Discovery of a Young Stellar Snake with Two Dissolving Cores in the Solar Neighborhood

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Received 2020 May 23; revised 2020 August 18; accepted 2020 September 30; published 2020 December 4

Abstract

We report the discovery of a young (only 30–40 Myr) snake-like structure (dubbed a stellar snake) in the solar neighborhood from Gaia DR2. The average distance of this structure is about 310 pc from us. Both the length and width are over 200 pc, but the thickness is only about 80 pc. The snake has one tail and two dissolving cores, which can be clearly distinguished in the 6D phase space. The whole structure includes thousands of members with a total mass of larger than 2000 $M_\odot$ in a uniform population. The population is so young that it cannot be well explained with the classical theory of tidal tails. We therefore suspect that the snake is hierarchically primordial, rather than the result of dynamically tidal stripping, even if the snake is probably expanding. The coherent 5D phase information and the ages suggest that the snake was probably born in the same environment as the filamentary structure of Beccari et al. If so, the snake could extend the sky region of the Vela OB2 association by a factor of ~2 and supplement the census of its coeval structures. This finding is useful to understanding the history of the formation and evolution of the Vela OB2 complex. The age of the snake well matches with that of the Gould Belt. In the sky region of our interest, we detect one new open cluster, which is named Tian 1 in this work.

Unified Astronomy Thesaurus concepts: Stellar kinematics (1608); Stellar associations (1582); Stellar dynamics (1596); Open star clusters (1160); Gould Belt (658); OB associations (1140); Young stellar objects (1834); Pre-main sequence stars (1290); Solar neighborhood (1509); Proper motions (1295); Tidal tails (1701); Filamentary nebulae (535)

Supporting material: machine-readable table

1. Introduction

It has long been recognized that O and B stars are not distributed randomly on the sky (Eddington 1910; Kapteyn 1914), but instead are concentrated in spatially loose, gravitationally unbound, and kinematically associated groups. Since Ambartsumian (1947) initially introduced the term association for the groups of OB stars, the historical name OB association has been widely used in the literature. Besides bright O and B members, these groups actually include a number of lower-mass stars and pre-main-sequence (PMS) stars over large areas, and follow a continuous mass function (Briceno et al. 2007b). As ideal test-benches, the nearby OB associations have been well studied for many years to understand the fundamental questions, e.g., how young stellar populations form in molecular clouds (MCs), and how they leave their natal gas and disperse into the Galactic field (Blauw 1964; de Zeeuw et al. 1999; Briceno et al. 2007a; Armstrong et al. 2018; Cantat-Gaudin et al. 2019b).

There are at least two typical mechanisms to explain the origin of OB associations in the literature. One is that associations are the unbound remnants of previously bound clusters (Tutukov 1978). In this monolithic model of star formation, it is generally understood that the vast majority of stars form in embedded clusters (Lada & Lada 2003), observed low density associations must have been formed as single dense stellar clusters that subsequently underwent a period of expansion to form the large scale and unbound structures caused by physical processes such as feedback from photoionizing radiation and stellar winds. This model has often been used to explain the low proportion of gas-free and gravitationally bound clusters after a few megayears (Hills 1980; Kroupa et al. 2001; Goodwin & Bastian 2006).

Alternatively, in a hierarchical model of star formation (e.g., Elmegreen 2002; Bonnell et al. 2011), stars form over substructured regions with various densities in MCs. Gravitationally bound stellar clusters arise naturally at high local density regions, while unbound and hierarchically structured associations form in situ at low density regions (Kruijssen 2012). This model can naturally explain the wide range of observed stellar densities.

