The Origin of a Distributed Stellar Population in the Star-forming Region W4

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Received 2020 May 6; revised 2020 June 24; accepted 2020 June 26; published 2020 August 19

Abstract

Stellar kinematics provides the key to understanding the formation process and dynamical evolution of stellar systems. Here, we present a kinematic study of the massive star-forming region (SFR) W4 in the Cassiopeia OB6 association using the Gaia Data Release 2 and high-resolution optical spectra. This SFR is composed of a core cluster (IC 1805) and a stellar population distributed over 20 pc, which is a typical structural feature found in many OB associations. According to a classical model, this structural feature can be understood in the context of the dynamical evolution of a star cluster. The core-extended structure exhibits internally different kinematic properties. Stars in the core have an almost isotropic motion, and they appear to reach virial equilibrium given their velocity dispersion $(0.9 \pm 0.3 \text{ km s}^{-1})$ comparable to that in a virial state $(\sim 0.8 \text{ km s}^{-1})$. On the other hand, the distributed population shows a clear pattern of radial expansion. From the $N$-body simulation for the dynamical evolution of a model cluster in subvirial state, we reproduce the observed structure and kinematics of stars. This model cluster experiences collapse for the first 2 Myr. Some members begin to radially escape from the cluster after the initial collapse, eventually forming a distributed population. The internal structure and kinematics of the model cluster appear similar to those of W4. Our results support the idea that the stellar population distributed over 20 pc in W4 originate from the dynamical evolution of IC 1805.

Unified Astronomy Thesaurus concepts: Star formation (1569); Stellar kinematics (1608); Stellar associations (1582); Stellar dynamics (1596); Open star clusters (1160)

Supporting material: machine-readable table

1. Introduction

OB associations are prominent stellar systems in galaxies (Regan & Wilson 1993; Bresolin et al. 1996; Pietrzyński et al. 2001; Garcia et al. 2009) because of the high-mass star population spread over a few tens of parsecs (Ambartsumian 1947). Massive stars in such systems are engines that generate giant H II bubbles and play a decisive role in the chemical evolution of host galaxies. In addition, the majority of stars form in associations or clusters within them (Lada & Lada 2003), and thereby field stars in the Galactic disk are considered to originate from the dissolution of these stellar systems (Miller & Scalo 1978; Briceño et al. 2007). Despite their significant contribution to stellar populations in host galaxies, our understanding of their formation and evolution is still incomplete.

These large stellar systems are, in general, composed of a single or multiple star clusters in the central region and a distributed stellar population (hereafter DSP) at a large spatial scale (Blauw 1964; Koenig et al. 2012). These structural features may contain a clue to the formation process of these stellar systems. A classical model suggests that embedded clusters could undergo expansion after rapid gas expulsion (Lada et al. 1984; Kroupa et al. 2001). This dynamical process results in scattering of cluster members, and eventually leads to the formation of unbound OB associations. In addition, the structure of young star clusters can be highly affected by stellar feedback as it impacts the timescale of gas expulsion and the dynamics of star clusters just before gas evacuation events (Gavagnin et al. 2017).

Some star clusters in several OB associations exhibit a sign of mass segregation (Hillenbrand & Hartmann 1998; Chen et al. 2007; Sung et al. 2013). Dynamical mass segregation occurs on a timescale comparable to the relaxation time of given stellar systems, and it takes longer than 10 crossing times for clusters with about 1000 members (Bonnell & Davies 1998). However, clusters in OB associations are mostly younger than their relaxation times (Massey et al. 1995; Hillenbrand & Hartmann 1998; Sung et al. 2000; Park & Sung 2002). The stellar velocity dispersions measured in the Orion Nebula Cluster, NGC 2244, and NGC 6530 are weakly correlated with stellar masses (Jones & Walker 1988; Chen et al. 2007). Hence, it has been claimed that the observed internal structures could have been formed by star formation in situ (Bonnell et al. 1998), rather than dynamical evolution via equipartition.

On the other hand, there have been some attempts to understand the origin of mass segregation in terms of early dynamical evolution (McMillan et al. 2007; Allison et al. 2009, 2010). These theoretical studies considered the situation where several subgroups of stars in subvirial state form along the substructures in molecular clouds. Merging of these subgroups results in mass-segregated star clusters on a short timescale. Hence, it is still necessary to investigate the dynamics of stellar associations to understand their formation process.

