Weather Forecast of the Milky Way: Shear and Stellar feedback determine the lives of Galactic-scale filaments

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ABSTRACT
The interstellar medium (ISM) is an inseparable part of the Milky Way ecosystem whose evolutionary history remains a challenging question. We trace the evolution of the molecular ISM using a sample of Young Stellar Objects (YSO) association–molecular cloud complex (YSO-MC complex). We derive their three-dimensional (3D) velocities by combining the Gaia astrometric measurements of the YSO associations and the CO observations of the associated molecular clouds. Based on the 3D velocities, we simulate the motions of the YSO-MC complexes in the Galactic potential and forecast the ISM evolution by tracing the motions of the individual complexes, and reveal the roles of shear and stellar feedback in determining ISM evolution: Galactic shear stretches Galactic-scale molecular cloud complexes, such as the G120 Complex, into Galactic-scale filaments, and it also contributes to the destruction of the filaments; while stellar feedback creates interconnected superbubbles whose expansion injects peculiar velocities into the ISM. The Galactic-scale molecular gas clumps are often precursors of the filaments and the Galactic-scale filaments are transient structures under a constant stretch by shear. This evolutionary sequence sets a foundation to interpret other gas structures.

Keywords: Galaxies: ISM – ISM: structure – ISM: clouds – Stars: formation – Physical data and processes: turbulence

1 INTRODUCTION
The interstellar medium (ISM) is an inseparable part of the Milky Way ecosystem whose evolutionary history remains a challenging question. Studies find that filaments of different sizes prevail in the molecular interstellar medium (Zucker et al. 2015; Li et al. 2016a; Wang et al. 2016). Among them, filaments whose sizes are larger than the thickness of the Milky Way molecular gas disk are basic units of the molecular gases in the Milky Way and other similar disk galaxies (Li et al. 2013; Ragan et al. 2014; Goodman et al. 2014; Wang et al. 2015; Alves et al. 2020). These have been reproduced in global simulations of the Milky Way disk (e.g. Wada et al. 2000; Dobbs et al. 2006; Dobbs 2015; Smith et al. 2016, 2020; Li & Chen 2022). The physics controlling the ISM evolution on the kpc scale and the nature of the Galactic-scale filaments are still open questions.

Young Stellar Objects (YSO) are newly-born stars and they inherit the motion of the gas where they originate from. The Gaia satellite (Gaia Collaboration et al. 2018a) allows for the measurement of the YSOs on this sky plane. This, combined with radial velocity measurements, allow us to derive the 3D velocities of YSOs. In this paper, we trace the evolution of the molecular ISM using a sample of Young Stellar Objects (YSO) association (Zhou et al. 2021)–molecular cloud complex (YSO-MC complex). We derive their three-dimensional (3D) velocities by combining the Gaia astrometric measurements (Gaia Collaboration et al. 2018a) of the YSO associations and the CO observations of the associated molecular clouds (Dame et al. 2001). Based on the 3D velocities, we simulate the motions of the YSO-MC complexes in the Galactic potential and forecast the ISM evolution, where the clouds are assumed to be isolated objects, and effects from external gravitational potential (Ballesteros-Paredes et al. 2009), spiral density wave, are neglected. This allows us to reveal the roles of shear and stellar feedback in determining ISM evolution.

2 DATA & METHOD
We start with a sample of Young Stellar Object (YSO) associations identified in a previous paper (Zhou et al. 2021). We identify the molecular cloud counterparts of the YSO associations from the CO observations (Dame et al. 2001). The entity, which contains a YSO association and the associated molecular cloud, is noted as a YSO association–molecular cloud complex (YSO-MC complex) in the current work. By combining the radial velocities of the associated molecular clouds derived using CO lines and the transverse velocities of the YSO associations, we obtain three-dimensional (3D)
motions of a sample of YSO-MC complexes. In this work, we adopt the convention that the Galaxy is viewed from the north, such that the disk rotates clockwise. The Sun is 8.34 kpc from the Galactic center, and we are 0.0208 kpc above the Galactic disk midplane (Reid et al. 2014; Bennett & Bovy 2019). We first derive the velocities in the Barycentric frame, then convert them to other reference frames (see online supplementary materials).