There has long been debate about whether the system forms in the monolithic or hierarchical models (Muench et al. 2008). Bressert et al. (2010) investigated the spatial distribution of the young stellar objects (YSOs) in the solar neighborhood and found that the nearby YSOs follow a smooth surface density distribution without features of multiple discrete modes. This is likely a result of star formation occurring over a continuous density distribution. However, this has been argued by studies showing that expanding clusters can reproduce a similar result (Gieles et al. 2012; Pfalzner et al. 2012). Significantly, some recent works have begun to challenge the first model. Ward & Kroupa (2017) quantified the kinematics of 18 nearby OB associations in Gaia TGAS and conclusively ruled out the monolithic cluster formation scenarios. Wright & Mamajek (2018) analyzed the kinematics of the Scorpius–Centaurus OB association from Gaia DR1 (Gaia Collaboration et al. 2016) and did not find the coherent evidence for the classical theory that OB associations are the expanded remnants of dense and compact star clusters. More recently, nevertheless, Kuhn et al. (2019) investigated the kinematics of 28 young star clusters and associations in Gaia DR2 and revealed that at least 75% of these systems are expanding with a median velocity of ~0.5 km s$^{-1}$. This suggests that some young clusters still exhibit the potential to expand into large scale associations.
The Vela OB2 is one of closest associations spanning a wide sky region near the border between the Vela and Puppis constellations. Since it was first reported by Kapteyn (1914), Vela OB2 has been known for decades as a sparse group of a dozen early-type stars (Blauw 1964; Brandt et al. 1971; Straka 1973), de Zeeuw et al. (1999) pioneered investigating its kinematical features based on the astrometry of Hipparcos, and noted that the space motion of the association is not clearly separate from the surrounding stars and the nearby open clusters NGC 2547 and Trumpler 10. Pozzo et al. (2000) reported a population of low-mass and PMS stellar association (often referred to as γ Vel cluster) nearby its brightest binary member γ Vel in a distance of 350–400 pc from us. Jeffries et al. (2009) claimed that the γ Vel cluster is a subcluster within the larger Vela OB2 association, and speculated that γ Vel (age 3–4 Myr) formed after the bulk of the low-mass stars (age ∼10 Myr), expelling gas, terminating star formation and unbinding the association. Making use of data from the Gaia-ESO Survey (Randich et al. 2013), Jeffries et al. (2014) detected two kinematic subgroups from the γ Vel cluster, and suggested that one group (Population A) might be related to γ Vel. Subsequently, Sacco et al. (2015) identified that the radial velocities in another group (Population B) are consistent with that of the nearby cluster NGC 2547 (age ∼35 ± 3 Myr from Jeffries & Oliveira 2005; distance 361 ± 11 pc from Jeffries et al. 2009). The bimodal feature is confirmed by Damiani et al. (2017) with TGAS data in the 2D proper motion space. Franciosini et al. (2018) used the Gaia DR2 data to resolve the 6D structure of the γ Vel cluster, and find that both of the nearby coeval populations differ not only kinematically, but are also located at different distances along the line of sight. Furthermore, Beccari et al. (2018) noted that the region might host not two but six kinematic groups, four of which are coeval with the γ Vel cluster, while the remaining two probably formed together with NGC 2547. Most recently, Cantat-Gaudin et al. (2019a, 2019b) identified at least seven groups from the Vela OB2 complex in the 6D phase space with the Gaia DR2 data, and confirmed that their overall structure is expanding, which suggests a common history for Vela OB2 and the IRAS Vela Shell (IVS, Sahu 1992). The current kinematics of the stars cannot be explained by internal processes alone, e.g., gas expulsion.

In this work we report a young and wide (over 200 pc) structure with two dissolving cores in the solar neighborhood from the data of Gaia DR2. The structure is so young (only 30 ~ 40 Myr) that it cannot be well explained with the classical theory of tidal tails. It may primordially form from a huge MC. Conservatively, we name it a stellar “snake” by its morphology in the sky plane. This morphology looks like the string-like populations reported by Kounkel & Covey (2019) and Kounkel et al. (2020), who identified thousands of such structures, also like the features of coronae, discovered by Meingast et al. (2020) around 10 nearby star clusters. Interestingly, the snake probably is a good extension to the census of coeval structures in the Vela OB2 complex, since its age is well consistent with the 260 pc wide filamental population uncovered by Beccari et al. (2020, hereafter B20), which bridges the NGC 2547 and the newly detected cluster BB1.1.

The main goal of this study is to depict the detailed features for the “snake” structure with the data of Gaia DR2, and to look for some clues to its formation and evolution. To do so, we organize this paper as follows. In Section 2, the sample selection and membership are briefly described. The population properties are derived in Section 3. The discussion and conclusion parts are in Sections 4 and 5, respectively.

Throughout the paper, we adopt the solar motion as (U⊙, V⊙, W⊙) = (9.58, 10.52, 7.01) km s⁻¹ (Tian et al. 2015) with respect to the local standard of rest (LSR), and the solar Galactocentric radius and vertical positions as (R⊙, z⊙) = (8.27, 0.0) kpc (Schönrich 2012). L° is used to denote the Galactic longitude in the gnomonic projection coordinate system, for example, µL° ≡ µL cos b. The proper motion (µL°, µb) for each star is calibrated from the effect of the solar peculiar motion in the Galactic coordinate.

