

A High-Mass Young Star-Forming Core Escaping from Its Parental Filament Postprint

Authors: Zhiyuan Ren, Xi Chen, Tie Liu, Emma Mannfors, Leonardo Bronfman, Fengwei Xu, Siyi Feng, Hongli Liu, Fanyi Meng, Amelia M. Stutz, Shanghuo Li, Chang Won Lee, Wang Ke, Jianwen Zhou, Di Li, Chen Wang, Chakali Eswaraiyah, Anandmayee Tej, Long-Fei Chen, Hui Shi, Zhiyuan Ren

Date: 2023-12-29T00:00:00+00:00

Abstract

We studied the unique kinematic properties in massive filament G352.63-1.07 at 1000-AU spatial scale with the dense molecular tracers observed with the Atacama Large Millimeter/submillimeter Array (ALMA). We find the central massive core M1 (12 Msun) being separated from the surrounding filament with a velocity difference of $v-v_{\text{sys}}=-2$ km/s and a transverse separation within 3 arcsec. Meanwhile, as shown in multiple dense-gas tracers, M1 has a spatial extension closely aligned with the main filament and is connected to the filament towards its both ends. M1 thus represents a very beginning state for a massive young star-forming core escaping from the parental filament, within a time scale of ~ 4000 years. Based on its kinetic energy (3.5×10^{44} erg), the core escape is unlikely solely due to the original filament motion or magnetic field, but requires more energetic events such as a rapid intense anisotropic collapse. The released energy also seems to noticeably increase the environmental turbulence. This may help the filament to become stabilized again.

Full Text

Preamble

Draft version October 12, 2023. Typeset using LATEX preprint2 style in AAS-TeX631.

A High-Mass Young Star-forming Core Escaping from Its Parental Filament

Zhiyuan Ren,^{1,2} Xi Chen,^{3,4} Tie Liu,⁴ Emma Mannfors,⁵ Leonardo Bronfman,⁶ Fengwei Xu,⁷ Siyi Feng,⁸ Hongli Liu,⁹ Fanyi Meng,¹⁰ Amelia M. Stutz,¹¹ Shanghuo Li,¹² Chang Won Lee,^{13,14} Ke Wang,⁷ Jianwen Zhou,⁷ Di Li,^{1,2,15}

Chen Wang,¹ Chakali Eswaraiah,¹⁶ Anandmayee Tej,¹⁷ Long-Fei Chen,¹⁸ and Hui Shi¹

¹National Astronomical Observatories, Chinese Academy of Sciences, Datun Rd. A20, Beijing, People's Republic of China

²CAS Key Laboratory of FAST, NAOC, Chinese Academy of Sciences, Beijing, China; University of Chinese Academy of Sciences, Beijing, China

³Center for Astrophysics, Guangzhou University, Guangzhou 510006, People's Republic of China

⁴Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, People's Republic of China

⁵Department of Physics, P.O. box 64, FI-00014, University of Helsinki, Finland

⁶Departamento de Astronomía, Universidad de Chile, Las Condes, Santiago, Chile

⁷Kavli Institute for Astronomy and Astrophysics, Peking University, 5 Yiheyuan Road, Haidian District, Beijing 100871, People's Republic of China

⁸Department of Astronomy, Xiamen University, Zengcuo'an West Road, Xiamen, 361005, People's Republic of China

⁹Department of Astronomy, Yunnan University, Kunming, 650091, PR China

¹⁰University of Chinese Academy of Sciences, Beijing 100049, China

¹¹Departamento de Astronomía, Universidad de Concepción, Casilla 160-C, Concepción, Chile

¹²Max Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany

¹³Korea Astronomy and Space Science Institute, 776 Daedeokdae-ro, Yuseong-gu, Daejeon 34055, Republic of Korea

¹⁴University of Science and Technology, Korea (UST), 217 Gajeong-ro, Yuseong-gu, Daejeon 34113, Republic of Korea

¹⁵NAOC-UKZN Computational Astrophysics Centre (NUCAC), University of KwaZulu-Natal, Durban 4000, South Africa

¹⁶Indian Institute of Science Education and Research (IISER) Tirupati, Rami Reddy Nagar, Karakambadi Road, Mangalam (P.O.), Tirupati 517 507, India

¹⁷Indian Institute of Space Science and Technology, Thiruvananthapuram, Kerala 695 547, India

¹⁸Research Center for Intelligent Computing Platforms, Zhejiang Laboratory, Hangzhou 311100, China

(Received January xx, 2022; Revised January xx, 2022; Accepted October 12, 2023)

Submitted to ApJ

ABSTRACT

We have studied the unique kinematic properties of the massive filament G352.63-1.07 at 10^3 – 10^4 AU spatial scales using dense molecular tracers observed with the Atacama Large Millimeter/submillimeter Array (ALMA). We find that the central massive core M1 (12 M) is separated from the

surrounding filament by a velocity difference of $v - v_{\text{sys}} = -2 \text{ km s}^{-1}$ and a transverse separation within 3 arcseconds. Meanwhile, as shown in multiple dense-gas tracers, M1 has a spatial extension closely aligned with the main filament and is connected to the filament toward both its ends. M1 thus represents a very early state of a massive young star-forming core escaping from its parental filament, within a timescale of 4000 years. Based on its kinetic energy ($3.5 \times 10^{44} \text{ erg}$), the core escape is unlikely to be due solely to the original filament motion or magnetic field, but requires more energetic events such as a rapid, intense anisotropic collapse. The released energy also appears to noticeably increase the environmental turbulence, which may help the filament become stabilized again.

