Characterizing filaments in regions of high-mass star formation: High-resolution submillimeter imaging of the massive star-forming complex NGC 6334 with ArTéMiS

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Context. Herschel observations of nearby molecular clouds suggest that interstellar filaments and prestellar cores represent two fundamental steps in the star formation process. The observations support a picture of low-mass star formation according to which ~0.1 pc-wide filaments form first in the cold interstellar medium, probably as a result of large-scale compression of interstellar matter by supersonic turbulent flows, and then prestellar cores arise from gravitational fragmentation of the densest filaments. Whether this scenario also applies to regions of high-mass star formation is an open question, in part because the resolution of Herschel is insufficient to resolve the inner width of filaments in the nearest regions of massive star formation.

Aims. In an effort to characterize the inner width of filaments in high-mass star forming regions, we imaged the central part of the NGC6334 complex at a factor of >3 higher resolution than Herschel at 350 μm.

Methods. We used the large-format bolometer camera ArTéMiS on the APEX telescope and combined the high-resolution ArTéMiS data at 350 μm with Herschel/HOBYS data at 70–500 μm to ensure good sensitivity to a broad range of spatial scales. This allowed us to study the structure of the main narrow filament of the complex with a resolution of 8′′ or <0.07 pc at ∼1.7 kpc.

Results. Our study confirms that this filament is a very dense, massive linear structure with a line mass ranging from ~ 500 M☉/pc to ~2 000 M☉/pc over nearly 10 pc. It also demonstrates for the first time that its inner width remains as narrow as W ∼ 0.15 ± 0.05 pc all along the filament length, within a factor of <2 of the characteristic 0.1 pc value found with Herschel for lower-mass filaments in the Gould Belt.

Conclusions. While it is not completely clear whether the NGC 6334 filament will form massive stars or not in the future, it is two to three orders of magnitude denser than the majority of filaments observed in Gould Belt clouds, and yet has a very similar inner width. This points to a common physical mechanism for setting the filament width and suggests that some important structural properties of nearby clouds also hold in high-mass star forming regions.

Key words. stars: formation – stars: circumstellar matter – ISM: clouds – ISM: structure – ISM: individual objects (NGC 6334) – submillimeter

1. Introduction

Understanding star formation is a fundamental issue in modern astrophysics (e.g., McKee & Ostriker 2007). Very significant observational progress has been made on this topic thanks to far-infrared and submillimeter imaging surveys with the Herschel Space Observatory. In particular, the results from the Herschel “Gould Belt” survey (HGBS) confirm the omnipresence of filaments in nearby clouds and suggest an intimate connection between the filamentary structure of the interstellar medium (ISM) and the formation process of low-mass prestellar cores (André et al. 2010). While molecular clouds were already known to exhibit large-scale filamentary structures for quite some time (e.g., Schneider & Elmegreen 1979, Myers 2009, and references therein), Herschel observations now demonstrate that these filaments are truly ubiquitous in the cold ISM (e.g., Molinari et al. 2010, Henning et al. 2010, Hill et al. 2011), probably make up a dominant fraction of the dense gas in molecular clouds (e.g., Schisano et al. 2014, Könyves et al. 2015), and present a high degree of universality in their properties (e.g., Arzoumanian et al. 2011). Therefore, interstellar filaments likely play a central role in the star formation process (e.g., André et al. 2014). A detailed analysis of their radial column density profiles shows that, at least in the nearby clouds of the Gould Belt, filaments are characterized by a very narrow distribution of inner widths W with a typical FWHM value ∼0.1 pc (much larger than the ~0.01 pc resolution provided by Herschel at the distance ~140 pc of the nearest clouds) and a dispersion of less than a factor of 2 (Arzoumanian et al. 2011, Koch & Rosolowsky 2015). The origin of this common inner width of interstellar filaments is not yet well understood. A possible interpretation is that it corresponds to the sonic scale below which interstellar turbulence becomes subsonic in diffuse, non-star-forming molecular gas (cf., Padoan et al. 2001, Federrath 2016). Alternatively, this
characteristic inner width of filaments may be set by the dissipation mechanism of magneto-hydrodynamic (MHD) waves (e.g. Hennebelle & André 2013). A possible manifestation of such MHD waves may actually have been found in the form of braided velocity-coherent substructure in the case of the Taurus B211–3 filament (Hacar et al. 2013). Another major result from Herschel in nearby clouds is that most (> 75%) low-mass prestellar cores and protostars are found in dense, “supercritical” filaments for which the mass per unit length $M_{\text{line}}$ exceeds the critical line mass of nearly isothermal, long cylinders (e.g. Inutsuka & Miyama 1997). $M_{\text{line, crit}} = 2c_s^2/G \sim 16 M_\odot/\text{pc}$, where $c_s \sim 0.2 \text{Kms}$ is the isothermal sound speed for molecular gas at $T \sim 10 \text{ K}$ (e.g. Könyves et al. 2015). These Herschel findings support a scenario for low-mass star formation in two main steps (cf. André et al. 2014). First, large-scale compression of interstellar material in supersonic MHD flows generates a cobweb of ~ 0.1 pc-wide filaments in the ISM; second, the densest filaments fragment into prestellar cores (and subsequently protostars) by gravitational instability above $M_{\text{line, crit}}$, while simultaneously growing in mass through accretion of background cloud material.