2. Data and Membership

In this study, we mainly use the astrometric and photometric data from Gaia DR2 (Gaia Collaboration et al. 2018) to search for members of the intended structure.

2.1. Data Selection

To build the sample, we select the sources that satisfy the following criteria:

1. 170° < l < 225°, and −30° < b < 10°, to make sure all the scattered members are included in this sky region.
2. 2.0 < σv < 5.0 mas, and σv/σω > 10.0, to restrict the sample to sources with distances between 200 and 500 pc. Here, we derive distances by inverting parallax with d = 1000.0/σv pc.
3. (µL° − µL°,m)² + (µb − µb,m)² < (5σµ,m)², to restrict to stars with proper motions within 5σµ,m of (µL°,m, µb,m). Here, µL°,m, µb,m, and σµ,m are the average and rms of proper motions of the members in the stellar snake. We noticed the structure in the space of (µL°, µb) initially as an overdensity centered on (µL°, µb) ≈ (−2.5, −2.0) mas yr⁻¹ with a dispersion σµ,m ≈ 1.0 mas yr⁻¹.
4. RUWE < 1.4, to limit to sources with acceptable astrometric solutions. RUWE is the renormalized unit weight error which is defined in Lindegren et al. (2018).

These selection criteria yield a sample of 21,949 stars in total. The interstellar extinction has been corrected for each source in the sample. According to the literature (Milne & Aller 1980; Wang et al. 2017), the interstellar extinction in the V band is around 0.7–1.0 mag kpc⁻¹ in the solar neighborhood. For simplicity, an average value (i.e., 0.85 mag kpc⁻¹) is adopted in this study (Liu et al. 2020). So for each individual star at distance d, its V-band extinction AV in magnitude is approximately 0.85 × d. The extinctions in Gaia’s bands for each star can be calculated from AV (Tian et al. 2014). Wang & Chen (2019) provide the extinction coefficients (AV/Av) for Gaia’s three bands, which are 1.002, 0.589, and 0.789 μm for the GP, Gbp, and G bands, respectively.

Figure 1 displays the sample distributions in the 5-dimensional (5D) phase space. For example, the l-b projected space (panel (a)) shows that there are several star-forming regions (black dashed rectangles) in this field, such as the Orion complex (Zari et al. 2019; Chen et al. 2020), which is grouped into several clustering components, e.g., λ Ori, 25 Ori, Belt, Orion A, BB1 1, and so on.

2.2. Membership

Considering that members of the structure are loosely concentrated in the 3D space, we adopt the friend-of-friend
(FOF) algorithm to search for members. This algorithm has been well implemented in ROCKSTAR (Behroozi et al. 2013), which employs a technique of adaptive hierarchical refinement in the 6D phase space to divide all stars into several FOF groups by tracking the high number density clusters and excluding those stars that could not be grouped in star aggregates.

The majority of sources in our sample have only 5D phase information, i.e., l, b, μ_l, μ_b, and distances, obtained from Gaia DR2. Line-of-sight velocities (v_{los}) are provided only for stars brighter than 13 mag in the G band. However, the inputs of ROCKSTAR were originally designed to be 6D phase-space data sets. We test using a version of ROCKSTAR that was smartly optimized by Tian (2017), and find that ROCKSTAR works well for group searching if we set v_{los} to zero, and keep only the other 5D data for all sample stars. In the process, ROCKSTAR will automatically adjust the linking space between members of friend stars, and divide them into several groups, simultaneously singling out those isolated individual stars. In this step, we get 2175 candidate members of the stellar snake from the input sample. This process is valid as we can recover the members of all the known clusters in this region simultaneously, i.e., λ Ori, 25 Ori, Belt, Orion A, and NGC 1662 from the FOF groups. This indicates that ROCKSTAR works very well for group searching.

Since the members are pretty sparse in space, and the proper motions are not uniform along the long tail, particularly close to the end of the tail, it is a challenge to obtain candidate members with a high fidelity for any clustering algorithm. Some very young candidates obviously deviate from PMS or main sequence (MS) in the color-absolute magnitude diagram (CAMD). To eliminate this contamination, we remove candidates whose ages are beyond 120 Myr or younger than 5 Myr (see the green dashed and dashed-dotted curves in the left panel of Figure 3). In this step, 186 stars are rejected. Finally, we obtain 1989 candidate members in the tidal tail.

