Birth Sites of Young Stellar Associations; Recent Star Formation in a Flocculent Corrugated Disk

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ABSTRACT
With backwards orbit integration we estimate birth locations of young stellar associations and moving groups identified in the solar neighborhood that are younger than 70 Myr. The birth locations of most of these stellar associations are at smaller galactocentric radius than the Sun, implying that their stars moved radially outwards after birth. Exceptions to this rule are the Argus and Octans associations, which formed outside the Sun’s Galactocentric radius. Variations in birth heights of the stellar associations suggest that they were born in a corrugated disk of molecular clouds, similar to that inferred from the current filamentary molecular cloud distribution and dust extinction maps. Multiple spiral arm features with different but near corotation pattern speeds and at different heights could account for the stellar association birth sites. We find that the young stellar associations are located in between peaks in the radial/tangential (UV) stellar velocity distribution for stars in the solar neighborhood. This would be expected if they were born in a spiral arm which perturbs stellar orbits that cross it. In contrast, stellar associations seem to be located near peaks in the vertical phase-space distribution, suggesting that the gas in which stellar associations are born moves vertically together with the low velocity dispersion disk stars.

1 INTRODUCTION
Coeval groups of stars are tracers of the past sites of star formation in the Milky Way disk (e.g., Zuckerman & Song 2004). As it orbits the Galaxy, a recently formed cluster, group or association of stars, retains information on its birth location. However, birth locations are more uncertain for older clusters, due to uncertainties in the cluster age and in the galactic potential in which orbits are integrated (e.g., Dias et al. 2019). Close encounters with star clusters and molecular clouds, cluster evaporation, and non-axisymmetric and time dependent gravitational forces associated with spiral arms, the Galactic bar, passage through the Galactic plane, and external tidal forces on the Galaxy disk perturb stellar orbits and increase the error in the estimated birth sites of stellar associations and clusters (e.g., Krause et al. 2020).

Because open clusters are expected to have predominantly been born in spiral arms, their orbits and ages have been used to probe the nature of spiral structure (Dias & Lepine 2005; Quillen et al. 2018a; Dias et al. 2019). The Lin-Shu hypothesis (Lin & Shu 1966; Shu 2016) posits that spiral structure is caused by density waves moving through a galactic disk. The speed of the wave is described with an angular rotation rate called the pattern speed. In the ‘modal’ view of spiral structure, a single multi-armed wave with a constant pattern speed dominates (Lin & Shu 1966; Bertin et al. 1989; Shu 2016). A direct method for measuring the pattern speed of spiral arms relies on estimating the birth places of open clusters by integrating their orbits backwards (e.g., Dias & Lepine 2005; Naoz & Shaviv 2007; Dias et al. 2019). However, this method can give spurious results if spiral arms are not steady-state. Spiral arms could be transient (Toomre 1981; Sellwood & Carlberg 1984; Wada et al. 2011; Grand et al. 2012; Baba et al. 2013, 2016), exhibiting variations in their amplitude, pitch angle and pattern speed. Additional gravitational perturbations arise from the time-dependent and flocculent nature of the gas response (and hence that of the young stars) even when there is a time-steady spiral structure in the old stars (Chakrabarti et al. 2003). Multiple patterns could simultaneously be present (e.g., Naoz & Shaviv 2007) and interfere (e.g., Quillen et al. 2011; Comparetta & Quillen 2012). External tidal perturbations on the Galaxy can induce spiral structure (e.g., Quillen et al. 2009;
Chakrabarti & Blitz 2009; Dobbs & Pringle 2010; de la Vega et al. 2015; Pettitt et al. 2017. The recent study by Dias et al. (2019) mitigates the errors inherent in backwards orbit integration and from assuming steady state spiral structure by focusing on nearby (distances less than 5 kpc from the Sun) and younger than 50 Myr old open clusters with accurately measured distances, space motions and ages.

While they are not gravitationally bound entities, a number of moving groups and stellar associations seen in the solar neighborhood are also comprised of coeval groups of stars (e.g., Eggen 1983; Zucker & Song 2004; Mamajek 2016; Riedel et al. 2017). Young stellar associations are predominantly identified in the solar neighborhood (within about 150 pc of the Sun), and they span a range of ages, including some younger than 50 Myr. As most open clusters are more distant than the known young stellar associations (the open clusters studied by Dias et al. 2019 are within a few kpc from the Sun), stellar associations give a complimentary view of recent star formation near the Sun. We aim to probe the locations of spiral arm density peaks in the recent past by estimating the birth locations of coeval young stellar associations and moving groups.

Members of a young stellar association or young moving group in the solar neighborhood share similar space velocities, or velocity components \( U, V, W \) in heliocentric polar Galactic coordinates, with typical velocity dispersions below a few km s\(^{-1}\) (e.g., Binks et al. 2015; Mamajek 2016; Riedel et al. 2017; Gagné et al. 2018a). Young stellar associations are discovered by searching for nearby stars with similar proper motions and evidence of youth, with more detailed studies identifying additional members, confirming stellar association membership and finding substructures in the association age, velocity and spatial distributions (e.g., Eggen 1983; de la Reza et al. 1989; de Zeeuw et al. 1999; Jayawardhana 2000; Mamajek et al. 1999; Binks et al. 2015; Pécaut & Mamajek 2016; Mamajek 2016; Gagné et al. 2018a,b; Gagné & Faherty 2018; Gagné et al. 2018c; Meingast et al. 2019; Kos et al. 2019; Binks et al. 2020; Tian 2020).

The brightest nearby young stars, are not randomly distributed in the Galaxy (de Zeeuw et al. 1999; Elias et al. 2006; Bouy & Alves 2015; Zari et al. 2018), rather those within 150 pc of the Sun appear to form a belt, known as the ‘Gould belt’, with an inclination of about 20° with respect to the Milky Way mid-plane (Herschel 1847; Gould 1874; Perrot & Grenier 2003). The Gould belt may be part of a larger vertical wavelike structure that is present in a filament of molecular cloud complexes (Zuckerman et al. 2020) dubbed the ‘Radcliffe wave’ (Alves et al. 2020). Vertical corrugations in molecular gas filaments could be related to the spiral seen in the distribution of solar neighborhood stars in the vertical components of phase-space \( z, \dot{z} \) (Antoja et al. 2018). The dynamics of the interstellar medium differs from that of stars. Shocks and associated linear density enhancements in the gas can be caused by the spiral structure, whereas phase wrapping after a tidal perturbation (e.g., Minchev et al. 2009; de la Vega et al. 2015) in the vertical components of phase-space (Candy 2014; Antoja et al. 2018; Bland-Hawthorn et al. 2019) occurs in the stars but not in the gas, and can persist in the phase-space structure of the stars for many crossing times. In contrast, density disturbances in the gas disk dissipate after a dynamical time. Prominent gas density perturbations in the Galaxy include the HI warp and planar disturbances (Levine et al. 2006b,a). The height above or below the Galactic plane of birth sites of young stars may reflect the past location of features like the Gould belt and the Radcliffe wave. Vertical corrugations in the molecular disk and the stellar phase-space spiral are suspected to have been excited by tidal perturbations on the outer Galaxy (e.g., Chakrabarti & Blitz 2009; Quillen et al. 2009; Purcell et al. 2011; de la Vega et al. 2015; Antoja et al. 2018; Darling & Widrow 2019).

Structure in the distribution of VLBI observations of masers associated with high mass star formation regions (Xu et al. 2016, 2018; Reid et al. 2019), resembles that seen in extinction maps (Rezaei Zh. et al. 2018; Green et al. 2019; Lallement et al. 2019), and in a 3D map of nearby molecular clouds that is based on combining stellar photometric data with stellar Gaia DR2 parallax measurements to infer the distances of nearby dust clouds (Zucker et al. 2020; Alves et al. 2020). Spiral features seen in extinction maps (Quillen 2002; Rezaei Zh. et al. 2018; Green et al. 2019; Lallement et al. 2019), masers (Xu et al. 2016, 2018; Reid et al. 2019) and molecular clouds (Zuckerman et al. 2020) suggest that within a few kpc of the Sun, the Milky Way contains multiple spiral arms with morphology more flocculent than grand design. The recent open cluster study by Dias et al. (2019) matched open cluster birth locations to Perseus, Local and Sagittarius arms as traced by masers and HII regions and following logarithmic functions describing spiral arm peaks by Reid et al. (2014). The study of open cluster kinematics by Dias et al. (2019) found that these three spiral structures have pattern speeds nearly corotating with the Sun.

With the recent advances in identifying and characterizing young stellar associations (e.g., Malo et al. 2013; Gagné et al. 2018a; Riedel et al. 2017), it is a good time to look for connections between them and spiral arm candidates seen in the recently improved the molecular cloud and extinction maps. To do this we integrate the orbits of young stellar associations backwards to estimate their birth locations. We focus here on what we can learn from integrating the orbits of recent compilations of young stellar associations and star formation regions (e.g., Gagné et al. 2018a). Backwards orbit integration has been used to estimate the kinematics of stellar associations by finding when their stellar members were likely to have been in proximity (de la Reza et al. 2006; Miret-Roig et al. 2018; Crumdale et al. 2019). Here we do not try to estimate kinematic ages, rather we search for patterns in the history of recent star formation near the Sun. We integrate orbits in three-dimensions to probe the relation between birth heights, the corrugated molecular and dust disk, and patterns seen in the stellar vertical phase-space distribution (Antoja et al. 2018; Bland-Hawthorn et al. 2019; Laporte et al. 2019).

In section 2 we specify coordinates, constants and the potential model needed for orbit integration. The sample of stellar associations, clusters and moving groups and their measurements are described in section 3.

Results of backwards orbit integrations are discussed in section 4. In section 4.2 we discuss estimated stellar association birth locations in two dimensions. Birth heights above and below the plane are discussed in section 4.3. In section 4.4 we look at birth sites in rotating frames and discuss possible molecular and extinction filaments that could be the current counterparts to past sites of star formation. In sect.
4.5 we compare stellar association phase-space coordinates to the distributions of stars in the solar neighborhood. A summary and discussion follows in section 5.