Keywords: Star formation (1569); Young stellar objects (1834); Dense interstellar clouds (371); Interstellar filaments (842); Gravitational collapse (662)

1. INTRODUCTION

Star-forming clouds can produce several prominent dynamical consequences. One is the escape and spreading of young stars into the surrounding space, which has attracted increasing attention in recent years (e.g., Tobin et al. 2009; Kraus et al. 2017; Herczeg et al. 2019; Cantat-Gaudin et al. 2019; Swiggum et al. 2021). The stars tend to gradually drift across the entire cloud, forming a similar but more extended spatial distribution (Großschedl et al. 2018; Jerabkova et al. 2019; Kuhn et al. 2020; Ward et al. 2020; Gupta & Chen 2022). This provides a unique proxy for inspecting cloud morphology and mass distribution. Furthermore, based on recent Gaia measurements of trigonometric parallax and stellar proper motion, one can explore the spatial-velocity structure with unprecedented accuracy and a historical perspective (e.g., Szegedi-Elek et al. 2019; Roccatagliata et al. 2020; Galli et al. 2020; Krolikowski et al. 2021; Kounkel et al. 2022; Tu et al. 2022; Ha et al. 2022; Dharmawardena et al. 2022; Duan et al. 2023). These works have substantially improved our understanding of the dynamical conditions and evolutionary trends of star-forming clouds.

As one critical but incomplete aspect of this study, the initial conditions of escaping young stars have not been widely examined. With the exception of some extremely high-velocity stars ($10\text{--}10^2 \text{ km s}^{-1}$) ejected from n-body ($n \geq 3$) interactions (Ducourant et al. 2017; Fernandes et al. 2019; Bally et al. 2020; Rivera-Ortiz et al. 2021), stellar motions could also be affected by their dense-gas structures. Young stars could directly inherit the turbulent field of the gas structure (Ha et al. 2021; Krolikowski et al. 2021; Quintana & Wright 2022; Gupta & Chen 2022) and obtain further acceleration due to gravitational instability or other interactions among parental filaments or clumps (Stutz & Gould 2016; Getman et al. 2019; Zamora-Avilés et al. 2019; Kim et al. 2019; Sharma et al. 2020; Álvarez-Gutiérrez et al. 2021). Stutz & Gould (2016) proposed a particular scenario where the filament in Orion A could oscillate, driving young stars toward transverse directions and eventually forming a broadened stellar distribution parallel to the filament. However, in all these studies, the young

stars are either completely separated from the filaments or have dissipated their surrounding gas (e.g., Jerabkova et al. 2019; Gupta & Chen 2022). Therefore, we still need to investigate the initial dynamical conditions when YSOs are leaving their parental structures.

G352.63-1.07 is a massive young star-forming region at a precisely measured distance of $D = 690$ pc (Chen et al. 2021, hereafter Chen21). It contains several massive cores aligned along a dense filament. As shown in Chen21, the massive filament has actively ongoing dynamical features, including prominent outflows and mass transfer flows that induce bright shock emissions. However, due to limited molecular tracers and sensitivities, the gas motions among the cores and filaments remain undetermined.

In this work, we explore the gas motions using optically thin lines, which demonstrate the unique tendency of the escaping massive core M1. The observational data are described in Section 2, the global dense-gas and velocity distribution is reported in Section 3, the dynamical origin and time-energy properties of the gas motion are discussed in Section 4, and a summary is given in Section 5.

2. OBSERVATION

G352.63-1.07 was observed with the Atacama Large Millimeter/submillimeter Array (ALMA) as part of the ATOMS survey (Liu et al. 2020, 2022). The observation was performed with both the Compact 7-m Array (ACA) and the 12-m array (C43-2 or C43-3 configurations) in Band 3. The restored data cube has an average beam size of $\theta_{\text{maj}} \times \theta_{\text{min}} = 2.5 \times 2.1$ (PA = -87°). The antenna baselines can cover extended structures with scales up to 100. The channel width and noise level vary with different spectral windows. The H^{13}CO^+ , CCH, and H^{13}CN (1-0) lines have $\Delta v_{\text{chan}} = 0.2$ km s $^{-1}$, $\sigma_{\text{rms}} = 5$ mJy beam $^{-1}$ (0.15 K). The HCO^+ (1-0) line has $\Delta v_{\text{chan}} = 0.1$ km s $^{-1}$, $\sigma_{\text{rms}} = 9$ mJy beam $^{-1}$ (0.25 K). The CH_3OH ($2_{11}-1_{10}$) lines have $v_{\text{chan}} = 1.4$ km s $^{-1}$, $\sigma_{\text{rms}} = 2$ mJy beam $^{-1}$ (0.08 K). More detailed observing conditions are presented in Liu et al. (2020).

3.1. Filament and cores

Figure 1a [Figure 1: see original paper] shows the 3 mm continuum emission and the integrated H^{13}CO^+ (1-0) emission (moment 0). Compared to the chemically fresh molecules CCH and HC_3N (Chen21, Figure 3 [Figure 3: see original paper] therein), the H^{13}CO^+ emission is more concentrated toward the inner region of the filament structures, revealing an S-shaped compact filament. The six major cores (Chen21) are clearly resolved therein. The line intensity decreases toward M4 and M5, which could be due to gas dissipation caused by their outflows (Appendix Figure 1b). Figure 1b shows the H^{13}CO^+ emission overlaid on the Spitzer/IRAC three-band color image (GLIMPSE survey, Benjamin et al. 2003; Churchwell et al. 2009). Among the dense cores, only M1 has a compact IR source, while M2 through M5 lack IR point sources. The other two IR sources

(M3b and M6) are located on the western side of the filament. The IRAC color magnitudes for M1 are $[3.6]-[4.5] = 2.1$ and $[5.8]-[8.0] = 1.0$, similar to the colors of Class 0 YSOs (Megeath et al. 2012). M1 is also detected in 6.7 GHz methanol maser emission but undetected in 6–8 GHz radio continuum emission above the noise level of $3\text{--}8 \text{ mJy beam}^{-1}$ (Walsh et al. 1998), indicating that M1 hosts a deeply embedded young massive star that has not yet caused significant ionization of the surrounding medium. Figure 1b also shows the CH_3OH (2–1) emission, which has a compact morphology concentrated at M1.