In addition to the relatively modest filaments found in non star forming and low-mass star forming clouds, where $M_{\text{line}}$ rarely exceeds ten times the thermal value of $M_{\text{line, crit}}$, significantly denser and more massive filamentary structures have also been observed in the most active giant molecular clouds (GMCs) of the Galaxy, and may be the progenitors of young massive star clusters. The DR21 main filament or “ridge” is probably the most emblematic case of such a massive elongated structure with about 20000 $M_\odot$ inside a 4.5 pc long structure (i.e., $M_{\text{line}} \sim 4500 M_\odot/\text{pc}$) (Motte et al. 2007; Schneider et al. 2010; Hennemann et al. 2012). Other well-known ridges include Orion A (Hartmann & Burkert 2007), Vela-C (Hill et al. 2011, 2012), IRDC G035.39–00.33 (Nguyen Luong et al. 2011), and W43-MM1 (Nguyen Luong et al. 2013). The NGC 6334 filament has a line mass approaching $M_{\text{line}} \sim 1000 M_\odot/\text{pc}$ and features column densities close to or above $10^{23} \text{cm}^{-2}$ over about 10 pc along its length (e.g. Matthews et al. 2008; Zernickel et al. 2013).

Here, we report the results of high-resolution (~’8”) 350 µm dust continuum mapping observations of the central part of NGC 6334 with the ArTéMiS bolometer camera on the APEX 12-m telescope. The ~’8” resolution of ArTéMiS at 350 µm, corresponding to ~ 0.068 pc at the distance of NGC 634, has allowed us to resolve, for the first time, the transverse size of the main filament in this complex. Section 2 describes the instrument and provides details about the observing run and data reduction. Section 3 presents our mapping results, which are discussed in Section 4.

2. ArTéMiS observations and data reduction

Our 350 µm observations of NGC 6334 were obtained in July–September 2013 and June 2014 with the ArTéMiS camera on the Atacama Pathfinder Experiment (APEX) telescope located at an altitude of 5100 m at Llano de Chajnantor in Chile. ArTéMiS is a large-format bolometer array camera, built by CEA/Saclay and installed in the Cassegrain cabin of APEX, which will eventually have a total of 4608 pixels observing at 350 µm and 450 µm simultaneously (Talvard et al. 2010; Reveret al. 2014). ArTéMiS employs the technology successfully developed by CEA for the PACS photometer instrument in the 60–210 µm wavelength regime on the Herschel Space Observatory (e.g. Billot et al. 2006). Unlike the LABOCA camera on APEX, the ArTéMiS instrument does not use feedhorns to concentrate the incoming submillimeter radiation, but planar bare arrays of 16 × 18 silicon bolometer pixels each which act like a CCD camera does in the optical domain. The 2013 and 2014 incarnations of ArTéMiS used for these observations were equipped with a 350 µm focal plane of four and eight such sub-arrays of 16 × 18 pixels, respectively. The number of working pixels was about 1050 in 2013 and 1650 in 2014. The instantaneous field of view of the camera was ~ 2.1’ × 2.4’ in 2013 and ~ 4.3’ × 2.4’ in 2014, and was essentially fully sampled. ArTéMiS features a closed-cycle cryogenic system built around a pulse tube cooler (40 K and 4 K) coupled to a double stage helium sorption cooler (~ 300 mK). During the 2013 and 2014 observing campaigns, the typical hold time of the cryostat at 260 mK between two remote recycling procedures at the telescope was > 48 hours.