Figure 1 displays the member (the red dots) distributions in the 5D phase space. A structure looking like a snake is clearly demonstrated in the ordinary space (i.e., α-δ, x-y-z).

3. Population Property

We have 1989 candidate members, which can be used to analyze the statistical properties for the stellar snake. Besides the astrometric and photometric data from Gaia DR2, we cross-match the sample with the spectroscopic data from LAMOST (Cui et al. 2012; Zhao et al. 2012) and APOGEE (Abolfathi et al. 2018) to supplement the measured stellar parameters of members. Within a radius of 3″, 78 and 15 candidate members are matched with LAMOST DR6 and APOGEE-2, respectively.
are the coordinates of the center of the core, and the average distances and radial velocities written on each of the panels. The Astrophysical Journal, (2019). We postpone its discussion to the stellar snake. We postpone its discussion to the
around 310.4 and 39.6 pc, respectively. The rms value is larger in panels (a)–(e). The average proper motion ($\mu_b^*, \mu_l$) is about ($-2.50 \pm 0.68, -1.84 \pm 1.07$) mas yr$^{-1}$ (see panel (b)), and the values become smaller toward the end of its tail. Meanwhile, the proper motion gradually vanishes in the b direction, as shown by the black arrows in panel (a). This should be due to the variation of the distances from us in the different parts of the snake.

Among the candidates, only 243 stars have radial velocities, of which 176 stars are from Gaia, 78 stars are from LAMOST (23 stars also have Gaia’s radial velocities), and 15 are from APOGEE (3 stars also have Gaia’s radial velocities). Figure 2 presents the histogram of the radial velocities of 243 unique stars in the left panel. The average and rms of the radial velocities are about 24.7 and 4.7 km s$^{-1}$. Figure 2 also shows the histogram of the distances of the 1989 candidate members in the left panel. The average and rms of the distances are around 310.4 and 39.6 pc, respectively. The rms value is larger than what one expects, as there exist two cores separated slightly in the stellar snake. We postpone its discussion to the next subsection.

The most prominent feature is that both the radial velocities and distances present two explicit peaks in their histograms (see the top two panels of Figure 2). This is the result of two cores (or clusters) in the structure of stellar snake. In order to explicitly display the two cores, we select two subsamples according to their coordinates, e.g., ($l - l_0^2 + (b - b_0)^2 < r_0^2$, where $l_0$, $b_0$, and $r_0$ are the coordinates of the center of the core, and the angular radius of the cluster. We roughly estimate ($l_0$, $b_0$, $r_0$) = (218°57’, –2°0, 2°0) for the first core, and ($l_0$, $b_0$, $r_0$) = (214°55’, –7°6, 1°5) for the second core (this core actually is the known open cluster NGC 2232). Thus, we obtain 323 and 261 stars from the sample of candidate members. They are separately color-coded with green and yellow in Figures 1 and 2.

As one can see, the two cores are clearly separated in the 6D phase space.

The average proper motions ($\mu_b^*, \mu_l$) are about ($-2.75 \pm 0.27, -2.91 \pm 0.40$) mas yr$^{-1}$, and ($-2.62 \pm 0.33, -1.76 \pm 0.37$) mas yr$^{-1}$ for the two cores, respectively (see the green and yellow dots in Figure 1(b)). The difference of the proper motions is larger than 1.0 mas yr$^{-1}$ between the two cores in the direction of Galactic latitude. The average distances are 288.95 ± 16.70 pc and 324.17 ± 18.32 pc for the two cores, respectively (the green and yellow histograms in the top left panel of Figure 2). The difference is about 35 pc. While the available radial velocities have only 19 stars for both cores, the $v_r$ of the two clusters can still be separated in their histograms (see the top right panel of Figure 2). The average values of $v_r$ are 22.3 ± 3.23 km s$^{-1}$ and 26.0 ± 3.5 km s$^{-1}$. The difference is of a few km s$^{-1}$.

3.3. Age and Mass

Isochrone fitting is a typical method to estimate stellar ages. Liu & Pang (2019) provides a reliable implementation for this method. First, we prepare a series of isochrones from the Padova database (Marigo et al. 2017) with ages ranging from log($\tau$/yr) = 6.6 to 10.13 with an interval of $\Delta$ log($\tau$/yr) = 0.01, and metallicities from log($Z/Z_\odot$) = –2.0 to 0.5 with an interval of 0.25. Then, we feed the color index ($G_{BP}-G_{RP}$), and the absolute magnitude $M_G$ of the member stars to the pipeline. Finally, the best-fit isochrone can be found by minimizing the distance (defined as Equation 2 in Liu & Pang 2019) between an isochrone and member stars.