The molecular spectra at the three inner cores are shown in Figure 1c. The H^{13}CO^+ (1–0) line exhibits a noticeable double-peak profile at M1, with the two components separated by $v_{\text{blue}} - v_{\text{red}} = -1.8 \text{ km s}^{-1}$. M2 and M3 each have a single-velocity component within $v_{\text{lsr}} = \pm 0.3 \text{ km s}^{-1}$, closeto the redshift component at M1. The HCO^+ and CH_3OH line profiles are less resolved due to high optical depth and low spectral resolution, respectively, but both lines still show inclination toward the blueshifted side. We also examined the other two dense-gas tracers CCH and H^{13}CN (1–0) (Figure 3), which show velocity components similar to H^{13}CO^+ (1–0). All the molecular lines consistently indicate a prominent blueshifted component at M1.

3.2. Physical parameters and gravitational instability

The physical parameters of the cores are presented in Table 1, with calculation details described in Appendix A. All the cores have comparable spatial sizes and are nearly uniformly distributed along the filament, with an average spatial interval of $\Delta s_{\text{cores}} = (10 \pm 2)$, or $(7 \pm 1.5) \times 10^3 \text{ AU}$.

From the observed parameters, we estimated the stability of the cores using the critical mass (Bertoldi & McKee 1992; McKee & Ostriker 2007; Li et al. 2013):

$$M_{\text{crit}} = M_{\text{BE}} + M_{\Phi} = \frac{5R_{\text{eff}}}{G} \left(\sigma_{\text{tot}}^2 + \frac{v_A^2}{6} \right)$$

wherein σ_{tot} is the effective velocity dispersion (see Appendix A), and M_{BE} and M_{Φ} represent the upper-limit masses that can be supported by turbulence and magnetic pressure, respectively. M_{Φ} depends on magnetic field strength B and mass density $\rho_0 = m_{\text{H}} n_0$, which are included in the Alfvén velocity $v_A = B/\sqrt{4\pi\rho_0}$. For the B value, we referred to B -field measurements in other similar cold dense filaments (e.g., Liu et al. 2018; Ching et al. 2018), which typically have bulk distributions of $B = 0.5$ to 1.0 mG . Adopting this range, we derive $M_{\Phi} = 0.6$ to $1.2 M_{\odot}$, which contributes only minimally to M_{crit} . As shown in Table 1, all the cores have $M_{\text{crit}} > M_{\text{core}}$, indicating a subcritical state if turbulence can support them against self-gravity.

The filament stability can be estimated from the critical line-mass density (Ostriker 1964; Arzoumanian et al. 2013):

$$\left(\frac{M}{l}\right)_{\text{crit}} = \frac{2\sigma_{\text{tot}}^2}{G}$$

Using the average $\Delta v_{\text{fila}}(\text{H}^{13}\text{CO}^+) = 2.0 \text{ km s}^{-1}$, we derive $\sigma_{\text{tot}} = 0.9 \text{ km s}^{-1}$ and $(M/l)_{\text{crit}} = 390 \text{ M pc}^{-1}$. In comparison, the observed total mass (48 M) and length (45) yield $(M/l)_{\text{obs}} = 300 \text{ M pc}^{-1}$. Considering projection effects, the actual value could be even smaller. Therefore, the property $(M/l)_{\text{obs}} < (M/l)_{\text{crit}}$ suggests a subcritical state for the entire filament as well.

The turbulent condition of the filament and cores should have a close interplay with other dynamical features, including core collapse and escaping motion, as discussed below.

4.1. Resolving the velocity components

As shown above, the filament has an overall smooth and compact morphology. The transfer flows (Chen21) and outflows appear to have only limited influence on the main filament. As seen in optically thin lines, the blueshift motion of M1 remains the most conspicuous feature across the entire structure, and its dynamical origin requires further examination.

Figure 2a [Figure 2: see original paper] shows the H^{13}CO^+ (1–0) emission in four different velocity channels, with ALMA 3 mm and SMA 1 mm (Chen21) dust continuum emissions plotted in sub-panels for comparison. Figure 2b presents the position-velocity (PV) plot of H^{13}CO^+ along the filament, revealing that the blue component lies mainly in the velocity range from -4 to -1 km s^{-1} and has a spatial extension from offset = -16 to $+6$. To better inspect the gas motion, we plot the emission regions in two velocity intervals, denoted as low- and high-velocity components (LVC and HVC), respectively. Figure 2a shows that the LVC peaks at M1 and has a weak elongation toward M2, while the HVC is more confined around M1. Their morphologies are both substantially different from the outflow lobes in Figure 6a [Figure 6: see original paper], indicating that they trace dense-core motion rather than outflow.

The filament component lies primarily in the velocity range $(-1.5, +1.5) \text{ km s}^{-1}$. Its emission region (false-color image in Figure 2a) traces nearly the entire gas structure and shows a noticeable gap at the M1 center. The redshift wing component (1.5 to 2.2 km s^{-1} , yellow contours) includes two separated patches, one extending from M4 and M5 and another around M3, which could trace denser gas affected by outflow or transfer flow. Around M1, no evident redshift feature appears at $v > 1 \text{ km s}^{-1}$.

The dust continuum emissions (Figure 2a, two right panels) show an overall spatial extent similar to the H^{13}CO^+ filament but have a compact intensity peak precisely at M1, which is 3 times more intense than the remaining filament. The spatial correlation of the velocity components can also be examined through

their intensity profiles, as shown in Figure 2b (lower panel). The dust continuum profiles (dashed and dotted lines) closely follow the blueshift component (blue solid line), all showing a shoulder-like decreasing trend from M1 to M2. This coherence suggests that the dense core M1 is primarily associated with the blueshifted gas.