A total of 35 individual maps, corresponding to a total telescope time of ~ 13 hr (excluding pointing, focusing, and calibration scans), were obtained with ArTéMiS at 350 µm toward the NGC 6334 region using a total-power, on-the-fly scanning mode. Each of these maps consisted in a series of scans taken either in Azimuth or at a fixed angle with respect to the Right Ascension axis. The scanning speed ranged from 20′′/sec to 30′′/sec and the cross-scan step between consecutive scans from 3′′ to 10′′.

1 See http://www.apex-telescope.org/instruments/pi/artemis/ArTéMiS stands for “Architecture de bolomètres pour des Télèspectromètres à grand champ de vue dans le domaine sub-Millimétrique au Sol” in French.
The sizes of the maps ranged from 3.5′ × 3.5′ to 11.5′ × 10′. The atmospheric opacity at zenith was measured using skydips with ArTeMiS and was found to vary between 0.45 and 1.85 at λ = 350 μm. This is equivalent to an amount of precipitable water vapor (PWV) from ∼ 0.25 mm to ∼ 0.9 mm with a median value of 0.53 mm. The median elevation of NGC 6334 was ∼ 58° corresponding to a median airmass of 1.18.

A dedicated pointing model was derived for ArTeMiS after the first days of commissioning observations in July 2013 and was found to yield good results (3′′ overall rms error) throughout the ArTeMiS observing campaign. Absolute calibration was achieved by taking both short ‘spiral’ scans and longer on-the-fly beam maps of the primary calibrators Mars and Uranus. During the mapping of NGC 6334, regular pointing, focus, and calibration checks were made by observing ‘spiral’ scans of the nearby secondary calibrators G5.89, G10.47, G10.62, and IRAS 16293. The maximum deviation observed between two consecutive pointing checks was ∼ 3′′. The absolute pointing accuracy is estimated to be ∼ 3′′ and the absolute calibration uncertainty to be ∼ 30%.

The median value of the noise equivalent flux density (NEFD) per detector was ∼ 600 mJy s^{1/2}, with best pixel values at ∼ 300 mJy s^{1/2}. The pixel separation between detectors on the sky was ∼ 3.9′, corresponding to Nyquist spacing at 350 μm. As estimated from our maps of Mars, the main beam had a full width at half maximum (FWHM) of 8.0 ± 0.1′ and contained ∼ 70% of the power, the rest being distributed in an “error beam” extending up to an angular radius of ∼ 40′ (see blue solid curve in Fig. 3 in Sect. 3 below for the beam profile).

Online data reduction at the telescope was performed with the BoA software developed for LABOCA (Schuller 2012). Offline data reduction, including baseline subtraction, removal of correlated sky noise and 1/f noise, and subtraction of uncorrelated 1/f noise was performed with in-house IDL routines, including tailored versions of the Scanamorphos software routines which exploit the redundancy in the mapping raw data, especially data taken with filled arrays. The Scanamorphos algorithm, as developed to process Herschel observations, is described in depth in Rousset (2013). To account for the specificities of the observations discussed here, it had to be modified. The destriping step for long scans had to be deactivated, as well as the average drift subtraction in scans entirely filled with sources, and a sophisticated filter had to be applied to subtract the correlated sky noise. This filter involves a comparison between the signal of all sub-arrays at each time, and a protection of compact sources by means of a mask initialized automatically, and checked manually.

3. Mapping results and radial profile analysis

By co-adding the 35 individual ArTeMiS maps of NGC 6334, we obtained the 350 μm mosaic shown in Fig. 1. The typical rms noise in this mosaic is σ ∼ 0.2 Jy/8′′-beam. As usual with total-power ground-based submillimeter continuum observations, the ArTeMiS raw data were affected by a fairly high level of sky noise, strongly correlated over the multiple detectors of the focal plane. Because of the need to subtract this correlated sky noise to produce a meaningful image, the mosaic of Fig. 1 is not sensitive to angular scales larger than the instantaneous
field of view of the camera ~ 2'. The large-scale background intensity (e.g. zero level) in the image of Fig. 1 is therefore not constrained by the ArTeMiS observations and has been arbitrarily set to a small positive value (corresponding approximately to ~ 5σr) to facilitate the display using a logarithmic intensity scale. To restore the missing large-scale information, we combined the ArTeMiS data with the SPIRE 350 µm data from the Herschel/HOBYS key project (Motte et al. 2010; Russell et al. 2013) employing a technique similar to that used in combining millimeter interferometer observations with single-dish data. In practice, this combination was achieved with the task “immerge” in the Miriad software package (Sault et al. 1995). Immerge combines two datasets in the Fourier domain after determining an optimum calibration factor to align the flux scales of the two input images in a common annulus of the uv plane. Here, a calibration factor of 0.75 had to be applied to the original ArTeMiS image to match the flux scale of the SPIRE 350 µm image over a range of baselines from 0.6 m (the baseline b sensitive to angular scales b/λ ~ 2’ at 350 µm) to 3.5 m (the diameter of the Herschel telescope). The magnitude of this factor is consistent with the absolute calibration uncertainty of ~ 30% quoted in Sect. 2. The resulting combined 350 µm image of NGC 6334 has an effective resolution of ~ 8″ (FWHM) and is displayed in Fig. 1b.

