
Supplementary information

A Solar System formation analogue in the Ophiuchus star-forming complex

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Supplementary Information

1 Distance distribution

One aspect of propagating the ^{26}Al from the sources, whose modelling we have discussed above in detail, to the cores is knowing the distance between the sources and the cores. The simplest assumption would be to take a fixed distance based on the present-day morphology of the ^{26}Al . However, given the uncertainties in the fine details of the γ -ray map, we opt instead to estimate the 3D distribution of possible ^{26}Al sources in Upper Sco relative to the locations of the present-day cores in L1688.

First, we assume that the massive stars in Upper Sco represent a random draw from some underlying 3D spatial distribution, and that past sources of ^{26}Al had positions drawn from the same distribution. Next, we combine the locations on the sky of the 21 most massive stars in Upper Sco, including the runaway star ζ Oph, with distances from Hipparcos, Gaia, and a recent distance catalogue of local molecular clouds⁸. We denote the estimated distances $\hat{d}_i$ and their reported Hipparcos errors $\hat{\sigma}_{d,i}$. We assume negligible errors in the sky locations of the stars, and for simplicity model their underlying 3D distribution as an isotropic gaussian, with unknown 3D center $\vec{r}_c$ and width w .

The likelihood of observing the collection of massive stars at their present locations is then

$$\mathcal{L}(\{\alpha_i\}, \{\delta_i\} | \vec{r}_c, w, \{d_i\}) = \prod_{i=1}^{21} \left[\frac{1}{\sqrt{2\pi}w} \exp\left(\frac{-(\vec{r}_i - \vec{r}_c)^2}{2w^2}\right) \right] \quad (1)$$

Quantities in brackets $\{x_i\}$ refer to properties of the individual stars, indexed by i . These are the observed right ascension and declination, α_i and δ_i , and the (unknown) true distances d_i . The position of the i th star in 3D is $\vec{r}_i$, which is set by α_i , δ_i , and d_i .

In order to incorporate our information about the distance to each star, we can treat the estimated

distances $\hat{d}_i$ and their reported uncertainties $\hat{\sigma}_{d,i}$ as a Gaussian prior on the true distances d_i . We do so with one modification, namely that the reported Hipparcos uncertainties are multiplied by a constant f_e which is the same for all stars. Applying Bayes' Theorem,

$$p(\{d_i\}, f_e, \vec{r}_c, w | \{\hat{d}_i\}, \{\hat{\sigma}_{d,i}\}, \{\alpha_i\}, \{\delta_i\}) \propto p(f_e, \vec{r}_c, w) \left(\prod_{i=1}^{21} p(d_i | f_e, \{\hat{d}_i\}, \{\hat{\sigma}_{d,i}\}) \right) \times \mathcal{L}(\{\alpha_i\}, \{\delta_i\} | \vec{r}_c, w, d_i), \quad (2)$$

where the prior distribution over the true distances is just taken to be a normal distribution,

$$p(d_i | f_e, \{\hat{d}_i\}, \{\hat{\sigma}_{d,i}\}) = \frac{1}{\sqrt{2\pi f_e^2 \hat{\sigma}_{d,i}^2}} \exp \left(\frac{-(d_i - \hat{d}_i)^2}{2 f_e^2 \hat{\sigma}_{d,i}^2} \right). \quad (3)$$

The advantage of writing the problem in this way is that, for our purposes, the true d_i are nuisance parameters that we can now marginalize out. This would ordinarily require a 21-dimensional integral over all d_i , but we can see from equations 1 and 2 that each integral over d_i can be performed separately, so that we are left with a marginalized posterior,

$$p(f_e, \vec{r}_c, w | \{\hat{d}_i\}, \{\hat{\sigma}_{d,i}\}, \{\alpha_i\}, \{\delta_i\}) \propto p(f_e, \vec{r}_c, w) \prod_{i=1}^{21} \int_0^\infty p(d_i | f_e, \{\hat{d}_i\}, \{\hat{\sigma}_{d,i}\}) \mathcal{L}_i(\alpha_i, \delta_i | \vec{r}_c, w, d_i) dd_i \quad (4)$$

where $\mathcal{L}_i$ refers to the i th factor in the likelihood given by equation (1). These integrals may be thought of as weighted sums along the line of sight through the assumed underlying 3D distribution. While they are not analytic, they are 1-dimensional, making them quite tractable and transforming the inference problem from 26-dimensional down to 5-dimensional.

