The Cassiopeia Filament: A Blown Spur of the Local Arm

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Abstract

We present wide-field and high-sensitivity CO(1–0) molecular line observations toward the Cassiopeia region, using the 13.7 m millimeter telescope of the Purple Mountain Observatory. The CO observations reveal a large-scale highly filamentary molecular cloud within the Galactic region of 132°0 > l > 122°0 and −1°0 < b < 3°0 and the velocity range from approximately +1 to +4 km s⁻¹. The measured length of the large-scale filament, referred to as the Cassiopeia Filament, is ~390 pc. The observed properties of the Cassiopeia Filament, such as length, column density, and velocity gradient, are consistent with those synthetic large-scale filaments in the inter-arm regions. Based on its observed properties and location on the Galactic plane, we suggest that the Cassiopeia Filament is a spur of the Local arm, which is formed due to the galactic shear. The western end of the Cassiopeia Filament shows a giant arc-like molecular gas shell, which extends in the velocity range from roughly −1 to +7 km s⁻¹. Finger-like structures, with systematic velocity gradients, are detected in the shell. The CO kinematics suggest that the large shell is expanding at a velocity of ~6.5 km s⁻¹. Both the shell and finger-like structures outline a giant bubble with a radius of ~16 pc, which is likely produced by the stellar wind from the progenitor star of a supernova remnant. The observed spectral line widths suggest that the whole Cassiopeia Filament was quiescent initially until its west part was blown by the stellar wind and became supersonically turbulent.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Interstellar filaments (842); Giant molecular clouds (653); Stellar wind bubbles (1635)

1. Introduction

Multiwavelength surveys found that filaments are ubiquitous in molecular clouds (see, e.g., Schneider & Elmegreen 1979; Molinari et al. 2010; Li et al. 2016; Mattern et al. 2018; Yuan et al. 2021), which connect the collapse of the molecular clouds to the final fragmentation to form dense cores and thus play a key role in the process of star formation (see, e.g., Myers 2009; Andrè et al. 2014; Motte et al. 2018; Hacar et al. 2022). Furthermore, large-scale filaments, with lengths in the order of 100 pc (see, e.g., Jackson et al. 2010; Ragan et al. 2014; Wang et al. 2015; Zucker et al. 2015; Abreu-Vicente et al. 2016; Colombo et al. 2021), are regarded as the “feathers,” “spurs,” or “skeletons” of spiral arms, which are important for understanding the Galactic structure (see, e.g., Goodman et al. 2014; Smith et al. 2014; Smith et al. 2020; Zucker et al. 2019).

Bubbles and/or shells are also ubiquitous in the multiwavelength surveys toward the Galactic plane (see, e.g., Churchwell et al. 2006, 2007; Simpson et al. 2012). Most of these bubbles, with radii ranging from a few to tens of pc, are created by the feedback from massive stars, such as UV radiation (e.g., Churchwell 2002; Deharveng et al. 2010) and/or stellar winds (e.g., Weaver et al. 1977; Fryer et al. 2003; Arthur 2007). Even larger structures with radii ~100 pc, the so-called superbubbles or supershells, are suggested to be produced by OB associations and/or supernovae in the Milky Way (e.g., McClure-Griffiths et al. 2002; Suad et al. 2014; Wright 2020; Zucker et al. 2022).

As both filaments and bubbles are ubiquitous in the Milky Way, the interaction between these two structures can be expected then. Indeed, previous observations found a few cases. Depending on the formation sequence and environment, the interaction may be divided into three different types: (a) Filaments are affected by bubbles produced by externally pre-existing stars. For example, a large-scale filamentary wisp in the Galactic region of 52°S > l > 49°5 is disturbed by a giant bubble, which is likely driven by the expansion of a supernova (see Li et al. 2013). (b) Filaments interact with bubbles created by stars formed therein, such as the N131 bubble (Zhang et al. 2016) and the “Nessie” filament (Jackson et al. 2021). (c) Filaments are formed through converging flows caused by (super-)bubbles (e.g., Inutsuka et al. 2015), and then continuously affected by parent bubbles. The filament B211/B213 in Taurus could be a promising case for this kind of interaction (see Shimajiri et al. 2019).

Wide-field observations of molecular lines provide physical, chemical, and dynamic information about molecular gas, which is essential to study the interaction between large-scale filaments and bubbles. These kinds of observations can help us to better understand the formation mechanism and kinematics of filamentary molecular clouds, as well as the feedback from stars on the interstellar medium (ISM). The Milky Way Imaging Scroll Painting (MWISP) project is an unbiased and sensitive CO(1–0) multiline survey toward the northern Galactic plane, using the 13.7 m millimeter telescope of the Purple Mountain Observatory (PMO; Su et al. 2019; Sun et al. 2021), which provides high-quality data for studying the distribution and property of molecular gas in the Milky Way. As part of the...
MWISP survey, we present in this work wide-field CO(1–0) observations toward the Cassiopeia region. Based on the CO observations, we report the discovery of a large-scale spur-like molecular filament in the Local arm, which is likely interacting with a giant bubble in the region. In Section 2 we describe the observations and data reduction. Observational results are presented in Section 3 and discussed in Section 4. The main conclusions of this study are summarized in Section 5.

2. Observations and Data Reduction

The CO(1–0) observations toward the Cassiopeia region were performed from 2011 November to 2020 September with the PMO 13.7 m telescope at Delingha in China. The nine-beam Superconducting Spectroscopic Array Receiver (SSAR; see Shan et al. 2012) was used at the front end in the sideband separation mode in the observations. Three CO(1–0) lines were simultaneously observed, 12CO at the upper sideband (USB) and two other lines, 13CO and C18O, at the lower sideband (LSB). A Fast Fourier Transform (FFT) spectrometer with a total bandwidth of 1 GHz and 16,384 channels was used as the back end. The corresponding velocity resolutions were ∼0.16 km s$^{-1}$ for the 12CO line and ∼0.17 km s$^{-1}$ for both the 13CO and C18O lines. The observed region was divided into individual 30′ × 30′ cells in the observations. Each cell was mapped with the on-the-fly (OTF) mode. In order to reduce scanning effects, each cell was mapped at least twice, along the Galactic longitude and latitude, respectively. The half-power beamwidth (HPBW) was ∼52″ for the 12CO line and ∼55″ for the 13CO and C18O lines, while the pointing accuracy was ∼5″.

The standard chopper-wheel method was used to calibrate the antenna temperature ($T_A$). The temperature $T_{mb} = T_A / B_{eff}$ was used to convert the antenna temperature $T_A$ to the main-beam temperature ($T_{mb}$), where the main-beam efficiencies ($B_{mb}$) during the observations were ∼44% for the USB and ∼48% for the LSB, respectively. The calibration errors were estimated to be within 10%. During the observations, typical system temperatures were around 210 K for the USB and around 130 K for the LSB, and the variations among different beams were less than 15%.

