Molecular contrails – triggered contraction by passages of massive objects through molecular clouds

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ABSTRACT
We study the effects of passages of compact objects such as stars, star clusters and black holes through molecular clouds, and propose that the gravitational interaction between the compact object and the ambient gas can lead to the formation of thin and collimated features made of dense gas, which we call “molecular contrails”. Supercritical contrails can collapse further leading to triggered star formation. The width of a molecular contrail is determined by the mass and velocity of the compact object and the velocity dispersion of the ambient molecular medium. Under typical conditions in the Milky Way, passages of stellar-mass objects lead to the formation of width \( d \approx 0.01 \) parsec contrails, and passages of star clusters lead to the formation of \( d \approx 1 \) parsec contrails. We present a few molecular contrail candidates from both categories identified from ALMA1.3mm continuum observations of star-forming regions and the \(^{12}\)CO(1-0) map from the Galactic Ring Survey respectively. The contrails represent an overlooked channel where stars and gas in the Galactic disk interact to form structures. They also present a potential way of detecting dark compact objects in the Milky Way.

Key words: ISM: clouds – ISM: structure – ISM: dynamics – stars: formation – black holes: stellar-mass

1 INTRODUCTION
Molecular clouds constitute an inseparable part of the interstellar medium, and the collapse of molecular clouds is the very process that leads to the formation of stars in the universe. Researches (e.g. Dobbs et al. 2014; Chevance et al. 2020, and references therein) have shown that the evolution of a molecular cloud is a complex process characterized by the interplay among turbulence, gravity, magnetic fields, stellar feedback, and galactic shear. However, gravity is the ultimate driver of molecular cloud collapse and star formation, on which we focus in this paper.

Star formation is mostly a result of molecular cloud collapse from its self-gravity. However, this process can be modulated by the global gravitational field in a galaxy contributed by other components e.g. stars. For example, spiral arms and bars in disk galaxies, believed to be caused by instabilities of a disk of stars (Shu 2016, and references therein), play important roles in triggering star formation (Roberts 1969; Pettitt et al. 2020). Also, in the center of galaxies such as the Milky Way, gravitational field from the stellar bulge may lead to a strong shear which suppresses star formation (Li & Zhang 2020). During the late stage of star formation, gravity of the stars can also influence the evolution of the circumstellar disk via gravity during stellar fly-bys (Clarke & Pringle 1993; Winter et al. 2018).

Can gravity from individual stars, star clusters and other compact objects such as black holes affect star formation? In this paper, we propose that gravity from compact objects can initiate wakes in the surrounding molecular gas via gravitational interaction during their passages, which could lead to the formation of thin and collimated features which we call the “molecular contrails”. Due to the prevalence of the turbulent motions, interstellar molecular gas is expected to appear chaotic as it usually does. On top of this, the contrails should stand out as straight concentrations of molecular gas of various lengths and widths.

We expect that the contrails with widths \( d \geq 1 \) pc can be identified from surveys of Milky Way disk such as the Galactic Ring Survey (Jackson et al. 2006) where molecular gas is traced at \( \approx 40'' \) resolution (which corresponds to a size of 1.6 pc at a distance of 8 kpc). Contrails with width \( d \geq 0.01 \) pc can be identified from interferometer observations of dense molecular clumps where clustered star formation is taking place. By inspecting existing observational data, we are able to identify some contrail candidates.

2 CONTRAIL FORMATION
We consider the passage of a compact object of mass \( m_c \) through the molecular medium. We are interested in the fast passages where the relative speed \( v_r \) is much larger than the typical velocity dispersion of the medium \( \sigma_{v, \text{medium}} \), and study the response of the medium.
2.1 Formation Mechanism

At a distance $r$ from the trajectory, the velocity injected due to gravity from the compact object into the medium is

$$v_{\text{inject}} = a \times r_{\text{inject}} = Gm_\odot r^2 \times r / v_s \approx Gm_\odot / (rv_s) .$$  \hspace{1cm} (1)

In order to trigger contraction or collapse, we require that the momentum injection measured in terms of $v_{\text{inject}}$ to be comparable to or larger than characteristic velocity of the medium $v_{\text{medium}}$.