We then sample from the posterior distribution with an affine-invariant ensemble sampler⁸¹. Our prior is that f_e is log-normal, with a median of 1 and a standard deviation in the log of 0.3 dex. The distance to the center of the putative 3D distribution is *a priori* uniform in the log from 10 pc to 1000 pc, and the size of the 3D distribution is uniform in the log from 0.1 pc to 100 pc. To ensure

a uniform prior on the celestial sphere for the location of r_c , namely α_c and δ_c , we impose a flat prior on α_c and the cosine of the angle from the north celestial pole $\cos(\pi/2 - \delta_c)$.

While the full posterior distribution may be of some interest, for our purposes we want a single instance of the model from which to draw 3D locations of SLR sources. A natural choice for which instance of the model to use is the maximum *a posteriori* model. The resulting distribution of distances between the SLR sources and L1688 is shown in Extended Data Fig. 7. In practice we use the best estimate of the 3D location of Elia 2-29 as a proxy for the location of L1688 to produce the distance distribution in this figure. The model 3D distribution shown here is employed in computing the salmon “Broad Distance Distribution” lines in Figure 4.

2 Accumulation

For a particular value of $\rho_{26\text{Al}}$, we estimate the values of the Pre-Enrichment and Accumulation terms as follows. In the Pre-Enrichment term, the ^{26}Al mass is simply the volume of the material that will eventually form the core times the density of ^{26}Al at the time the core formed, times the appropriate exponential decay factor,

$$M_{26\text{Al,core,pre}} = \frac{4}{3}\pi r_c^3 \chi \rho_{26\text{Al}}(t = t_{\text{obs}} - t_c) 2^{-t_c/\tau_{1/2}}. \quad (5)$$

Here $\chi > 1$ is the density contrast between the cores and the lower-density medium from which they form. We adopt $\chi = 100$ and $r_c = 8000$ AU. The latter is consistent with the cores shown in Extended Data Figure 1, though there is some dispersion. We can estimate the density contrast by noting that typical dust column densities in L1688 are about a factor of 10 lower than the columns through the cores. If we assume that the spatial extent of the cores, and of L1688 itself, is comparable to its size on the plane of the sky, we would conclude that the volume density contrast is just the column density contrast times the ratio of the objects’ sizes. For L1688 and its cores, we have $0.5\text{pc}/r_c \approx 13$, so $\chi = 100$ is reasonable, though the true value may vary by factors of several given the uncertainties and the physical variation between the different cores.

Meanwhile the accumulation term requires summing up the contributions from material flowing past the core over the course of its lifetime,