To determine the location of the crest of the main filament in NGC 6334, we applied the DisPerSE algorithm (Sousbie 2011) to the combined 350 µm image. The portion of the filament analyzed in some detail below was selected so as to avoid the confusing effects of massive young stars and protostellar “massive dense cores” (MDCs) (cf. Tige et al. 2016). It nevertheless includes one candidate starless MDC at its northern end (see Fig. 2c). The corresponding crest is shown as a magenta solid curve in Fig. 1b.

By taking perpendicular cuts at each pixel along the crest, we constructed radial intensity profiles for the main filament. The western part of the resulting median radial intensity profile is displayed in log-log format in Fig. 3. Since at least in projection there appears to be a gap roughly in the middle of the filament crest (cf. Fig. 1), we also divided the filament into two parts, a northern and a southern segment, shown by the white and the magenta curve in Fig. 2a, respectively. The gap between the two segments may have been created by an HII region visible at near-infrared wavelengths with the ESO VISTA telescope (see ESO photo release http://www.eso.org/public/images/eso1341a – Credit: ArTeMiS team/ESO/J. Emerson/VISTA).

$$I_c(r) = I_0 \times \exp \left[ -4 \ln 2 \times \left( \frac{r}{FWHM} \right)^2 \right] + I_{Bg},$$

and a Plummer-like model function of the form:

$$I_p(r) = \frac{I_0}{\left[ 1 + \left( \frac{r}{R_{Pl}} \right)^2 \right]^{1/2}} + I_{Bg},$$

where $I_c(r)$ and $I_p(r)$ are, respectively, the crest and profile intensities, $I_0$ is the maximum intensity, $R_{Pl}$ is the Plummer radius, and $I_{Bg}$ is the background intensity.

Following Arzoumanian et al. (2011) and Palmeirim et al. (2013) we fitted each radial profile $I(r)$ observed as a function of radius $r$ with both a simple Gaussian model:
where $I_0$ is the central peak intensity, $\text{FWHM}$ is the physical FWHM width of the Gaussian model, $R_{\text{flat}}$ the characteristic radius of the flat inner part of the model profile, $p > 1$ is the power-law index of the underlying density profile (see below), and $I_{BG}$ is a constant background level. The above functional forms were convolved with the approximately Gaussian beam of the ArTéMiS data ($\text{FWHM} \sim 8''$) prior to comparison with the observed profile. The best-fit Gaussian and Plummer-like models for the median radial intensity profile observed on the western side of the entire filament are shown by the blue dotted and red dashed curves in Fig. 3, respectively. Note that only the inner part of the radial profile was fitted by a Gaussian model since the observed profile includes an approximately power-law wing which cannot be reproduced by a Gaussian curve (cf. Fig. 3b). In practice, a background level was first estimated as the intensity level observed at the closest point to the filament’s crest for which the logarithmic slope of the radial intensity profile $d \ln I / d \ln r$ became significantly positive. This allowed us to obtain a crude estimate of the width of the profile at half power above the background level, and the observed profile was then fitted with a Gaussian model over twice this initial width estimate. The deconvolved diameter of the best-fit Gaussian model is $\text{FWHM} = 0.15 \pm 0.02 \text{pc}$ and the diameter of the inner plateau in the best-fit Plummer model is $2 R_{\text{flat}} = 0.11 \pm 0.03 \text{pc}$. The power-law index of the best-fit Plummer model is $p = 2.2 \pm 0.3$. Assuming optically thin dust emission at $350 \mu \text{m}$ and using the dust temperature map derived from Herschel data at 36.3'' resolution (Russell et al. 2013; Tigé et al. 2016), we also converted the $350 \mu \text{m}$ image of Fig. 1b (I$_{350}$) into an approximate column density image (see Fig. 2b) from the simple relation $N_{H_2} = I_{350}/(B_{350}T_d[\kappa_{350}I_{350}])$, where $B_{350}$ is the Planck function, $T_d$ the dust temperature, $\kappa_{350}$ the dust opacity at $\lambda = 350 \mu \text{m}$, and $\mu_1 = 2.8$ the mean molecular weight. We adopted the same dust opacity law as in our HGBS and HOBYS papers: $\kappa_\lambda = 0.1 \times (\lambda/300 \mu \text{m})^{-\beta} \text{ cm}^2 \text{ g}^{-1}$ (of gas + dust) with an emissivity index $\beta = 2$ (Hildebrand 1983; Roy et al. 2014). The $y$-axis shown on the right of Fig. 3a gives an approximate column density scale derived in this way for the median radial profile of the filament assuming a uniform temperature $T_d = 20$ K, which corresponds to the median dust temperature derived from Herschel data along the crest of the filament. We also derived and fitted a median radial column density profile for the filament directly using the column density map (see Fig. A.5 in Appendix A). The results of our radial profile analysis for the whole filament and its two separate segments are summarized in Table 1, which also provides a comparison with similar measurements reported in the recent literature for four other well-documented filaments.