$$v_{\text{inject}} \geq v_{\text{medium}} .$$  \hspace{1cm} (2)

From these we obtain an analytical estimate of the radius within which the passage has an effect

$$r_{\text{wake}} \approx \frac{Gm_\odot}{v_s v_{\text{medium}}} .$$  \hspace{1cm} (3)

Note that here we are focusing on the effect of momentum injection. There are other ways through which the object and the medium can interact. For example, during the passages, the compact objects might accrete matter from the medium. We note that in our case where $v_s > v_{\text{medium}}$, the Bondi radius -- radius within which gas is expected to accrete onto the compact object is $r_{\text{Bondi}} \approx Gm_\odot v_s^2$ (Hoyle & Lyttleton 1941; Bondi 1952). Thus $r_{\text{wake}} / r_{\text{Bondi}} \approx v_s / v_{\text{medium}}$, and the mass accretion rate scales as $M \propto (v_s / v_{\text{medium}})^3$. For a compact object with a large velocity $v_s \gg v_{\text{medium}}$, we have $r_{\text{wake}} \gg r_{\text{Bondi}}$, and the mass accretion from the medium is inefficient, i.e. the wake is the dominant effect compared to accretion. We also note that during the passage, a wake is formed on the trailing side. Although the wake should exert a drag force on the compact object, the drag force weakens rapidly (approximately following $v_s^{-2}$) as $v_s$ increases (Ostriker 1999). For high-velocity passages, the slow-down of the compact object by the drag force is not significant.

Within $r_{\text{wake}}$, the passage injects a momentum that is comparable to the velocity dispersion of the medium. As a result, we expect the gas to contract which leads to a significant amount of density enhancement. This density enhancement has a collimated, contrail-like morphology, and the contrail should be spatially aligned with the orbit of the object measured in the rest frame of the cloud, thus we name it as “molecular contrail”.

We are only interested in fast passages where the encounter velocity $v_s$ is larger than the velocity dispersion of the medium, since this is a necessary condition for the contrail to stay aligned spatially. We note that after formation, the contrail is subject to destruction by the velocity dispersion of the medium. Considering that the contrail can be destroyed in a crossing time by the random motion of the molecular cloud, the survival time of a contrail of width $d$ is

$$t_{\text{survival}} \approx d / v_{\text{medium}} .$$  \hspace{1cm} (4)

Thus, $v_s >> v_{\text{medium}}$ is equivalent to the aspect ratio of the contrail, which can be estimated by

$$A = v_s t_{\text{survival}} / d = v_s / v_{\text{medium}} ,$$  \hspace{1cm} (5)

is much greater than unity.

From these calculations we can conclude that, in general, compact objects with higher velocities lead to more collimated contrails, and those with higher masses lead to contrails of larger widths. Both the width and the aspect ratio of the contrails are inversely proportional to the velocity dispersion of the molecular clouds.

2.2 Formation condition in the Milky Way

It has been established observationally that in the Milky Way, the turbulent motion of the molecular gas is described by the Larson’s relation (Larson 1981), where the velocity dispersion $\sigma_{\text{medium}}$ of the medium is related to the scale $l$ by $\sigma_{\text{medium}} \approx \beta l^{1/3}$ with $1/3 < \beta < 1/2$ (e.g. Heyer et al. 2009). We adopt $\beta = 1/3$ which is consistent with the Kolmogorov turbulence spectrum, and write the total velocity dispersion of the molecular gas as

$$\sigma_{\text{medium}} = \frac{c_s}{1 \text{ km/s}} \left[ \left( \frac{l}{1 \text{ pc}} \right)^{2/3} + \left( \frac{c_s}{1 \text{ km/s}} \right)^2 \right]^{1/2} .$$  \hspace{1cm} (6)

The first term in the parentheses describes the turbulence contribution as found in Larson (1981), and the second term describes the contribution from the sound speed $c_s$ of the medium. For contrail formation and disruption, the relevant scale of the turbulence is $l \approx r_{\text{wake}} \approx d$. As the typical temperature of molecular cloud in the Milky Way is $T \approx 10$ Kelvin corresponding to a sound speed of $c_s \approx 0.2$ km/s. The sound speed of the isothermal molecular cloud is computed as $c_s = \sqrt{k_B T / m_H}$, where $k_B$ is the Boltzmann constant, $\mu = 2.7$ is the mean molecular weight, and $m_H$ is the hydrogen atomic mass. The sound speed contribution can be safely neglected for $d \gtrsim 1$ pc contrails, and is only relevant for thin contrails such as the $d \leq 0.01$ pc (where $\sigma_{\text{medium}} < c_s$) contrails.