After removing bad channels and abnormal spectra, and correcting the first-order (linear) baseline fitting, the data were regridded into standard FITS files with a pixel size of 30$''$ × 30$''$ (approximately half of the beam size). The average rms noises of all final spectra were about 0.5 K for 12CO (at a velocity resolution of ∼0.16 km s$^{-1}$) and about 0.3 K for 13CO and C18O (at a velocity resolution of ∼0.17 km s$^{-1}$). Velocities were all given with respect to the local standard of rest (LSR) in this work. Finally, we mosaicked the data cubes toward the Cassiopeia region to analyze the distribution and properties of molecular gas. All data were reduced using the GILDAS package$^4$.

3. Results

The MWISP CO data toward the Galactic Cassiopeia region were partially presented by Sun et al. (2021) 141°54′ $\geq l$ $\geq$ 104°75′ and $-3°528 \leq b \leq 5°007′$ and Yan et al. (2021) 150°25′ $\geq l$ $\geq$ 104°75′ and $-3°025 \leq b \leq 5°25′$, respectively. The work by Sun et al. (2021) provided global properties of the MWISP CO data and examined CO completeness through a comparison between three independent CO surveys, while Yan et al. (2021) measured distances toward 76 medium-sized molecular clouds in the second Galactic quadrant. In this work, we investigate the Galactic region of 135°0 $\geq l$ $\geq$ 120°0 and $-3°25 \leq b \leq 4°25′$ and the velocity range between $-5$ and $+10$ km s$^{-1}$, and present insights into the structure, physical properties, and kinematics of the molecular gas therein.

3.1. A Giant Molecular Filament Associated with a Shell

Figure 1 shows the velocity channel maps of the 12CO(1–0) emission toward the observed region. As seen in the channel maps, a large-scale, highly filamentary molecular cloud is detected in the velocity range between about +1 and +4 km s$^{-1}$. This filamentary cloud extends roughly 10 degrees along the longitude direction (from ∼122° to ∼132°), with an inclination angle of ∼20° to the Galactic plane. Figure 2 shows the velocity channel maps of the 13CO(1–0) emission, which traces dense molecular gas along the filamentary cloud.

Figure 3 shows the CO velocity-integrated intensity images. We adopt the Discrete Persistent Structures Extractor (DisPerSE) algorithm (Sousbie 2011), a method for identifying filamentary structures in the ISM, to outline filaments in the 12CO image. After testing several different combinations between the Persistence and Robustness threshold (see DisPerSE website$^5$ for more details), we set the value of 10 K km s$^{-1}$ ($\sim 17\sigma$) for persistence and 1 K km s$^{-1}$ ($\sim 2\sigma$) for robustness. This setting would not only guarantee a clear skeleton construction with high contrast with the surroundings but also retain the information of persistence in morphology as far as possible. The blue line in Figure 3 shows the main filament identified by the DisPerSE algorithm, which is consistent with the large-scale filament found by visual inspection in the 12CO channel maps. The aspect ratio of the main filament is measured to be ∼28 in the intensity image. Several subfilaments are also identified by DisPerSE, which are shown by the orange lines in Figure 3. These subfilaments are roughly perpendicular to the main filament, which together may be morphologically interpreted in terms of a hub-filament system (see, e.g., Myers 2009). Hereafter we refer to the large-scale main filament as the Cassiopeia Filament and focus on it in this work.

Interestingly, as seen in Figure 3, the western part of the Cassiopeia Filament presents a clear arc-like shell$^6$, which opens to the north and covers an extent with coordinates of 125°5 $\geq l$ $\geq$ 121°5 and $-1°3 \leq b \leq 0°5$. Figure 4 shows the enlarged 12CO velocity channel maps for this western shell. The shell appears at the velocity of about $-1$ km s$^{-1}$ and fades away at the velocity of $-7$ km s$^{-1}$, with its peak emission at the velocity of $-3$ km s$^{-1}$. Figure 5 shows the 18CO intensity image integrated over the velocity range from $-1$ to $+7$ km s$^{-1}$. Finger-like structures, all pointing toward the south, are clearly seen in this shell, and are named after numbers according to their positions from west to east (see Figure 5). The arc-like shell, as well as the finger-like structures on the shell, are also clearly detected in the 13CO images (see $^5$ http://www2.iap.fr/users/sousbie/web/html/index55a0.html?category=Quick-start

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$^4$ https://www.iram.fr/IRAMFR/GILDAS/

$^5$ We note that a bubble-like structure is seen in the east of the main filament (see Figures 1 and 3). After checking the CO spectra, we find that the molecular gas therein is quiescent (12CO line width less than 1 km s$^{-1}$). No expansion signature is seen in the CO position–velocity diagrams either. Therefore, we do not further discuss this structure in the work.
We also note that no C$^{18}\text{O}$(1–0) emission is detected from the main filament and its associated shell, except the tips of Finger 1 (∼7σ) and Finger 4 (∼5σ; see Figure 6).

3.2. The Length and Mass of the Cassiopeia Filament

The distance, which is a fundamental parameter for deriving physical properties, is unclear yet for the Cassiopeia Filament. We note that the LSR velocity ranges of spiral arms in the observed direction are about [−60, −30] km s$^{-1}$ for the Perseus arm and [−25, +10] km s$^{-1}$ for the Local arm, respectively (see Dame et al. 2001; Sun et al. 2021). The CO velocity range of the Cassiopeia Filament and its associated shell is roughly from −1 to +7 km s$^{-1}$, which is covered by the velocity range of the Local arm.

Based on the MWISP CO and Gaia DR2 data (Gaia Collaboration et al. 2018), we measure the distance toward the Cassiopeia Filament, using the same method as described in Yan et al. (2021). This method uses the principle that molecular clouds usually impose higher optical extinction than other phases of the ISM. Aided by Bayesian analyses, we derive distances by identifying the breakpoint in the stellar extinction toward the molecular cloud (on-cloud region) and using the extinction of Gaia stars around the molecular cloud (off-cloud regions) to confirm the breakpoint. The systematic error in the measurement is approximately 5%.

The Cassiopeia Filament extends roughly 10$^\circ$ along the longitude direction. Therefore, the distance along the filament may be changed largely, as suggested by the pattern of the Local arm in this direction (see, e.g., Reid et al. 2019; Xu et al. 2021). Indeed, the measured distance to the east filament end is roughly 188$^{\pm5}$ pc (see Figure 7(a), while the distance to the west shell is about 553$^{\pm8}$ pc (Figure 7(b)). Taking 10$^\circ$ as the viewing angle (on the Galactic plane) and 20$^\circ$ as the inclination angle (to the Galactic plane), the calculated length of the Cassiopeia Filament is roughly 390 pc.

Two methods have been used to derive the H$_2$ gas column density. In the first method, on the assumption of local thermodynamic equilibrium (LTE) and optically thick $^{12}\text{CO}$ line ($T_\text{exc} \gg 1$), we can derive the excitation temperature $T_\text{exc}$ from the peak radiation temperature of the $^{12}\text{CO}$ line by the following formula:

$$T_{\text{mb}} = [J(T_{\text{exc}}) - J(T_{\text{bg}})][1 - e^{(-\tau)}], \quad (1)$$

where $T_{\text{mb}}$ is the main-beam temperature, $T_{\text{bg}}$ is the background temperature with the value of 2.7 K; $J$ = $T_0/[e^{(h\nu/k_BT)} - 1]$,
here $T_0$ is the intrinsic temperature of $^{12}\text{CO}$ and $T_0 = h\nu/k_B T$, $k_B$ is the Boltzmann constant, $h$ is the Planck constant.