2 GALACTIC POTENTIAL MODEL FOR ORBIT INTEGRATION

We specify the Galactic coordinate systems, and our notation for them in section 2.1. We also review constraints on Galactic constants which are needed to carry out backwards orbit integrations. The gravitational potential we use to integrate the orbits is described in section 2.2.

2.1 Coordinate system and Galactic constants

Numerous works have used the transformations given by Johnson & Soderblom (1987) to take stellar parallaxes, proper motion, position, and radial velocity measurements and compute a heliocentric coordinate \((x_h, y_h, z_h)\) and velocity vector, \((U, V, W)\). A heliocentric right-handed Cartesian coordinate system with origin at the Sun has Galactic coordinates \((x, y, z)\) where \(x = \cos b \cos l, y = \cos b \sin l, z = \sin b\),

\[
(x_h, y_h, z_h) = d \cos b \cos l, \cos b \sin l, \sin b, \tag{1}
\]

where \(b, l\) are Galactic latitude and longitude, respectively, and \(d\) is the distance of the point from the Sun. The positive \(z_h\) axis is along the north Galactic pole. Longitude \(l = 0\), latitude \(b = 0\) and positive \(x_h\) corresponds to a point that is closer to the Galactic center than the Sun. Galactic longitude \(l = \pi/2\) and latitude \(b = 0\) gives positive \(y_h\) axis pointing in the direction of Galactic Rotation. Heliocentric \(U, V, W\) velocity components are in cylindrical coordinates with \(U\) the radial component of velocity, \(V\) is a tangential component and \(W\) a vertical velocity component. These velocity components are positive toward the Galactic center, in the direction of Galactic rotation and in the direction of the North Galactic pole. The velocities are in a heliocentric frame, so must be corrected for the Solar motion with respect to the local standard of rest (LSR).

The Galactocentric Cartesian coordinate system \((x_g, y_g, z_g)\), has origin at the Galactic center. We compute Galactocentric Cartesian coordinates \((x_g, y_g, z_g)\) from heliocentric \((x_h, y_h, z_h)\) Cartesian coordinates with

\[
x_g = -R_\odot + x_h
\]

\[
y_g = y_h
\]

\[
z_g = z_h + z_\odot, \tag{2}
\]

where \(z_\odot\) is the location of the Sun above or below the Galactic plane and \(R_\odot\) is the galactocentric radius of the Sun. Based on trigonometric parallaxes of high-mass star forming regions Reid et al. (2019) find

\[
z_\odot = 5.5 \pm 5.8 \text{ pc} \tag{3}
\]

which agrees with that found by Anderson et al. (2019) based on positions of HI regions. We adopt the value of \(z_\odot = 5.5\) pc in our orbit integrations. However, we note that Bennett & Bovy (2019) find that \(z_\odot = 20.8 \pm 0.3\) pc from measurements of the vertical stellar distribution function. In this galactocentric coordinate system, Galactic rotation in the \(x_g, y_g\) plane is clockwise about the origin. Galactocentric cylindrical coordinates \(R_g, \theta_g, z_g\) can be computed using galactocentric azimuthal angle and radius

\[
\theta_g = \tan2(y_g, x_g)
\]

\[
R_g = \sqrt{x_g^2 + y_g^2}. \tag{4}
\]

The galactocentric azimuthal angle of the Sun, \(\theta_\odot = \pi\) and the local standard of rest has clockwise rotation with angular rotation rate \(\dot{\theta}_\odot < 0\).

From heliocentric \(U, V, W\) velocity components we compute galactocentric velocity in cylindrical coordinates

\[
\begin{align*}
V_R &= -(U + U_\odot) \\
V_\theta &= -(V + V_\odot + V_{LSR}) \\
V_z &= W + W_\odot
\end{align*} \tag{5}
\]

where \((U_\odot, V_\odot, W_\odot)\) is the peculiar velocity of the Sun in cylindrical coordinates with respect to the local standard of rest (LSR). For this velocity transformation we adopt a peculiar Solar motion of

\[
(U_\odot, V_\odot, W_\odot) = (11.1^{+0.69}_{-0.75}, 12.24^{+0.47}_{-0.47}, 7.25^{+0.37}_{-0.36}) \text{ km s}^{-1} \tag{6}
\]

based on an analysis of local stellar kinematics (Schönrich et al. 2010).

Using the pericenter passage of a star around the Galaxy’s central supermassive black hole, the GRAVITY Collaboration et al. (2018) measures the galactocentric radius of the Sun

\[
R_\odot = 8.122 \pm 0.031 \text{ kpc}. \tag{7}
\]

This radius, the proper motion of the radio source associated with the Galaxy’s central black hole, Sgr A* and the tangential component of the solar peculiar motion measured by Schönrich et al. (2010) gives local standard of rest (LSR) rotational velocity

\[
V_{LSR} = 233 \pm 1.4 \text{ km s}^{-1}. \tag{8}
\]

These values are consistent with those computed from trigonometric parallaxes of high mass star formation regions (Reid et al. 2019) and we use these values in our orbit integrations. These values give LSR angular rotation rate

\[
\Omega_\odot = V_{LSR}/R_\odot = 28.7 \text{ km s}^{-1}\text{kpc}^{-1}. \tag{9}
\]

2.2 The Galactic potential and backwards orbit integration

The stars in young stellar associations are in nearly circular orbits that remain within 150 pc of the Galactic plane. Rather than use a mass model for the entire galaxy comprised of disk, bulge and halo components (e.g., Robin et al. 2003; Deg et al. 2019), we use a local axisymmetric potential model that matches the slope of the rotation curve near the Sun’s galactocentric radius and measurements of the vertical acceleration of stars above the Galactic plane. A multiple mass component Milky Way model is not needed as we only integrate low eccentricity and low inclination orbits. In cylindrical coordinates, we approximate the potential as

\[
\Phi(R_g, z_g) = \Phi_R(R_g) + \Phi_z(z_g). \tag{9}
\]
As did Darling & Widrow (2019), we adopt a static, axisymmetric potential function that is separable in the radial and vertical coordinates.

The tangential velocity of a star in a circular orbit in the Galactic plane

\[ v_\phi(R_g) = \begin{cases} 
V_{\text{LSR}} & \text{for } \beta = 0 \\
\left(\frac{R_g}{R_\odot}\right)^\beta V_{\text{LSR}} & \text{for } \beta \neq 0
\end{cases} \tag{10} \]

For this power law rotation curve, the radius of a circular orbit with \( z \) component of angular momentum \( L \) is

\[ R_L(L) = R_\odot \left( \frac{L}{R_\odot V_{\text{LSR}}} \right)^{\frac{1}{\beta + 1}} \tag{11} \]

(Dehnen 1999). The rotation curve (equation 10) is consistent with radial potential function

\[ \Phi_R(R_g) = \begin{cases} 
V_{\text{LSR}}^2 \ln \left( \frac{R_g}{R_\odot} \right) & \text{for } \beta = 0 \\
V_{\text{LSR}}^2 \left( \frac{R_g}{R_\odot} \right)^{2\beta} & \text{for } \beta \neq 0.
\end{cases} \tag{12} \]

With a mass model and atomic and molecular gas line emission based terminal velocity constraints, McGaugh (2019) estimates a rotation curve slope at the Solar position

\[ \frac{dv_\phi(R_g)}{dR_g} \bigg|_{R_\odot} = -1.7 \pm 0.1 \text{ km s}^{-1} \text{ kpc}^{-1} \tag{13} \]

over \( 9 < R_g < 19 \) kpc. This slope is the same as inferred from recent measurements of Oort’s \( A \) and \( B \) constants (Li et al. 2019) and is similar to the slope

\[ \frac{dv_\phi(R_g)}{dR_g} \bigg|_{R_\odot} = -1.34 \pm 0.21 \text{ km s}^{-1} \text{ kpc}^{-1} \tag{14} \]

measured from Cepheids (Mróz et al. 2019). The slope is related to the slope exponent

\[ \beta = \frac{dv_\phi}{dR_g} \bigg|_{R_\odot} \frac{R_\odot}{V_{\text{LSR}}} = \frac{dv_\phi}{dR_g} \bigg|_{R_\odot} \frac{1}{\Omega_\odot} \tag{15} \]

Using \( R_\odot = 8.12 \text{ kpc} \) and \( V_{\text{LSR}} = 233.3 \text{ km/s} \), the slopes by McGaugh (2019); Li et al. (2019) give \( \beta = -0.059 \) whereas the slope by Mróz et al. (2019) gives \( \beta = -0.045 \). The slope by McGaugh (2019) is measured in the range \( 9 < R_g < 19 \) kpc whereas that by Mróz et al. (2019) is for \( 4 < R_g < 20 \) kpc. The slope by Li et al. (2019) is based on stars in the solar neighborhood. We adopt \( \beta = -0.05 \) as a compromise.