In this study, we report the signature of early dynamical evolution in the massive star-forming region (SFR) W4 within the Cassiopeia OB6 association. W4 hosts a large number of
massive OB stars and low-mass young stellar objects (Wolff et al. 2010; Sung et al. 2017; Roman-Lopes et al. 2019). This young stellar population forms a single central cluster (IC 1805) and a large structure that extends over 20 pc (Sung et al. 2017). This simple structural feature, compared to the other associations, provides us with a better chance to isolate the history of the dynamical evolution in massive SFR. The observation and data that we used are described in Section 2. The selection of the kinematic members are addressed in Section 3. We probe the motions of stars using the Gaia proper motions (PMs; Gaia Collaboration et al. 2018) and radial velocities (RVs) in Section 4. The dynamical state of this SFR is also investigated from velocity dispersions. From comparison with the results of an N-body simulation, a plausible explanation for the formation process of W4 is suggested in Section 5. Finally, we summarize our results in Section 6.

2. Data

Member candidates were obtained from the photometric catalog of Sung et al. (2017). We selected stars with either “E” or “e” flag in this catalog as early-type (O- or B-type) star candidates. On the other hand, stars satisfying at least one of the following criteria:

1. Hα emission stars or candidates,
2. X-ray emission stars or candidates,
3. young stellar objects showing a flat spectrum,
4. Class II young stellar objects,
5. young stellar objects with transition disks or pre-transition disks, and
6. Class III young stellar objects in PMS locus (see Figure 22 of Sung et al. 2017)

are considered as pre-main-sequence (PMS) star candidates. The RVs of these PMS star candidates have not yet been measured. Since PMS stars down to \( \sim 1 M_\odot \) in W4 can be observed with large telescopes, we selected PMS star candidates brighter than 19 mag in the visual band (or \( G \lesssim 18 \) mag) for spectroscopic observation. The number of targets in our sample is 358 (115 early-type stars and 243 PMS star candidates) in total.

2.1. Radial Velocities

The optical spectra of low-mass stars contain a large number of metallic absorption lines. In addition, the rotational velocities of these low-mass young stars are smaller than those of high-mass stars. Therefore, we can more precisely measure their RVs from high-resolution spectra compared to high-mass stars. We observed 198 low-mass PMS star candidates on 2018 November 29 using the high-resolution (\( R \sim 34,000 \)) multi-object spectrograph Hectochelle (Szentgyorgyi et al. 2011) on the 6.5 m telescope of the MMT observatory. The spectra of these stars were taken with the RV31 filter in 2 \times 2 binning modes to achieve good signal-to-noise ratios. Dome flat and ThAr lamp spectra were also obtained just before and after the target observations. All mosaiced frames were merged into single frames after overscan correction using the IRAF/MSCCRED packages. We extracted one-dimensional (1D) spectra from the merged frames using the dofiber task in the IRAF/SPECCRED package. Dome flat spectra were used to correct for the pixel-to-pixel variation. The solutions for the wavelength calibration obtained from ThAr spectra were applied to the target spectra. We obtained a master sky spectrum with an improved signal-to-noise ratio by median combining the spectra from a few tens of fibers assigned to the blank sky for a given setup. Target spectra were subtracted by an associated master sky spectrum and then combined into a single spectrum for the same target. Finally, target spectra were normalized by using continuum levels.

Our optical spectra contain a number of metallic absorption lines between 5150 and 5300 Å. To measure the RVs of the PMS stars, we applied a cross-correlation technique to the observed spectra. Several synthetic spectra adopting the solar abundance were generated in the wide temperature range of 3800–9880 K using the MOOG code and Kurucz ODFNEW model atmosphere (Sneden 1973; Castelli & Kurucz 2004). These spectra were used as template spectra. We derived cross-correlation functions (CCF) of the observed spectra using the xcsao task in the RVSAO package (Kurtz & Mink 1998) and selected the synthetic spectra that have the strongest CCF peak values. RVs were measured from the derived CCF peaks. The errors on RVs were estimated from the relation expressed as \( 3w/8(1 + h/\sqrt{2}\sigma_c) \), where \( w \), \( h \), and \( \sigma_c \) represent the FWHMs of CCFs, their amplitudes, and the rms from antisymmetric components, respectively (Tonry & Davis 1979; Kurtz & Mink 1998). We measured the RVs of 172 out of 243 PMS star candidates in total. These RVs were converted to velocities in the local standard of rest frame using the IRAF/RVCOR task. The spectra of the other 26 stars have insufficient signals to derive CCFs.