The intensity gap in the filament is more clearly visible in the intensity profile (red line in Figure 2b, lower panel), coinciding precisely with the M1 center in both the dust continuum and blueshift H^{13}CO^+ profiles. For the H^{13}CO^+ emission, if we consider the total intensity profile (black solid line), the blueshift component nicely fills the gap, making the entire profile much flatter.

The CCH emission regions of the two components are shown in Figure 3a [Figure 3: see original paper]. The PV diagrams of CCH and H^{13}CN are shown in Figure 3b [Figure 3: see original paper]. The lower intensity around M1 along the filament is also visible in CCH (Figure 3a). Although its blue component is more extended than that of H^{13}CO^+ , it remains mainly concentrated at the central cavity of the filament. The H^{13}CN emission is more concentrated at M1, so the central intensity decline is not evident, but its PV diagram still shows a comparable velocity separation of $v - v_{\text{lsr}} = -2 \text{ km s}^{-1}$ between the blueshift component and the main filament. It also closely overlaps with the H^{13}CO^+ and CCH spectra for the blueshift peak (Figure 6c [Figure 6: see original paper]). The three molecular lines thus consistently indicate that the blueshift component is dominant at M1, meaning the dense core has bulk motion relative to the rest of the filament.

Based on their spatial and velocity features, M1 and the main filament could have two possible configurations: M1 could be leaving the filament on the front side or moving toward it from behind. The PV plot (Figure 2b) shows the blue component connected to the main filament both toward the north and south, around offset = +5 and -15, respectively. The PV diagrams of CCH and H^{13}CN (1-0) lines (Figure 3, right column) show similar connection features between M1 and the main filament in both directions. M1 should therefore have originally formed in the filament and acquired its blueshift motion only recently.

4.2. Driving force of the blue component

The multiple velocity components in G352 are comparable to those in other filaments with prominent kinematic features. As shown in previous studies, undisturbed linear filaments tend to have moderate fluctuations of $|v - v_{\text{sys}}| \leq 1.0 \text{ km s}^{-1}$ around their internal cores (e.g., Puanova et al. 2018; Bhadari et al. 2020). More complex fiber-composed filaments also show similar velocity variations within 1 km s^{-1} (Hacar et al. 2017; Clarke et al. 2018). Stronger kinematic features of several km s^{-1} are seen in filaments undergoing collapse (Henshaw et al. 2014; Chen et al. 2019; Ren et al. 2021; Li et al. 2022; Cao et al. 2022) or interactions (Shimajiri et al. 2019; Anathpindika & Francesco 2021).

The velocity fluctuations in G352 resemble those of the most active filaments. The blueshift motion (-2 km s^{-1}) and its spatial scale (5 or 3500 AU) produce a gradient of $250 \text{ km s}^{-1} \text{ pc}^{-1}$, similar to those in the most intensely collapsing filaments (e.g., Peretto et al. 2013; Montillaud et al. 2019; Hu et al. 2021; Beuther et al. 2021; Cao et al. 2022).

In collapsing or fiber-composed filaments, the global velocity field is often entangled with individual core motions, making it uncertain whether the cores are co-moving with the filament or already separated. In contrast, G352 presents an example of clearly separated velocity components. In fact, the filament is also inclined toward the blueshift side around M1 at approximately -0.5 km s^{-1} (Figure 2b), suggesting the filament could have a co-moving tendency with M1. In particular, as shown in Figure 2a, the HVC ($v = (-4, -3) \text{ km s}^{-1}$) is narrowly confined between the northern and southern segments of the entire filament, further evidence that the core and filament motions are closely related.

The mass transfer flows (Chen21) provide a viable mechanism to initiate filament collapse. Since the flows are observed as one-sided molecular line wings rather than strong infall signatures, they would provide moderate mass accumulation to the inner filament (between M2 and M3). If the mass assembly once exceeded the threshold of $(M/l)\{crit\}$ or $M\{crit\}$, it could possibly induce a major collapse. The transfer flows show no evident mass assembly at their arrival points on the inner filament (Figure 2), indicating that the flows should have further propagation toward M1.

4.3. Energy scales of the gas components

The filament collapse and core escape can also be examined through their energy scales. From the core mass and its escaping velocity, the kinetic energy of M1 is estimated to be $E_k = m_{\text{core}}(v_{\text{blue}} - v_{\text{red}})^2/2 = 3.5 \times 10^{44} \text{ erg}$, which represents a lower limit due to projection effects. In comparison, the turbulent energy of the entire filament is $E_{\text{turb}} = m_{\text{tot}}\sigma_{\text{nt}}^2/2 = (2.5 \pm 0.5) \times 10^{44} \text{ erg}$. For the magnetic energy, from the speculated B-range (Section 3.2), we estimate $E_B = m_{\text{tot}} v_A^2/2 = 2 \text{ to } 8 \times 10^{43} \text{ erg}$. Since E_{turb} and E_B characterize the entire filament, the fraction reaching M1 could be even lower and thus cannot be solely responsible for the core motion.

The collapsing energy can be estimated as $\Delta E_{\text{p,coll}} = Gm_{\text{coll}}^2[(1/r_1) - (1/r_0)]$, which involves the initial and final radii (r_0 and r_1) of the collapsing mass m_{coll} . Assuming the major collapse occurs between M2 and M3, we adopt $r_0 = \Delta s_{\text{cores}}$. Together with the current radius and mass of M1, we derive $\Delta E_{\text{p,coll}} = 6 \times 10^{44} \text{ erg}$, which could be sufficient to accelerate M1.