Combining this expression of $\sigma_{\text{medium}}$ with Eqs. 3 and 5, we extract a diagram of contrail formation (Fig. 1) describing the dependencies of the contrail width and aspect ratio on $m_\odot$ and $v_s$. In the large $d$ limit where the turbulence contribution dominates $\sigma_{\text{medium}}$, we have

$$d \approx 0.017 \left( \frac{m_\odot}{m_\odot} \right)^{3/4} \left( \frac{v_s}{1 \text{ km/s}} \right)^{-3/4} ,$$  \hspace{1cm} (7)

and

$$A \approx 3.8 \left( \frac{m_\odot}{m_\odot} \right)^{-1/4} \left( \frac{v_s}{1 \text{ km/s}} \right)^{5/4} .$$  \hspace{1cm} (8)

As examples, we consider the following types of contrails: the $d > 0.01$ pc contrails which can be observed with interferometers, as well as the $d > 1$ pc contrails which should be observable by single-dish telescopes. In addition to this, if we demand that the minimum aspect ratio of a contrail to be $A \approx 5$ (which we consider as the “birthline” for contrails, see Fig. 1), we can derive the minimum masses and impact velocities for contrails of different widths: For example, to form a $d \geq 0.01$ pc contrail, one requires at least a stellar-mass object, and for a $d \geq 1$ pc contrail, at least a 1000 $m_\odot$ object. These minimum masses at the birth line are associated with typical minimum impact velocities of a few km/s. Contrails of the same widths but potentially higher aspect ratios can be formed by objects with higher masses and velocities but the same $m_\odot / v_s$ ratio. For instance, for compact objects with velocities on the order of the virial velocity of the Galactic halo, $v_s \approx 10^2$ km/s, forming $d \geq 0.01$ pc contrails requires $m_\odot \approx 10^5 m_\odot$ and forming $d \geq 1$ pc contrails requires $m_\odot \approx 10^9 m_\odot$.

2.3 Formation routes and theoretical formation rates

The dense objects which can cause contrails include stars, star clusters as well as black holes of different masses. To estimate the occurrence rates of different contrails, we consider an ensemble of compact objects of a number density of $n_c$ and a velocity dispersion of $\sigma_{v_\star}$, and consider their encounter with molecular clouds/clumps of size $l$. The mean free path of the encounter is

$$\lambda_{\text{mfp}} = 1 / (n_c l^2) .$$  \hspace{1cm} (9)
Figure 1. Contrail formation in the Milky Way. The $x$-axis is the logarithm of the velocity of the compact object measured with respect to the molecular cloud or clump, and the $y$-axis is logarithm of the mass of the object. Different initial conditions lead to different contrail widths and aspect ratios, which are indicated by the red and black lines, respectively. The gray shaded region indicate the parameter range where the contrails have aspect ratios that are too small to be identified. Our candidate contrail-producing objects include stars, star clusters as well as globular clusters. Their locations are indicated in the plot. See Sec. 2.3 for details.

and the typical encounter time is

$$t_{\text{encounter}} = \frac{\lambda_{\text{mpf}}}{\sigma_v} = \frac{1}{(n_\star \ell^2 \sigma_v)}.$$  \hfill (10)

Then, the occurrence rate can be estimated as the ratio of contrail survival time and the encounter time,

$$t_{\text{survival}}/t_{\text{encounter}} = n_\star d \ell^2 \left( \frac{\sigma_v}{\sigma_{\text{medium}}} \right).$$  \hfill (11)

We use this equation to estimate the occurrence rates of contrails formed through different channels.