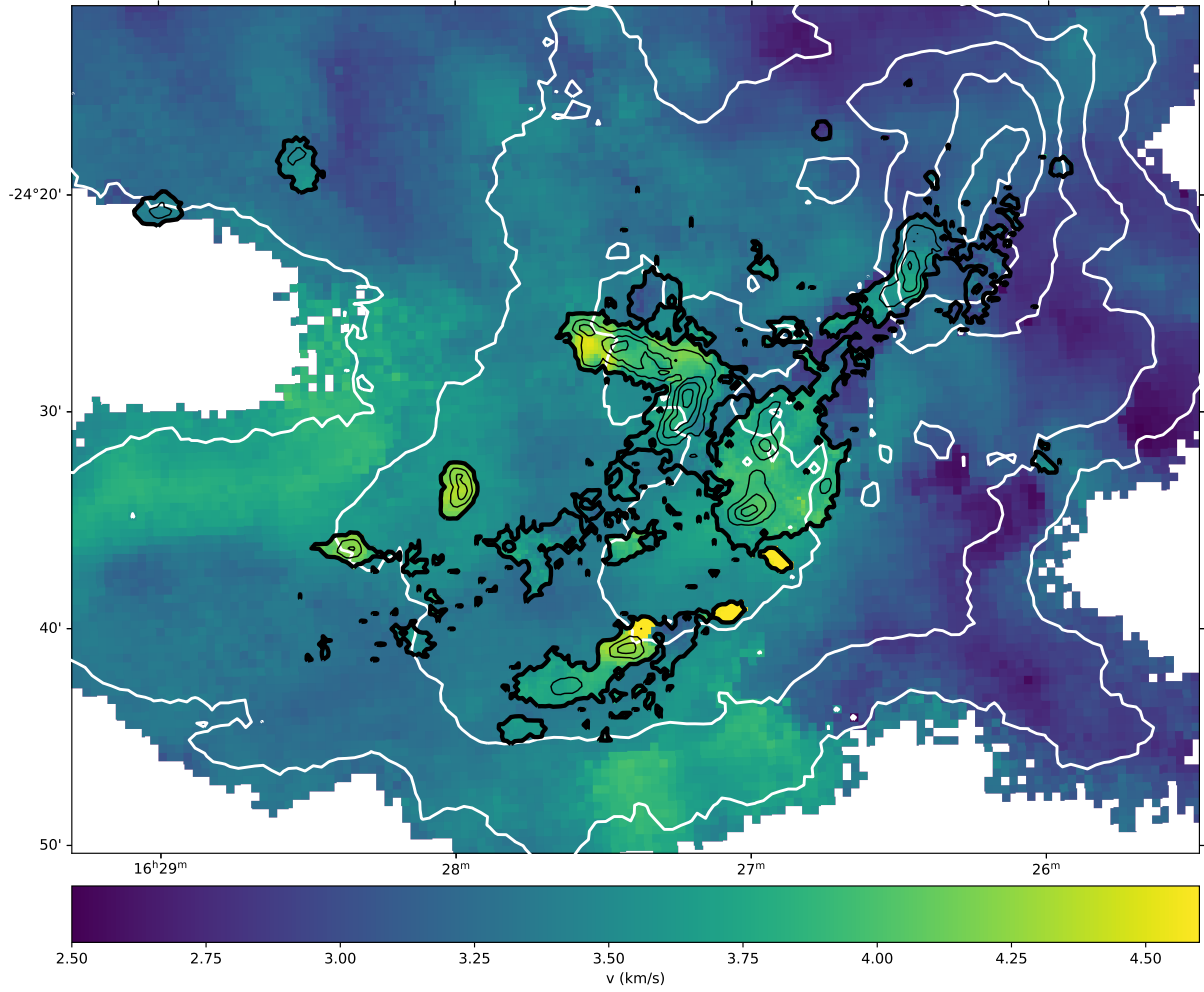
$$M_{26\text{Al,core,accum}} = \pi r_c^2 v_{\text{rel}} \epsilon \int_{t_{\text{obs}} - t_c}^{t_{\text{obs}}} \rho_{26\text{Al}}(t') 2^{-(t_{\text{obs}} - t')/\tau_{1/2}} dt'. \quad (6)$$

We include an efficiency factor ϵ since only a fraction of the material that intersects the core's path through the inter-core medium is actually accreted onto the core. Several arguments suggest that $\epsilon \sim 1\%$. First, idealized simulations of shockwaves triggering the collapse of cores^{13,82} measure this quantity directly, and find values of this order depending on the state of the gas, especially the Mach number⁸³. The ratio of the cross-sectional area described by the Bondi radius $\propto r_{\text{Bondi}}^2 = G^2 M_c^2 / v_{\text{rel}}^4$ to the physical cross-section of the core $\propto r_c^2$ also turns out to be $\sim 1\%$ for a solar mass core of size 8000 AU and relative velocity 1 km s⁻¹. While there is substantial uncertainty in this parameter, it will turn out to be largely irrelevant as long as $\epsilon \ll 1$. The relative velocity between the core and the lower-density material, v_{rel} may be estimated observationally by examining the line-of-sight velocity of the gas in the region as traced by ¹³CO and NH₃. Individual cores traced by the latter are seen to have distinct velocities offset from the surrounding ¹³CO by a few km/s (see Figure 1).