2.2. Gaia Data

The parallaxes and PMs of the member candidates were obtained from the Gaia Data Release 2 (DR2; Gaia Collaboration et al. 2018). Their counterparts were searched for in this catalog with a searching radius of 170. All but one have counterparts in the Gaia DR2. Errors on parallax and PMs from the Gaia catalog (Gaia Collaboration et al. 2018) were adopted. These errors are correlated with the brightness of stars. The errors on parallax are about 0.03 mas on average for stars brighter than \( G \sim 13 \) mag and better than 0.20 mas for stars brighter than \( G \sim 18 \) mag. The mean values of PM errors along the R.A. and decl. are about 0.04 and 0.05 mas yr\(^{-1}\), respectively, and these errors increase up to 0.20–0.25 mas yr\(^{-1}\) for faint stars.

We did not use stars with negative parallaxes or close companions (duplication flag = 1), or without astrometric parameters in the analysis. The distances to individual stars were computed by the inversion of the parallaxes (Gaia Collaboration et al. 2018) after correction for a systematic zero-point of 0.03 mas from Lindegren et al. (2018).

3. Membership Validation

In Sung et al. (2017), the member candidates were selected using multicolor photometric diagrams and a list of X-ray sources (Rauw & Nazé 2016). However, their selection criteria are insufficient to isolate genuine members because a number of objects with similar properties to young stars can scatter along the line of sight. The most reliable members can be selected when combined with astrometric parameters.

Figure 1 displays the distributions of PMs, RVs, and distances for the member candidates. The most probable members form a dense group in the PM plane, while some
candidates are distributed over a wide range of PMs. Similarly, the RV distribution has a strong peak at $-45$ $\text{km s}^{-1}$ with an extended wing component. In the distance distribution, there are foreground stars closer than 1.3 kpc. Thus, the candidates in the extended components are nonmembers.

In order to select genuine members, stars that are either closer than 1.3 kpc or farther than 3.0 kpc were first excluded. We set a circular region around a median PM value to encompass probable members (see the left panel in Figure 1). In this region, stars with PMs within three times the standard deviations from the weighted mean values were selected as members, where the inverse of the squared PM error was used as the weight value. We obtained a new median PM value from the PMs of stars satisfying this criterion, and this procedure was repeated three times. A total of 127 members (55 early-type and 72 PMS stars) were selected. RVs were measured for about 62% of these PMS members (45/72). The RVs of the PMS members show a single Gaussian distribution (see the middle panel of Figure 1).

Their distance distribution also has a single Gaussian peak at 2.1 kpc with a width of 0.2 kpc (the right panel of Figure 1). We adopted this value as the distance to W4. Systematic errors of $\pm 0.2$ kpc may exist due to the reported zero-point offsets (Lindegren et al. 2018; Stassun & Torres 2018; Zinn et al. 2018); however, this distance is reasonably consistent with previous studies within errors (Johnson & Svolopoulos 1961; Humphreys 1978; Massey et al. 1995; Sung et al. 2017; Cantat-Gaudin et al. 2019). We present a list of the kinematic members and their data in Table 1.

Cantat-Gaudin et al. (2019) also selected the member candidates of IC 1805 using the Gaia DR2 (Gaia Collaboration et al. 2018) and published their catalog. The number of members with membership probabilities greater than 0.5 is 136 in total, of which 83 overlap with our members. However, some member candidates in their catalog are found below the PMS locus in the $(G, B_p - R_p)$ color-magnitude diagram. In addition, there are a few member candidates with far different PMs from the mean PM of IC 1805. We thus suggest to use member candidates with higher membership probabilities.

4. Dynamical State of W4

Figure 2 displays the spatial distribution of the selected members. While a number of stars are found in the central region, some stars form a large structure that extends out to about 40' (equivalent to 24 pc). This extended structure is not featured by inclusion of nonmembers. A half-number radius ($r_h$) of this SFR obtained from our sample is about 6' (3.7 pc), which is consistent with that (6.7') determined by Cantat-Gaudin et al. (2019). We define the structure within $r_h$ as the core and that outside this radius as the DSP.