The sensitivity of the gravitational potential to height above or below the Galactic plane, \( z_g \), depends on the density distribution in thick and thin stellar disks, gas disk and halo. The recent local 3D models (Barros et al. 2016) are based on measurements for the different galactic components (Holmberg & Flynn 2000, 2004; Flynn et al. 2006). We fit simple analytical functions to the vertical acceleration as a function of height above the Galactic plane found from solar neighborhood K-giants that is shown in Figure 8 by Holmberg & Flynn (2004). We found a good fit to this curve within \( z_g < 750 \text{ pc} \) with vertical acceleration a polynomial function

\[ \ddot{z}_g = -\frac{d\Phi_g(z_g)}{dz_g} = -\alpha_1 z_g - \alpha_2 z_g^2 \text{sign}(z_g), \tag{16} \]

and constants

\[ \alpha_1 = 4207.0 \text{ Gyr}^{-2} \quad (17) \]
\[ \alpha_2 = -2792.2 \text{ Gyr}^{-2} \text{ kpc}^{-1}. \quad (18) \]

This vertical acceleration is derived from a vertical potential function

\[ \Phi_g(z_g) = \frac{1}{2} \alpha_1 z_g^2 + \frac{1}{3} \alpha_2 |z_g|^3 + \text{constant}. \quad (19) \]

Poisson’s equation applied in the mid-plane at \( R_\odot \) gives a value for the frequency of low amplitude vertical oscillations,

\[ \nu^2 = \frac{d^2\Phi_g(z_g)}{dz_g^2} \bigg|_{z_g=0} = 4\pi G\rho_0 - 2\beta \Omega_\odot^2 \quad (20) \]

where \( \rho_0 \) is the mid-plane mass density and we have used the potential of equation 12 for the radial derivative terms. The estimated value for the mid-plane density near the Sun is \( \rho_0 = 0.10 M_\odot \text{pc}^{-3} \) (Holmberg & Flynn 2004). This value is comparable to the value for the local density of matter found in recent work (McKee et al. 2015), which includes the density of visible stars (with improvements to prior work particularly for the density of M dwarfs and white dwarfs), the gas density, and the inferred dark matter density. Using our adopted value for \( \Omega_\odot \) and this midplane density, the frequency of low amplitude vertical oscillations \( \nu \approx 0.076 \text{ rad/Myr} \) and the period of vertical oscillations is 83 Myr. The frequency of oscillations computed using \( \alpha_1 \) is somewhat lower, \( \nu = \sqrt{\alpha_1} = 0.065 \text{ rad/Myr} \). These frequencies are lower than that used by Candlish (2014) whose Galactic models have \( \nu \approx 0.095 \text{ rad/Myr} \) near the mid-plane (see their Figure 6). We attribute the discrepancies to the different conventions adopted for \( R_\odot \) and \( V_{\text{LSR}} \).

Orbits are integrated backwards using the Galactic potential model of equations 9 – 18 and with python’s general purpose integration routine odeint which calls the LSODA routine from the FORTRAN77 library odepack. Each orbit consists of a series of positions and velocities as a function of time \( t \) where \( t = 0 \) is the present and \( t < 0 \) corresponds to the times in the past. We integrate multiple separate orbits for each stellar association, each with slightly different initial conditions. The initial conditions for each orbit are the mean estimated value of the stellar association central position \( x_b, y_b, z_b \) and velocity \( U, V, W \) plus randomly generated offsets in these six quantities that are based on estimates for the spatial extent and velocity dispersion of the association. The initial position and velocity offsets for integration are generated using a normal distribution and standard deviations \( \sigma_x, \sigma_y, \sigma_z, \sigma_U, \sigma_V, \sigma_W \) in the phase-space coordinates for each association. Because we desire estimates for both spatial extent and velocity dispersion of each association, we use measurements for stellar associations that are based on a multivariate fitting algorithm (Malo et al. 2013; Gagné et al. 2018a).

3 SAMPLE OF YOUNG STELLAR ASSOCIATIONS, CLUSTERS AND MOVING GROUPS

Most of the young stellar associations, clusters and moving groups we use for this study are taken from Table 9.
by Gagné et al. (2018a). This table lists values for central coordinates and velocities \( x, y, z, U, V, W \) and standard deviations for these quantities from the multivariate Gaussian model found via the BANYAN algorithm Gagné et al. (2018a). BANYAN (Bayesian Analysis for Nearby Young Associations) models the distribution of stars in the young stellar associations with multivariate Gaussian distributions in 6 dimensional phase-space. The standard deviations, \( \sigma_x, \sigma_y, \sigma_z, \sigma_U, \sigma_V, \sigma_W \), reflect the spatial extent and velocity dispersions of the associations, not errors in measuring these quantities.

The longer orbits are integrated, the larger the errors in the orbit positions. To mitigate this uncertainty, we restrict our study to associations that are younger than 70 Myr. We have discarded the 118 Taurus group and the Platais 8 cluster (Platais et al. 1998) because they have been neglected in recent studies and the constraints on their ages are poor. To the associations listed by Gagné et al. (2018a) we add the Argus association, but with measurements from the BANYAN analysis using the members and measurements by Zucker (2019) and a recently discovered \( \approx 62 \) Myr old stellar association, \( \mu \) Tau (Gagné et al. 2020). We have checked that the results of the BANYAN analyses by Gagné et al. (2018a) are consistent with the mean position and velocity measurements by other recent works (Binks et al. 2015; Riedel et al. 2017; Miret-Roig et al. 2018).

For some associations (e.g., those associated with the Scorpius-Centaurus OB association), more recent Gaia based observations have improved upon central positions and velocity dispersion (e.g., Wright & Mamajek 2018) but have not fit the spatial extent of the association. We have adopted not to use these more precise measurements as there are correlations between the measured variables from the BANYAN analysis (Gagné et al. 2018a) and we would like to integrate multiple trial orbits for each association. Recent studies have uncovered additional substructure (in age, velocity and position) in some star formation regions, such as Corona Australis – (Galli et al. 2020), Taurus – (Fleming et al. 2020), Scorpius-Centaurus – (Pecaut & Mamajek 2016; Wright & Mamajek 2018) and Orion – (Kos et al. 2019; Tian 2020). Such substructure corresponds to gradients over small distances in the Galaxy compared to distances travelled since birth in the orbit. We ignore substructure in the associations and star formation regions here, but keep in mind that a fuller and more accurate picture of the pattern of star formation in the Galaxy might be sensitive to stellar association substructures.

The star formation regions, moving groups, open clusters and stellar associations used here, their abbreviations and their measured ages \( t_{age} \), are listed in Table 1. Standard deviations for the ages \( \sigma_{age} \), are estimated from the ranges and uncertainties given in the literature with citations for the age estimates also listed in this Table. The central positions and velocities and the standard deviations from the BANYAN analyses are listed in Table 2.

4 RESULTS

Using backwards orbit integration we first look at stellar association birth sites in two-dimensions or equivalently projected into the Galactic plane. In section 4.3 we discuss birth heights above or below the Galactic plane. In section 4.4 we discuss the birth sites in rotating frames. In section 4.5 we discuss the stellar associations in context with the solar neighborhood’s stellar velocity and vertical phase-space distribution.

4.1 Estimated Birth locations

Estimated birth locations and velocities computed from our orbit integrations, along with their uncertainties, are listed in Table 3. Birth height, galactocentric radius and azimuthal angle, \( z_b, R_b, \theta_b-\theta_z \), and birth velocity components \( v_{R,b}, v_{\theta,b} \) are mean values at the association age \( t_{age} \) of 10 integrated orbits with randomly generated initial conditions, chosen as described at the end of section 2.2. We computed a standard deviation from the scatter of the values in the 10 orbits at \( t_{age} \). We also computed a standard deviation from a single orbit by weighting points in the orbit with a factor that depends on the age uncertainty or spread

\[
\sigma(t) = \exp \left( -\frac{(|t| - |t_{age}|)^2}{2\sigma_{age}^2} \right). \tag{21}
\]

The uncertainties for birth positions and velocities listed in Table 3 are the result of summing these two estimated standard deviations in quadrature. Errors caused by the spread in initial conditions usually dominate those arising from the age uncertainty.

In this Table 3 we also list the maximum height above or below the Galactic plane \( |z|_{max} \) reached in the orbit. We measured these from the backwards orbit integrations by integrating longer than a full vertical oscillation period. This is a measure of the orbit’s amplitude of vertical oscillations. The uncertainty is the standard deviation computed from the scatter in \( |z|_{max} \) for 10 orbits with different initial conditions. We also list the radius \( R_L \) of a planar circular orbit with the same \( z \) component of angular momentum computed using equation 11. As the potential is axisymmetric, the \( z \) component of angular momentum per unit mass, \( L_z \), is a conserved quantity and only depends on an orbit’s initial conditions. The standard deviation of \( R_L \) is computed by propagating the errors in the initial conditions. The birth tangential velocity component \( v_{\theta,b} \) can be computed from \( R_L \) and birth radius \( R_b \) by inverting equation 11, giving

\[
L = R_b V_{LSR} \left( \frac{R_b}{R_{12}} \right)^{3+1} \quad \text{and} \quad v_{\theta,b} = L/R_b.
\]

Birth locations and velocities and maximum orbital height are plotted as a function of stellar association age in Figure 1. In this plot the vertical error bars are uncertainties due to the spread in the initial (and current) positions and velocities. Horizontal error bars show age spread or uncertainty. Horizontal coordinates are listed in Table 1 and vertical coordinates are listed in Table 3. In Figure 1 the horizontal grey lines are at a vertical coordinate of zero except in the fourth panel where it is at the galactocentric radius of the Sun, \( R_S = R_0 \). The bottom panel in Figure 1 shows the angle \( \theta_b - \theta_0 - |\theta_z|_{t_{age}} \) in degrees. This angle gives birth azimuthal angle in a frame corotating with the local standard of rest.

Figure 1 shows some trends with age. The youngest stellar associations are born both above and below the Galactic plane and are on nearly circular orbits. Intermediate age associations (20 - 30 Myr) have lower vertical amplitudes
The ages of these points can be estimated using the angular rotation rate of an object in a circular orbit at the Galactocentric radius of the Sun, \((θ - θ_0)/Ω_⊙\). This approximate age is shown with the top axis in Figure 2 in Myr.

The x axis in Figure 2, showing Galactic azimuthal angle, is reversed so that Galactic rotation is to the right. We chose this convention so that the plots can be more easily compared to maps of Milky Way spiral structure, extinction and molecular clouds. The direction of Galactic rotation (clockwise) is shown with an arrow on the top right. The assumed Galactocentric radius of the Sun is marked with a horizontal dotted grey line. The azimuthal angle of the Sun is marked with a dotted vertical line, so the current position of the Sun is on the right-hand side of the plot where the two dotted grey lines cross. In Figure 2, increasing galactocentric \(R_⊙\) upwards along the \(y\) axis increases the heliocentric \(y_⊙\) coordinate. Moving to the right along the \(x\) axis in Figure 2 increases the heliocentric coordinate \(x_⊙\).

We find that most of the stellar associations have moved outwards radially from their birth locations. Exceptions to this trend are very young associations such as Corona Australis (CRA) and ρ Ophiucus (ROPH) associations that are still in proximity to their birth clouds. Among the older associations, the Octans (OCT) and Argus (ARG) associations have orbits that differ from the other associations. These two are also exceptions as they have moved inward to reach the solar neighborhood since their birth.