As seen in the PV diagram (Figure 2b), the inner region has a typical line width of $\Delta v \geq 1.8 \text{ km s}^{-1}$ for both the blueshift component and the main filament, rapidly declining toward the outer part to a trans-sonic level of $\Delta v = 0.7 \text{ km s}^{-1}$ ($\sigma_{\text{nt}} = 0.4 \text{ km s}^{-1}$) at offset = $\pm 20''$. The low Δv areas over the filament could represent the fraction less affected by the collapse. Adopting the average value (0.9

1}\$, which is much smaller than $(M/l)\{\text{obs}\}$ and should reflect the supercritical condition before the major collapse.

Figure 4 [Figure 4: see original paper] shows the velocity distributions over the core and filament in all three lines. Low-turbulence areas with Δv down to 0.6 km s^{-1} are visible in all three species. The CCH and H^{13}CO^+ emission regions both exhibit low values down to $\Delta v = 0.7 \text{ km s}^{-1}$, while higher values mainly appear between M1 and M3. The H^{13}CN line is more concentrated on dense cores, possibly due to its chemical bias toward the protostellar stage. Along the filament, the H^{13}CN line width variation is mainly between 1.2 and 1.4 km s^{-1} , comparable to the average values of the CCH and H^{13}CO^+ lines.

4.4. Time scales of the gas motion

Figure 5a [Figure 5: see original paper] shows the ridge lines of the main filament and the blueshift component (M1 and southern extension). The two components have a transverse offset of $\Delta s_{\text{esc}} = 0$ to 2.3 arcseconds along the filament. We plot the Δs_{esc} and $|v_{\text{blue}} - v_{\text{red}}|$ profiles along the filament in Figure 5b. Both quantities show a coherent variation trend, reaching local maxima at M1 and the second velocity peak near M2 (offset = -10).

The transverse separation as a function of time can be estimated as $\Delta s_{\text{esc}} = t_{\text{esc}}(v_{\text{blue}} - v_{\text{red}}) \tan \theta$, where θ is the inclination angle between the gas motion and the line of sight. Adopting $\theta = (45 \pm 10)^\circ$, we derive a timescale of $t_{\text{esc}} = (4 \pm 2) \times 10^3$ years for the blueshift motion, notably close to the outflow age of $t_{\text{out}} = 3.6 \times 10^3$ years (Appendix A). These two values should together characterize the star-forming age in G352.

If the core escape began during filament collapse, one would expect an overall collapsing time substantially longer than t_{esc} . From recent semi-analytical work (Clarke & Whitworth 2015), the filament could have a collapsing time $t_{\text{coll}} = (0.49 + 0.26A_0)(G_0)^{-1/2}$, where A_0 is the aspect ratio of the filament. Assuming the major collapse occurred in the inner region between M2 and M3, from the filament length ($l = 22$) and width ($w = 5$), we derive $t_{\text{coll}} = 6 \times 10^4$ years, which could roughly represent the dense-core formation time. For M1, this implies a mass accretion rate of $M_{\text{acc}} = M_{\text{core}}/t_{\text{coll}} = 1.8 \times 10^{-4} \text{ M yr}^{-1}$, comparable to the rate of the transfer flows (Chen21). The collapse toward the center could be dominated by two colliding flows along the filament, which would rapidly increase the central density and develop an anisotropic instability. The highly compressed gas would then move toward transverse directions, initiating the observed motion. A schematic view of the collapse and core acceleration is shown in Figure 5c.

The collapsing time can be compared with the turbulence-increasing time of the filament. From the turbulence level of the inner filament ($\sigma_{\text{nt}} = 0.8 \text{ km s}^{-1}$), we derive a dynamical timescale of $t_{\text{dyn}} = \Delta s_{\text{cores}}/\sigma_{\text{nt}} = 8 \times 10^4$ years, also similar to t_{coll} . As shown in Figure 4, the line-width distributions of H^{13}CO^+ and CCH both increase steeply between M1 and M3 with a scale

of $\Delta V \geq 1.0 \text{ km s}^{-1}$, providing evidence that the turbulence was increased by recent dynamical evolution and has not yet reached a uniform state across the filament.

Although filament collapse could have sufficient energy and time to initiate the core motion, other dynamical origins for the blue component are not fully excluded. In particular, it could also be a fiber-like component. Fibers in massive filaments are observed on larger spatial scales ($>0.2 \text{ pc}$) in a few recent studies (Shimajiri et al. 2019; Cao et al. 2022). Those fibers are only loosely aligned or intertwined along the filament axis, have transverse separations up to several 0.1 pc , and lack the two-end connections seen in M1. Fibers could become increasingly separated with filament age. For G352, the separation would be $\Delta s_{\text{esc}} \geq (v_{\text{blue}} - v_{\text{red}})t_{\text{coll}} \approx 2.5 \times 10^4 \text{ AU}$ (36), unreasonably large compared to the observed spatial scales. To maintain the observed Δs_{esc} , the fibers would need to have originally had a much smaller velocity difference (2 km s^{-1}) and still require a recent collapse to provide the kinetic energy and reach the escaping velocity.

5. SUMMARY

Based on the velocity distribution of H^{13}CO^+ and other dense-gas tracers, we find that the most massive core M1 (12 M_{\odot}) is connected to the main filament but has a blueshift of $v_{\text{core}} - \bar{v}_{\text{sys}} \approx -2 \text{ km s}^{-1}$. The core motion has a kinetic energy of $3.5 \times 10^{44} \text{ erg}$ and a timescale of only 4000 years. As a unique example, M1 reveals the very beginning of a massive YSO escaping from its birth site, confirming that YSOs can leave the filament along the transverse direction.

Among the available mechanisms, only filament collapse could provide enough energy to initiate the core escape. A recent collapse is also needed to generate the massive star therein and can be responsible for the drastic velocity and turbulence variations across the filament. As the core motion occurs, a central gap forms precisely at its location in the remaining part of the filament.