We computed the tidal radius ($r_t$) of this SFR using Equation (3) of King (1962). The total masses of the cluster and the Galaxy were taken from previous studies (2700 $M_\odot$ from Sung et al. 2017 and $1.3 \times 10^{12} M_\odot$ from McMillan 2017, respectively). The tidal radius is estimated to be about 12 pc. The majority of the members exist within the tidal radius, which implies that the origin of the DSP is not the tidal disruption by the Galaxy.

The median PMs of the members are $-0.706 \text{mas yr}^{-1}$ and $-0.643 \text{mas yr}^{-1}$ along the R.A. and decl., respectively. These values are in good agreement with the mean PMs ($-0.702 \text{mas yr}^{-1}$, $-0.669 \text{mas yr}^{-1}$) obtained by Cantat-Gaudin et al. (2019). The PM vectors of the members relative to the median PMs show outward motions (Figure 2). This is the typical pattern of expansion as seen in other OB associations (Kuhn et al. 2019; Lim et al. 2019). To investigate these motions in detail, we computed the angle ($\Phi$) between the radial vector of a given star from the cluster center (median coordinates) and its relative PM vector as introduced in our previous paper (Lim et al. 2019). Note that a $\Phi$ value of 0° indicates radial expansion. Members in the core exhibit a uniform $\Phi$ distribution (see the lower panels of Figure 2), which indicates that the directions of their motions are almost isotropic. On the other hand, the members belonging to the DSP clearly show a radial expansion. Thus, the DSP seems to be a group of stars radially escaping from the core. These results are very similar to the kinematic properties of escaping stars from the Orion Nebula Cluster (Platais et al. 2020).

We investigate the dynamical state of this SFR using the velocity dispersions among the members. The 1D velocities along R.A. and decl. were calculated multiplying PMs by the distance of 2.1 kpc. The errors due to the differences of
## Table 1