The left panel of Figure 3 displays the member candidates (red dots) and the initial sample (blue dots) distribution and its best-fit isochrone (black solid curve) in the CAMD. The result shows that the age of the stellar snake is around 33.8 Myr, and the corresponding metallicity is around 0.027. But if we remove the member candidates with large color indexes, e.g., $G_{BP} - G_{RP} > 3.0$, then the best-fit age is 24.5 Myr, and the corresponding metallicity is about 0.0152. The isochrone in

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**Figure 2.** Histograms of the distances and radial velocities of all the candidates (red), the two dissolving cores (green and yellow), the open cluster BBJ 1 (cyan), and Tian 1 (black). The average distances are 310.4 ± 39.6 pc, 288.95 ± 16.70 pc, 324.17 ± 18.32 pc, 371.9 ± 3.4 pc, and 466.7 ± 16.7 pc for all the candidates, the two cores, and the open clusters BBJ 1 and Tian 1. The corresponding radial velocities are 24.8 ± 1.8 km s$^{-1}$, 22.3 ± 3.23 km s$^{-1}$, 26.0 ± 3.5 km s$^{-1}$, 15.1 ± 5.9 km s$^{-1}$, and 24.8 ± 3.7 km s$^{-1}$, respectively. The yellow dashed vertical lines mark the average distances and radial velocities written on each of the panels.
| Gaia ID        | \( \ell^a \) | \( b \) | \( \mu_\ell^b \) (mas yr\(^{-1}\)) | \( \mu_b \) | Distance pc | \( v_r \) (km s\(^{-1}\)) | \([\text{Fe}/\text{H}]\) | \( \log g \) |  \( G \) | BP–RP (mag) |
|---------------|--------------|-------|------------------|--------|-------------|------------------|----------------|--------|------|-----------|
| 310420675558178816 | 214.81       | −7.79 | −2.70 ± 0.04    | −1.69 ± 0.04 | 327.61 ± 2.44 | 25.77 ± 0.04 | 0.04 ± 0.01 | 5.83   | 1.21 |
| 3118540642272975872 | 210.39       | −7.80 | −2.59 ± 0.05    | −1.35 ± 0.05 | 304.22 ± 2.84 | 25.62 ± 0.04 | 0.08 ± 0.01 | 6.88   | 1.63 |
| 3118203882476896768 | 211.32       | −7.59 | −2.41 ± 0.06    | −1.44 ± 0.05 | 306.67 ± 2.93 | 25.18 ± 0.03 | −0.01 ± 0.01 | 6.36   | 1.39 |
| 3121980223881083264 | 208.91       | −7.66 | −2.51 ± 0.06    | −1.22 ± 0.06 | 293.89 ± 4.02 | 24.68 ± 0.04 | 0.14 ± 0.01 | 7.23   | 1.79 |
| 3409223204229856640 | 180.58       | −11.75 | −0.89 ± 0.07    | 0.02 ± 0.04  | 334.11 ± 4.12 | 21.78 ± 0.02 | 0.13 ± 0.01 | 6.59   | 1.52 |
| 3418236450799000320 | 180.36       | −11.50 | −1.73 ± 0.09    | −0.04 ± 0.06 | 288.61 ± 3.71 | 20.78 ± 0.03 | 0.06 ± 0.01 | 7.14   | 1.71 |
| 3394387382983956864 | 186.61       | −12.21 | −0.56 ± 0.09    | −0.02 ± 0.07 | 370.87 ± 5.79 | 24.80 ± 0.03 | 0.05 ± 0.01 | 6.45   | 1.43 |
| 3389597883746236800 | 191.07       | −11.14 | −2.37 ± 0.06    | −0.36 ± 0.05 | 267.96 ± 2.61 | 22.71 ± 0.02 | 0.08 ± 0.01 | 7.16   | 1.74 |
| 3394543177810189312 | 186.18       | −11.35 | −0.43 ± 0.07    | −0.15 ± 0.05 | 385.07 ± 5.31 | 25.57 ± 0.04 | 0.03 ± 0.01 | 6.20   | 1.41 |
| 3336872762142253824 | 196.00       | −8.16  | −2.69 ± 0.05    | −1.18 ± 0.04 | 248.25 ± 1.89 | 24.87 ± 2.48 | −0.02 ± 0.08 | 4.50   | 1.42 |

Notes.