We stress that the presence of cores along the filament has virtually no influence on the results reported in Table 1. First, as already mentioned the portion of the filament selected here contains only one candidate starless MDC at the northern end (cf. Tigé et al. 2016), and the width estimates are unchanged when the immediate vicinity of this object is excluded from the analysis (see also Fig. 3). Second, low-mass prestellar cores typically contribute only a small fraction ($\leq 15\%$) of the mass of dense filaments (e.g. Könyves et al. 2015). Third, we performed the same radial profile analysis on a source-subtracted image generated by getsources (Men'shchikov et al. 2012) and obtained very similar results.

One advantage of the Plummer-like functional form in Eq. (2) is that, when applied to a filament column density profile

\[ \text{Column density} N_{H_2} = I_{350}/(B_{350}T_d[\kappa_{350}I_{350}]) \]
Table 1. Derived properties of the NGC 6334 filament and comparison with other well-documented filaments

| Filament        | \( \langle M_{\text{line}} \rangle \) \(^a\) (M\(_{\odot}\)/pc) | \( ⟨N_H^d⟩ \) \(^b\) (cm\(^{-2}\)) | \( N_{H_2}^c \) (pc) | \( p^d\) | \( R_{\text{flat}}^e\) (pc) | Width, \( W^f\) (pc) | Length (pc) | Refs |
|-----------------|-------------------------------------------------|---------------------------------|-----------------|---------|----------------|----------------|-------------|------|
| NGC 6334 north-south (western side) | 800–1300 | 1–2×10\(^{22}\) | 1.8 × 10\(^2\) | 2.2 ± 0.3 | 0.05 ± 0.01 | 0.15 ± 0.03 | > 7 | 1 |
| NGC 6334 north-south (eastern side) | (900–1300) | (1–2×10\(^{22}\)) | (2–4×10\(^2\)) | (1.9 ± 0.4) | (0.05 ± 0.02) | (0.19 ± 0.03) | > 7 | 1 |
| NGC 3343 north (western side) | 1600 | 2.5 × 10\(^{23}\) | 2.1 × 10\(^2\) | 2.4 ± 0.3 | 0.06 ± 0.02 | 0.15 ± 0.03 | > 3.5 | 1 |
| NGC 3343 north (eastern side) | (800–1600) | (1.5–2.5×10\(^{23}\)) | (1.1 × 10\(^2\)) | – | – | (0.20 ± 0.03) | > 3.5 | 1 |
| NGC 3343 south (western side) | 500–600 | 0.7–1×10\(^{23}\) | 1.2 × 10\(^2\) | (2.3 ± 0.3) | (0.07 ± 0.02) | 0.16 ± 0.04 | ~ 3 | 1 |
| NGC 3343 south (eastern side) | 700–2000 | 0.9–1×10\(^{23}\) | 1.2 × 10\(^2\) | 1.8 ± 0.3 | 0.09 ± 0.02 | 0.16 ± 0.04 | ~ 3 | 1 |
| Vela C\(^b\) | 320–400 | 8.6 × 10\(^{22}\) | 3.6 × 10\(^1\) | 2.7 ± 0.2 | 0.05 ± 0.02 | 0.12 ± 0.02 | 4 | 2 |
| Serpens South | 290 | 6.4 × 10\(^{22}\) | 3.7 × 10\(^1\) | 2.0 ± 0.3 | 0.03 ± 0.01 | 0.10 ± 0.05 | 2 | 3 |
| Taurus B211/B213 | 50 | 1.5 × 10\(^{22}\) | 0.7 × 10\(^1\) | 2.0 ± 0.3 | 0.03 ± 0.02 | 0.09 ± 0.02 | > 5 | 4 |
| Musca | 20 | 4.2 × 10\(^{21}\) | 0.8 × 10\(^1\) | 2.2 ± 0.3 | 0.08 | 0.14 ± 0.03 | 10 | 5, 6 |

