, to trace distances of young objects within the Orion A cloud, shown here projected on the Planck–Herschel dust column-density.

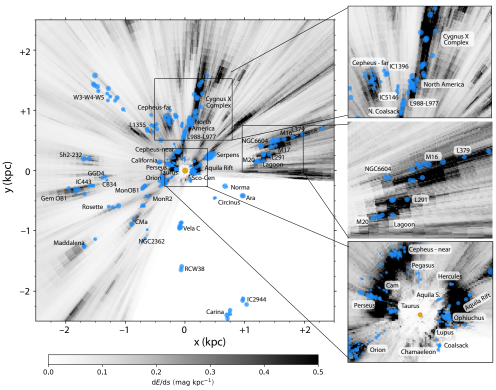
They concluded that Orion A is not the straight filamentary cloud seen in projection, but instead a cometary-like cloud with aspect ratio 30:1, and two distinct components: a denser and enhanced star-forming 'head', and a lower density 75 pc long 'tail'. The true extent, 90 pc rather than the projected 40 pc, makes it the largest molecular cloud in the local neighbourhood.

Zucker et al. (2019) also used DR2 parallaxes to derive distances and extinctions to tens of thousands of stars towards several dozen molecular clouds within 2 kpc. They gave average distances (accurate to 5–6%) to most of the major named clouds in the CO survey of Dame et al. (2001), including Perseus, Orion A, Taurus, Ophiuchus, California, and Cepheus. An interactive version of their Fig. 1 shows their distance–extinction relations towards the Perseus cloud as characterised before and after Gaia, with the most probable distance and extinction to each star indicated with a red cross.

Yan et al. (2019) similarly used DR2 parallaxes and G-band extinctions to derive distances to 52 high Galactic latitude ($|b| \geq 10^\circ$) molecular clouds, 13 for the first time, and again with errors of typically 5%.

The 2-volume Star Formation Handbook (Reipurth, 2008a; 2008b) contains 60 star forming regions within 2 kpc. Although well studied, their distances have remained poorly constrained. Amongst them, several have pre-Gaia estimates that vary by more than a factor of two (e.g. Circinus, Coalsack, NGC 2362, IC 5146).

Zucker et al. (2020) derived DR2-based star distances and extinctions in sightlines towards these clouds. They used an implementation of the method pioneered by Wolf (1923), viz. by fitting a line-of-sight dust model to identify the distance at which a discontinuity appears in the stellar reddening. Comparison with maser (parallax) distances results in consistent estimates, with 10% scatter, across their entire distance range 150–2500 pc.



Zucker et al. (2020)

An alternative to identifying molecular clouds from their CO emission is from dust extinction measurements. Already from 2MASS colour excess maps, Dobashi (2011) had identified 7000 new molecular clouds, although without distance information.

With Gaia DR2, focusing on low Galactic latitudes, $|b| < 10^\circ$, and using the Gaia-based colour excesses of 56 million stars previously derived by Chen et al. (2019), Chen et al. (2020) identified 567 dust/molecular clouds with a hierarchical structure identification method, with distance uncertainties ∼5%. The clouds lie along the known Sagittarius, Local and Perseus Arms, with a possible spur connecting the Local and Sagittarius arms.

Several studies have exploited the Gaia distances and photometry in various combinations to probe the 3D structure of several of these molecular clouds. Leike et al. (2020) used Gaia, 2MASS, PANSTARRS, and ALLWISE data to create resolved dust maps of clouds out to 400 pc with a resolution of 1 pc.

These were then used by Zucker et al. (2021), who first established the skeleton-like 'spines' of each cloud, thereafter determining the radial volume density profile around each of these spines. Well-described by a two-component Gaussian, they inferred that the clouds are characterised by broad lower-density outer envelopes, with narrow higher-density inner layers, consistent with a transition between atomic and diffuse molecular gas.

Other works employing extinctions, dust-mapping, and Gaia DR2 distances to recover the molecular cloud structures include 3D modelling of the thin disk structures (Babusiaux et al., 2020); mapping the disk extinction beyond the range of Gaia parallaxes (Hottier et al., 2020); and using 18 million stars over 450 deg^2 to obtain the extinction and morphology of the Vela complex (Hottier et al., 2021).

Dharmawardena et al. (2023) used their 3D dust-mapping algorithm `dustribution`, which makes use of the stellar distance and extinction estimates from Fouesneau et al. (2022), to recover the 3D structure of 16 Galactic molecular clouds at 1 pc resolution. They then used the `astrodendro` package (Robitaille et al., 2019), which creates dendrograms of hierarchical structures in astronomical data, applied to the dust regions around each complex. From this, Dharmawardena et al. (2023) estimated the volume, mass, and density for each cloud and its associated substructures.

As summarised by Cahlon et al. (2024), in the absence of the third dimension, pre-Gaia catalogues of molecular clouds were derived using position–position data ('$p-p$' space) on the plane of the sky, and sometimes using position–position–velocity data ('$p-p-v$' space), in which spectral-line observations of the ISM can add a third (non-spatial) dimension. They considered that, previous to their work, only the Chen et al. (2020) and Dharmawardena et al. (2023) catalogues were based on true 3D '$p-p-p$' data from 3D dust mapping.

In their own work, Cahlon et al. (2024), started with the 3D dust map of Leike et al. (2020), and performed a similar dendrogram analysis to produce a catalogue of 65 distinct local molecular clouds, now in true $p-p-p$ space, and at 1 pc resolution. Projecting back into 2D, they could perform a detailed comparison with the previous 2D maps, for example finding a steeper power law of the mass–size relation than in previous 2D mappings.

Gaia is also contributing to an understanding of the internal dynamics of molecular clouds. Zhou et al. (2022) studied 150 Young Stellar Objects with $d \lesssim 3$ kpc, finding their associated clouds to be elongated, and oriented parallel to the disk mid-plane. As probed by the YSOs, the turbulence is isotropic, and the 2D velocity dispersion is related to size by $\sigma_v \propto r^{0.67}$. The turbulent energy dissipation rate decreases with Galactocentric radius which, they suggest, can be explained if the turbulence is driven by cloud collisions.

Xu et al. (2023) relate this to the formation of wide binaries, a topic which I will pick up in essay 193.

All these studies (none so far using DR3) underline the expectation that the new, Gaia-enabled, 3D mapping of local molecular clouds will contribute to many advances in star-formation studies.