\(^a\) The online coordinate for each star will be given in the precision of double float. Table 1 is published in its entirety in the machine-readable format.

\(^b\) The effect of the peculiar motion of the Sun is removed from the proper motions.

(This table is available in its entirety in machine-readable form.)
Figure 3. Left: CAMD for the 1989 candidate members (the red dots), initial sample (the blue dots), and the open cluster Tian 1 (the black dots). The black dashed curve is the best-fitted isochrone from a subsample with $G_{BP} - G_{RP} < 3$. The green dashed and dashed-dotted curves are two isochrones to remove contaminations with ages $>120$ Myr or $<5$ Myr from the candidate members. Right: CAMD for 634 members (red dots), which is a subsample purified with more stringent criteria from the 1989 candidates. In order to present the TOn point, we compare the best-fit isochrone with a series of isochrones with different ages, e.g., 20 Myr (the black dashed-dotted curve), 50 Myr (the blue dashed curve), and 100 Myr (the green solid curve). The TOn point is clearly shown in the zoomed inset in the right panel. In both panels, the black solid curves represent the best-fit PARSEC isochrone, the corresponding age is 33.8 Myr, and metallicity (Z) is 0.027.

In order to resolve the TOn point, we further purge the candidate members with more stringent criteria: (1) $(\mu_V - \mu_{V,p}^\prime)^2 + (\mu_b - \mu_{b,p}^\prime)^2 < 0.7\sigma_{\mu_{b,p}^\prime}$; (2) keep only candidates with distances between 280 and 340 pc (see Figure 2); and (3) RUWE $< 1.2$. The first two conditions can strictly constrain the members to be in the two cores (see Figure 1(a)). In these two dense regions, the field contaminants are relatively few. The third condition makes sure the members have excellent astrometric solutions. Finally, we obtain a subsample of 634 candidate members with a very high confidence. Figure 3 demonstrates the CAMD of the subsample in the right panel. From the zoomed inset in the right panel, one can easily see the TOn point, which is located at $G_{BP} - G_{RP} \sim 1.0$ mag where the stellar mass is $\sim 3.0 M_\odot$. This indicates that the age of this young population is around 30–40 Myr. This result is consistent with the age derived with the method of isochrone fit.

In estimating the age, we have already determined the best-fit isochrone. With this isochrone, stellar masses are then estimated. More than 80% of members still do not pass the TOn point and enter the stage of MS, i.e., $G_{BP} - G_{RP} < 1.0$ mag. This suggests that more than 80% of members have masses smaller than 1.0 $M_\odot$. The remaining $\sim 20\%$ members have masses larger than the solar mass, the maximum mass is $\sim 3.0 M_\odot$. From the best-fit isochrone, it is easy to derive the present-day mass function of the tidal tail. By fitting the mass function with a series of initial mass functions (IMF) of Kroupa et al. (2001), a total mass of $\sim 2500 M_\odot$ is estimated for the stellar snake (the blue curve is the best-fitted mass function in the top panel of Figure 4). Using the color as a proxy of stellar mass, we try to check the theory of mass segregation (Binney & Tremaine 1987), which is usually followed by the classical tidal tails. As one might expect, we do not find any strong evidence for mass segregation within 125 pc from the cluster center. Beyond 170 pc, however, there is a weak tendency for massive stars to move toward the center of a system, while lower-mass stars can more easily evaporate from a cluster, as shown in the bottom panel of Figure 4. Note that the tendency of first rising then descending between 10 and 110 pc is similar to what was found in the tidal tails of the Hyades discovered by Meingast & Alves (2019), who thought that mass segregation remains unsuccessful, most likely because of the sensitivity limit for radial velocity measurements with Gaia. In this work, no strong evidence is found for mass segregation, probably because the snake actually is not a dynamically tidal tail, but a primordial morphology.