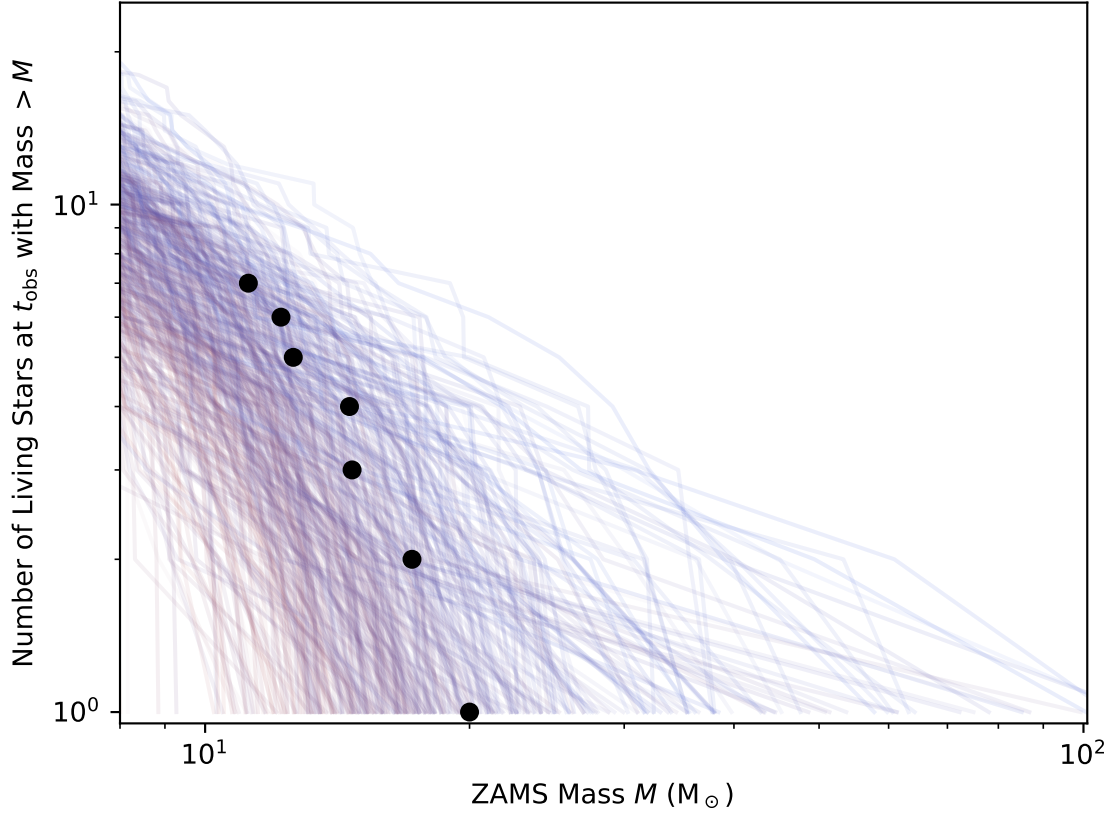
We now turn to the value of the concentration parameter $\mathcal{C}$. The simplest approach would be to set $\mathcal{C} \approx 1$. This assumption is reasonable in the low-density high-temperature gas within Upper Sco, but is less plausible as the ²⁶Al-bearing material mixes with the denser gas of L1688 and its surroundings. Simulations of mixing in the interstellar medium provide some guidance. First, zoom-in simulations¹⁹ beginning from an isolated galaxy simulation²⁴ demonstrate that during the collapse of structure in the molecular clouds, metal inhomogeneities on scales $\lesssim 1$ pc are efficiently mixed together, suggesting that as the ²⁶Al-bearing gas interacts with L1688 and the gas from which it formed, the ²⁶Al available (as determined by the constant-density sphere of radius $\mathcal{R}_i$) would not have great difficulty mixing with the denser gas such that $\mathcal{C}$ really may be described by a constant. In the space of density vs. ²⁶Al/²⁷Al, i.e. concentration, simulations of a turbulent periodic box with sink particles and SLR injection by supernovae²³ showed¹⁸ (their Fig. 2) that