Assuming an equal $T_{\text{ex}}$ of the isotopic pair, the $^{13}\text{CO}$ column density $N^{13}$ can be estimated over the velocity ($V$) by

$$N^{13} = 2.42 \times 10^{14} \times \frac{(1 + 0.88/T_{\text{ex}}) \times \int T_{\text{mb}}^{13}\text{CO} \, dV}{1 - e^{-T_0(T_{\text{CO}})/T_{\text{ex}}}}.$$  

(2)

The $\text{H}_2$ column density could then be derived by multiplying the $^{13}\text{CO}$ column density by the ratio of $N_{\text{H}_2}/N^{13}\text{CO} \sim 7 \times 10^5$ (Frerking et al. 1982). In the second method, the $\text{H}_2$ column density can be estimated by integrating the main-beam temperature of $^{12}\text{CO}$ over the velocity, using a mean CO-to-$\text{H}_2$ conversion factor $X = 1.8 \times 10^{20} \text{ cm}^{-2} \text{K}^{-1} \text{km}^{-1} \text{s}$ (Dame et al. 2001):

$$N_{\text{H}_2} = X \int T_{\text{mb}} \, \nu^{1\text{CO}} \, dV.$$  

(3)

Figure 8 shows the distributions of excitation temperature and $\text{H}_2$ column densities derived from the above methods for the Cassiopeia Filament.

The gas mass can then be derived from the $\text{H}_2$ column density $N_{\text{H}_2}$ by

$$M = \mu m_\text{H} D^2 \int N_{\text{H}_2} d\Omega,$$

where $\mu$ is the mean molecular weight per hydrogen molecule which is assumed to be 2.8, $m_\text{H}$ is the mass of the atomic hydrogen, $D$ is the distance to the molecular cloud, and $d\Omega$ is the solid angle element. For the arc-like shell, we adopt the distance of 553 pc, and the derived mass is roughly $\sim 1200 M_\odot$ (LTE method) and $\sim 6100 M_\odot$ (X-factor method), respectively. For the rest filamentary cloud, a mean distance of 400 pc is adopted, and the estimated mass is roughly $\sim 860 M_\odot$ (LTE method) and $\sim 8300 M_\odot$ (X-factor method), respectively. The difference between the masses derived by the two methods is mainly caused by the small filling factors of the $^{13}\text{CO}$ emission, because there is much less $^{13}\text{CO}$ emission than $^{12}\text{CO}$ emission in the cloud (see Figures 3 and 8).

3.3. The Gas Kinematics of the Cassiopeia Filament

Figure 9 shows the $^{12}\text{CO}$ intensity-weighted velocity field (first moment image) of the observed region, where the
distribution of the mean velocities ($V_{LSR}$) of the molecular gas can be seen. As seen in Figure 9, the Cassiopeia Filament shows a velocity gradient increasing from the east to the west. This velocity gradient is also seen in the CO position-velocity (PV) diagram along the filament shown in Figure 10. The whole Cassiopeia Filament is velocity-coherent and the measured velocity gradient is roughly 0.4 km s$^{-1}$ deg$^{-1}$ or $\sim$0.013 km s$^{-1}$ pc$^{-1}$ (adopting a filament length of 390 pc).

Figure 9 also shows the velocity field for the shell. As seen in the image, the shell also shows clear systematic velocity gradients increasing from north to south. The gradients are much clearer in the finger-like structures, in particular, Fingers 1, 2, 4, and 7 (see Figure 9). The measured typical velocity gradient is roughly 1.0 $\pm$ 0.2 km s$^{-1}$ pc$^{-1}$ at the distance of 553 pc for the shell. The PV diagrams of these finger-like structures show curve-shaped morphologies at their tips. This feature is most obvious in Fingers 2 and 4, which could be well fitted by the ellipses with velocity radii of $\sim$6.5 $\pm$ 0.5 km s$^{-1}$ (see Figure 11). The results imply that the shell is expanding.

Figure 12 shows the distribution of the line widths (second moment image) in the CO observations. For a molecular cloud, the thermal line width is calculated as $\Delta v_{\text{thermal}} = \sqrt{8 \ln 2 \frac{k_B T_{\text{kin}}}{\mu_{\text{obs}} m_n}}$, where $k_B$ is the Boltzmann constant and $\mu_{\text{obs}}$ is the molecular weight of the observed species (2.33 for H$_2$). Adopting the kinetic temperature $T_{\text{kin}}$ of 10 K (similar to excitation temperature; see Figure 8(a), the $\Delta v_{\text{thermal}}$ is estimated to be $\sim$0.45 km s$^{-1}$ for the Cassiopeia Filament. The nonthermal line width $\Delta v_{\text{NT}}$ is calculated as $\sqrt{\Delta v_{\text{obs}}^2 - \Delta v_{\text{thermal}}^2 - \Delta v_{\text{res}}^2}$, where $\Delta v_{\text{obs}}$ is the measured FWHM line width of the observed spectra and $\Delta v_{\text{res}}$ is the velocity resolution in the observations (0.16 km s$^{-1}$ for $^{12}$CO). For the east filament, the observed $^{12}$CO line widths range from $\sim$0.8 to $\sim$1.1 km s$^{-1}$, with a median value of $\sim$0.9 km s$^{-1}$ (see also PV diagram shown in Figure 10). The nonthermal line widths are then calculated to be about 0.6–1.0 km s$^{-1}$, with a median value of $\sim$0.8 km s$^{-1}$. For the west shell, the observed $^{12}$CO line widths are roughly 2–3 km s$^{-1}$, and the calculated nonthermal line widths are in the same range. Generally, the ratio of $\Delta v_{\text{NT}}/\Delta v_{\text{thermal}}$ is defined as...
the observed Mach number $M$, which is used to distinguish between the subsonic ($M < 1$), transonic ($1 \leq M \leq 2$), and supersonic ($M > 2$) hydrodynamical regimes in isothermal, nonmagnetic fluids. Therefore, in the $^{12}$CO observations toward the Cassiopeia Filament, its east filament is transonic, while the west shell is supersonic. We also note that the observed $^{13}$CO line widths in the east filament are roughly 0.5–0.6 km s$^{-1}$, and the calculated nonthermal line widths are about 0.2–0.4 km s$^{-1}$. Therefore, the east filament is subsonic in the $^{13}$CO observations (see discussion in Section 4.3.2).