| No. | Sq.  | R.A. (2000)         | Decl. (2000)       | π     | e(π) | μ(α) cos δ | μ(α) sin δ | μ(δ) | e(μ(α)) | e(μ(δ)) | G     | e(G) | R_P  | e(R_P) | R_V  | e(R_V) | RV   | e(RV) | Binarity flag |
|-----|------|---------------------|--------------------|-------|------|------------|------------|-------|---------|---------|-------|------|------|--------|------|--------|------|-------|----------------|
| 1   | 02:29:45.93 | +61:34:42.1 | 0.3577 | 0.0587 | −0.531 | 0.062 | −0.471 | 0.097 | 16.3977 | 0.0005 | 17.4011 | 0.0056 | 15.3683 | 0.0016 | −43.785 | 0.445 |
| 2   | 02:30:12.25 | +61:24:45.7 | 0.3473 | 0.0848 | −0.914 | 0.085 | −0.877 | 0.136 | 16.7894 | 0.0014 | 18.0058 | 0.0094 | 15.6706 | 0.0055 | −110.530 | 1.163 |
| 3   | 02:30:15.39 | +61:23:42.1 | 0.4242 | 0.0206 | −1.040 | 0.022 | −0.685 | 0.033 | 13.2875 | 0.0002 | 13.9044 | 0.0012 | 12.5116 | 0.0008 | ... | ... |
| 4   | 02:30:57.84 | +61:14:26.7 | 0.3402 | 0.1175 | −0.902 | 0.128 | −0.648 | 0.203 | 17.7242 | 0.0023 | 18.8353 | 0.0315 | 16.6204 | 0.0095 | −44.269 | 3.120 |
| 5   | 02:31:11.81 | +61:43:38.4 | 0.3308 | 0.0412 | −1.011 | 0.042 | −0.839 | 0.068 | 13.6276 | 0.0004 | 13.9894 | 0.0011 | 13.0748 | 0.0016 | ... | ... |
| 6   | 02:31:13.95 | +61:30:46.0 | 0.4859 | 0.1148 | −0.807 | 0.144 | −0.610 | 0.194 | 17.7973 | 0.0019 | 18.9303 | 0.0152 | 16.6720 | 0.0058 | ... | 0.000 |
| 7   | 02:31:37.48 | +61:28:13.9 | 0.4994 | 0.1216 | −0.913 | 0.138 | −0.476 | 0.211 | 17.9111 | 0.0017 | 19.0084 | 0.0182 | 16.7412 | 0.0077 | −28.168 | 4.415 |
| 8   | 02:31:47.85 | +61:27:32.5 | 0.4902 | 0.0279 | −0.897 | 0.031 | −0.560 | 0.050 | 15.0796 | 0.0003 | 15.6026 | 0.0019 | 14.3635 | 0.0011 | −10.097 | 1.564 |
| 9   | 02:31:48.48 | +61:34:56.0 | 0.4104 | 0.0176 | −0.869 | 0.020 | −0.427 | 0.031 | 13.6410 | 0.0006 | 14.1459 | 0.0026 | 12.9615 | 0.0024 | ... | ... |
| 10  | 02:31:49.79 | +61:32:41.4 | 0.4580 | 0.0167 | −0.865 | 0.020 | −0.523 | 0.032 | 13.2861 | 0.0002 | 13.6591 | 0.0014 | 12.7244 | 0.0008 | ... | ... |
| 11  | 02:31:50.22 | +61:35:59.9 | 0.4067 | 0.0369 | −0.816 | 0.039 | −0.595 | 0.066 | 15.6844 | 0.0007 | 16.6313 | 0.0036 | 14.6993 | 0.0025 | −72.868 | 0.714 |
| 12  | 02:31:50.73 | +61:33:32.3 | 0.4089 | 0.0388 | −0.683 | 0.045 | −0.313 | 0.067 | 15.9216 | 0.0006 | 16.8135 | 0.0051 | 14.9518 | 0.0032 | −38.942 | 7.406 |
| 13  | 02:31:55.15 | +61:31:22.9 | 0.3927 | 0.0756 | −0.915 | 0.095 | −0.458 | 0.130 | 17.0618 | 0.0014 | 18.1185 | 0.0100 | 15.9640 | 0.0044 | −46.485 | 6.412 |
| 14  | 02:32:02.43 | +61:37:13.2 | 0.4941 | 0.0297 | −0.827 | 0.034 | −0.491 | 0.052 | 15.2706 | 0.0003 | 15.9645 | 0.0016 | 14.4432 | 0.0011 | ... | 0.000 |
| 15  | 02:32:06.48 | +61:29:54.3 | 0.4419 | 0.0178 | −0.846 | 0.020 | −0.683 | 0.031 | 13.5996 | 0.0002 | 14.1713 | 0.0014 | 12.8521 | 0.0007 | ... | ... |
| 16  | 02:32:07.03 | +61:45:33.8 | 0.4831 | 0.0467 | −0.941 | 0.052 | −0.322 | 0.085 | 15.8931 | 0.0010 | 16.9697 | 0.0067 | 14.8460 | 0.0029 | ... | 0.000 |
| 17  | 02:32:07.91 | +61:24:51.4 | 0.4220 | 0.0352 | −0.736 | 0.042 | −0.962 | 0.062 | 15.4726 | 0.0040 | 16.3413 | 0.0149 | 14.4963 | 0.0075 | −57.268 | 1.667 |
| 18  | 02:32:09.63 | +61:38:23.5 | 0.4338 | 0.0277 | −0.914 | 0.033 | −0.415 | 0.047 | 11.3079 | 0.0042 | 11.5875 | 0.0086 | 10.8703 | 0.0129 | ... | ... |

**Note.** Column (1): sequential number. Columns (2) and (3): the equatorial coordinates of members. Columns (4) and (5): absolute parallax and its standard error. Columns (6) and (7): PM in the direction of R.A. and its standard error. Columns (8) and (9): PM in the direction of decl. and its standard error. Columns (10) and (11): G magnitude and its standard error. Columns (12) and (13): R_P magnitude and its standard error. Columns (14) and (15): R_V magnitude and its standard error. Columns (16) and (17): RV and its error. Column (18): binarity flag. SB2 represents a double-lined spectroscopic binary candidate. The parallax and PM were taken from the Gaia Data Release 2 (Gaia Collaboration et al. 2018).

(This table is available in its entirety in machine-readable form.)
from different samples; all members of W4 are distributed with spherical symmetry. The two white circles (dashed and solid lines) represent the mean values of the radial PM and radial vector from the cluster center to a given star. Each dashed line represents the relative PM and radial vector (from the cluster center to a given star) plotted with respect to the central distances. Each dashed line represents \( r_s \) and \( r_r \). The lower right panel displays the number distributions of stars with different \( \Phi \) values from different samples; all members (red filled circle) and members within \( r_s \) (blue open circle). These numbers were normalized by the total number of the kinematic members.