3.4. The Two Open Clusters

In the sky region of our interest, we notice two interesting open clusters (as shown in Figure 1): one is the open cluster BBJ 1 (the cyan dots) discovered by B20, the other is an unknown open cluster (the black dots), which has not been reported so far (Kharchenko et al. 2013; Cantat-Gaudin et al. 2018; Liu & Pang 2019; Sim et al. 2019; Cantat-Gaudin & Anders 2020), we temporarily name it as Tian 1 in this study. To compare the two clusters with the snake, we select the candidate members for the Tian 1 and BBJ 1 according to their coordinates, similar to what was done for the above two cores.
We roughly estimate \((l_0, b_0, \epsilon_0) = (213°, 8°7, 1°5)\) for the Tian 1, and \((l_0, b_0, \epsilon_0) = (224°, -13°8, 1°7)\) for the BBJ 1. Additionally, we remove the obvious outliers for both the clusters in the 2D proper motion space. Thus, we obtain 117 and 174 candidate members for the Tian 1 and BBJ 1, respectively. The bottom two panels in Figure 2 display the distance and radial velocity distributions of the Tian 1 (black) and BBJ 1 (cyan), respectively. The average distances (the radial velocities) are \(466.7 \pm 16.7\) pc \((15.1 \pm 5.9\) km s\(^{-1}\)) and \(371.9 \pm 3.7\) pc \((24.8 \pm 3.7\) km s\(^{-1}\)) for the two clusters, respectively. The distance of BBJ 1 we measured are consistent with the value \((\sim 374\) pc) obtained in B20. The distributions of the radial velocities do not look so good, because there are only 8 and 23 available radial velocities for the two clusters. Unfortunately, no available metallicity is obtained for the open cluster BBJ 1.

The age of BBJ 1 is about 35 Myr derived by B20. This age is consistent with the snake, which indicates that they probably originate from the same population. The age of the Tian 1 is about 120 Myr, which is simply estimated by the isochrone fitting (see the CMD for the Tian 1, shown by the black dots and black dashed curve in the left panel of Figure 3).

4. Discussion

In this section, we will simply analyze the possible mechanism of the snake formation and then briefly discuss its potential values for the future study.

With the population properties derived in Section 3, we know that the stellar snake has a long tail and two dissolving cores in the same population. To be the first choice, one easily considers that this is a structure of the tidal tail. According to theoretical and numerical studies, the so-called tidal tails are usually thought to form from star clusters. Due to the impacts of the Galactic gravitational tides, e.g., by passing molecular clouds, disk shocking, spiral arm passages, or other unknown events, star clusters will continuously lose members if members are no longer gravitationally bound. The tails consist of stars that escaped from the cluster, which lead and/or trail their parent cluster along the orbit (Chumak & Rastorguev 2006).

Under this prevailing theory of tidal tail formation and evolution, Kharchenko et al. (2009) carried out a set of high resolution \(N\)-body simulations to investigate how the shape parameters of open clusters vary with the time that the Galaxy’s external force acts on star clusters with different initial masses, Galactocentric distances, and rotation velocities. The results tell us that the mass loss is only around 10% of the initial masses whatever the initial conditions are (see their Figure 2). Their Figure 3 also clearly shows that at \(t = 50\) Myr the star cluster is just stretched into an ellipsoid. Though the predicted picture can well match the tidal tail of Hyades with an age of several hundred megayears discovered by Meingast & Alves (2019) and Röser et al. (2019), it cannot explain our stellar snake with an age of only 30–40 Myr (an order of magnitude younger than the ages of previously known tidal tails). Therefore, these kinds of structures are generally considered to form primordially from a huge MC in the hierarchical models (B20; Kounkel & Covey 2019; Kounkel et al. 2020).

We select four stars whose radial velocities are well measured (with errors \(<0.1\) km s\(^{-1}\)) by APOGEE from the two cores and the end part of the tail, respectively. The orbits of the four stars can be solved accurately under the potential model of Bovy (2015). Figure 5 displays the four orbits, which are obtained by integrating back 40 Myr (the solid curves) and 70 Myr (the dashed curves) for the four stars. As the figure shows, the four stars seem to stay closer 40 or 70 Myr ago. This indicates that the snake is probably expanding. But more radial velocities with high precision are needed for further validation.