The line mass $M_{\text{line}}$ of the Cassiopeia Filament is $\sim 37 M_{\odot}$ pc$^{-1}$, estimated from the gas mass ($\sim 14400 M_{\odot}$; X-factor method) and length ($\sim 390$ pc). The critical line mass of an unmagnetized isothermal filament can be described in the following form (Ostriker 1964; Inutsuka & Miyama 1997): $M_{\text{crit}} = 2 c_s^2 / G \approx 16.4 \times \left( \frac{T}{10 \text{ K}} \right) M_{\odot}$ pc$^{-1}$, where $c_s = \sqrt{\frac{k T_{\text{gas}}}{\mu m_{\text{H}}}}$ is local thermal sound speed ($\sim 0.19$ km s$^{-1}$ at 10 K) and $G$ is the gravitational constant. For the Cassiopeia Filament, the $M_{\text{crit}}$ is estimated to be $\sim 16.4 M_{\odot}$ pc$^{-1}$. As line mass $M_{\text{line}}$ is larger than critical equilibrium mass $M_{\text{crit}}$, the Cassiopeia Filament is in a thermally supercritical state, which will be gravitationally unstable to collapse radially and subject to fragmentation along the length (see Inutsuka & Miyama 1997).
4. Discussion

4.1. The Origin of the Cassiopeia Filament: A Spur of the Local Arm

Large-scale molecular filaments, with lengths of order 100 pc, play an important role in both star formation and Galactic structure. A number of large-scale molecular filaments were found in the past decade (see, e.g., Jackson et al. 2010; Li et al. 2013; Ragan et al. 2014; Zucker et al. 2015; Wang et al. 2015, 2016; Abreu-Vicente et al. 2016; Li et al. 2016; Du et al. 2017; Colombo et al. 2021; Guo et al. 2021). Depending on searching tracers and identifying methods, these filaments have various properties and can be generally divided into “giant molecular filaments” (GMFs; e.g., Ragan et al. 2014; Abreu-Vicente et al. 2016) and “bone-like” filaments (e.g., Wang et al. 2015; Zucker et al. 2015) two groups (see properties summarized by Zucker et al. 2018).

The measured length of the Cassiopeia Filament is roughly 390 pc, which is comparable to the 500 pc wisp found by Li et al. (2013) and the 430 pc “Nessie Optimistic” found by Goodman et al. (2014). It then belongs to the longest molecular

![Figure 5](image-url)

**Figure 5.** Top panel: the $^{12}$CO(1–0) velocity-integrated intensity image of the shell region. The unit of the scale bar is K km s$^{-1}$. The $^{12}$CO emission is integrated between −1 and +7 km s$^{-1}$ (1σ ∼ 0.8 K km s$^{-1}$). Bottom panel: the enlarged view of the shell and finger-like structures.

7 In Zucker et al. (2018), four catalogs, i.e., giant molecular filaments (from Ragan et al. 2014 and Abreu-Vicente et al. 2016), Milky Way bones (from Zucker et al. 2015), large-scale Herschel filaments (from Wang et al. 2015), and MST bones (from Wang et al. 2016), are compared. The “bone-like” filaments, including both Milky Way bones and large-scale Herschel filaments, have similar physical properties (e.g., column density and aspect ratio), which are clearly different from those of the giant molecular filaments. As discussed in Zucker et al. (2018), the MST bones could be elongated dense core complexes tracing out networks of dense compact sources embedded in giant molecular clouds.
filaments in the Galaxy. Its relatively low H$_2$ column density ($\sim 2 \times 10^{21}$ cm$^{-2}$) is comparable to those of GMFs (with a median value of $4.8 \times 10^{21}$ cm$^{-2}$), but much lower than those of “bone-like” filaments ($\sim 7.8-10.0 \times 10^{21}$ cm$^{-2}$). We note that the aspect ratio of the Cassiopeia Filament ($\sim 28$) is larger than those of GMFs (with a median value of $\sim 8$) and similar to “bone-like” filaments (with a median value of $\sim 34$; see Zucker et al. 2018).

The line mass of the Cassiopeia Filament is $\sim 37$ $M_\odot$ pc$^{-1}$ (see Section 3.3). This value is much smaller than those of the GMFs (with a median value of $\sim 1500$ $M_\odot$ pc$^{-1}$) and “bone-like” filaments ($\sim 500$ $M_\odot$ pc$^{-1}$). Colombo et al. (2021) recently identified a sample of outer Galaxy large-scale filaments (OGLSF), whose physical properties (such as low gas masses and low line masses) can be distinguished from those of the GMFs and “bone-like” filaments found in the inner Galaxy. As suggested by Colombo et al. (2021), these OGLSF are located within inter-arm regions. Interestingly, the observed line mass of the Cassiopeia Filament is more similar to the line masses of the OGLSF ($\sim 10-600$ $M_\odot$ pc$^{-1}$, with a median value of $\sim 50$ $M_\odot$ pc$^{-1}$; see Colombo et al. 2021).

The formation of large-scale filaments is still in the study. Several formation mechanisms are suggested, such as galactic dynamics, including galactic potential in spiral arms and differential shear in the inter-arm regions (see, e.g., Smith et al. 2014; Smith et al. 2020, Duarte-Cabral & Dobbs 2016, 2017; Zucker et al. 2019), and localized dynamics, including self-gravity (e.g., Burkert & Hartmann 2004; Hartmann & Burkert 2007; Gómez & Vázquez-Semadeni 2014), stellar feedback (e.g., Inutsuka et al. 2015), or supersonic turbulence (e.g., Ballesteros-Paredes et al. 1999; Hennebelle 2013).

Based on the observed velocity range and estimated distance, we suggest that the Cassiopeia Filament is associated with the Local arm. For comparison, the FWHM thickness of molecular disk at the Galactocentric radius of about 8 kpc is roughly 100–200 pc (see Heyer & Dame 2015), while the width of the Local arm is roughly $\sim 300$ pc (see Reid et al. 2019). Therefore, we consider that the Cassiopeia Filament, with a length of $\sim 390$ pc, is difficult to be formed by localized mechanisms within the Local arm. On the other hand, the observed properties of the Cassiopeia Filament, such as large length, low column density ($\sim 2 \times 10^{21}$ cm$^{-2}$), and small velocity gradient ($\sim 0.013$ km s$^{-1}$ pc$^{-1}$), are consistent with those synthetic large-scale molecular filaments in the inter-arm regions from the galactic-scale simulations (e.g., Smith et al. 2014; Duarte-Cabral & Dobbs 2017; Zucker et al. 2019). Furthermore, its observed low line mass is comparable to those large-scale filaments found in the outer Galaxy inter-arm regions (see Colombo et al. 2021).

Figure 13 shows multiscale CO longitude–velocity diagrams in the observed direction. The velocity range of the Cassiopeia Filament ([$+1, +4$] km s$^{-1}$) is at the edge of the velocity range of the Local arm, roughly 10 km s$^{-1}$ away from the central mean velocity of the arm (about $-8$ km s$^{-1}$; see Figure 13). Figure 14 shows the position of the Cassiopeia Filament with respect to the Galactic molecular gas disk. It is seen that the filament is vertically located at the boundary of the disk, which is different from those “bone-like” filaments found in the midplane of the inner Galaxy. Figure 15 shows the projected location of the Cassiopeia Filament on the plane of the Milky Way (face-on view; see Reid et al. 2019). As seen in Figure 15, the filament is just like a spur of the Local arm. Based on the observed properties and location, we then suggest that the Cassiopeia Filament is formed due to the galactic shear.