3 RESULTS

3.1 Interpreting 3D motions

Shear occurs when gas located at different radii from the Galaxy center and rotates at different angular speeds. In Fig. 1, the effects of shear appear as the radial dependence of the Y direction velocities (the dependence of \( v_Y \) on \( X \)). In the Solar neighborhood, the shear rate is \( \kappa = 2A \) where \( A \) is the Oort constant (Oort 1927) with updated values (Wang et al. 2021). We further define a reference frame called the Local Co-Rotating Frame (LCF). The LCF follows a circular orbit, and it is rotating such that its \( x \)-axis is locked to the center of the Galaxy. Because of the rotation, the LCF is non-inertial, and gas in this frame experiences the Coriolis force. We choose this frame as it allows us to observe the effect of shear on the gas with convenience.

The clouds also contain peculiar velocities, which are the additional velocities from the cloud when measured against the mean motion of stars. To derive the peculiar velocities \( v_{\text{peculiar}} \) of our sample YSO-MC complexes in the LCF, we further subtract their shear component (see online supplementary materials). The results are also shown in Fig. 1. Most sample YSO-MC complexes have \( v_{\text{peculiar}} \) of about 6 km s\(^{-1}\), while some of those sources exhibit very significant deviations.

3.2 Bubble-Induced Peculiar Velocities

Superbubbles are cavities filled with hot gas and radiation. They are prominent structures resulting from energies produced during the lifetime of stars, including energy from the stellar wind, radiation from massive stars, and the supernova explosions (Tenorio-Tagle & Bodenheimer 1988). The Sun is located inside one such bubble called the Local Bubble (Cox & Reynolds 1987). The Local Bubble appears to be connected to a neighboring bubble called the GSH238 Bubble (Heiles 1998), and from a dust map (Lallement et al. 2019; Chen et al. 2019), these two bubbles form a peanut-shaped cavity which we call the “Peanut Superbubble” (Fig. 2). Systems like this should be common in our Galaxy, as previous studies modeled the evolution of superbubble populations in Milky Way-like galaxy disks and concluded that bubble mergers are inevitable (Krause et al. 2015). An expansion-induced peculiar velocity of 5.5 km s\(^{-1}\) can be measured from the map of the peculiar velocities at a scale of 0.3 kpc. This expansion velocity is small compared to other bubbles, indicating that the expansion of the Local Bubble has reached its end (Krause et al. 2015). The expansion rate, which is around 30 km s\(^{-1}\) kpc\(^{-1}\), is significant yet comparable to that from shear measured in terms of Oort constant (Oort 1927), where the shear rate is \( \kappa = 2A \approx 30 \) km s\(^{-1}\) kpc\(^{-1}\).

3.3 Forecasting ISM evolution

With the measurements of the 3D positions and 3D velocities of our sample YSO-MC complexes, we can forecast the future evolution of the system of clouds by tracking the motions of the individual YSO-MC complexes in the Galactic-scale potential (see online supplementary materials). We integrate the system to a time of 30 Myr, which is comparable to the shear time.

Our approach should capture the crucial causal connection between the current motion of a cloud and its future positions. There are some other physical processes, which are not modeled but should be negligible for our purposes. These include the stellar feedback processes and the self-gravity from the gas. In galaxies, multiple supernovas can act collectively, creating superbubbles (Tenorio-Tagle & Bodenheimer 1988). They can reach the size of \( \sim 10^5 \) pc, and affect the dynamics of the ISM during their expansions. In our case, the expansion of the Local Bubble and the GSH238 Bubble leads to a peculiar velocity of about 6 km s\(^{-1}\). This small value of peculiar velocity is typical for bubbles whose expansion has reached an end (Krause et al. 2015). We thus do not expect additional velocity injections from existing bubbles.

Self-gravity from gas might give rise to some additional alignments. We conclude that the self-gravity of the molecular gas is not important on the Galactic scale. To evaluate its importance, we focus on the dense regions, i.e., the Galactic-scale filaments. The line-mass of the Galactic-scale filaments has \( \delta_{\text{ml}} \leq 1000 M_{\odot} \) pc (Li et al. 2016b). The characteristic velocity signifying the importance of the gas self-gravity can be estimated by \( v_c = \sqrt{\frac{\Delta \delta_{\text{ml}}}{2}} \approx 2 \) km s\(^{-1}\), which is small compared to the shear effect.