As the rotation curve is nearly flat the epicyclic frequency \(κ \sim \sqrt{2Ω}\) with \(Ω\), the angular rotation rate of a particle in a planar circular orbit. This gives an epicyclic oscillation period of about 155 Myr at \(R_⊙\). For the Argus and Octans associations, their ages correspond to only about a quarter of an epicyclic oscillation period. This implies that they must have been moving radially inward soon after birth, rather than outwards after birth as are most of the other associations.

The distance moved radially or equivalently the epicyclic amplitude is larger for the older associations than the youngest ones. If we assume that these associations were born in spiral arms, then the parent spiral features for the older associations were likely more massive than the parent features of the youngest associations, therefore causing a greater degree of non-circular motion.

N-body simulations usually exhibit lower spiral pattern speeds at larger radii (e.g., Quillen et al. 2011; Grand et al. 2012; Kawata et al. 2014). As the Octans and Argus associations were born at larger Galactic radius, perhaps their birth arm had a slower pattern speed. The interstellar medium, with a sound speed similar to 10 km/s, is shocked as it passes over a spiral arm (e.g., Shetty et al. 2007; Dobbs & Pringle 2010; Pettitt et al. 2015; Shu 2016). The shock compresses the gas, increases the gas density and lowers the gas velocity in the frame moving with the spiral pattern. The compressed gas should have an angular rotation rate that is approximately the same as that of the spiral pattern. In other words, in the frame moving with the spiral arm, the molecular clouds should have low angular rotation rate (e.g., Dobbs & Pringle 2010). A star formed in molecular cloud that has an angular rotation rate that is faster than that of a circular orbit has higher angular momentum than a circular orbit and should move radially outward after birth. A star born at an angular rotation rate that is lower than that of a cir-

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Figure 1. Birth locations and velocities of stellar associations plotted as a function of their age. Top to bottom panels show birth height \(z_b\) (in pc), vertical component of velocity at birth \(v_{z,b}\) (in km/s), birth galactocentric radius \(R_b\) (in kpc), radial component of velocity at birth \(v_{R,b}\) (in km/s), maximum height reached in the orbit \(|z|\text{max}\) (in pc) and angle in a frame rotating with the local standard of rest (in degrees). The \(y\) coordinates of points plotted here are listed in Table 3. The \(x\) coordinates are listed in Table 1. Vertical error bars are uncertainties due to spread in the initial coordinates and velocities. Horizontal error bars are uncertainties due to age spread or uncertainty.

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4.2 Birth locations in the Galaxy

In Figure 2, we show the galactocentric radius and azimuthal angle \(θ - θ_0\) for each of 10 orbits for each stellar association. The orbits of each association are shown in a different color with colors identified in the key. At time \(t\), the opacity of the point is weighted by the weight function \(w(t)\) (equation 21) which peaks at 1 when \(|t|\) is the age of the association and has width dependent on the association age spread. This way points are only visible in the plot near the estimated association birth location. Points on the left side of the plot are older associations that were born further away from the Sun.
circular orbit would move inward soon after birth. Perhaps the Octans and Argus associations were born in spiral features with pattern speeds that are lower than the angular rotation rate of a circular orbit, |Ω| < |Ω|, at their birth radius. The opposite could be true of most of the rest of the associations if |Ω| > |Ω| for their birth spiral arm.

Dobbs & Pringle (2010) compared simulations of different galactic morphologies to assess their impact on the spread of cluster ages, inferred from the locations of densest gas elements (rather than a specific sub-grid star formation prescription). These models include a flocculent galaxy, a galaxy with a steady spiral and a tidally perturbed galaxy. A steady spiral pattern shows a gradient in the ages of recently formed stars across each spiral arm. However if star formation not only occurs along the arm but in spurts and features emanating from the arm the gradients are shallower. Spiral arms caused by their tidal perturbation are more complex, exhibiting positive or negative age gradients across spiral arms. However, this galaxy-companion orbital configuration is notably complex, involving multiple out of plane encounters that make the dynamics considerably more complex than a more standard prograde, in-plane, fly-by (e.g., Pettitt et al. 2017). The simulated flocculent galaxy by Dobbs & Pringle (2010) shows localized bursts of star formation. Because there is no simple trend in age vs birth locations and kinematics (see also Figure 1), continuous star formation without spurs or armlets along a single steady spiral arm seems ruled out. The other scenarios could be consistent with the stellar association birth locations and kinematics. Unfortunately we have not found a study measuring young star epicyclic phases as a function of age from simulations (whether moving radially inward or outward) but perhaps this additional information could in future help differentiate between spiral structure models.

To illustrate which side of an arm stars would be located, we show in Figure 3 a trailing logarithmic spiral arm in frames rotating with the pattern speed of the arm. Figure 3a illustrates the case with arm pattern speed moving faster than the location rotation, |Ω| > |Ω| and Figure 3b illustrates the opposite case. In polar coordinates a logarithmic spiral arm pattern can be described with peak at galactocentric radius $R_{\text{peak}}(\theta, t)$ where

$$\alpha_s \ln \left( \frac{R_{\text{peak}}(\theta, t)}{R_{\theta_0}} \right) = \theta - \theta_0 - \Omega_s t.$$  \hspace{1cm} (22)

At time $t = 0$, the current time, the arm has a peak at galactocentric radius $R_{\theta_0}$ and at angle $\theta_0$. The arm pitch angle is $p = \arctan \alpha_s^{-1}$ and its pattern speed is $\Omega_s$. As we have adopted a coordinate system giving clockwise Galactic rotation, $\theta < 0$, a trailing arm has winding angle $\alpha_s > 0$. The pattern moves in the same sense as rotation, so the pattern speed $\Omega_s < 0$. A logarithmic trailing arm is linear on a plot of log $R_\theta$ vs $\theta$. In the illustration of Figure 3, galactic rotation is to the right. The arm’s pitch angle determines slope of the arm on this illustration with negative slope corresponding to a trailing arm.

With stars exceeding the pattern speed, as shown in Figure 3a, stars born on the arm pass the arm and are located to the right of the arm, and near the direction of Galactic longitude $l \sim 90^\circ$. With pattern speed exceeding that of that of a circular orbit, the pattern moves faster than the stars. In a frame rotating with the pattern, the arm is fixed and the stars move in the opposite direction and to the left, as shown in Figure 3b.

N-body simulations that exhibit spiral structures that are approximately corotating with the local angular rotation rate, |Ω| ∼ |Ω|, have peculiar velocities with radial velocities that point outward on the trailing side and inward on the leading side of the arm (Grand et al. 2015; Baba et al. 2016). In an annulus, the tangential peculiar velocities are slower than the mean on the trailing side and faster on the leading side (Grand et al. 2015). When its tangential velocity is slower than that of a circular orbit, a star has lower angular momentum than a circular orbit and so must spend most of its orbit at lower radius. If the pattern moves faster

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{example.png}
\caption{Backwards integration of young stellar associations younger than 70 Myr that are listed in Tables 1 and 2. We plot orbits as a function of galactocentric radius and azimuthal angle from that of the Sun, $\theta - \theta_0$ in degrees. Ten orbits are shown for each stellar association and each association is shown with a different color point. The colors are labelled in the key. The opacity of the points is only high for points at times near the estimated stellar association birth age. Points on the left side of the plot are older associations that were born further away from the Sun. The ages of these points can be estimated using the angular rotation rate of an object in a circular orbit at the Galactocentric radius of the Sun, $(\theta - \theta_0)/\Omega$. This age coordinate is shown with the top axis. Associations were plotted in order of seniority, oldest ones first. Most of these associations were born at lower Galactocentric radius and moved radially outward into the solar neighborhood where they are found today. Dotted grey lines intersect at the location of the Sun and the direction of Galactic rotation is shown with an arrow. Note that the azimuthal angle increases to the left.}
\end{figure}
than the angular rotation rate $\Omega_0$, then the associations are currently found on the trailing side of the arm, as shown in Figure 3b. Stellar associations with birth radius lower than their current values are consistent with the outward radial velocities and sub-circular tangential velocity reported in the simulations by Grand et al. (2015), on the trailing side of approximately corotating bars, if the spiral pattern speed is slightly higher than $\Omega_0$. If the spiral bar or arms in which Octans and Argus associations formed has the opposite relation, $|\Omega_s| < |\Omega_0|$, then the associations are currently on the leading side of the arm and the trends noted by Grand et al. (2015) would be consistent with birth site exterior to $R_{\odot}$, as we have observed from their orbits.

For most of the associations, candidates for the birth arm could be an extension of the local arm at Galactic longitude $l \sim 90^\circ$ or the local spur at $l \sim 50^\circ$ (Xu et al. 2018) or an extinction feature denoted the ‘Split’ at $l \sim 30^\circ$ (Lallemand et al. 2019). Candidates for the birth arm of the Octans and Argus associations would be in the opposite direction, such as that associated with the Vela C cloud at $l = 265^\circ$.

Stars and gas in proximity to a spiral arm can gain or lose angular momentum due to the torque exerted by the gravitational pull of the spiral arm. When the spiral arm is approximately corotating with the galactic rotation, the change in angular momentum of nearby stars and gas clouds is larger because they remain on one side of the arm longer (e.g., Kawata et al. 2014). Stars and gas clouds trailing the arm, and stars born in these clouds, gain angular momentum and would then move outward in radius, whereas those leading the arm lose angular angular momentum and would move inward (Kawata et al. 2014). An alternative explanation for the few associations that have moved radially inward after birth is that they were born on the leading side of a spiral arm that decreased their angular momentum rather than in a spiral arm that has a slower pattern speed than corotation. In this scenario, we might expect that stars are born on both leading and trailing sides of arms. If the Octans and Argus associations were born on the leading side of an arm, then we could look for stars that were born at the same time and in the same arm but on the trailing side. These would be moving outward from their birth site so would not be near the Sun, but might they be near enough to find in a deeper survey of young stars. We estimate the birth galactocentric radius of the Octans association at 8.3 kpc so trailing arm birth counterparts to the the Octans association might be less than a kpc away from the Sun. The youngest associations include Corona -Australis association (CRA) and $\rho$-Ophiucus star formation (ROPH) that are currently moving radially inward and were born moving radially inward. The Taurus-Auriga star forming region (TAU) is currently moving outward and was born moving radially outward. However, it is unlikely that these were born on opposite sides of the same arm because they are still in proximity to their birth clouds and they are at different heights.