2.3.1 Stellar passages

First we consider the formation of contrails of $\geq 0.01$ pc by passages stellar-mass objects through molecular clumps. The clumps are pc-sized regions of high densities (e.g. $n_{H_2} \approx 10^4$ cm$^{-3}$ for a typical, $10^3 M_\odot$ clump, Urquhart et al. 2018) and they have steep density profiles $n_{\text{clump}} \approx r^{-2}$ (Li 2018, and references therein). To produce the $d \approx 0.01$ pc contrails, we require a minimum mass of $10 M_\odot$ and a velocity of $30$ km/s. Out candidates are mostly located in the inner part of the Galactic disk. Using results from McGaugh (2016), we estimate a stellar mass surface density of $300 M_\odot$ pc$^{-2}$ at $r_{\text{gal}} = 4$ kpc where $r_{\text{gal}}$ is the galactocentric distance. From this, we estimate a volume mass density of $2 M_\odot$ pc$^{-3}$. Assuming a standard IMF (Salpeter 1955), we estimate a number density of $0.04$ pc$^{-3}$ and a mean free path of $25$ pc for stars with $M \geq 10 M_\odot$. This implies a encounter time of $t_{\text{encounter}} = 30$ pc/30 km/s = 0.8 Myr. The survival time is $t_{\text{survival}} \approx 0.01$ pc/(0.3 km/s) = 0.03 Myr. We thus expect to be able to observe contrails in around $t_{\text{survival}}/t_{\text{encounter}} = 4$ \% of the clumps.

Note that apart from gravity, massive stars can influence the ambient ISM thorough radiation pressure and photoionization. At high densities, radiation pressure dominates the momentum feedback (Krumholz & Matzner 2009). For massive stars , the radiation pressure approach the Eddington limit when $m_\star \geq 40 M_\odot$ (Sanyal et al. 2015) such that the momentum feedback on the ambient medium becomes non-negligible. However, as the number density of stars decreases very rapidly as the stellar mass increases, the radiation pressure is relevant only to a small fraction of the cases and that we are concerned with.

2.3.2 Passages of stellar-mass black holes

The detections of gravitational waves by the Laser Interferometer Gravitational-Wave Observatory (LIGO) has revealed the existence of a population of binaries where the mass of the black hole can reach a few tens of solar masses (Abbott et al. 2016, 2017). These stellar-
mass black holes are massive enough to cause contrails. The total number and the mass distribution of the stellar-mass black holes in the Milky Way remain uncertain. According to recent models (e.g. Caputo et al. 2017; Elbert et al. 2018), the Milky Way may contain up to $10^5$ black holes whose masses are larger than $10 M_\odot$. These black holes should be able to trigger the formation of a significant number of $d \geq 0.01$ pc contrails.

We estimate the occurrence rate of contrails caused by black hole passages. The spatial distribution of these black holes is not known yet. We assume that they follow a distribution which resembles that of the stellar disk. Using results from Elbert et al. (2018), and assuming a volume of $10 \, kpc \times 10 \, kpc \times 0.3 \, kpc$ and a velocity dispersion of $30 \, km/s$ for these objects, we find a mean free path of $l_c \approx 300$ pc and a collision time of $10.0 \, Myr$, and these passages can produce contrails of $d \geq 0.01$ pc. If the contrail survives for a crossing time, which is around $0.03 \, Myr$, we estimate that that $0.3\%$ of the clumps should contain contrails of this type.

### 2.3.3 Passages of star clusters

Next, we consider the production of contrails of $\geq 1$ pc by passages of star clusters through molecular clouds in the Galactic disk. Stellar associations can shape the structure of the ambient ISM through radiation (e.g. Krause et al. 2018). Passages of star clusters through clouds are regular events, and such passages can contribute to the destruction of star clusters (Gieles et al. 2006). These star clusters have a typical size of $1-2$ pc (Higuchi et al. 2009), which is comparable to the width of the contrails that they will be creating. From some recent observations (e.g. Bica et al. 2019), the number density of star clusters is estimated to be $n_c \approx 2 \times 10^4 \, kpc^{-3}$. With $\zeta_c = 10 \, pc$ and $\sigma_{vc} = 30 \, km/s$, the mean free path is estimated to be $0.5 \, kpc$ and the encounter time is around $15 \, Myr$. The survival time for such contrails is around $t_{survival} = 3 \, pc/(1 \, km/s) = 3 \, Myr$, the chance of seeing such contrails in a molecular cloud is around $20\%$.