4.2. The Formation of the Shell: A Giant Wind-blown Bubble

The observed morphology and kinematics suggest that the arc-like shell at the west end of the Cassiopeia Filament resulted from the expansion of a large bubble. Under this
Figure 7. (a) The measured distance toward the filament’s east end. The middle panel shows the MWISP $^{12}$CO intensity image. The green contour shows the edge of the molecular cloud (3σ threshold), while green and blue dots represent on- and off-cloud Gaia DR2 stars. In the top right panel, green and blue points represent on- and off-cloud stars (binned every 5 pc), respectively. The dashed red line is the modeled extinction $A_V$. The distance is derived with raw on-cloud Gaia DR2 stars, which are represented with gray points. The black vertical lines indicate the distance ($D$) estimated with Bayesian analyses and Markov Chain Monte Carlo (MCMC) sampling, and the shadow area depicts the 95% highest posterior density (HPD) distance range. The corner plots of the MCMC samples are displayed in the left panel (distance, the extinction of foreground and background stars and uncertainties). The mean and 95% HPD of the samples are shown with solid and dashed vertical lines, respectively. (b) The measured distance toward the west shell, and Gaia $G$-band data are used.
assumption, we try to search for the center of the bubble by measuring the convergence point of the finger-like structures (see Figure 16). The measured geometric center is $I = 124.06^\circ$ and $b = 1.15^\circ$, with an error radius of $\sim 0.20^\circ$. The estimated dimension of the bubble is about $3.4 \times 2.8^\circ$, corresponding to $\sim 34$ pc $\times$ 28 pc at the distance of 553 pc.

It is well-known that OB stars are able to produce bubbles in the ISM through strong feedback, such as UV radiation, stellar winds, and supernova explosions (see, e.g., reviews by Krumholz et al. 2014 and Dale 2015). To better understand the interstellar environment of the shell, we show in Figure 16 the MWISP $^{13}$CO contours, plotted on the Urumqi 6 cm radio continuum image from Sun et al. (2007). As seen in Figure 16, there are several known H II regions toward the bubble suggested by the shell, such as S183 (to the northeast of the shell), S185 (to the south of the shell), and S186 (to the east of the shell). Nevertheless, radio recombination line observations suggested that the systemic velocity of S183 is about $-63$ km s$^{-1}$ (Landecker et al. 1992); The distance of S185 was estimated to be $\sim 200$ pc (e.g., Soam et al. 2017); For S186, the systemic velocity of the CO gas was found to be about $-43$ km s$^{-1}$ (Qin et al. 2008). Hence, we could exclude the association between these H II regions and the shell found in this work. We further checked archival H$\alpha$ images (not shown here), but did not find any ionized structure spatially coincident with the molecular gas shell. Therefore, we consider

Figure 8. (a) The excitation temperature image of the observed Cassiopeia region. The unit of the scale bar is K. (b) The H$_2$ column density image derived from the $^{13}$CO data within the velocity range of [1, 4] km s$^{-1}$, assuming the LTE condition. The unit of the scale bar is $10^{21}$ cm$^{-2}$. (c) The H$_2$ column density image derived from the $^{12}$CO data within the velocity range of [1, 4] km s$^{-1}$, adopting the CO-to-H$_2$ conversion factor. The unit of the scale bar is $10^{21}$ cm$^{-2}$.
that the gas shell does not result from the expansion of an HII region.

As found by Chen et al. (2013), there is a linear relationship between the radius of a wind-blown bubble in a molecular cloud ($R_b$) and the initial mass of the energy source star ($M_{\text{star}}$): $R_b (\text{pc}) \approx 1.22M_{\text{star}}/M_\odot - 9.16 \text{ pc}$, assuming a constant inter-clump pressure (see Chen et al. 2013 for more details). For the giant bubble suggested by the shell (effective radius of $\sim 16$ pc), a massive star with a mass of $\sim 21M_\odot$ (O7 or earlier types) is required to supply stellar wind. Previous observations showed a stellar cluster, Cassiopeia OB7, toward the center of the giant bubble (see Garmany & Stencel 1992;
Nevertheless, the distance of the Cassiopeia OB7 cluster is about 2 kpc (e.g., Cazzolato & Pineault 2003), far away from the shell. Therefore, we consider no association between the Cassiopeia OB7 cluster and the shell/bubble. We also note that no O-type stars were found yet in the bubble/shell region in the Local arm (see, e.g., Xu et al. 2021). Based on the Gaia data, we further search for new OB stars in the shell region (see Appendix). However, we do not find any candidates associated with the shell.

We investigated known supernova remnants (SNRs) in this Galactic region. Large shell-type SNRs G126.2+1.6 and G127.1+0.5 (see Zhou et al. 2014) were found to the east of the bubble (see Figure 16). Nevertheless, we did not find any known SNRs enclosed by the giant bubble. As seen in Figure 16, a faint and extended radio continuum source, with a dimension of $\sim 55' \times 60'$, is detected toward the center of the giant bubble in the Urumqi 6 cm radio continuum survey (see Sun et al. 2007), which was named after G124.0+1.4. Sun et al. (2007) suggested that this extended radio source could be an H II region, as a B-type star was found at the center of the extended radio source. If this extended radio source is really associated with the B-type stars in the center, its distance should be more than 3 kpc. On the other hand, we note that the spectra index of the radio source G124.0+1.4 is about $-0.22$ (see Sun et al. 2007). This index is comparable with those of SNRs measured in the Urumqi 6 cm radio continuum survey.

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Figure 10. The CO position–velocity (PV) diagram along the Cassiopeia Filament (from east to west). The gray-scale background image represents the $^{12}$CO emission, with the 5σ contour (blue; $1\sigma \sim 0.2$ K). The green contour shows the 4σ $^{13}$CO emission ($1\sigma \sim 0.12$ K).

Figure 11. The CO PV diagrams along Fingers 4 (left) and 2 (right). The gray-scale background image represents the $^{12}$CO emission. The $^{12}$CO contours (black) start from 1 K and increase by a step of 1 K ($1\sigma \sim 0.2$ K). The $^{13}$CO emission contours (green) start from 0.4 K and increase by a step of 0.4 K ($1\sigma \sim 0.12$ K). The red ellipse shows the fitting toward the PV diagram with a velocity radius of 6.5 km s$^{-1}$.