Notes. Values given in parentheses are more uncertain due to, e.g., large error bars in the corresponding filament properties, and should be understood as being only indicative.

\(^{(a)}\) Average mass per unit length of the cylindrical filament derived from one-sided integration of the observed radial column density profile after background subtraction. The actual mass per unit length of each filament segment corresponds to the mean of the eastern-side and western-side values (not explicitly given here). The outer radius of integration was 0.7 pc on the western side, 0.3 pc on the eastern side of the northern segment, and 1.4 pc on the eastern side of the southern segment, respectively, corresponding to the radius where the background starts to dominate (see Figs. A.1–A.3).

\(^{(b)}\) Average value of the central column density derived along the filament crest after background subtraction. Typical uncertainties are a factor \(\sim 1.5–2\) for values < 10\(^3\) cm\(^{-2}\) and a factor \(\sim 2–3\) for values > 10\(^5\) cm\(^{-2}\), dominated by uncertainties in the dust opacity and in the distribution of dust temperature along the line of sight (Roy et al. 2014).

\(^{(c)}\) Background column density. This is estimated as the column density observed at the closest point to the filament’s crest for which the logarithmic slope of the radial column density profile d ln \(N_H\)/d ln r becomes positive.

\(^{(d)}\) Power-law index of the best-fit Plummer model [see Eq. (2)].

\(^{(e)}\) Radius of the flat inner plateau in the best-fit Plummer model [see Eq. (2)].

\(^{(f)}\) Deconvolved FWHM width from a Gaussian fit to the inner part of the filament profile.

\(^{(g)}\) The eastern side of the radial column density profile of the northern filament is poorly constrained due to confusion with the two massive protostellar clumps NGC 6334 I and I(N) (cf. Fig. 2a); no meaningful Plummer fit is possible.

\(^{(h)}\) According to Minier et al. (2013), the Vela C filament is not a simple linear structure or “ridge”, but is part of a more complex ring-like structure at least partly shaped by ionization associated with the RCW 36 HII region.

References. (1) this paper; (2) Hill et al. (2012); (3) Könyves et al. (2015); (4) Palmeirim et al. (2013); (5) Cox et al. (2016); (6) Kainulainen et al. (2016).

\((I_0 \text{ becoming } N_{H_2,0}, \text{ the central column density}), \) it directly informs about the underlying volume density profile, which takes a similar form, \(n_{H_2}(r) = n_{H_2,0} \left[ \frac{r}{R_{\text{flat}}} \right]^{0.5} \), where \(n_{H_2,0}\) is the central volume density of the filament. The latter is related to the projected central column density \(N_{H_2,0}\) by the simple relation, \(n_{H_2,0} = N_{H_2,0} / (A_p R_{\text{flat}})\), where \(A_p = \frac{1}{3} \cos^2 i \times B \left( \frac{2}{H_2,0} \right) \) is a constant factor taking into account the filament’s inclination angle to the plane of the sky, and \(B\) is the Euler beta function (cf. Palmeirim et al. 2013). Here, assuming \(i = 90^\circ\), we estimate the mean central density to be \(n_{H_2,0} \sim 2.2 \times 10^5 \text{ cm}^{-3}, \sim 5 \times 10^5 \text{ cm}^{-3}\), and \(\sim 1.5 \times 10^5 \text{ cm}^{-3}\) in the entire filament, the northern segment, and the southern segment, respectively.