We have checked that variations in the adopted value of Galactocentric Solar radius $R_{\odot}$, local standard of rest velocity $V_{LSR}$ and rotation curve slope $\beta$, within the errors of recent measurements, do not significantly affect the morphology of the orbits in Figures 1 and 2 or trends discussed above. With a flat rotation curve corresponding to exponent $\beta = 0$, the birth radii of the oldest associations on this plot are at somewhat smaller (a few hundred pc lower) galactocentric radii.

In summary, birth sites for most of the stellar associations are interior to the Sun’s galactocentric radius and moved outward after birth. This would be consistent with birth in a spiral arm with pattern speed that is higher than $\Omega_0$, placing these associations currently on the trailing side of their birth arm. This expectation follows from birth in a shock moving with the spiral arm and so with higher angular momentum than a circular orbit. The direction of motion is consistent with peculiar velocities seen in simulations of approximately corotating transient spiral structures by Grand et al. (2012). Alternatively the associations that moved out-

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**Figure 3.** We illustrate a logarithmic spiral arm. Here the $y$ axis is log galactocentric radius and the $x$ axis is galactic azimuthal angle in the frame moving with pattern speed of $\Omega_0$. Clockwise galactic rotation is to the right. We show a trailing logarithmic spiral arm (equation 22) with a wide diffuse black bar. The arm’s pitch angle determines the slope of the bar with negative slope corresponding to a trailing arm. a) If the angular rotation of a circular orbit is faster than the spiral pattern speed, $|\Omega| > |\Omega_s|$, stars born on the arm peak (shown as a blue star) pass the spiral arm leaving them to the right of the spiral arm (shown as an open circle). If the Sun is located at the open circle the 4 arrows show different viewing directions with Galactic longitude of $90^\circ$ in the direction of rotation and GC representing toward the Galactic center. b) If the angular rotation of a circular orbit is slower than the spiral pattern speed, $|\Omega| < |\Omega_s|$, stars born on the arm peak would move to the left of the arm.
ward were born on the trailing side of a corotating spiral arm that increased their angular momentum through its gravitational torque (Kawata et al. 2014). The Octans and Argus associations are exceptions as they were born outside \( R_\odot \) and this suggests that their parent spiral arm has a pattern speed slower than \( \Omega_\odot \). Alternatively they could have been born on the leading side of a nearly corotating spiral feature and pulled inward by the arm itself (Kawata et al. 2014). Other scenarios, such as involving tidally excited spiral structure or spurs and armlets extending from strong arms might also account for these inferences (e.g., Dobbs & Pringle 2010).

4.3 Birth Heights

We examine the estimated stellar association birth heights listed in Table 3. Figure 4a is similar to Figure 2 and shows young stellar association orbits except we only plot orbit points in different \( z_g \) ranges. Each panel corresponds to a planar slab with width 25 pc. The vertical slab upper and lower \( z_g \) values are labelled on each panel. Figure 4b is similar to Figure 4a except the \( y \) axis in each panel is \( z_g \) and each panel only shows points in different ranges of galactocentric radius.

Among the youngest star formation regions that formed below the Galactic plane, the Taurus-Auriga (TAU) star formation region is at a larger radius than the Corona-Australis (CRA) one. The intermediate-age associations (\( \sim 20 \) Myr) such as the \( \beta \)-Pictoris moving group (BPMG) and the 32 Orionis group (THOR) were born near the Galactic plane (also see Figure 1). The Octans (OCT) and Argus (ARG) associations were probably born above the Galactic plane at larger radii than \( R_\odot \). The Columba (COL) and Tucana-Horologium (THA) associations and IC 2602 were probably born above the Galactic plane, whereas IC 2391 and the Carina association (CAR) were probably born near or below the Galactic plane. These inferences are based on a fixed and axisymmetric Galactic potential, so could be updated or corrected for orbits integrated in more complex potential models.

The birth locations of similar age associations that are at different heights are also at different radii and angles. Thus Figure 4 does not necessarily imply that more than one molecular filament must exist simultaneously at the same \( R_g, \theta_g \) but at different heights above or below the Galactic plane. Transitions in the birth sites of the different age associations seen in Figure 4 suggest that there are spatial variations in the parent molecular cloud distribution. Recent star formation could have taken place in a corrugated molecular disk, as suggested by the current distribution of molecular clouds near the Sun (Zucker et al. 2020; Alves et al. 2020).

The youngest associations are born in at least two different filamentary extinction and molecular cloud structures. The Scorpius-Centaurus star formation region includes the \( \rho \) Ophiucus star formation region (ROPH), the Upper Scorpius (USCO), Lower Centaurus Crux (LCC), and Upper Centaurus Lupus (UCL) groups that lie above the Galactic plane and connect to a molecular filament that contains to the Aquila Rift molecular clouds (Bell et al. 2015; Mamajek 2016; Pecaut & Mamajek 2016) at Galactic longitude \( l \sim 18^\circ \) and a distance of \( d \sim 200 \) pc (Zucker et al. 2020).

In contrast, the Taurus-Auriga star formation region (TAU) and 32 Orionis group (THOR) are below the Galactic plane and might instead be associated with the filament showing the Radcliffe wave contains the Orion star formation region (Alves et al. 2020). Maps of the current locations of stellar associations are shown in Figures 4 and 5 by Gagné et al. (2018a). We will discuss association locations in context with the extinction and molecular gas filaments in more detail in subsequent sections when we plot their orbits in rotating frames.

We have checked that the patterns shown in Figure 4 are present with 20% higher or lower values of parameter \( \alpha_1 \) which we have used to describe the vertical acceleration in the Galaxy (see equation 16). Setting the height of the Sun \( z_{\odot} \) to 20 pc does not significantly alter the overall appearance of the orbits.

Stars born above or below the Galactic plane, or with non-zero vertical velocity components, will undergo vertical oscillations. The maximum heights reached above or below the Galactic plane measured from the backwards orbit integration are listed in Table 3, and plotted as a function of stellar association age in the fourth panel of Figure 1. The youngest stellar associations (less than 10 Myr old) have a range of maximum heights \( |z|_{\max} \sim 20 \) to 60 pc (see Figure 4b). However the intermediate age association \( \beta \) Pictoris moving group (BPMG) and 32 Orionis (THOR) moving groups, with age \( \sim 20 \) Myr, the Columba and Carina associations (COL and CAR; age \( \sim 45 \) Myr) have lower vertical amplitudes, less than 30 pc. The associations with the largest vertical amplitudes tend to be the older ones. The Octans and Argus associations (\( \sim 40 \) Myr old) that were born at larger radius, have maximum heights in the range of 35 to 60 pc. The Tucana Horologium and \( \mu \) Tauri associations (THA, MTAU) and IC2602 have the highest maximum heights in the range 60 to 100 pc.

The wavelike or undulating structure seen in the filament of molecular clouds associated with the Local arm (Alves et al. 2020) could be comprised of clouds undergoing similar amplitude vertical motions but at different phases of oscillation. Alternatively there might be spatial variations in the amplitudes of the vertical motions. The dip in the vertical amplitudes (the \( |z|_{\max} \)-age plot in 1) of the intermediate age stellar associations such as the \( \beta \) Pictoris moving group suggests that there are spatial variations in the vertical amplitudes of the parent molecular clouds. Tightly wound bending waves that travel through the disk (e.g., Hunter & Toomre 1969) would be expected to have amplitudes that are slowly varying with galactocentric radius and angle. In contrast, a phase wrapping model with Galactic disk perturbed in the past and then passively evolving since, could give a disk that shows variations in vertical amplitude over short distances (de la Vega et al. 2015). A tidal perturbation on the disk would excite stars in one region of the Galaxy more than other and stars or gas clouds from different regions during the perturbation event could be currently near the Sun (e.g. Candlish 2014; de la Vega et al. 2015; Darling & Widrow 2019). An additional possibility one may consider is that these structures arise from orbits of stars moving in a dark matter halo that significantly departs from spherical symmetry due to past mergers with dwarf galaxies. However, it is likely that such an effect is minimal close to the midplane as prior work studying the evolution of halo shapes.
finds that baryonic-dominated regions are nearly spherical (Debattista et al. 2008; Prada et al. 2019).

In summary, trends in the birth heights of the stellar associations suggest that they were born in a corrugated disk of molecular clouds. Maximum vertical heights or vertical amplitudes reached above or below the galactic plane are high for the youngest and oldest stellar associations. This implies that there were spatial variations in the amplitudes of the vertical motions in the parent molecular cloud distributions.

### 4.4 Birth locations in rotating frames and birth spiral arm candidates

Keeping in mind that different associations were born at different heights, we now discuss orbits in different rotating frames. We explore the possibility that molecular cloud filaments near the Sun are spiral features, moving as waves, in which stellar associations were born.

In Figure 5 we show backwards orbit integrations for the same sample of stellar associations as in Figure 2, however, instead of plotting orbit positions at prior times $t$ as a function of galactocentric angle, we plot association positions as a function of angle $\theta_g - \theta_\odot - \Omega_s t$ where $\Omega_s$ is an assumed pattern speed. Each panel shows the stellar associations in a frame that is rotating with a different possible pattern speed. On the top axis we show the distance along the solar circle, $R_\odot(\theta_g - \theta_\odot - \Omega_s t)$ to give a sense of scale for the $x$ axis. Trailing spiral arms should have a negative slope on this plot (as shown in Figure 3). In Galaxies, the angular rotation rate is often higher in the center than the outskirts. A linear radial feature that winds up due to differential rotation would exhibit ‘trailing’ spiral.