8 After checking the SIMBAD Astronomical Database (http://simbad.cds.unistra.fr/simbad/) we found two Be stars, 2MASS J01005124+6413271 and 2MASS J01013802+6413500, located in the center of the radio source G124.0+1.4. The parallaxes of the two stars, measured by the Gaia observations, are 0.3086 and 0.3097, respectively.
This implies that G124.0+1.4 might be a candidate SNR. We show multiwavelength archived radio continuum images of G124.0+1.4 in Figure 17, in order to better understand its nature. After comparing the Green Bank 4850 MHz (6 cm) image with the Urumqi 6 cm image (see Figure 17(a)), we find that the extended radio emission of G124.0+1.4 is actually dominated by three radio sources, in which Source 1 is spatially confident with the bubble center referred from the CO shell and fingers. The three radio sources are also detected in the low-frequency radio observations. The measured fluxes of the three sources are listed in Table 1. The fitted spectra indexes indicate that the radio emission of the three sources is nonthermal. The results further support that G124.0+1.4 is a candidate SNR. In this picture, the giant bubble could be produced by the stellar wind from the progenitor star of this SNR.

In a short summary, based on the CO morphology and kinematics, we suggest that the arc-like shell is originally a part of the Cassiopeia Filament, which is blown into current morphology by the strong stellar wind. The wind is likely driven by the progenitor star of an SNR in the region. Further observations are needed to search for massive stars in the bubble region on the one hand and to study the nature of radio source G120.0+1.4 on the other hand, in order to better understand the driving source of this expanding shell.

4.3. The Origin of Nonthermal Line Widths: From Sonic to Supersonic

The observed spectral line widths in the molecular clouds are generally larger than thermal line widths (see, e.g., reviews by Dobbs et al. 2014; Heyer & Dame 2015; Ballesteros-Paredes et al. 2020). Taking the Cassiopeia Filament as an example, the observed 12CO nonthermal line widths are about 0.6–1.0 km s⁻¹ (with a median value of ∼0.8 km s⁻¹) in the east filament and about 2–3 km s⁻¹ in the west shell (see Section 3.3). The observed 13CO nonthermal line widths are larger than the thermal line width (∼0.45 km s⁻¹) in the Cassiopeia Filament.
The origin of nonthermal line widths in molecular clouds is still in debate. Several scenarios, such as global collapse, externally driven turbulence, and internally driven turbulence, were suggested (see, e.g., Dobbs et al. 2014). Numerous observations and simulations find that stellar feedback (including outflows, H II regions, winds, and supernovae), no matter whether external or internal to clouds, can drive turbulence and explain large line widths (Dobbs et al. 2014; Krumholz et al. 2014). By a comparison between the east filament and west shell, we suggest that large nonthermal line widths seen in the shell resulted from stellar wind, which blew the west end of the Cassiopeia Filament and also drove supersonic turbulence in the shaped shell.

It is of interest to note that the east filament is transonic in the $^{12}$CO observations and subsonic in the $^{13}$CO observations (see Section 3.3). This means that thermal motion plays an important role in the east filament, while the nonthermal line widths could have resulted from gravitational radial collapse or potential star formation (e.g., mass accretion) along the filament. Based on the observations, we suggest that the whole Cassiopeia Filament could be quiescent initially until its west part was blown by the stellar wind. Compared with other large-scale molecular filaments (see, e.g., Li et al. 2013; Elia et al. 2021).

The angular length of the east filament is roughly 9° (see, e.g., Figure 10), corresponding to a linear length of $\sim 65 \times \frac{400}{d}$ pc (where a mean distance of 400 pc is adopted in this work).

Indeed, several prestellar and protostellar sources were detected along the filament (see Figure 12) in the Herschel Hi-Gal survey (Elia et al. 2021). With similar molecular gas velocities, these Hi-Gal sources are likely associated with the filament, indicating early-phase star formation therein.
the Cassiopeia Filament stands out by its large length and small line widths. This kind of quiescent and long molecular filament is rare in the observations. Another well-known example is Musca, a nearby ∼6 pc long filament with low column density (∼2 × 10^{21} cm^{-2}; Cox et al. 2016) and transonic/subsonic gas motion in the $^{12}$CO/C$^{13}$O observations (Hacar et al. 2016).

As found in Zhang et al. (2019), there is a scaling relation between line width ($\Delta v$) and size ($R$): $\Delta v \propto R^{0.42 \pm 0.1}$, in the statistic toward the filaments with lengths ranging from ∼10 pc to ∼100 pc (see also a recent review by Hacar et al. 2022). This relation is reminiscent of the line width-size relation observed in the molecular clouds (Larson 1981; Solomon et al. 1987), which is generally explained by the increasing contribution of turbulence at larger cloud scales (see also discussion in Heyer et al. 2009; Ballesteros-Paredes et al. 2011 and Dobbs et al. 2014). However, the transonic properties of the Cassiopeia (east) Filament show a large departure from this expected relation. The Cassiopeia Filament, together with Musca, shows observational evidence of filamentary molecular clouds clearly decoupled from the turbulent regime over multiscales (from roughly 10 pc to ∼100 pc). Therefore, the Cassiopeia Filament may offer us a unique case to study not only the formation of large-scale filaments in the Galaxy but also the origin of nonthermal line widths in the molecular clouds.

Figure 14. Top panel: the velocity-integrated $^{12}$CO intensity map of the Milky Way obtained from the CfA 1.2 m survey (Figure 2 in Dame et al. 2001). Middle panel: also the CfA 1.2 m $^{12}$CO image, but the enlarged view toward the second quadrant (including the Cassiopeia region). Bottom panel: the MWISP $^{12}$CO image, integrated between −25 and +10 km s$^{-1}$ (i.e., Local arm only). For each panel, the blue line shows the Cassiopeia Filament. Note that all CO images in this work are from the MWISP survey and only the two panels here are from the CfA 1.2 m survey (to provide a complete molecular gas view of the Milky Way).
4.4. The Effects of Stellar Feedback

By ejecting energy, momentum, and material into the surrounding environment, stellar feedback plays an important role in the distribution and properties of the ISM and also drives the recycling of the ISM and the evolution of the Galaxy. Assuming that the observed shell results from a wind-blown bubble, we discuss the effects of stellar feedback on the Cassiopeia Filament, in addition to the broad line widths discussed above.

4.4.1. The Inputted Energy

Using the method suggested by Weaver et al. (1977), the value of the mechanical luminosity of the stellar wind ($L_{\text{wind}}$) can be calculated by $L_{\text{wind}} \approx \frac{1}{3} n_{\text{gas}} \rho_{b} \left(\frac{V_{b}}{16 \text{ km s}^{-1}}\right)^{3} \times 10^{30}$ erg s$^{-1}$, in order to excavate a bubble with a radius of $R_{b}$ and expansion velocity of $V_{b}$ in a gas cloud with a density of $n_{\text{gas}}$. The density can be measured from the radius and column density by $n_{\text{gas}} = \frac{N_{\text{shell}}}{2 \pi R_{b}^{2} V_{b}}$ (see Weaver et al. 1977), where $N_{\text{shell}}$ is the column density observed at the shell (roughly $2 \sim 3 \times 10^{21}$ cm$^{2}$; see Figure 8(c)). Adopting the radius $R_{b}$ of 16 pc, the estimated $n_{\text{gas}}$ is about 150 cm$^{-3}$. For the giant bubble inferred in this work ($V_{b} \sim 6.5 \text{ km s}^{-1}$), the estimated $L_{\text{wind}}$ is then $\sim 3.5 \times 10^{36}$ erg s$^{-1}$. The timescale of the wind needed for opening such a bubble ($\frac{16 \rho_{b}}{n_{\text{gas}} V_{b}} \times 10^{6}$ yr; Weaver et al. 1977) is $\sim 1.4 \times 10^{6}$ yr.