Based on energy and time comparisons, the core escape process could have three major steps: (i) the filament had relatively low turbulence with moderate contraction and fragmentation into dense cores; (ii) due to transfer flows, the inner region became more massive and unstable, eventually initiating a major collapse; (iii) M1 was strongly compressed by the collapsing gas to begin its escaping motion, while the remaining energy could be transferred to the filament to increase turbulence.

Based on the G352 results, one can examine other filaments with steep velocity gradients to see if similar core motions are occurring. A larger sample will help evaluate the universality of such collapse-induced YSO escape and estimate its contribution to YSO dispersion across molecular clouds.

APPENDIX

A. Deriving the Dense Core Properties

The total column density of a molecular species is estimated from optically thin lines (Caselli et al. 2002; Henshaw et al. 2014) as:

$$N_{\text{tot,mol}} = \frac{8\pi I_{\text{tot}}}{A_{ij}\lambda^3} \frac{Q_{\text{rot}}(T_{\text{ex}})}{g_u \exp(-E_l/k_B T_{\text{ex}})} \left[\frac{1}{J_\nu(T_{\text{ex}}) - J_\nu(T_{\text{bg}})} \right] \frac{1}{1 - \exp(-h\nu/k_B T_{\text{ex}})}$$

where $I_{\text{tot}} = \int T_{\text{b}} dv$ is the total intensity of the line profile, A_{ij} is the Einstein coefficient for spontaneous decay, g_u and g_l are the statistical weights for the upper and lower states, respectively, $J(T) = T_0 / [\exp(T_0/T) - 1]$ is the Planck-corrected brightness temperature with reference value $T_0 = h\nu/k$, $Q_{\text{rot}}(T_{\text{ex}})$ is the partition function, λ and ν are the wavelength and frequency of the line transition, and $T_{\text{bg}} = 2.73$ K is the cosmic background temperature. k_B and h are the Boltzmann and Planck constants, respectively.

The total gas column density is $N(\text{H}_2) = N_{\text{tot,mol}}/X_{\text{mol}}$, where X_{mol} is the molecular abundance. For the H^{13}CO^+ abundance, Gerner et al. (2014) measured $X_{\text{mol}}(\text{H}^{13}\text{CO}^+) = 0.9$ to 1.5×10^{-9} from a large sample of dense cores from IRDC to hot-core stage. We adopt $X_{\text{mol}}(\text{H}^{13}\text{CO}^+) = (1.2 \pm 0.3) \times 10^{-9}$ for G352.

We also attempted to use CCH and H^{13}CN (1–0) lines to calculate N_{tot} , which provide comparable values on the 10^{23} cm^{-2} scale. The optical depth of the molecular lines is examined using (Bell et al. 2014):

$$\tau = \frac{c^3 A_{ij} g_u N_{\text{tot}} \Delta v}{8\pi\nu^3 Q_{\text{rot}}} \left[\exp\left(\frac{h\nu}{k_B T_{\text{rot}}}\right) - 1 \right]^{-1}$$

In the calculation, we also adopted average abundances in young high-mass protostellar objects (HMPOs) from Gerner et al. (2014): $X_{\text{mol}}(\text{CCH}) = 5.0 \times 10^{-8}$ and $X_{\text{mol}}(\text{H}^{13}\text{CN}) = X_{\text{mol}}(\text{HCN})/80 = 4.7 \times 10^{-11}$. From the physical conditions at M1 of $N_{\text{tot,mol}} = 2.6 \times 10^{23} \text{ cm}^{-2}$ and $T_{\text{ex}} = 37$ K, we estimate $\tau(\text{CCH}) = 1.1$, $\tau(\text{H}^{13}\text{CO}^+) = 0.12$, and $\tau(\text{H}^{13}\text{CN}) = 0.06$.

From the $N(\text{H}_2)$ distribution, we estimate the core mass as $m_{\text{core}} = \int N(\text{H}_2) dA$, where integration is performed over the core area. The cores are irregular and not fully separated from the filament. To avoid complexity, we assumed the cores have spherical or elliptical shapes. M3 and M5 show noticeable elongation and are assumed to be elliptical, while other cores are considered spherical. The core region is adjusted to cover emission above the extended filament emission (3 K km s^{-1}). The core areas are plotted in Figure 1a.

In deriving $N_{\text{tot},\text{mol}}$, we adopt the excitation temperature from HCO^+ (1–0) lines (Figure 1). Assuming optically thick conditions, it can be estimated using:

$$T_b = J(T_{\text{ex}}) - J(T_{\text{bg}})$$

The calculation yields $T_{\text{ex}} = 37$ K for M1 and 22 ± 3 K for other cores. The second value is comparable to the dust temperature derived from SED fitting (Chen21), whereas the higher value at M1 likely reflects stellar heating. From CH_3CN population diagram, Chen21 derived a much higher temperature of $T_{\text{rot}} = 165$ K at M1, which should be biased toward a small amount of shocked gas, while the major fraction of the filament remains much cooler due to the absence of ionized gas and strong IR emission. This temperature range is comparable to values for prestellar cold dense cores (e.g., Xie et al. 2021), suggesting an early evolutionary stage on average for the filament. Moreover, if we assume $T_{\text{ex}}(\text{H}^{13}\text{CO}^+) = 165$ K, we derive $N(\text{H}_2) = 7 \times 10^{23} \text{ cm}^{-2}$ and $m_{\text{core}} = 30 M$ for M1, an unreasonably high value as it would comprise more than half of the total filament mass.