With a faster pattern speed, $\Omega_s = -30.3 \text{ km s}^{-1}\text{kpc}$, as shown on the top panel of Figure 5, most of the associations (excepting IC 2391) could have been born in a single spiral feature. An even higher pattern speed would be unlikely as the spiral arm would no longer be trailing. The associations younger than 10 Myr could have been born in a compact region and on the same arm if that arm is nearly at its own corotation radius, $\Omega_s \approx \Omega_\odot = 28.7 \text{ km s}^{-1}\text{kpc}^{-1}$ (see the middle panel). This would support some recent estimates of the spiral pattern speed (e.g., Naoz & Shaviv 2007; Dias et al. 2019). Can the Octans (OCT) and Argus (ARG) associations have been born on the same arm? If that arm has a faster pattern speed than $\Omega_\odot$, then a quite open rather than tightly wound arm would be required to parent both of these associations. The Octans and Argus associations only
Figure 5. Backwards orbit integrations of young stellar associations plotted in rotating frames. Each panel is similar to Figure 2 except we plot galactocentric radius versus azimuthal angle in a frame rotating with a spiral arm pattern. The assumed pattern speeds for each panel are labelled on the top left of each panel in units of km s\(^{-1}\) kpc\(^{-1}\). The middle panel has a corotating pattern speed, \(\Omega_s = \Omega_\odot\). To give a sense of scale for the x axis, the top axis shows distances in kpc along the solar circle of radius \(R_\odot\).

lie on the same tightly wound arm if that arm has a slower pattern speed, \(|\Omega_s| \lesssim |\Omega_\odot|\) (bottom panel of Figure 5).

In Figure 6 we compare the distribution of stellar association birth locations in various rotating frames to molecular cloud positions using the database of molecular clouds by Zucker et al. (2020) and features labelled in the 3D local extinction map by Lallement et al. (2019). Figure 6 is similar to Figure 5 except extinction features based on maps by Lallement et al. (2019) are plotted as grey bars and molecular clouds listed by Zucker et al. (2020) are plotted as black dots. The y axis is log galactocentric radius (instead of radius as in Figure 5). A logarithmic spiral arm would be linear on Figure 6. The same pattern speeds are used in Figure 6 and Figure 5 but we show the values at the top of each panel in units of \(\Omega_\odot\).

Unfortunately many of the masers identified in the feature called the Local Spur at Galactic longitude \(l \sim 50^\circ\) by (Xu et al. 2016, 2018) are further than 2 kpc away from the Sun and outside the region spanned by Figures 5 and 6. The Local Spur may be connected to an extinction feature at \(l \sim 50^\circ\) and distance from the Sun \(d < 500\) pc labelled as ‘Vul’ by Lallement et al. (2019) (see their Figure 14). A filament denoted the ‘Split’ by Lallement et al. (2019) contains the Serpens molecular clouds at longitude \(l \sim 18\) to 30\(^\circ\) and distance \(d \sim 500\) to 1200 pc, the Aquila Rift at \(l \sim 18^\circ\) and a distance of \(d \sim 200\) pc, and connects to the nearby Scorpius-Centaurus star formation region. The Vela C cloud
at $l \sim 256^\circ$ and $d \sim 900$ pc is also prominent in the extinction maps. The extinction filament associated with the Local Arm contains the Orion star formation region (at $l \sim 200^\circ$ and $d \sim 400$ pc), Cepheus Near (at $l \sim 110^\circ$ and $d \sim 340$ pc), North America (at $l \sim 84^\circ$ and $d \sim 800$ pc) and Cygnus X clouds (at $l \sim 80^\circ$ and $d \sim 1000$ pc). The longitudes and distances given here for these molecular clouds are based on those listed in Table A1 by Zucker et al. (2020). There is a nearby or lower component to the Sagittarius Carina arm denoted ‘Low’ in figure 14 (for Lower Sagittarius Carina arm) by Lallement et al. (2019) that is approximately at $l \sim 330^\circ$ and $d \sim 1$ kpc. These are the extinction features that are shown as grey bars and labelled on Figure 6.

In Figure 6, the higher pattern speeds put the birth locations of the younger associations between the local arm filament and the Split and Vul filaments seen in dust extinction maps. However a spiral pattern near corotation (the middle panel) allows the younger associations to have been born in the same arm that is an extension of Split or Vul filaments. However, a single molecular filament would not be consistent with the scatter in birth heights in the youngest associations. Two nearby nearly corotating molecular filaments, one associated with Split or Vul filaments and the other near the Taurus-Auriga association, at different heights, could have been birth sites for most of the younger stellar associations. At slower pattern speeds, (the bottom panel), the Argus and Octans associations could have been born in a filament that is related to the Vela C molecular cloud complex. Low pattern speeds extend the birth locations along a line that has the positive slope of a leading spiral arm. This suggests that many of the stellar associations were born in nearly corotating features. None of the pattern speeds clearly link current molecular cloud filaments to the birth sites of the older associations such as the Carina (CAR) and 32 Orionis (THOR) associations. This suggests that in the past 50 Myr the pattern of spiral structure cannot be decomposed into a set of a few steady moving filaments. Transient behavior and multiple molecular filaments seem necessary to explain even the most recent history of star formation near the Sun.

Using equation 20, the vertical oscillation period near the Sun is about 83 Myr. A quarter period is only 20 Myr. This implies that the stellar associations that are younger than 20 Myr right now have heights that are fairly near their birth heights. Figure 7 is similar to Figure 6 except each set of panels shows shows a single pattern speed and in each panel we only plot positions that lie within specific planar slabs. The height ranges ($z_h$) of each slab are printed on the top left of each panel. Figure 8 is similar to Figure 7 except the $y$ axes are height and in each panel we only plot positions that lie within a range of radius. Each set of panels also shows a single pattern speed. The molecular cloud positions by Zucker et al. (2020) are plotted as black dots in each panel in Figures 7 and 8.

The groups related to the Scorpius Centaurus star formation region (USCO, LCC, ROPH and UCL) are above the Galactic plane and were born above the Galactic plane (see top panel in Figure 1). There are some molecular clouds currently near their birth locations, however there are more molecular clouds below the Galactic plane. We had hoped to estimate how the height of a spiral feature varied in the last few million years, but these plots do not clearly pick out specific current molecular cloud counterparts for the different stellar associations.

In summary, many stellar associations could have been born on one or two nearly corotating filaments that are associated with nearby dust extinction features. The Octans and Argus associations could have been born on the same arm. If its pattern speed were slower, $\Omega_1 \sim 0.94 \Omega_2$, its current counterpart could be the Vela C cloud. Multiple arms with different pattern speeds and heights seem required to account for the stellar association birth locations. This suggests that spiral arms or molecular cloud filaments exhibited transient behavior in the past 50 Myr near the Sun.

### 4.5 Stellar associations in comparison to the local velocity distribution

We discuss the stellar associations in context with the velocity distribution and vertical phase-space distributions of stars that are present in the solar neighborhood. Quillen et al. (2018c) proposed that arcs in local velocity distributions separate stars that have recently crossed and been more strongly perturbed by a particular arm from those that have not. A boundary or locus in a local velocity distributions could separate stars that have recently crossed and been more strongly perturbed by a particular arm from those that haven’t. Since stellar associations could have been born in a nearby arm, we can test this hypothesis with them. They might be more likely to lie near the locus or underpopulated region in the velocity distribution. Stars on one side of the locus would not cross an arm, stars on the other side would cross it, and stars that graze the arm would lie on the locus. Stars born on the arm might be near or on the locus.

In Figure 9 we show stellar association velocity components plotted as points on top of the velocity distribution (shown with a color map) that is generated from nearby (within 200 pc) Gaia DR2 stars with radial velocity measurements (Gaia Collaboration et al. 2018). The bottom two rows in Figure 9 are similar to the top row except only stars and associations above or below the plane are used to make the plot. This figure was generated with the same database, selection criteria and numerical scripts as the figures previously presented by Quillen et al. (2018c). The axes for the left panels are galactocentric tangential and radial velocity components $v_\theta$, $-v_r$ and those on the right panels are $v_\theta$ and $v_r$. Each stellar association is plotted with a different point shape but their colors and plotting order are the same as we have used in our previous figures.

Stellar associations are expected to have been born in spiral features. This implies that their current velocities should be on loci separating orbits that cross an arm from those that do not cross the same arm. Figure 9 shows that the stellar associations studied here tend to be located between peaks in the local velocity distribution. The peak at $(v_\theta, v_r) \sim (220, 0)$ km s$^{-1}$ is often called the Pleiades moving group or stream and that at $(v_\theta, v_r) \sim (240, 0)$ km s$^{-1}$ often called the Coma Berenices moving group or stream (following the names used by Dehnen 1998). These streams contain stars with a wide range of ages (e.g., Dehnen 1998). The Coma Berenices moving group is more prominent in stars below the Galactic plane (Quillen et al. 2018b; Monari et al. 2018). The interpeak locations of the stellar associations on the $v_\theta$, $v_r$ velocity distribution is consistent with the
hypothesis that dips in the velocity distribution are associated with orbits that touch nearby spiral density features.

The associations that currently are above the Galactic plane (Figure 9 middle panels) are young groups related to the Scorpius-Centaurus star formation region. The rest of the associations are currently below the Galactic plane. Other than this, we do not see any obvious trends in the comparison between stellar association and velocity distributions above and below the Galactic plane in Figure 9.

In the Gaia DR2 sample, Antoja et al. (2018) discovered a spiral in the vertical phase-space distribution of stars in the solar neighborhood by plotting the distribution of stars as a function of $z_g$ and $v_z$. How are the stellar associations distributed with respect to this spiral? To answer this question we plot in Figure 10 the current coordinates of the stellar
Figure 7. Orbits in rotating frames. Similar to Figure 6 except each set of panels shows shows a single pattern speed and in each panel we only plot positions that lie in a single planar slab. The range in height $z_g$ is denoted on the top left of each panel. The assumed pattern speed $\Omega_s$ is written on the top of each set of panels.

Figure 8. Orbits in rotating frames. Similar to Figure 7 except the $y$ axes are height and in each panel we only plot positions that lie in a range of radius. The range in galactocentric radius $R_g$ is denoted on the top left of each panel. The assumed pattern speed $\Omega_s$ is written on the top of each set.
associations on top of the vertical phase-space distribution of stars in the solar neighborhood.