Adopting the gas mass of $\sim 6100 M_{\odot}$ (X-factor method) for the shell and an expanding velocity of $\sim 6.5 \text{ km s}^{-1}$, the estimated kinetic energy of the arc-like shell is $\sim 2.3 \times 10^{48}$ erg. The estimated wind mechanical energy ($L_{\text{wind}} \times$ timescale) is roughly $1.5 \times 10^{50}$ erg, which implies that about 2% of the wind mechanical energy is transferred into the kinetic energy of the expanding gas shell.

4.4.2. The Triggered Star Formation

Stars are formed in dense molecular cloud cores. It has been long suggested that new generation star formation can be triggered in the dense shells of the large bubbles produced by massive stars (e.g., Elmegreen 1998). This so-called “collect and collapse” mode has been extensively studied in the past decades (see, e.g., Dale et al. 2015 and references therein). Indeed, in the infrared observations, young stellar objects (YSOs), Class I and Class II objects (see Evans 1999; McKee & Ostriker 2007), are frequently seen around the bubbles associated with H II regions (see, e.g., Watson et al. 2010), stellar winds (e.g., Cichowolski et al. 2015), and even SNRs (e.g., Billot et al. 2010; Zhou et al. 2014). However, after comparing the characteristic lifetimes of the YSOs with the dynamical ages of the bubbles, the general conclusion is that the formation of those YSOs started before the formation of the bubbles (see discussion in Dale et al. 2015).

In the MWISP CO observations of the shell, faint C$^{18}$O(1–0) line emission is detected at the tips of Fingers 1 and 4 (see Figure 6). Compared with $^{12}$CO and $^{13}$CO, C$^{18}$O traces higher density gas. Assuming the LTE condition and an isotopic ratio of $^{18}$O/$^{16}$O = 560 (Wilson & Rood 1994), the mass of the two C$^{18}$O clumps is estimated to be $\sim 4.7 M_{\odot}$ (Finger 4) and 35.6 $M_{\odot}$ (Finger 1), respectively. The virial parameter, representing the ratio between the kinetic and half gravitational potential energy, can be estimated as $a_{\text{vir}} = \frac{M_{\text{gas}}}{M_{\text{vir}}}$, and the virial mass can be expressed as

$$M_{\text{vir}} = \frac{5\kappa_{\text{vir}}^{2}R}{G} \approx 209 \left(\frac{R_{\text{pc}}}{\text{km s}^{-1}}\right)^{2} M_{\odot},$$

where $\kappa_{\text{vir}}$ is the virial parameter.

11 The typical lifetime of the Class I YSOs is $\sim 0.5 \times 10^{6}$ yr, while the lifetime of the Class II YSOs ranges from a few to several million years (see McKee & Ostriker 2007 and Evans et al. 2009).
where $\Delta v$ is the FWHM line width. Based on the MWISP C$^{18}$O observations, the virial mass of the two clumps is estimated to be $\sim 3.5 M_\odot$ (Finger 4) and $16.5 M_\odot$ (Finger 1), leading to the $\alpha_{\text{vir}}$ of $\sim 0.74$ and $\sim 0.45$, respectively.

In analyses, the virial parameters are used to evaluate whether objects are gravitationally bound or unbound, and $\alpha_{\text{vir}} = 2$ is generally regarded as the upper limit of the critical virial parameter (see, e.g., Kauffmann et al. 2013). The low virial parameters of the two C$^{18}$O clumps suggest that the two clumps are gravitationally bound. After checking infrared archival images (e.g., WISE data, not shown here), we do not find any infrared sources spatially coincident with the two C$^{18}$O clumps. Therefore, the two clumps are likely still in the prestellar phase, which is consistent with the dynamical age of the bubble/shell estimated above. We then suggest that early-phase star formation has been triggered in the finger tips of the wind-blown bubble. It is of interest to note that a number of prestellar and protostellar cores were also detected in the east shell of the bubble (see Figure 12 in the Herschel Hi-Gal survey (Elia et al. 2021). This may imply that early-phase star formation is also triggered in this region. Further observations are needed to study star formation in the shell and analyze the effects of the “collect and collapse” mode in the Cassiopeia Filament.

4.4.3. The Rayleigh–Taylor Fingers?

The fingers detected in the shell look like the fingers or pillars found in the numerical simulations (e.g., Frey et al. 2003; Wareing et al. 2017) and observations (e.g., Deharveng et al. 2012; Schneider et al. 2016) in the studies of massive stellar feedback. Nevertheless, the observed fingers in this work show two interesting characteristics: (1) all the fingers protrude outward, different from those fingers/pillars found in the massive star-forming regions (which protrude inward toward driving stars or clusters), and (2) the shell is not spatially associated with ionized gas (H II regions).

As we discussed in Section 4.2, the expanding arc-like shell could be produced by the stellar wind of the progenitor star of an SNR. This may explain the nonassociation between the shell (stellar wind feedback) and ionized gas (stellar ionization feedback). Interestingly, in the numerical studies (see, e.g., Chevalier et al. 1992; Chevalier & Blondin 1995; Blondin et al. 1996; Tutone et al. 2020), finger-like structures, due to the
Rayleigh–Taylor (RT) instability, are seen in the circumstellar shells around supernovae. These RT fingers, all protruding outward, are the results of the interaction between the supernova ejecta and the shocked shell. In the observations, the RT fingers are used to explain the protrusions frequently detected around the peripheries of the SNRs, such as Cassiopeia A (Orlando et al. 2021) and Vela (Wang & Chevalier 2002; Miceli et al. 2013). The fingers found in this

Figure 17. The multiwavelength radio continuum images of G120.0+1.4. The unit of the scale bar is Jy beam$^{-1}$ for each panel. The red dashed circle shows the bubble center referred from the CO observations, while the blue-filled circle at the bottom right corner shows the beam size. (a) The comparison between the Green Bank (GB) 4850 MHz (6 cm) image (Condon et al. 1994) and Urumqi 6 cm image (Sun et al. 2007). The GB 4850 MHz contours represent 9 mJy emission (about 3$\sigma$), while the Urumqi 6 cm contours (white) represent 5, 10, 15, 22, and 29 mK emission. (b) The GB 4850 MHz image. (c) The NRAO VLA Sky Survey (NVSS) 1.4 GHz image (Condon et al. 1998). (d) The Westerbork Northern Sky Survey (WENSS) 325 MHz image (Rengelink et al. 1997). (e) The TIFR GMRT (Giant Metrewave Radio Telescope) Sky Survey (TGSS) 150 MHz image (Intema et al. 2017). (f) The VLA Low-Frequency Sky Survey (VLSS) 74 MHz image (Cohen et al. 2007; Lane et al. 2014).
work are likely also the RT fingers, given that the shell was produced by the stellar wind of a progenitor star.