Figure 2. Relative motions of the members in W4. In the upper panel, the spatial distribution of members is overplotted on the zeroth moment map of the \(^{13}\)CO \( J = 1 \rightarrow 0 \) line from Heyer et al. (1998). The size of yellow dots is proportional to the brightness of individual stars, and green arrows denote relative PM vectors. The two white circles (dashed and solid lines) represent \( r_s \) and \( r_r \), respectively. In the lower left panel, the angles \( \Phi \) between the relative PM and radial vector (from the cluster center to a given star) are plotted with respect to the central distances. Each dashed line represents \( r_s \) and \( r_r \). The lower right panel displays the number distributions of stars with different \( \Phi \) values from different samples; all members (red filled circle) and members within \( r_s \) (blue open circle). These numbers were normalized by the total number of the kinematic members.

distances among individual members are expected to be less than 1% because the extent of internal structure along the line of sight is very small compared to the distance to W4 assuming spherical symmetry. For the spectroscopic sample, stars in the RV range of \(-75 \) to \(-15 \) km s\(^{-1}\) were used to minimize the contributions of close binary candidates with large amplitudes.

Figure 3 displays the distributions of 1D velocities along R.A., decl., and the line of sight (\( V_{\text{R.A.}}, V_{\text{decl.}}, \) and \( \text{RV} \)). All the distributions appear close to the Gaussian distribution. Velocity dispersions were measured from the best-fit Gaussian widths. However, since the DSP is considered to be a group of stars escaping from the central cluster, including these stars can overestimate the kinematic velocity dispersion of this SFR. A similar aspect was found in the central region of the Orion Nebula Cluster (Kim et al. 2019). We therefore used only the members in the core. Indeed, the velocity dispersions for all the members appear larger than those for stars in the core (see Figure 3 and Table 2).

The representative observational errors were estimated from the weighted mean of errors; where the weights were adopted from the probability functions presented in the lower panels of Figure 3. The intrinsic velocity dispersions of \( \sigma_{\text{int,R.A.}}, \sigma_{\text{int,decl.}}, \) and \( \sigma_{\text{int,RV}} \) were then calculated to be about 0.74, 1.24, and 0.79 km s\(^{-1}\), respectively, after quadratic subtraction of the typical errors from the measured velocity dispersions. Systematic errors of \( \pm 0.1 \) km s\(^{-1}\) due to the zero-point offsets in parallax can be considered for \( \sigma_{\text{int,R.A.}} \) and \( \sigma_{\text{int,decl.}} \). We adopted the mean value of these intrinsic velocity dispersions \( [0.9 \pm 0.3 \text{ (s.d.)}] \text{ km s}^{-1} \) as the 1D velocity dispersion of W4.

The 1D velocity dispersion in virial state is given by the following equation (Parker & Wright 2016):

\[
\sigma_{\text{vir}} = \sqrt{\frac{2G \text{M}_{\text{total}}}{\eta \rho R}},
\]

where \( G \), \( \text{M}_{\text{total}} \), \( R \), and \( \eta \) represent the gravitational constant, total mass, radius, and the structure parameter, respectively. This SFR contains little gas inside the H II bubble (Heyer et al. 1998; see Figure 2). Therefore, the total mass was assumed to be the total stellar mass of 2700\( M_{\odot} \) derived by Sung et al. (2017). The \( r_h \) of 3.7 pc was adopted in Equation (1). For \( \eta \), star clusters have a value between 1 to 11 depending on their surface densities (Portegies Zwart et al. 2010). W4 has a surface density profile with a core radius \( r_c \) of 0.7 pc (Sung et al. 2017). Since the concentration parameter \( \log \eta/r_c \sim -1.2 \) is smaller than 1.8, the \( \eta \) value of 9.75 was adopted (Portegies Zwart et al. 2010). The virial velocity dispersion of this SFR was then estimated to be about
0.8 km s$^{-1}$. The error on total stellar mass ($\pm 300 M_\odot$) from Sung et al. (2017) does not significantly affect the resultant velocity dispersion (less than $\pm 0.1$ km s$^{-1}$). The virial velocity dispersion is comparable to the measured one within the observational error. Therefore, our result indicates that the motions of stars in the core are close to virial equilibrium.