The total velocity dispersion of the core is estimated from the observed line width Δv as:

$$\sigma_{\text{tot}} = \sqrt{\sigma_{\text{th}}^2 + \sigma_{\text{nt}}^2}$$

where the thermal component is:

$$\sigma_{\text{th}} = \sqrt{\frac{k_B T_{\text{kin}}}{m_{\text{mol}}}}$$

and the non-thermal component is:

$$\sigma_{\text{nt}} = \sqrt{\frac{\Delta v^2}{8 \ln 2} - \frac{k_B T_{\text{kin}}}{m_{\text{mol}}}}$$

In the calculation, we adopted a kinetic temperature of $T_{\text{kin}} = 37$ K for M1 and $T_{\text{kin}} = 22$ K for other cores, yielding $\sigma_{\text{th}} = 0.29$ to 0.36 km s^{-1} . In comparison, the average line width of $\Delta v = 1.5 \text{ km s}^{-1}$ gives $\sigma_{\text{nt}} = 0.64 \text{ km s}^{-1}$, which is not strongly affected by T_{kin} and σ_{th} .

B. Outflow Properties

Outflow emission is detected in high-velocity line wings of the HCO^+ (1–0) lines, with its emission region and spectra shown in Figures 6a and 6b [Figure 6: see original paper], respectively. The blue- and redshifted line wings are both

strongly detected at M4, showing velocity ranges of $(-20, -6)$ km s⁻¹ for the blue lobe and $(5, 20)$ km s⁻¹ for the red lobe. As seen in Figure 6a, compared to the CO outflow (Chen21), the HCO⁺ emission is concentrated around M4 and M5, suggesting the outflow is launched from this area. From the spatial extensions of the outflow lobes, we identify at least two bipolar outflows, indicated by dashed lines. The outflow extensions are not fully overlapped with M4 and M5, and it is uncertain whether this is due to additional driving sources or time-variation of the outflow morphology.

One thing is certain: the outflow intensity is much weaker at M1, and the red lobe is almost undetected. If M1 also contributes to the blueshifted gas, it is more likely ejected during core collapse and escape than due to protostellar outflow.

From the HCO⁺ line-wing intensities and outflow emission areas, we find masses $m_{\text{blue}} = 0.20 M$ and $m_{\text{red}} = 0.24 M$, with an average radius $R_{\text{out}} = (8 \pm 3) = (5.5 \pm 2) \times 10^3$ AU. Assuming an average velocity of $v_{\text{out}} = 8$ km s⁻¹, the outflow age is derived as $t_{\text{out}} = R_{\text{out}}/v_{\text{out}} = (3.5 \pm 1) \times 10^3$ years.

ACKNOWLEDGMENTS

The authors thank the referees for their constructive comments. This work is supported by the National Key R&D Program of China No. 2022YFA1602901, the National Natural Science Foundation of China (NSFC Grant Nos. 12041302, 11973051, U1931117, 11988101, 11725313, U2031117, and 12103069), and the International Partnership Program of the Chinese Academy of Sciences (grant No. 114A11KYSB20210010). T.L. acknowledges support from the international partnership program of the Chinese Academy of Sciences through grant No. 114231KYSB20200009 and the Shanghai Pujiang Program 20PJ1415500. L.B. gratefully acknowledges support from the ANID BASAL project FB210003. A.S. gratefully acknowledges support from the Fondecyt Regular (project code 1220610) and ANID BASAL projects ACE210002 and FB210003. C.W. was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (NRF-2019R1A2C1010851) and by the Korea Astronomy and Space Science Institute grant funded by the Korea government (MSIT; project No. 2023-1-84000). C.E. acknowledges financial support from grant RJF/2020/000071 as part of the Ramanujan Fellowship awarded by the Science and Engineering Research Board (SERB), India. E.M. is funded by the University of Helsinki doctoral school in particle physics and universe sciences (PAPU).

This paper makes use of the following ALMA data: ADS/JAO.ALMA 2019.1.00685.S. ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan region), and KASI (Republic of Korea), in

cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ. The Spitzer GLIMPSE legacy survey data can be downloaded at NASA/IPAC Infrared Science Archive (<https://irsa.ipac.caltech.edu/irsaviewer/>).