Another assumption adopted in the current work is that the clouds need to be long-lived, with \( t_{\text{cloud}} > t_{\text{simulation}} = t_{\text{shear}} \). This condition can be satisfied, as the molecular clouds are estimated to live up to a few tens of Myr (Meidt et al. 2015; Koda 2021; Zhou et al. 2021), which is comparable or longer than the shear time\(^1\). Our evolution forecast results are plotted in Fig. 3, and a movie is attached.

3.4 Birth and death of Galactic-scale Filaments

In this paper, the term “Galactic-scale filaments” (Li et al. 2013; Ragan et al. 2014; Goodman et al. 2014; Wang et al. 2015), refers to filaments whose length exceeds the thickness of the Galactic molecular gas disk (\( \sim 100 \) pc (Heyer & Dame 2015; Guo et al. 2021)). In the Solar vicinity, this includes the Radcliffe Wave (Alves et al. 2020; Li & Chen 2022), and the “Split” (Lallement et al. 2019; Chen et al. 2020). One end of the “Split” stays at the edge of the Peanut Superbubble, which is a connected entity made of the Local Bubble and the GSH238 Bubble (Heiles 1998).

This picture of a dynamically-evolving Galaxy molecular gas, first revealed in this study, bears a striking resemblance to the results from simulations of disk Galaxies (Dobbs et al. 2011; Duarte-Cabral & Dobbs 2017). We trace the evolution of three structures: the G120 Complex, the Radcliffe Wave, and the “Split”. We propose that the three structures form an evolutionary sequence, with the G120 Complex being a filament precursor, the Radcliffe Wave being a typical example of the Galactic-scale filament and the “Split” being a Galactic-scale filament at a slightly later stage of evolution. Our conclusion is based on the evolution forecast results: As the simulation goes, the G120 Complex is turned into a filament, and

\(^1\) This, of course, depends on the lifetime of cloud, and the forecast becomes inaccurate if clouds are short (Hartmann et al. 2001). Recently studies point to a picture where gas in a cloud can stay for a long time in the cold phase and circulate between different spiral arms (Pringle et al. 2001; Dobbs & Pringle 2013).
the Radcliffe Wave, as well as the “Split”, is stretched significantly, where the “Split” would be barely recognizable by then. Here, the disruption is mostly caused by shear alone. New supernova explosions should also contribute to the disruption of the filament, further shortening their lifetimes.

4 CONCLUDING REMARKS

We present the first study of the evolution of the local molecular ISM by combining the proper motions and parallaxes of the YSO associations with radial velocity measurements towards their molecular cloud counterparts. The complete kinematic information reveals
Figure 3. Forecasting the evolution of molecular ISM. Here, different structures are indicated by different symbols. We forecast the ISM evolution by modeling the motions of the individual YSO-MC complexes in the Galactic potential. At \( t = 30 \) Myr, The “split” and the Radcliffe Wave will be stretched significantly, while the G120 Complex can evolve into a long filament of width \( L \approx 1 \) kpc. In the first panel, we added a color-scale image of the gas distribution traced by dust, and the 3D velocities measured in the LCF for reference.

We conclude that hidden under a complex appearance, it is the shear and stellar feedback which control the evolution of the molecular ISM on the kpc scale. In addition, we identify a sequence where Galactic-scale gas clumps evolve into filaments that disperse because of shear and stellar feedback. The G120 Complex is one filament precursor, which deserves further investigations.

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A possible evolution sequence

G120 Complex

Radcliffe Wave

Dispersal

Alves et al. 2020

Figure 4. Evolution sequence of Galactic scale structures. The map of the G120 complex is taken at 870 μm by the Planck Satellite (Planck Collaboration et al. 2014). A illustrate of the 3D structure of the Radcliffe Wave is taken from Alves et al. (2020).

DATA AVAILABILITY

The paper makes use of published data from Marton et al. (2016) and Gaia DR2 (Gaia Collaboration et al. 2018b). Our Table containing the location and classification type information will be available as Zhou, Li & Chen 2022 in prep.