The new discovery is important at least in two aspects. On the one hand, the snake structure may be a good extension to the sky coverage and census of the Vela OB2 complex. As is known, the Vela OB2 region hosts a complex constellation of subpopulations with ages in the range of 10–50 Myr. The age of the snake is consistent with that of the open cluster BBJ 1, which is one of most important parts of the 260 pc wide filamentary structure discovered by B20 in the Vela OB2 region. Additionally, the motion of the snake is coherent with the structure of B20 in the two directions, i.e., \(v_r\) and \(\mu_{\alpha*}\), but the values of \(\mu_{\delta*}\) are not. This perhaps is induced by some unknown perturbations. Moreover, the two structures are located in the coherent distances from us. The sky coverage of the snake spans at least the three constellations, i.e., Monoceros, Orion, and Taurus. If the snake really formed in the same environment (e.g., a giant molecular cloud) with the structure of B20, the region of the Vela OB2 complex will be extended by a factor of \(\sim 2\). However, we need more
observational information, e.g., the radial velocities and metallicities with high precision for more member stars of both the snake and BBJ 1, to further confirm the relationship of the two structures. We are preparing for the follow-up observations in the LAMOST Medium-Resolution Spectroscopic Survey (LAMOST-MRS; Liu et al. 2020).

On the other hand, a number of member stars of the snake are located in the Orion region, particularly in the λ Ori (see Figure 1). The Orion complex is thought to form part of the Gould Belt (Poppel 1997), which is a large (~1 kpc), young (30–40 Myr), and ring-like structure tilted ~20° to the Galactic plane discovered by Herschel in 1847. For a long time, this is not consistent with the age measured in the Orion complex. The oldest part of the Orion complex was believed to be no more than 13 Myr old until early 2019, when Kos et al. (2019) extended its oldest age to 21 Myr. However, there still exists a gap between the Gould Belt and the Orion complex in the history of star formation. Remarkably, the age of the stellar snake agrees well with the history of Gould Belt. However, it is worth mentioning that the existence of the Gould Belt has been challenged by a recent structure—the Radcliffe Wave, i.e., a Galactic-scale gas wave in the solar neighborhood, discovered by Alves et al. (2020). This finding is inconsistent with the notion that the clouds are part of a ring, disputing the Gould Belt model. So the stellar snake probably bridges the gap between star formation near the region of the Orion complex and the history of Gould Belt’s formation (if the Belt exists). The stellar snake is perhaps a fine structure on top of the Radcliffe Wave.

5. Conclusion

A young snake-like structure (dubbed stellar snake) in the solar neighborhood is found from the Gaia DR2. Using the FOF algorithm, we find 1989 candidate members from the stellar snake. Its average distance is about 310 pc from the Sun. The length (x-direction) and width (y-direction) are over 200 pc, but thickness (z-direction) is only about 80 pc. Interestingly, the stellar snake includes two dissolving cores in its head. The two cores can be clearly distinguished in the 6D phase space, which probably form primordially from a huge MC with two subgroups. Using the techniques of the isochrone fitting and TO, we measure the age of the stellar population. Surprisingly, the age of this population is so young (only 30–40 Myr) that its formation cannot be explained with the theory of tidal tails. This suggests that this filamentary structure may be hierarchically primordial, rather than the result of tidal stripping or dynamical processing, even though the snake is probably expanding. This also could be deduced by the fact that no strong evidence can be found for the theory of mass segregation (Binney & Tremaine 1987), which is usually followed by the classical tidal tails. By fitting the mass function with a series of IMF of Kroupa et al. (2001), we estimate a total mass of ~2500M☉, for the stellar snake.

The finding may be a good extension to the sky coverage and census of the Vela OB2 complex. According to the 5D phase information and the age, we suspect that the snake and the open cluster BBJ 1 were born in the same environment. If so, the snake could extend the region of the Vela OB2 to another three constellations, i.e., the Monoceros, Orion, and Taurus, and supplement more substructures for the census of the Vela OB2 complex. This finding is useful for understanding the history of the Vela OB2 formation and evolution, and provide some clues to connect the complex with the Galactic-scale structures, such as the Gould Belt and the Radcliffe Wave (Alves et al. 2020). The age of the snake matches that of the Gould Belt well. In the sky region of our interest, we detect one new open cluster, which is named Tian 1 in this work.

H.-J.T. thanks Min Fang, Jiaming Liu, Hao Tian, Lei Liu, Boquan Chen, Chao Liu, Di Li, Hongsheng Zhao, and Yougang Wang for helpful discussions, and thanks Hongshe Zhao for revising the whole manuscript; H.-J.T. also acknowledges the National Natural Science Foundation of China (NSFC) under grants 11873034. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. The Guo Shou Jing Telescope (the Large Sky Area Multi-Object Fiber Spectroscopic Telescope, LAMOST) is a National Major Scientific Project built by the Chinese Academy of Sciences. Funding for the project has been provided by the National Development and Reform Commission. LAMOST is operated and managed by National Astronomical Observatories, Chinese Academy of Sciences.

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