REFERENCES

- Álvarez-Gutiérrez, R. H., Stutz, A. M., Law, C. Y., et al. 2021, *ApJ*, 908, 86
- Anathpindika, S. V., & Francesco, J. D. 2021, *MNRAS*, 502, 564
- Arzoumanian, D., André, P., Peretto, N., & Könyves, V. 2013, *A&A*, 553, A119
- Bally, J., Ginsburg, A., Forbrich, J., & Vargas-González, J. 2020, *ApJ*, 889, 178
- Beuther, H., Gieser, C., Suri, S., et al. 2021, *A&A*, 649, A113
- Bell, T. A., Cernicharo, J., Viti, S., et al. 2014, *A&A*, 564, A114
- Benjamin, R. A., Churchwell, E., Babler, B. L., et al. 2003, *PASP*, 115, 953
- Bertoldi, F., & McKee, C. F. 1992, *ApJ*, 395, 140
- Bhadari, N. K., Dewangan, L. K., Pirogov, L. E., & Ojha, D. K. 2020, *ApJ*, 899, 167
- Cantat-Gaudin, T., Jordi, C., Wright, N. J., et al. 2019, *A&A*, 626, A17
- Cao, Y., Qiu, K., Zhang, Q., & Li, G.-X. 2022, *ApJ*, 927, 106
- Caselli, P., Walmsley, C. M., Zucconi, A., et al. 2002, *ApJ*, 565, 344
- Chen, H.-R. V., Zhang, Q., Wright, M. C. H., et al. 2019, *ApJ*, 875, 24
- Chen, X., Ren, Z.-Y., Li, D.-L., et al. 2021, *ApJL*, 923, L20
- Ching, T.-C., Lai, S.-P., Zhang, Q., et al. 2018, *ApJ*, 865, 110
- Churchwell, E., Babler, B. L., Meade, M. R., et al. 2009, *PASP*, 121, 213
- Clarke, S. D., & Whitworth, A. P. 2015, *MNRAS*, 449, 1819
- Clarke, S. D., Whitworth, A. P., Spowage, R. L., et al. 2018, *MNRAS*, 479, 1722
- Dharmawardena, T. E., Bailer-Jones, C. A. L., Fouesneau, M., et al. 2022, arXiv e-prints, arXiv:2210.03615
- Duan, Y., Li, D., Goldsmith, P. F., et al. 2023, *ApJ*, 943, 182
- Ducourant, C., Teixeira, R., Krone-Martins, A., et al. 2017, *A&A*, 597, A90
- Fernandes, B., Montmerle, T., Santos-Silva, T., & Gregorio-Hetem, J. 2019, *A&A*, 628, A44
- Galli, P. A. B., Bouy, H., Olivares, J., et al. 2020, *A&A*, 643, A148
- Gerner, T., Beuther, H., Semenov, D., et al. 2014, *A&A*, 563, A97
- Getman, K. V., Feigelson, E. D., Kuhn, M. A., & Garmire, G. P. 2019, *MNRAS*, 487, 2977
- Großschedl, J. E., Alves, J., Meingast, S., et al. 2018, *A&A*, 619, A106
- Gupta, A., & Chen, W.-P. 2022, *AJ*, 163, 233
- Ha, T., Li, Y., Kounkel, M., et al. 2022, *ApJ*, 934, 70
- Ha, T., Li, Y., Xu, S., Kounkel, M., & Li, H. 2021, *ApJL*, 907, L40
- Hacar, A., Tafalla, M., & Alves, J. 2017, *A&A*, 606, A123
- Henshaw, J. D., Caselli, P., Fontani, F., Jiménez-Serra, I., & Tan, J. C. 2014, *MNRAS*, 440, 2860
- Herczeg, G. J., Kuhn, M. A., Zhou, X., et al. 2019, *ApJ*, 878, 111
- Hu, B., Qiu, K., Cao, Y., et al. 2021, *ApJ*, 908, 70

- Jerabkova, T., Boffin, H. M. J., Beccari, G., & Anderson, R. I. 2019, MNRAS, 489, 4418
- Kim, D., Lu, J. R., Konopacky, Q., et al. 2019, ApJ, 927, 106
- Kounkel, M., Stassun, K. G., Covey, K., & Hartmann, L. 2022, MNRAS, 517, 161
- Kraus, A. L., Herczeg, G. J., Rizzuto, A. C., et al. 2017, ApJ, 838, 150
- Krolikowski, D. M., Kraus, A. L., & Rizzuto, A. C. 2021, AJ, 162, 110
- Kuhn, M. A., Hillenbrand, L. A., Carpenter, J. M., & Avelar Menendez, A. R. 2020, ApJ, 899, 128
- Li, D., Kauffmann, J., Zhang, Q., & Chen, W. 2013, ApJL, 768, L5
- Li, S., Sanhueza, P., Lee, C. W., et al. 2022, ApJ, 926, 165
- Liu, H.-L., Tej, A., Liu, T., et al. 2022, MNRAS, 511, 4480
- Liu, T., Evans, N. J., Kim, K.-T., et al. 2020, MNRAS, 496, 2790
- Liu, T., Li, P. S., Juvela, M., et al. 2018, ApJ, 859, 151
- McKee, C. F., & Ostriker, E. C. 2007, ARA&A, 45, 565
- Megeath, S. T., Gutermuth, R., Muzerolle, J., et al. 2012, AJ, 144, 192
- Montillaud, J., Juvela, M., Vastel, C., et al. 2019, A&A, 631, A3
- Ostriker, J. 1964, ApJ, 140, 1056
- Peretto, N., Fuller, G. A., Duarte-Cabral, A., et al. 2013, A&A, 555, A112
- Punanova, A., Caselli, P., Pineda, J. E., et al. 2018, A&A, 617, A27
- Quintana, A. L., & Wright, N. J. 2022, MNRAS, 515, 687
- Ren, Z., Zhu, L., Shi, H., et al. 2021, MNRAS, 505, 5183
- Rivera-Ortiz, P. R., Rodríguez-González, A., Cantó, J., & Zapata, L. A. 2021, ApJ, 916, 56
- Roccatagliata, V., Franciosini, E., Sacco, G. G., Randich, S., & Sicilia-Aguilar, A. 2020, A&A, 638, A85
- Sharma, E., Gopinathan, M., Soam, A., et al. 2020, A&A, 639, A133
- Shimajiri, Y., André, P., Ntormousi, E., et al. 2019, A&A, 632, A83
- Stutz, A. M., & Gould, A. 2016, A&A, 590, A2
- Swiggum, C., D'Onghia, E., Alves, J., et al. 2021, ApJ, 917, 21
- Szegedi-Elek, E., Kun, M., Móor, A., Marton, G., & Reipurth, B. 2019, MNRAS, 484, 1800
- Tobin, J. J., Hartmann, L., Furesz, G., Mateo, M., & Megeath, S. T. 2009, ApJ, 697, 1103
- Tu, A. J., Zucker, C., Speagle, J. S., et al. 2022, ApJ, 936, 57
- Walsh, A. J., Burton, M. G., Hyland, A. R., & Robinson, G. 1998, MNRAS, 301, 640
- Ward, J. L., Kruijssen, J. M. D., & Rix, H.-W. 2020, MNRAS, 495, 663
- Xie, J., Fuller, G. A., Li, D., et al. 2021, arXiv e-prints, arXiv:2103.12985
- Zamora-Avilés, M., Ballesteros-Paredes, J., Hernández, J., et al. 2019, MNRAS, 488, 3406

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.