The phase-space spiral (Antoja et al. 2018; Bland-Hawthorn et al. 2019; Laporte et al. 2019) is present at larger scales in both $v_z$ and $z_R$ than we show in Figure 10. The ranges in our figure are chosen to encompass the coordinates of the stellar associations, however the innermost edge of the spiral seen by Antoja et al. (2018) is at about 20 km/s and 250 pc and would lie outside our plot. Our plot only shows stars that have orbits that remain near the Galactic plane. In Figure 10 we plotted associations younger than 20 Myr with a larger point size. The top panel shows the distribution of stars (again from Gaia DR2) within 200 pc with the young stellar associations in our sample. The middle panels only plot stars and associations that have tangential velocity $v_\theta > V_{\theta,SR}$ so shows stars and associations that spend more time at larger galactocentric radius. The bottom panels show stars and associations with $v_\theta < V_{\theta,SR}$. We have checked that the stellar vertical phase-space distributions look similar if the vertical component of angular momentum is used to choose stars rather than the tangential velocity component.

The morphology of the vertical phase-space distribution shows streaks and clumps rather than a spiral. The sensitivity of these peaks to $v_\theta$ and $v_R$ must be related to the sensitivity of peaks in the $v_\phi$, $v_R$ stellar velocity distribution to galactic hemisphere (Quillen et al. 2018b; Monari et al. 2018). A tidal perturbation on the disk would excite both epicyclic and vertical oscillations. Even when integrating test particles in a fixed potential, the stellar disk response can be quite complex (de la Vega et al. 2015). As stressed by Hunter & Toomre (1969); Sparke & Casertano (1988); Darling & Widrow (2019), when a disk bends, the potential associated with the perturbation also acts on the unperturbed disc, so phase wrapping in a fixed potential (e.g., Candlish 2014; de la Vega et al. 2015) does not capture the full complexity of the stellar disk response (e.g., D’Onghia et al. 2016). The clumps seen in the vertical phase-space distribution could be showing a rippled disk that was perturbed in the past (Quillen et al. 2009; Minchev et al. 2009; Purcell et al. 2011; Chakrabarti et al. 2011; Gómez et al. 2013; D’Onghia et al. 2016; Bland-Hawthorn et al. 2019; Darling & Widrow 2019).

Gas dynamics differs from stellar dynamics as gas can shock, and disturbances in the gas disk will dissipate after a dynamical time. However, in all three panels in Figure 10, the stellar associations seem to be associated with peaks in the vertical phase-space distribution. This implies that the vertical motions of gas where the stellar associations formed is related to the vertical motions of stars that are in nearly planar orbits in the Galactic disk. Perhaps the gas and stars in nearly planar orbits move vertically together. Recent tidal perturbations, such as the interaction of the Antlia 2 dwarf galaxy, on a nearly co-planar orbit with the Milky Way (Chakrabarti et al. 2019) or the Sagittarius dwarf Galaxy (e.g., Laporte et al. 2019), would leave visible traces in the gas distribution at present day.

In summary, stellar associations are located in between peaks in the $v_\theta$, $v_R$ stellar velocity distribution for stars in the solar neighborhood. This is consistent with the hypothesis that the dips in the velocity distribution are associated with orbits that touch and are perturbed by nearby spiral density features (Quillen et al. 2018c) as the stellar associations were likely to have been born in a spiral arm. In contrast, stellar associations seem to be located near peaks in the vertical phase-space distribution ($z_R$, $v_\theta$), suggesting that the vertical motions of gas in which stellar associations are born is similar to that of the low velocity dispersion disk stars.

5 SUMMARY AND DISCUSSION

In this study we have used recent compilations of membership, space motions, distances and ages of young (less than 70 Myr old) clusters, stellar associations, and star formation regions near the Sun to estimate their birth locations. Our works builds upon efforts of hundreds of prior observational and statistical studies of stars (e.g., Eggen 1983; de la Reza et al. 1989; de Zeeuw et al. 1999; Jayawardhana 2000; Mamajek et al. 1999; Binks et al. 2015; Pecaut & Mamajek 2016; Mamajek 2016; Gagné et al. 2018a). Our backwards
We thank Eric Mamajek, Borja Anguiano, Dechen Dolker, scientific Advancement’s Time Domain Astrophysics Scialog. knowledges support from NASA ATP NNX17AK90G, NSF Foundation under Grant No. NSF PHY-1748958. SC acknowledges support from the Heising-Simons Foundation and the National Science Foundation under Grant No. NSF PHY-1748958. SC acknowledges support from NASA ATP NNX17AK90G, NSF AAG grant 1517488, and from Research Corporation for Scientific Advancement’s Time Domain Astrophysics Scialog. We thank Eric Mamajek, Borja Anguiano, Dechen Dolker, orbit integrations are done in a gravitational potential that is an approximation to the Galactic gravitational potential near the Sun. This potential is static, separable and axisymmetric and matches recent estimates for the local standard of rest, the rotation curve slope and the vertical acceleration as a function of height above the Galactic plane.

Most of the stellar associations were born within the radius of the Sun and have moved out to the solar neighborhood where they are now found. The Octants and Argus associations are exceptions and were born at larger Galactocentric radius than the Sun. One way to account for these trends is with a spiral structure model where nearby spiral features have different pattern speeds. A spiral arm with pattern speed that is higher than \( \Omega_{LSR} \) places associations currently on the trailing side of their birth arm. In this case, N-body simulations of flocculent approximately corotating spiral structure (Grand et al. 2012) and shock models can predict outwards radial motion after birth. Alternatively the associations that moved outward were born on the trailing side of a corotating spiral arm that increased their angular momentum through its gravitational torque (Kawata et al. 2014). Other scenarios, such as involving tidally excited spiral structure or spurs and armlets extending from strong arms might also account for the radial motions after birth (e.g., Dobbs & Pringle 2010).

Variations in birth heights of the stellar associations suggest that they were born in a corrugated disk of molecular clouds, similar to that inferred from the current filamentary molecular cloud distribution (Alves et al. 2020) and extinction maps (Rezaei Zh. et al. 2018; Green et al. 2019; Lallement et al. 2019). Maximum vertical heights reached above or below the galactic plane are high for the youngest and oldest stellar associations, but only about 30 pc for the 20–30 Myr older associations such as the \( \beta \) Pictoris moving group. This implies that there were spatial variations in the amplitudes of the vertical motions in the molecular cloud distributions in the recent past.

We examined birth locations in frames rotating at different pattern speeds. Multiple arms with different pattern speeds and different heights seem required to account for the stellar association birth locations, suggesting that spiral arms or molecular cloud filaments exhibited transient behavior in the past 50 Myr near the Sun.

We find that the stellar associations are located in between peaks in the \( v_{\theta}, v_{\phi} \) stellar velocity distribution for stars in the solar neighborhood. This supports the hypothesis that the dips in the velocity distribution are associated with orbits that touch nearby spiral density features (Quillen et al. 2018c). In contrast, stellar associations seem to be located near peaks in the vertical phase-space distribution \((z_g, v_z)\), suggesting that the gas in which stellar associations are born moves together with the low velocity dispersion disk stars.

Ongoing efforts are discovering new stellar associations (e.g., Meingast et al. 2019; Gagné et al. 2020; ?, ?), substructure in known star formation regions and associations (e.g., Kos et al. 2019; Tian 2020), improving upon the accuracy of membership age distributions, and position and velocity measurements (e.g., Újwal et al. 2020). A backwards integration study can be redone in the future with additional and better measurements and in time dependent and non-axisymmetric potential models. More distant stellar associations may reveal patterns of star formation in the Local and other arms. Lastly, improved dissection of N-body simulations that include gas dynamics and star formation could help differentiate between potential spiral arm models and the nature of the vertical motions seen in the stars, gas and stellar associations in the solar neighborhood.

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**Table 1.** Stellar associations and moving groups, abbreviations and ages

| Name | Abbreviation | Age (Myr) | σ_age (Myr) | Reference |
|------|--------------|-----------|-------------|-----------|
| ρ Ophiucus star-forming region | ROPH | 1 | 1 | Wilking et al. (2008) |
| Taurus-Auriga star-forming region | TAU | 1.5 | 1 | Reipurth (2008) |
| ϵ Chamaeleontis association | EPSC | 4 | 1 | Murphy et al. (2013) |
| Corona-Australis star-forming region | CRA | 4.5 | 0.5 | Gennaro et al. (2010) |
| TW Hydrae association | TWA | 10 | 3 | Bell et al. (2015) |
| Upper Scorpius group | USCO | 10 | 3 | Pecaut & Mamajek (2016) |
| Upper Corona-Australis association | UCRA | 10 | 3 | Gagné et al. (2018a) |
| η Chamaeleontis cluster | ETAC | 11 | 3 | Bell et al. (2015) |
| Lower Centaurus Crux group | LCC | 15 | 3 | Pecaut & Mamajek (2016) |
| Upper Centaurus Lupus group | UCL | 16 | 2 | Pecaut & Mamajek (2016) |
| 32 Orionis group | THOR | 22 | 4 | Bell et al. (2015) |
| β Pictoris moving group | BPMG | 24 | 3 | Bell et al. (2015) |
| Octans association | OCT | 35 | 5 | Murphy & Lawson (2015) |
| Columba association | COL | 42 | 5 | Bell et al. (2015) |
| Argus association | ARG | 45 | 5 | Zuckerman (2019) |
| Carina association | CAR | 45 | 8 | Bell et al. (2015) |
| Tucana-Horologium association | THA | 45 | 4 | Bell et al. (2015) |
| IC2602 cluster | IC2602 | 46 | 5 | Dobie et al. (2010) |
| IC2391 cluster | IC2391 | 50 | 5 | Barrado y Navascués et al. (2004) |
| µ Taurus association | MTAU | 62 | 10 | Gagné et al. (2020) |

References: Notes. Standard deviations in age are estimated from the age range or uncertainty in age in the associated reference. Pecaut & Mamajek (2016) found a larger age spread of about 7 Myr in the Sco-Cen star formation regions. We adopted the age range of 3 Myr for UCRA and 10 Myr for MTAU as references lacked age range or error estimates. We adopted the age range for ETAC based on discussion by Bell et al. (2015), but also see Gennaro et al. (2010); Murphy et al. (2013). For more discussion on ages and their errors and age distributions see discussions by Riedel et al. (2017); Gagné et al. (2018a), references therein and the references we have listed here.