### 2.3.4 Passage of globular clusters

We consider the production of the contrails by passages of globular clusters through the Galactic disk. Globular clusters have typical masses of $10^5 - 10^6 \, M_\odot$ and typical velocities measured with respect to the molecular clouds of $10^3 \, km/s$. They are thus capable of producing $\sim 1$ pc wide contrails. Globular clusters are far from point masses, but they have concentrated/cored density profiles. Their density profiles can be described approximately as $ho \propto r^{-2} (1 + (r/r_c)^2)^{-\alpha}$ (King 1962) and their half-mass radius range from sub-pc to a few parsec (e.g. Table 4 of Krause et al. 2016). When such globular clusters pass through a cloud to produce the 1 pc-wide contrails, only the stars at the very center of the clusters are effective in injecting momentum. Around $N_{GC} \approx 10^2$ globular cluster candidates have been identified around the Milky Way halo (Palma et al. 2019). They pass through our Galaxy every $t_{orbit} \approx 10^8 \, yr$. Due to this relatively small number, rather than estimating the contrail occurrence rate for each molecular cloud, we estimate the total number of contrails associated with globular clusters using $N_{Contrail}^{GC} \approx t_{survival}/t_{orbit} \times N_{Encounter}$, where $t_{survival} \approx 1 \, pc/(1 \, km/s)$, and $N_{Encounter}$ is the number of clouds a globular cluster encounters at a single passage through the Galactic disk. Assuming $N_{Encounter} = 10$, we expect to see a few of these contrails in the Milky Way. Due to the high relative speed, the globular cluster encounters should be responsible for the production of some of the longest and most collimated contrails.

### 2.4 Criticality and Collapse

The criticality of a contrail can be estimated roughly from the ratio between gravitational and turbulence energy densities, ( Chandrasekhar & Fermi 1953; Stodólkiewicz 1963; Ostriker 1964)

$$\delta_{contrail} = \frac{GM/L}{2 \sigma_{medium}^2}, \quad (12)$$

where $M/L$ is the line mass and $\sigma_{medium}$ is the estimated velocity dispersion of the contrail measured at the radial direction. Contrails with $\delta_{contrail} > 1$ are prone to fragmentation. Note that Eq. 12 also suffers from uncertainties arising from i.e. the equation of state of the gas and the radial density profile, and the measured values of $\delta_{contrail}$ are also affected by the inclination angle.

### 3 OBSERVATIONAL SIGNATURES

#### 3.1 Contrail candidates

In Fig. 2, we present a few contrails identified from published observational data on the surface density distribution of molecular gas in different regions. The contrails in the upper panels (W43 contrail, G33.92 contrail) are identified from dust continuum observations towards high-mass star-forming regions (Motte et al. 2018; Liu et al. 2019) carried out using the ALMA telescope (Wootten & Thompson 2009). In these interferometer observations, because of the unavoidable incompleteness of the UV coverages, only structures with significant, localised surface density variations are recovered. The lower panel is constructed using the CO(1-0) data from the Galactic Ring Survey (GRS, Jackson et al. 2006) carried out by the Five College Radio Astronomy Observatory (FCRAO) 14m telescope, in which we have identified the G46 contrail, the G47 contrail, together with a few additional contrail candidates. The velocity structure of some contrails are presented in Fig. 3. The estimated parameters for the four contrails with names are listed in Table 1. Details concerning how we derive these values can be found in Appendix A. Since the contrails do not have well-defined boundaries, these values are only rough estimates. Limited by the line of sight confusion, we are not able to measure the velocity dispersion of the contrails directly. The velocity dispersions of the contrail in the radial direction are inferred assuming that the medium is dominated by a turbulent motion described by Eq. 6.

These contrails share a striking similarity in that they consist of spatially-aligned density enhancements, which leads to high aspect ratios ($\sim 10$). They exist, however, on a wide range of spatial scales, with widths ranging from $\sim 0.01$ pc to a few pc and lengths ranging from 0.1 pc to $10^2$ pc. Using data from the GRS survey, we find that the G46 and G47 contrails seem to exhibit coherent yet turbulent velocity structures (Fig. 3). The contrails also exhibit different degrees of fragmentation. The more “fragmented” W43 contrail is basically a linear chain of dense cores.