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DERIVING 3D VELOCITIES

Our sample is taken from our previous paper (Zhou et al. 2021), which contains a sample of YSO associations within ~ 3 kpc from the Sun. We identify their molecular cloud counterparts from the CO observations (Dame et al. 2001) by visual inspection. The radial velocities of the clouds are calculated by fitting Gaussians to the line profiles of the individual subfields overlapped to the cloud.

The radial velocities are combined with the Gaia data release 2 (Gaia DR2) (Gaia Collaboration et al. 2018a) measurements of proper motions and parallaxes of the YSO associations to derive 3D velocities. The Gaia measurements are presented in the Barycentric Reference Frame, whose center locates at the center of gravity of the Solar system. We have obtained the transverse velocities of the individual YSO associations from their Gaia DR2 proper motions and parallaxes (Zhou et al. 2021). The radial velocities are obtained from a CO survey (Dame et al. 2001), where the majority of the Milky Way disk is covered. For each complex, the transverse velocities can be measured to the accuracy of around 1.3 km s\(^{-1}\). The combined uncertainties are within 2 km s\(^{-1}\), which is small. In radio observations, the radial velocity measurements have uncertainties of around 1.3 km s\(^{-1}\). Limited by the velocity resolution of CO observations (Dame et al. 2001) by visual inspection. The radial velocities derived in this fashion are called the v\(_{LSR}\) velocities.

The radial velocities are combined with the Gaia data release 2 to convert them into the Local Standard of Rest (LSR) by assuming Barycentric velocities, which values are outdated (Reid et al. 2009). Radial velocities derived in this fashion are called the v\(_{LSR,std}\) velocities.

We then combine the radial and transverse velocity measurements to derive the 3D velocities in the Barycentric frame, obtaining v\(_{Barycentric}\) and the corresponding locations r\(_{Barycentric}\). In the next step, we correct for the effect that the Sun is 20.8 pc above the Galactic Plane (Bennett & Bovy 2019), and is 8.34 kpc from the Galaxy center and drive the 3D locations of the YSO associations in the kinematic LSR reference frame x\(_k\)-LSR. The velocities in the kinematic LSR reference frame v\(_{L\text{SR}}\) are obtained assuming v\(_{LSR,std}\) = 11.69 km s\(^{-1}\), v\(_{std}\) = 10.16 km s\(^{-1}\), w\(_{std}\) = 7.6 km s\(^{-1}\) (Wang et al. 2021).

The dynamical-LSR also follows the mean motion of stars. Compared to the kinematic-LSR, this frame follows a circular orbit, where the acceleration towards the Galaxy center is removed. The dynamical-LSR is an inertial frame.

The local co-rotating frame is a frame defined in this paper. Similar to the dynamical-LSR, the frame follows a circular orbit around the center of the Galaxy. In addition, it contains a rotation around the Z axis. The rotational speed is of order v\(_{circ}/R_0\). We added this rotation to ensure that the X-axis of the frame is locked toward the center of the Galaxy. In this frame, we can observe the motion of gas in a frame similar to those adopted in the shearing-box simulations of accretion disks. Because of the added rotation, the frame is non-inertial. Calculations done in this frame should take the Coriolis force into account.

Differences between different reference frames as well as the conversions are illustrated in Fig. 1. Finally, to reveal the peculiar motions, we further subtract the expected shear assuming Keplerian rotations, and derive v\(_{peculiar}\). In the solar vicinity, at location \(\vec{r}\), the rotation curve is approximated as v\(_{circ,x}\) = (R\(_x\) - R\(_0\))(A + B) + v\(_{circ}\), where A and B are Oort constants (Oort 1927) with updated values (Wang et al. 2021).

FORECASTING CLOUD EVOLUTION

We compute the motion of clouds in the dynamical-LSR reference frame, by solving the following equations

\[
\dot{\vec{r}}(t) = \vec{v}(t) \quad (1)
\]

\[
\dot{\vec{v}}(t) = \vec{a}(\vec{r}) \quad (2)
\]

where the computation is limited to the X-Y plane, e.g. \(\vec{r} = (X, Y)\) and \(\vec{v} = (v_x, v_y)\), where \(\vec{r}\), \(\vec{v}\) and \(\vec{a}\) stand for the positions, velocities and acceleration, respectively. Because this frame rotates around the Galaxy center in a circular orbit, at time \(t\), the Galactic center locates at (R\(\cos(\theta_1)\), -R\(\sin(\theta_1)\)) where \(\theta_1 = v_{circ}/R\). Because in the dynamical-LSR, the gravitational force of the Galaxy is cancelled out by the circular motion, at \((0, 0)\) the acceleration is zero, and the residual acceleration at location \(\vec{x}\) is