the maximum SLR concentration for a given density scales approximately as $\rho^{-1/3}$ interspersed with a constant scaling as individual objects collapse and cease to mix. In contrast, if SLR-free gas is mixed with a fixed volume of SLR-bearing gas as in the $\mathcal{C} = 1$ case, the concentration would scale as ρ^{-1} . The dust column density in the unambiguously ^{26}Al -bearing region is roughly 100 times lower than the column density within L1688. Given the difference in physical scale on the sky of these two regions, about a factor of 6, the volume density contrast is likely $\lesssim 10^3$. One can consider $\mathcal{C}$ to be a factor accounting for the difference between $^{26}\text{Al}/^{27}\text{Al} \propto \rho^{-1}$ and the true scaling. If we adopt $\rho^{-1/3}$ as the true scaling, we obtain $\mathcal{C} \propto \rho^{2/3}$, so for L1688, $\mathcal{C} \sim 100$, which we adopt going forward.

Adopting fiducial values for χ , r_c , v_{rel} , $\mathcal{C}$ and ϵ , and assuming each has an independent factor of 2 uncertainty owing to geometric and line-of-sight uncertainties, we use our ensemble of $M_{^{26}\text{Al}}(t)$ histories of Upper Sco to compute the median and central 68% of the values of $M_{^{26}\text{Al,core,accum}}$ and $M_{^{26}\text{Al,core,pre}}$ under the two different assumed source distance $\mathcal{R}_i$ distributions (fixed, and broad, corresponding to a reasonable estimate of the 3D distribution of massive stars in Upper Sco). Figure 4 shows the results for a varying value of t_c , along with an errorbar representing an observational estimate and its quoted factor-of-two uncertainty¹⁷ of t_c in this region. Note that the shaded regions around each line represent the uncertainty from both the ^{26}Al production model and the assumed factor of 2 uncertainties in the fiducial parameters determining how the ^{26}Al is incorporated into cores. In the case of the “Broad Distance Distribution,” it also includes dispersion from the spread in distances $\mathcal{R}$ between the sources of SLRs and L1688.



Supplementary Figure 1: Relative motion of the cores and background gas. L1688 is shown here in a combination of ^{13}CO from the GAS survey⁵¹ and NH_3 from the COMPLETE survey⁵². For each tracer, we compute the mean velocity map. In regions where data from both tracers are available, we show only the NH_3 . Black contours show the intensity of NH_3 , and white contours show the intensity of ^{13}CO . Outside of the NH_3 , i.e. outside of the thick black contour line, the color shows the mean velocity of the ^{13}CO . Cores, clearly visible in the NH_3 , tend to have $1\text{--}2\text{ km s}^{-1}$ offsets in mean line-of-sight velocity from the surrounding gas.



Supplementary Figure 2: The predicted distribution of stars alive today in Upper-Sco. The black dots show estimates⁴⁶ for the 6 most massive stars in Upper-Sco, plus ζ Oph, which is a runaway star from Upper-Sco. Lines are colored by the age of the association in that realization of the model with the reddest colors corresponding to the oldest ages. The fact that the points lie in the most likely part of the distribution provides some validation of our model, and demonstrates that in the future using information about the mass of currently-living stars, in addition to the mass of living ^{26}Al , could substantially narrow down the range of possible scenarios for the evolution of Upper-Sco.