4. Discussion and conclusions

Our ArTeMiS mapping study confirms that the main filament in NGC 6334 is a very dense, massive linear structure with \(M_{\text{line}}\) ranging from \(\sim 500 M_{\odot}/\text{pc}\) to \(\sim 2000 M_{\odot}/\text{pc}\) over nearly 10 pc, and demonstrates for the first time that its inner width remains as narrow as \(W \sim 0.15 \pm 0.04\) pc all along the filament length (see Fig. 3b), within a factor of \(< 2\) of the characteristic 0.1 pc value found by Arzoumanian et al. (2011) for lower-density nearby filaments in the Gould Belt.

While the NGC 6334 filament is highly supercritical, and of the same order of magnitude in line mass as high-mass star-forming ridges such as DR21 (Schneider et al. 2010; Hennebmann et al. 2012), it is remarkably simple and apparently consists of only a single, narrow linear structure. In contrast, a massive ridge is typically resolved into a closely packed network of sub-filaments and “massive dense cores” (MDCs) (Motte et al. 2016). This is at variance with the NGC 6334 filament which exhibits a surprisingly low level of fragmentation. The maximum relative column density fluctuations observed along its long axis (cf. black curve in Fig. 3b) are only marginally non-linear (\(\delta N_{H_2}/(N_{H_2}) \approx 1\)), while for instance most of the supercritical low-mass filaments analyzed by Roy et al. (2015) have stronger fluctuations (with \(\delta N_{H_2}/(N_{H_2}) \) up to \(\sim 2–5\)). Most importantly, the NGC 6334 filament harbors no MDC, except perhaps at its two extremities (Tigé et al. 2016, see Fig. 4a). It is therefore unclear whether the filament will form high-mass stars or not. On the one hand, the lack of MDCs suggests that the filament may not form any massive stars in the near future. On the other hand, the presence of a compact HII region (radio source

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C from [Rodriguez et al. 1982] at the north-east end of the southern part of the filament, near the gap between the two filament segments (see Fig. 2), suggests that it may have already formed massive stars in the past. Based on observations in the HCO+(3–2) and H13CO+(1–0) lines with APEX and MOPRA, Zernickel et al. (2013) showed that the filament is coherent in velocity and found a velocity gradient of ∼2 km s⁻¹/pc from both ends of the filament toward its center. They proposed that the whole filament is in a state of global collapse along its long axis toward its center (estimated to be close to the gap between the two segments in Fig. 2). This proposal is qualitatively consistent with the identification of candidate MDCs at the two ends of the filament (Tigges et al. 2010), and with the theoretical expectation that the longitudinal collapse of a finite filament is end-dominated due to maximal gravitational acceleration at the edges (e.g., Burkert & Hartmann 2003; Clarke & Whitworth 2015). It is difficult, however, to explain the presence of HII regions – significantly more evolved than MDCs – near the central gap in this picture, unless these HII regions did not form in the filament but in the vicinity and disrupted the central part of the filament.

The low level of fragmentation poses a challenge to theoretical models since supercritical filaments are supposed to contract radially and fragment along their length in only about one free-fall time or ∼4.5–8×10⁴ yr in the present case (e.g., Inutsuka & Miyama 1997). One possibility is that the NGC 6334 filament is observed at a very early stage after its formation by large-scale compression. Another possibility is that the filament is “dynamically” supported against rapid radial contraction and longitudinal fragmentation by accretion-driven MHD waves (cf. Hennebelle & André 2013). The average one-dimensional velocity dispersion σ in estimated from the 40'' resolution N2H+(1–0) observations of the MALTA90 survey with the MOPRA telescope (Jackson et al. 2013) is ∼1.1 km/s in the northern part of the filament and ∼0.7 km/s in the southern segment. Compared to the sound speed c_s ∼0.3 km/s given an estimated gas temperature T ∼20–25 K, this velocity dispersion is supersonic by a factor ∼2–4, implying that there may be significant velocity structure (such as the presence of several sonic velocity components – cf. Fiege & Pudritz 2000), which is consistent with the filament being within a factor of 2 of virial balance. A static magnetic field can easily modify M©/ by a factor of 2 (cf. Fiege & Pudritz 2000), and a significant static field component perpendicular to the long axis of the filament would help to resist collapse and fragmentation along the filament. Higher-resolution observations in molecular line tracers of dense gas would be needed to investigate whether the NGC 6334 filament contains a bundle of intertwined velocity-coherent fibers similar to the fibers identified by [Hacar et al. 2013] in the low-mass B211–3 filament in Taurus. The detection of such braided-like velocity substructure may provide indirect evidence of the presence of internal MHD waves.