5. Summary

We present large-field CO(1–0) molecular line observations toward the Galactic Cassiopeia region, using the PMO 13.7 m telescope. The main results of this work are summarized below.

(1) The CO observations reveal a large-scale highly filamentary molecular cloud within the region of 132°0 < l < 122°0 and −1°0 < b < 3°0 and the velocity range from approximately +1 to +4 km s⁻¹. Based on the CO data, we derive the excitation temperature, column density, and mass of the filamentary molecular cloud.

(2) The measured length of the filament, named after the Cassiopeia Filament, is ~390 pc, making it one of the longest molecular filaments in the Galaxy. The observed properties of the Cassiopeia Filament are similar to the synthetic large-scale filaments in the inter-arm regions, as well as the large-scale filaments observed in the outer Galaxy inter-arm regions. Based on its observed properties and location on the Galactic plane, we suggest that the Cassiopeia Filament is a spur of the Local arm, which is formed due to the galactic shear.

(3) A giant arc-like molecular gas shell is found in the west of the Cassiopeia Filament, which covers an extent with coordinates of 125°5 < l < 121°5 and −1°3 < b < 0°5, and a velocity range between −1 and +7 km s⁻¹. Finger-like structures, with systematic velocity gradients, are detected in the shell. The observed CO gas kinematics suggest that the large shell is expanding at a velocity of ~6.5 km s⁻¹.

(4) Both the shell and finger-like structures outline a giant bubble with a radius of ~16 pc, centered at l = 124°06, b = 1°15. We suggest that the bubble is produced by stellar wind, which is likely from the progenitor star of an SNR in the region. Nevertheless, further observations are needed to verify the candidate SNR suggested in this work.

(5) The observed CO line widths in the west shell are much larger than those found in the east filament, implying that strong turbulence is driven by the stellar wind into the shell. Based on the observations, we suggest that the whole Cassiopeia Filament could be quiescent initially until its west part was blown by the stellar wind. Without external disturbances, the east filament is still transonic in the $^{12}$CO observations and subsonic in the $^{13}$CO observations.

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Appendix
The Massive Stars in the Shell Region

In this Appendix, we try to search for potential massive stars in the shell region by comparing Gaia EDR3 data with the PARSEC model (Bressan et al. 2012; Marigo et al. 2017). We first apply the quality cuts to Gaia sources to eliminate the data with high uncertainties. Referring to the summary of Gaia EDR3 contents (Gaia Collaboration et al. 2021), we set the quality criteria as below:

\[ \text{ruwe} < 1.4, \]
\[ \text{err}_{\text{G}} < 0.2, \]
\[ \text{visibility}_\text{periods}\_\text{used} > 6, \]
\[ 3 \text{ mag} < G < 21 \text{ mag}, \]
\[ \text{err}_{\text{G}} < 0.01 \text{ mag}, \]
\[ \text{err}_{\text{G}_{\text{RP}}} < 0.1 \text{ mag}, \]

where ruwe and err represent renormalized unit weight error and parallax, respectively. We then select the sources with distances in the range between 350 and 750 pc, which are considered to be associated with the shell (d ~ 553 pc). Figure 18 shows the Gaia sources and the 10 Myr isochrone in the $G - G_{\text{RP}}$ versus $G$ color–magnitude diagram (CMD). The location of each source in the CMD is determined both by its intrinsic color and the extinction. Combining the extinction law from Wang & Chen (2019), we derive a sample of sources with a mass larger than $8 M_\odot$. We further remove the giant branch from the sample by simply using the criterion of $G - G_{\text{RP}} > 0.5$ and consider that the rest are all massive stars. The identified massive stars are marked with red circles in Figure 18. The masses of these stars are obtained from the intersection between the isochrone and the reddening vector, which are listed in Table 2. The positions and parallaxes of massive stars are shown in Figure 19.
Figure 18. Color–magnitude diagram of Gaia EDR3 sources in the shell region. The dashed–dotted line represents the 10 Myr isochrone from the PARSEC model (Bressan et al. 2012; Marigo et al. 2017). The arrow line is the reddening vector of $A_V = 2$ mag, and the gray dashed line parallel to it is the isomass line of $8 M_\odot$. The gray dashed line perpendicular to x-axis is set to distinguish main-sequence stars from the giant branch. The blue dots represent the Gaia sources and the red-filled circles are the identified massive stars.

Table 2

| Star Number | Gaia EDR3 Name | $l$ (°) | $b$ (°) | Parallax (mas) | Mass ($M_\odot$) | PM$_l$ (mas yr$^{-1}$) | PM$_b$ (mas yr$^{-1}$) |
|-------------|----------------|---------|---------|----------------|-----------------|----------------------|----------------------|
| Star 1      | 426670370548306432 | 123.507 | -1.612  | 1.959 ± 0.0221 | 8.37            | 5.581                | -0.559               |
| Star 2      | 427743322095240576 | 122.393 | -0.312  | 1.4182 ± 0.0168 | 12.19           | -3.357               | -4.658               |
| Star 3      | 430852294030966080 | 121.256 | -0.590  | 1.9904 ± 0.0220 | 10.47           | -8.464               | -1.969               |
| Star 4      | 510516825178315264 | 126.413 | -1.425  | 1.5332 ± 0.0146 | 8.17            | -4.133               | -2.448               |
| Star 5      | 510732295100464128 | 126.930 | -0.899  | 1.3901 ± 0.0146 | 10.05           | -0.432               | -1.520               |
| Star 6      | 522682955701497472 | 124.902 | -0.565  | 1.5479 ± 0.0148 | 9.69            | -5.526               | -2.818               |
| Star 7      | 523068643761377280 | 125.089 | -0.238  | 1.6709 ± 0.0140 | 9.41            | -7.335               | -1.489               |
| Star 8      | 523305073121434880 | 124.742 | 0.538   | 1.4887 ± 0.0107 | 12.10           | -23.008              | -14.009              |
| Star 9      | 523550779611689984 | 123.486 | -0.644  | 1.4061 ± 0.0141 | 8.19            | -5.066               | -1.932               |
| Star 10     | 524312053972337024 | 123.891 | 2.260   | 1.6701 ± 0.0181 | 10.20           | -1.587               | -1.729               |
| Star 11     | 525362809132485248 | 125.712 | 3.434   | 1.4144 ± 0.0201 | 9.63            | 2.782                | -4.319               |
| Star 12     | 525945447214106752 | 124.404 | 3.141   | 2.5769 ± 0.0226 | 9.72            | 3.875                | -8.298               |
| Star 13     | 527151538450395776 | 121.044 | 2.066   | 1.5879 ± 0.0152 | 8.48            | 3.921                | -0.817               |

Note. The table lists the number (see also Figure 19), Gaia EDR3 name, Galactic position ($l$ and $b$), parallax, mass, and proper motion (PM; $l$ and $b$) for each identified star.
Figure 19. The massive stars identified in the shell region by using the Gaia data (see also Table 2), plotted on the 13CO intensity image. For each star, its distance and mass are labeled, while the proper motion is marked by the arrow.

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