**Table 2.** Central Locations and Variances from the BANYAN Gaussian Models for the Young Stellar Associations

| Name | Kin. ref. | x_h (pc) | y_h (pc) | z_h (pc) | U (km/s) | V (km/s) | W (km/s) | σ_x (pc) | σ_y (pc) | σ_z (pc) | σ_U (km/s) | σ_V (km/s) | σ_W (km/s) |
|------|-----------|----------|----------|----------|----------|----------|----------|-----------|----------|----------|------------|------------|------------|
| ROPH | G18a | 124.8 | -15.2 | 37.6 | -9.9 | -13.5 | -7.9 | 1.33 | 0.51 | 0.66 | 1.3 | 4.7 | 4.3 |
| TAU | G18a | -116.3 | 6.7 | -35.9 | -14.3 | -9.3 | -8.8 | 11.4 | 10.8 | 10.1 | 3.1 | 4.5 | 3.4 |
| EPSC | G18a | 49.9 | -84.8 | -25.6 | -9.9 | -19.3 | -9.7 | 2.5 | 3.6 | 4.0 | 1.6 | 2.2 | 2.0 |
| CRA | G18a | 132.4 | -0.2 | -42.4 | -3.7 | -15.7 | -8.8 | 3.71 | 0.75 | 2.04 | 1.3 | 2.2 | 2.2 |
| TWA | G18a | 14.4 | -47.7 | 22.7 | -11.6 | -17.9 | -5.6 | 12.2 | 9.7 | 3.9 | 1.8 | 1.8 | 1.6 |
| USCO | G18a | 121.2 | -17.0 | 48.9 | -4.9 | -14.2 | -6.5 | 17.0 | 8.2 | 8.9 | 3.7 | 3.2 | 2.3 |
| UCRA | G18a | 142.1 | -1.2 | -39.2 | -3.7 | -17.1 | -8.0 | 7.3 | 2.4 | 5.9 | 3.0 | 1.8 | 1.2 |
| ETAC | G18a | 33.6 | -81.4 | -34.8 | -10.0 | -22.3 | -11.7 | 0.65 | 0.98 | 0.71 | 1.6 | 2.8 | 1.8 |
| LCC | G18a | 54.3 | -94.2 | 5.8 | -7.8 | -21.5 | -6.2 | 11.9 | 12.4 | 13.7 | 2.7 | 3.8 | 1.8 |
| UCL | G18a | 107.5 | -60.9 | 26.5 | -4.7 | -19.7 | -5.2 | 21.0 | 19.6 | 13.5 | 3.8 | 3.0 | 1.7 |
| THOR | G18a | 121.2 | -17.0 | 48.9 | -4.9 | -14.2 | -6.5 | 17.0 | 8.2 | 8.9 | 3.7 | 3.2 | 2.3 |
| BPMG | G18a | 4.1 | -96.9 | -59.7 | -13.7 | -3.3 | -10.1 | 78.3 | 25.8 | 8.8 | 2.4 | 1.3 | 1.4 |
| OCT | G18a | 4.0 | -96.9 | -59.7 | -13.7 | -3.3 | -10.1 | 78.3 | 25.8 | 8.8 | 2.4 | 1.3 | 1.4 |
| COL | G18a | 29.5 | -25.9 | -21.4 | -11.9 | -21.3 | -5.7 | 12.1 | 23.0 | 17.8 | 1.04 | 1.29 | 0.75 |
| ARG | Z19/G20 | 4.9 | -43.3 | -7.8 | -22.8 | 14.1 | -5.0 | 28.9 | 41.3 | 19.2 | 1.2 | 2.0 | 1.7 |
| CAR | G18a | 6.7 | -50.5 | -15.5 | -10.7 | -21.9 | -5.5 | 10.0 | 18.1 | 12.6 | 0.67 | 1.02 | 1.01 |
| THA | G18a | 5.4 | -20.1 | -36.1 | -9.8 | -20.9 | -1.0 | 19.4 | 12.4 | 3.8 | 0.87 | 0.79 | 0.72 |
| IC2602 | G18a | 47.4 | -137.6 | -12.6 | -8.2 | -20.6 | -0.6 | 1.5 | 5.4 | 1.1 | 1.18 | 0.61 | 0.65 |
| IC2391 | G18a | 1.9 | -148.1 | -18.0 | -23.0 | -14.9 | -5.5 | 1.3 | 6.4 | 1.4 | 1.10 | 0.34 | 0.78 |
| MTAU | G20 | -130.7 | 0.2 | -79.7 | -14.2 | -24.2 | -6.2 | 21.9 | 20.8 | 12.4 | 3.0 | 1.7 | 2.4 |

References: G18a = Gagné et al. (2018a); Z19 = Zuckerman (2019); G20 = Gagné et al. (2020)
Table 3. Birth sites and other orbital parameters for Young Stellar Associations

| name       | $z_b$ (pc) | $v_{z,b}$ (km/s) | $R_b$ (kpc) | $v_{R,b}$ (km/s) | $\theta_b - \theta_{\odot}$ (rad) | $R_L$ (kpc) | $|z|_{max}$ (pc) |
|------------|------------|-----------------|-------------|-----------------|-----------------------------------|-------------|-----------------|
| ROPH       | 58 ± 4     | -0.4 ± 4.5      | 8.002 ± 0.004 | -5.1 ± 1.6      | 0.031 ± 0.021                     | 8.045 ± 0.140 | 53 ± 37         |
| TAU        | -14 ± 14   | -1.6 ± 2.8      | 8.234 ± 0.011 | 2.9 ± 3.4       | 0.042 ± 0.023                     | 8.320 ± 0.103 | 47 ± 17         |
| EPSC       | 4 ± 6      | -2.5 ± 3.6      | 8.074 ± 0.003 | 0.4 ± 0.8       | 0.123 ± 0.026                     | 7.801 ± 0.051 | 36 ± 20         |
| CRA        | -15 ± 12   | -1.9 ± 2.6      | 8.021 ± 0.009 | -6.3 ± 1.7      | 0.129 ± 0.014                     | 7.843 ± 0.082 | 52 ± 13         |
| TWA        | 19 ± 16    | 3.0 ± 1.1       | 8.087 ± 0.030 | 3.6 ± 2.3       | 0.287 ± 0.080                     | 7.893 ± 0.056 | 39 ± 16         |
| USCO       | 48 ± 31    | 3.2 ± 2.3       | 8.053 ± 0.037 | -4.5 ± 4.5      | 0.289 ± 0.081                     | 8.028 ± 0.150 | 55 ± 11         |
| UCRA       | -8 ± 7     | -1.3 ± 0.7      | 8.038 ± 0.024 | -4.0 ± 2.3      | 0.284 ± 0.080                     | 7.790 ± 0.063 | 45 ± 6          |
| ETAC       | 34 ± 23    | -4.0 ± 1.6      | 8.066 ± 0.022 | 5.1 ± 2.6       | 0.314 ± 0.078                     | 7.683 ± 0.104 | 66 ± 17         |
| LCC        | 1 ± 29     | 2.0 ± 1.5       | 8.057 ± 0.035 | 4.7 ± 4.1       | 0.427 ± 0.079                     | 7.668 ± 0.180 | 38 ± 15         |
| UCL        | -3 ± 24    | 3.6 ± 1.4       | 8.057 ± 0.068 | 1.3 ± 4.3       | 0.455 ± 0.053                     | 7.725 ± 0.099 | 55 ± 17         |
| THOR       | 26 ± 26    | -0.5 ± 0.8      | 8.095 ± 0.056 | 8.2 ± 2.4       | 0.618 ± 0.107                     | 7.956 ± 0.051 | 31 ± 10         |
| BPMG       | 27 ± 18    | 0.2 ± 0.4       | 8.064 ± 0.036 | 4.3 ± 1.3       | 0.683 ± 0.081                     | 7.998 ± 0.042 | 34 ± 17         |
| OCT        | 60 ± 17    | -0.2 ± 1.3      | 8.324 ± 0.109 | -12.3 ± 1.7     | 1.041 ± 0.135                     | 8.440 ± 0.058 | 72 ± 12         |
| COL        | -9 ± 23    | -1.5 ± 0.9      | 7.769 ± 0.076 | 13.0 ± 1.6      | 1.201 ± 0.142                     | 7.794 ± 0.035 | 38 ± 10         |
| ARG        | -21 ± 24   | -2.0 ± 1.8      | 9.033 ± 0.211 | -39.2 ± 2.9     | 1.364 ± 0.123                     | 9.089 ± 0.082 | 41 ± 21         |
| CAR        | -11 ± 17   | -1.6 ± 0.7      | 7.698 ± 0.115 | 13.9 ± 2.1      | 1.294 ± 0.230                     | 7.764 ± 0.040 | 28 ± 12         |
| THA        | -21 ± 3    | -6.3 ± 0.7      | 7.765 ± 0.063 | 12.7 ± 0.9      | 1.285 ± 0.114                     | 7.813 ± 0.021 | 102 ± 13        |
| IC2602     | -33 ± 29   | -6.3 ± 1.1      | 7.761 ± 0.139 | 12.6 ± 4.1      | 1.330 ± 0.142                     | 7.762 ± 0.097 | 107 ± 8         |
| IC2391     | 0 ± 8      | -1.8 ± 1.0      | 7.726 ± 0.127 | -2.4 ± 3.9      | 1.536 ± 0.148                     | 8.018 ± 0.084 | 26 ± 10         |
| MTAU       | 53 ± 29    | 2.0 ± 2.3       | 7.445 ± 0.101 | 7.4 ± 5.6       | 1.829 ± 0.217                     | 7.844 ± 0.055 | 84 ± 8          |