In any case, and regardless of whether the NGC 6334 filament will form massive stars or not, our ArTeMiS result shows that the filament inner width is within a factor of 2 of 0.1 pc having interesting implications. Our NGC 6334 study is clearly insufficient to prove that interstellar filaments have a truly universal inner width, but it shows that the finding obtained with Herschel in nearby clouds is not limited to filaments in low-mass star forming regions. It is quite remarkable that the NGC 6334 filament has almost the same inner width as the faint subcritical filaments in Polaris (cf. Men'shchikov et al. 2010 [Arzoumanian et al. 2011]), the marginally supercritical filaments in Musca and Taurus (Cox et al. 2016 [Palmeirim et al. 2013]), or the lower-mass supercritical filaments in Serpens South and Vela C (Hill et al. 2012), despite being three orders of magnitude, and at least a factor of ∼3 denser and more massive than these filaments, respectively (see Table 1). While not all of these filaments may have necessarily formed in the same way, this suggests that a common physical mechanism is responsible for setting the filament width at the formation stage and that the subsequent evolution of dense filaments – through, e.g., accretion of background cloud material (cf. Heitsch 2013; Hennebelle & André 2013) – is such that the inner width remains at least approximately conserved with time. A promising mechanism for creating dense filaments, which may be quite generic especially in massive star-forming complexes, is based on multiple episodes of large-scale supersonic compression due to the interaction of expanding bubbles (Inutsuka et al. 2015). With about 7 bubble-like HII regions per square degree (Russel et al. 2013) see also Fig. 2, there is ample opportunity for this mechanism to operate in NGC 6334. More specifically, at least in projection, the NGC 6334 filament appears to be part of an arc-like structure centered on the HII region Gum 63 (see Fig. 2a), suggesting the filament may partly result from the expansion of the associated bubble. Interestingly, the background column density is one order of magnitude higher for the NGC 6334 filament than for the other filaments of Table 1 which is suggestive of a significantly stronger compression. Further observational studies will be needed to investigate the structure and environment of a larger number of filaments in massive star forming regions, and will determine whether the characteristics of the NGC 6334 filament are generic or not. More theoretical work is also needed to better understand the physics controlling the width of interstellar filaments.

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Appendix A: Additional radial profiles
Fig. A.1. (a) Median radial intensity profile of the northern part of the NGC 6334 filament (black solid curve) measured in the combined ArTeMiS + SPIRE 350 µm image (Fig. 1b) perpendicular to, and on the eastern side of, the filament crest shown as a white curve in Fig. 2. The yellow and green error bars are as in Fig. 3a. The blue solid curve shows the effective beam profile of the ArTeMiS 350 µm data as measured on Mars, on top of a constant level corresponding to the typical background intensity level observed at large radii. The blue dotted curve shows the best-fit Gaussian (+ constant offset) model to the inner part of the observed profile. The red dashed curve shows the best-fit Plummer model convolved with the beam [cf. Sect. 3 and Eq. (2)]. (b) Same as in (a) but for the median radial intensity profile of the northern part of the filament measured on the western side of the filament crest shown as a white curve in Fig. 2.

Fig. A.2. (a) Median radial intensity profile of the southern part of the NGC 6334 filament (black solid curve) measured in the combined ArTeMiS + SPIRE 350 µm image (Fig. 1b) perpendicular to, and on the eastern side of, the filament crest shown as a magenta curve in Fig. 2. The yellow and green error bars are as in Fig. 3a. The blue solid curve shows the effective beam profile of the ArTeMiS 350 µm data as measured on Mars, on top of a constant level corresponding to the typical background intensity level observed at large radii. The blue dotted curve shows the best-fit Gaussian (+ constant offset) model to the inner part of the observed profile. The red dashed curve shows the best-fit Plummer model convolved with the beam [cf. Sect. 3 and Eq. (2)]. (b) Same as in (a) but for the median radial intensity profile of the southern part of the filament measured on the western side of the filament crest shown as a magenta curve in Fig. 2.
Fig. A.3. (a) Same as Fig. A.1 but for the median radial column density profile measured on the eastern side of the northern part of the NGC 6334 filament in the approximate column density map shown in Fig. 2a. (b) Same as Fig. A.1 but for the median radial column density profile measured on the western side of the northern part of the filament in the column density map shown in Fig. 2a.