The adopted distance (2.1 kpc) is slightly smaller than that (2.4 kpc) derived by Sung et al. (2017). To test the effect of different distances on the total stellar mass, we simulated a simple stellar population with an age of 3.5 Myr using a Monte Carlo technique. A total of 4500 stars were generated, based on the initial mass function of Kroupa (2001). Its total stellar mass is about 2771 M$_\odot$. The bolometric magnitudes and effective temperatures of these stars were obtained by interpolating their masses to evolutionary models for main-sequence (Ekström et al. 2012) and PMS stars (Siess et al. 2000). We then dimmed their bolometric magnitudes by 0.3 mag. The masses of the artificial stars were rederived by interpolating the bolometric magnitudes and effective temperatures to the evolutionary tracks (Siess et al. 2000; Ekström et al. 2012). A total stellar mass was derived from the sum of these masses. As a result, the difference of 0.3 mag in distance modulus resulted in only about 5% error in total stellar mass.

### 5. The Origin of the Distributed Star Population

Using the NBODY6++GPU code (Wang et al. 2015), we conducted the $N$-body simulation of a model cluster to understand the observed structural and kinematic features in the context of dynamical evolution. The initial number of stars was set to 5000, and their masses were drawn from the Kroupa initial mass function in the range from 0.1 to 100 M$_\odot$ (Kroupa 2001). We adopted the density profile of King (1966) with the dimensionless concentration parameter $W_0 = 3$. The initial half-mass—radius and cutoff radius were set to be 2.3 pc and 8.6 pc, respectively. We considered the situation that the model cluster is initially in the extremely subvirial state; the initial virial ratio was set to 0.02, which is 25 times smaller than that of the virialized stellar system. However, the effects of the stellar evolution and gas expulsion affecting the potential of the cluster were ignored because there is no clear evidence for supernova explosions in this SFR.

We monitored the dynamical evolution of the model cluster by taking snapshots at given times. The model cluster undergoes collapse for the first 2 Myr and then begins to radially expand. The $\Phi$ and tangential velocities ($V_t$) of the simulated stars were computed for comparison with those of stars in W4, where $V_t$ was calculated from the quadratic sum of $V_{R.A.}$ and $V_{decl.}$ after subtracting the system velocity. Random errors on PM were introduced to the $V_t$ of these stars, based on the observational error distributions. In addition, the number ratio of low-mass stars in mass bins between 1 and 3 M$_\odot$ from the Kroupa initial mass function (Kroupa 2001) was adjusted to that of the observed stars (Sung et al. 2017) to reproduce the incompleteness of our observations.

Figure 4 compares the observed radial distributions of $\Phi$ and $V_t$ with the simulated results at 3.9 Myr after the initial collapse. Note that this timescale does not necessarily mean the stellar age (3.5 Myr—Sung et al. 2017). Our simulation well reproduces the global trend in the radial variation of $\Phi$: the isotropic motion in the inner regions ($r \leq 6'$) and the outward motion in the outer regions (upper panels of Figure 4). This result is also compatible with the simulation of early dynamical evolution of young star clusters that are dynamically cold and isolated from the external tidal field, and the discrepancy around $r \sim 20'$ between the simulation and observation is presumably due to the effect of the Galactic tide (see Figure 4 of Vesperini et al. 2014).

The $V_t$ of stars in the outer region (lower panels of Figure 4) appear to increase with their radial distances in both simulation and observation. This radial variation is the consequence of close three-body encounters with massive stars during the collapse (Banerjee et al. 2012; Perets & Šubr 2012; Oh & Kroup 2016; Gavagnin et al. 2017). Several young runaway stars that presumably originated from this dynamical process have been identified around the Orion Nebula (McBride & Kounkel 2019). The $V_t$ distribution of simulated stars in the outer region does not exactly match the observed one. The number of the escaping stars and their velocities can be

### Table 2: Velocity Dispersions

| Sample | $\sigma_{R.A.}$ (km s$^{-1}$) | $\sigma_{decl.}$ (km s$^{-1}$) | $\sigma_{R.A.}$ (km s$^{-1}$) | $\sigma_{decl.}$ (km s$^{-1}$) | $\sigma_{RV}$ (km s$^{-1}$) | $\sigma_{int,obs}$ (km s$^{-1}$) | $\sigma_{ext,obs}$ (km s$^{-1}$) | $\sigma_{int,RV}$ (km s$^{-1}$) | $\sigma_{ext,RV}$ (km s$^{-1}$) |
|--------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| All    | 1.88             | 0.50             | 1.81             | 2.21             | 0.74             | 2.08             | 2.78             | 2.64             | 0.87             |
| $r < r_h$ | 0.86             | 0.43             | 0.74             | 1.44             | 0.74             | 1.24             | 2.76             | 2.64             | 0.79             |

Note. Velocity dispersions were obtained for all members and members within $r_h$, respectively. Columns (2), (5), and (8) represent the measured velocity dispersions along R.A, decl., and RV, respectively. The errors corresponding to each measurement are shown in columns (3), (6), and (9). Columns (4), (7), and (10) denote intrinsic velocity dispersions.