Considering the population of compact objects in the Milky Way and their typical velocities, $d \geq 0.01$ pc contrails like the W43 contrail and the G33.92 contrail are most likely formed by massive stars, binaries, and stellar-mass black holes, and $d \geq 1$ pc contrails like the W43 contrail and the G33.92 contrail are most likely formed by star clusters.

Since our sample is still limited, the occurrence rate of the contrails is not well constrained. Nevertheless, the appearance of

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1 It contains possible contributions from compression, shear, etc.
**3.2 Velocity structure**

Using publicly-available data from the GRS survey (Jackson et al. 2006), we construct the position-velocity diagram of two $d \approx 1$ pc contrails (Fig. 3). The contrails appear to be coherent in the position-velocity space, confirming that our contrails are coherent objects.

One can also see that these contrails still contain significant amounts ($\approx 3$ km/s) of line-of-sight turbulent motion.

This is barely surprising since the observed velocity distributions contain contributions from both the turbulent cloud (roughly a few tens of pc in size) and contributions from the contrails ($\approx 1$ pc in size). From Eq. 6, we estimate a velocity dispersion of a few km/s for the background cloud and a velocity dispersion of around 1 km/s for the contrail. Since the background cloud contains a velocity dispersion that is much larger than that of the contrail, the velocity structure seen in Fig. 3 is dominated by the longitudinal turbulent motion. This explains the fact that the position-velocity diagrams of our contrails do not appear to be different from those of ordinary molecular clouds.
Table 1. List of contrail candidates and their physical properties. See Appendix A for details.

| Name        | Length $L$  | Width $d$  | Aspect ratio $A$ | Mean surface density $\sigma$ | M/L | $\sigma_{\text{medium}}$ | $\delta_{\text{crit}}$ |
|-------------|-------------|------------|------------------|-------------------------------|-----|--------------------------|------------------------|
| W43 contrail| 0.5 pc      | 0.02 pc    | 24               | $4 \text{ g cm}^{-2}$         | 200 $M_\odot$/pc | 0.37 km/s                  | 5                      |
| G33.92 contrail | 0.2 pc      | 0.01 pc    | 20               | $0.6 \text{ g cm}^{-2}$       | 27 $M_\odot$/pc | 0.36 km/s                  | 0.5                    |
| G46 contrail | 80 pc       | 3 pc       | 10               | $0.02 \text{ g cm}^{-2}$       | 300 $M_\odot$/pc | 1.5 km/s                  | 0.3                    |
| G47 contrail | 60 pc       | 3 pc       | 6                | $0.03 \text{ g cm}^{-2}$       | 450 $M_\odot$/pc | 1.5 km/s                  | 0.4                    |

3.3 Criticality

In Fig. 4 we present a criticality diagram, where most of our contrails stay close or above the critical line defined as $\delta_{\text{contrail}} \approx 1$, meaning that the gravitational energy density is comparable or larger than the kinetic energy density of the turbulent motion. Contrails with even smaller criticality parameters should exist in principle, but are probably more difficult to identify. The only contrail which has a very high critical parameter is the W43 contrail, where $\delta_{\text{contrail}} \approx 10$. This corresponds well to the fact that it is the one with the highest degree of fragmentation.

4 DISCUSSIONS AND CONCLUSIONS

The Milky Way is a complex system made of gas, stars and dark matter. We investigate the effect of compact objects such as stars black holes and star cluster on the molecular gas when they pass through it, and find that fast passages – passages where the relative velocity is much larger than the velocity dispersion of the medium, leads to the formation of spatially aligned concentration of dense gas called the molecular contrails. We derive the necessarily conditions for the formation of contrails of different widths. According to our analysis, contrails of $d \geq 0.01$ pc are caused by passages of stellar-mass objects, and contrails of $d \geq 1$ pc are caused by passages of star clusters. We predicted that the formation of these contrails, especially the $d \geq 1$ pc ones, should be a regular event.