\[
\vec{a}(\vec{r})_{\text{dynamical-LSR}} = \vec{a}(\vec{r}) - \vec{a}(0, 0) \quad (3)
\]

where

\[
\begin{align*}
\vec{a}(\vec{r}) & = (a_x, a_y) \\
a_x & = a_0 \cos \theta \\
a_y & = -a_0 \sin \theta \\
\theta & = \arctan\left(\frac{R\sin\theta_1}{R\cos\theta_1 - X}\right) \\
a_0 & = \frac{\nu_{circ}^2}{R_0}
\end{align*}
\]

and

\[
\begin{align*}
\vec{a}(0, 0) & = (a_x, a_y) \\
a_x & = a_0 \cos \theta_1 \\
a_y & = -a_0 \sin \theta_1 \\
\theta & = \theta_1 \\
a_0 & = \frac{\nu_{circ}^2}{R_0}
\end{align*}
\]

where \(\nu_{circ}\) is the circular velocity measured at the origin, \(R_0\) the Galactocentric distance of the origin, \(\nu_{circ,r}\) the circular velocity...
Weather Forecast of the Milky Way

LSR de-accelerated LSR Local Co-rotating Frame (LCF)

|               | LSR          | de-accelerated LSR | Local Co-rotating Frame (LCF) |
|---------------|--------------|-------------------|-------------------------------|
| Velocity of the Center | (0, $v_{\text{circ},0}$) | (0, $v_{\text{circ},0}$) | (0, $v_{\text{circ},0}$) |
| Acceleration  | 0            | $a = \frac{v_{\text{circ}}^2}{R_0}$ | $a = \frac{v_{\text{circ}}^2}{R_0}$ |
| Frame Rotation| 0            | 0                 | $(0, 0, -v_{\text{circ}}/R_0)$ |
| Notes         | non-inertial | inertial          | similar to shearing-box simulations. |
| Centered around| The Sun     |                   |                               |

Table 1. Different reference frames discussed in the current work. $R_0$ is the Sun’s Galactocentric distance, and $v_{\text{circ}}$ is the velocity of a perfectly circular orbit around the center of the galaxy at the Sun’s galactocentric distance.

Figure 1. Velocity field viewed in the dynamical LSR frame, Local Co-rotating Frame, a plot of the peculiar velocities, as well as the the conversions between them.

measured at the location $\tilde{r}$, and $R_f$ is Galactocentric distance of the position $\tilde{r}$. The circular velocity can be approximated using

$$v_{\text{circ},r} = (R_f - R_0)(A + B) + v_{\text{circ},0}$$

where $A = 16$ km s$^{-1}$ kpc$^{-1}$ and $B = -12$ km s$^{-1}$ kpc$^{-1}$ (Wang et al. 2021) are Oort constants (Oort 1927). This frame is chosen only for our convenience. One can, of course, perform the calculation in a different frame and obtain identical results. Fig. 2 illustrating this configuration and the acceleration calculation.

MEASURING BUBBLE EXPANSION

We choose two groups of YSO-MC complexes located at the opposite of the Local Bubble to measure the expansion velocity, each group has an expansion-induced peculiar velocity of around 5.5 km s$^{-1}$, they are separated by 0.3 kpc. This is illustrated in Fig. 3.
Figure 2. The configuration used in our simulation forecast. In the dynamical LSR frame, a moving body experiences a residual acceleration should be computed as \( \vec{a}(\vec{r})_{\text{dynamical-LSR}} = \vec{a}(\vec{r}) - \vec{a}(0,0) \), where \((0,0)\) is the origin.

\[
\theta_t = \frac{v_{\text{circ}} t}{R_0}
\]
Figure 3. Measuring bubble-induced peculiar velocities around the Local Bubble. Background images is a dust map in the Galactic $l$-$b$ produced by Lallement et al. (2019), and the velocities are denoted using arrows. We also added Planck 870 μm images of two the clouds which are used to measure the expansion velocity. In these plots, the locations of the member YSOs are indicated using red dots.