![Figure 4](image-url)
increased or decreased depending on the strength of stellar feedback (Gavagnin et al. 2017) and the levels of substructures (Schoettler et al. 2019). In addition, the latter condition can lead to violent dynamical evolution on a very short timescale (McMillan et al. 2007; Allison et al. 2009, 2010).

In conclusion, a single star cluster (IC 1805) with or without substructures formed in the W4 molecular cloud, and then this cluster might have experienced a cold collapse in the early epoch. Subsequently, a group of stars escaping from the cluster during the expanding phase might form the current DSP. Hence, the formation of the structure that extends over 20 pc in W4 can be understood in the context of dynamical evolution.

On the other hand, several groups of young stars are found at the border of the H II bubble surrounding W4 (Panwar et al. 2019). The current positions of these stars cannot be explained because the crossing time is larger than their age. These groups are mostly composed of low-mass PMS stars (<4M_☉), and they are ≈2 Myr younger than the IC 1805 members (Panwar et al. 2019). Therefore, the origin of these young stars may be related to feedback-driven star formation, rather than dynamical evolution of IC 1805. Indeed, circumstantial evidence for feedback-driven star formation has been steadily reported in other SFRs (Fukuda et al. 2002; Sicilia-Aguilar et al. 2004; Koenig et al. 2008; Lim et al. 2014, etc.). In the case of the SFR W8, the fraction of the second generation of stars accounts for at least 18% of the total stellar population (Lim et al. 2018), which implies that their contribution is far from being negligible. Hence, combining two different origins (dynamical evolution and feedback-driven star formation) can help us better understand star formation taking place in OB associations.

6. Summary

OB associations are the birth places of the young stellar population in the Galactic disk, and they are ideal sites to understand star formation taking place at large spatial scales. W4 in the Cas OB6 association is one of the active massive SFRs in the Galaxy. This SFR is composed of the young open cluster IC 1805 and a DSP surrounding the cluster. This structural feature is probably the relic of the formation process of W4. In this work, we investigated the origin of this structure using stellar kinematics.

The PMs from the recent Gaia DR2 (Gaia Collaboration 2018) and RVs measured from high-resolution spectra were used to select bona fide members and to probe their velocity fields. A total of 127 out of 358 candidates were confirmed to be kinematic members of W4. Members in the core have an almost isotropic motion, and their dynamical state is close to equilibrium. On the other hand, members belonging to the DSP show a clear pattern of radial expansion.

We considered the early dynamical evolution of a star cluster in subviralial state and performed an N-body simulation. The properties of a model cluster were compared with the observed ones. Although we did not take into account the effects of stellar evolution and gas expulsion on the dynamics of the cluster, this simulation well reproduced the radial variation of projected stellar motions. Hence, our results suggest that the origin of the DSP distributed over 20 pc is the result of the dynamical evolution of IC 1805.

The authors thank the anonymous referee for many constructive comments and suggestions. B.L. would like to express thanks to Professor Gregor Rauw and Dr. Yaël Nazé for a helpful discussion, Professor Hwankyung Sung and Professor Mark Heyer for providing supplementary data, and Dr. Nelson Caldwell and ShiAnne Kattner for assisting with Hectochelle observations. Observations reported here were obtained at the MMT Observatory, a joint facility of the University of Arizona and the Smithsonian Institution. In addition, this paper has made use of data obtained under the K-GMT Science Program (PID: MMT-2018B-1) funded through Korean GMT Project operated by Korea Astronomy and Space Science Institute (KASI) and 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. This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (grant No. NRF-2019R1C1C1005224). N.H. acknowledges support from the Large Optical Telescope Project operated by KASI. B.-G.P. acknowledges support from the K-GMT Project operated by KASI.

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