From observational data, we identify a set of spatially-aligned
Molecular contrails

DATA AVAILABILITY

The data used to produce the bottom panel of Fig. 2 and Fig. 3 are available at https://www.bu.edu/galacticring/new_data.html.

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APPENDIX A: ESTIMATION OF OTHER CONTRAIL PARAMETERS

The estimated parameters for the four contrails with names are listed in Table 1. The length $l$, widths $d$ and mean surface densities are measured directly from the data. Note that (a) the contrails exhibit...
density variations along its ridges, such that the definition of contrail length can be vague. (b) the contrail widths are defined by the FWHM of the intensity distribution on the observation maps. Limited by resolutions of available observations, an accurate determination of the density profiles of these contrails is not possible, and the contrail widths could be over-estimated by a small margin. The aspect ratio is taken as the ratio between filament length $\ell$ and width $d$, and in some cases, their aspect ratios are reevaluated using method described in in Appendix B. (c) while measuring the contrail surface densities from the ALMA maps, we have used the conversion factors adopted by the authors. To compute the surface density from the GRS (Jackson et al. 2006) observations, we have used the conversion factor from Simon et al. (2001). From these directly measured quantities, we have further derived several parameters important in the proposed physical picture of contrail formation, including the line mass $M/L$, the velocity dispersion $\sigma_{\text{medium}}$ of the molecular gas measured on a scale that is comparable to the contrail width (see Section 2.2), and a criticality parameter $\delta_{\text{contrail}} = G(M/L)/2\sigma^2_{\text{medium}}$ (see Section 2.4). The line mass is estimated using $M/L = \Sigma_{\text{gas}} \times d$ where $\Sigma_{\text{gas}}$ is the estimated surface density. The velocity dispersion $\sigma_{\text{medium}}$ of the ambient molecular gas on scale $d$ is dominated by turbulence dispersion for large $d \gtrsim 1$ pc (W51 contrail and G46 contrail), and the thermal velocity dispersion is important only for small $d \lesssim 0.01$ pc contrails (W43 contrail and G33.92 contrail). Thus, we estimate the $\sigma_{\text{medium}}$ for the W51 contrail and the G46 contrail using the empirical Larson relation (see Section 2.2 for details), and that for the W43 contrail and the G33.92 contrail using additional information of molecular gas temperatures estimated in the corresponding papers (23K for the W43 contrail and 30K for the G33.92 contrail).

**APPENDIX B: CONTRAIL SEPARATION AND MEASUREMENT OF ASPECT RATIO**

To refine the estimation of the aspect ratios of the contrails, we adopt the following two-step approach: first, we make the use of the ransac (RANdom SAmple Consensus) algorithm (Fischler & Bolles 1981) to separate the contrails. The ransac algorithm is an iterative method capable of fittings models to data where a significant number of outliers are present in a robust fashion. In our case, the model is chosen to be a straight line, and by fitting it to our data we separate the contrails. After that, we fit ellipses to the points found to be associated with the contrails by diagonalising the tensor of second moments of positions of points that are associated with the contrails, and the aspect ratios of contrails are taken as the ratios between the long and short axes of the ellipses. The values we obtained through fitting do not differ significantly from the values we measured by hand. The results are presented in B1. We note that ransac is an algorithm that works on a set of data points. Therefore, to begin with, we have used the rejection sampling method to convert our images into points upon which the ransac algorithm is applied. The ransac algorithm is not capable of dealing with cases where the outliers outnumbered the inliers. Therefore, we cropped our images in the position-position-velocity space such that the majority of the emission originates from the contrails.

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2 https://en.wikipedia.org/wiki/Rejection_sampling
Figure B1. Contrail separation and measurement of aspect ratios. The left and right panel present results from the G46 contrail and the G47 contrail, where the grayscale image represent the velocity-integrated $^{13}$CO(1-0) emission. The green crosses mark the region considered to be inside the contrails where as the yellow crosses mark the region that does not belong to the contrails. The red ellipses are obtained by diagonalising the tensor of second moments of positions of points that are associated with the contrails. From these fittings, we estimate an aspect ratio of 10 for the G46 contrail and an aspect ratio of 6 for the G47 contrail.