Gravity or turbulence? –III. Evidence of pure thermal Jeans fragmentation at $\sim 0.1$ pc scales

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ABSTRACT

We combine previously published interferometric and single-dish data of relatively nearby massive dense cores that are actively forming stars to test whether their ‘fragmentation level’ is controlled by turbulent or thermal support. We find no clear correlation between the fragmentation level and velocity dispersion, nor between the observed number of fragments and the number of fragments expected when the gravitationally unstable mass is calculated including various prescriptions for ‘turbulent support’. On the other hand, the best correlations are found for the case of pure thermal Jeans fragmentation, for which we infer a core formation efficiency in the range 12–34%, consistent with previous works. We conclude that the dominant factor determining the fragmentation level of star-forming massive dense cores seems to be thermal Jeans fragmentation.

Key words: stars: formation, clusters — ISM: lines and bands — ISM: structure — radio continuum: ISM

1 INTRODUCTION

For more than 60 years it has been thought that turbulence is an agent capable of providing support to molecular clouds against gravitational collapse (e.g., Chandrasekhar 1951, Bonazzola et al. 1987, Léorat et al. 1990, McKee & Tan 2003), while simultaneously producing local density enhancements that may become Jeans-unstable and collapse (e.g., Sasao 1973, Elmegreen 1993, Padoan 1995, Vázquez-Semadeni & Gazol 1995, Klessen et al. 2000, Vázquez-Semadeni et al. 2003). However, recent studies suggest that this may not be the case. For instance, molecular clouds are now thought to form by large-scale compressions in the diffuse, warm, HI medium. The compressed gas undergoes a transition to the cold, dense atomic phase (e.g., Hennebelle & Pérault 1999, Heitsch et al. 2005, Vázquez-Semadeni et al. 2006), which is highly prone to Jeans instability (Hartmann et al. 2001), and thus soon begins to collapse, in spite of the turbulence generated inside it by the original compression (Koyama & Inutsuka 2002, Audit & Hennebelle 2005, Vázquez-Semadeni et al. 2007, Heitsch & Hartmann 2008). Moreover, once molecular clouds achieve column densities $\sim 10^{21}\,\text{cm}^{-2}$, they are able to form molecular gas (Bergin et al. 2004) so that the formation of molecules may be essentially a byproduct of the gravitational collapse of the clouds (Hartmann et al. 2001). In this scenario, the observed non-thermal motions of molecular clouds, rather than consisting of random, small-scale, isotropic motions that can act as a pressure, are actually dominated by inward motions caused by the gravitational collapse, which occurs both at large and small scales in a hierarchical and chaotic fashion (Vázquez-Semadeni et al. 2009, Ballesteros-Paredes et al. 2011a). This...
implies that the bulk of the observed non-thermal motions cannot provide support against the self-gravity of the clouds.

In previous papers of this series, we have presented evidence that the dynamics of molecular clouds are indeed dominated by gravity by showing that this scenario unifies molecular clouds and massive clumps in a single scaling relation (Heyer et al. 2009) that extends those by Larson (1981, Ballesteros-Paredes et al. 2011a), and by showing that numerical simulations of cloud evolution including self-gravity develop power-law high-density tails in their column density probability distribution functions as a consequence of the gravitational collapse (see also Kritsuk et al. 2011, Ballesteros-Paredes et al. 2011b), in agreement with observations (Kainulainen et al. 2009). In the present contribution, we present a further line of evidence, by examining the mechanism responsible for fragmentation of dense cores. Indeed, a still unsolved and highly debated question is what are the main drivers of fragmentation in massive dense core, which are believed to be the precursors of stellar clusters. The crucial parameter to estimate the fragmentation level of a dense core is the Jeans mass, which in its general form takes into account the different mechanisms of support against gravity, through the use of the ‘effective sound speed’ (e.g., Mac Low & Klessen 2004). Among the most debated forms of support are turbulent and thermal support. Thus, if the average turbulence level, average temperature and average density of a massive dense core are known, one can easily calculate the Jeans mass in both cases and estimate, given the mass of the core, the number of fragments expected in each case, so that one can assess which form of support against gravity is controlling the fragmentation process.

Up to now, this simple question could not be answered because of a lack of statistically significant samples of massive dense cores where the fragmentation level has been assessed in a uniform way and down to spatial resolutions comparable to separations between cluster members (∼1000 AU). Recently, Palau et al. (2013, 2014) compiled a sample of 19 massive dense cores with on-going star formation and studied the fragmentation level within the cores down to ∼1000 AU, and ∼0.5 M⊙ of mass sensitivity. This would be a first approach to study the number of protostars (compact fragments will most likely become protostars, see Palau et al. 2013, 2014) within a massive dense core (assumed to become a cluster). In these works, the fragmentation level was assessed by counting the number of millimetre sources within a field of view of 0.1 pc of diameter, Nnum. Furthermore, by fitting the spectral energy distributions and submillimetre intensity profiles of the cores, Palau et al. (2014) modelled their density and temperature structure, so that densities and temperatures at different spatial scales could be estimated and thermal Jeans masses could be calculated. In this work, we compile observational data based on dense gas tracers for the sample of cores of Palau et al. (2013, 2014), in order to assess the turbulence level and estimate the turbulent Jeans mass, and finally compare the fragmentation level observed to the fragmentation level expected for each form of support, turbulent or thermal.

The plan of the present contribution is as follows: we presents the compiled data we used. In §2 we present the fragmentation level of our cores, and how this fragmentation correlates (or not) with their physical parameters. Finally, in §4 we discuss the physical implications of our results and present our main conclusions.

2 THE SAMPLE AND DATA COMPILATION

The present work is based on the sample of massive dense cores presented in Palau et al. (2013, 2014), whose masses, luminosities and densities range from 15 to 3000 M⊙, from 300 to 105 L⊙, and from 0.45 to 3 kpc, respectively. The sample was selected from deeply embedded intermediate/high-mass star-forming regions published in the literature that have been studied in the millimetre range down to mass sensitivities of ∼0.5 M⊙, and spatial resolutions of ∼1000 AU. Palau et al. (2014) modelled the massive dense cores with temperature and density profiles decreasing with radius following power-laws, and determined a number of properties of the density and temperature structure in a uniform way for all the sample.

In order to estimate the turbulence level in each core and compare it to the ‘turbulent fragmentation’ level, we used Very Large Array (VLA) NH3(1,1) data in C/D configuration, available for 13 (out of 19) massive dense cores (Torrelles et al. 1989; Zhou et al. 1990; Mangum et al. 1992; Tiefftrunk et al. 1998; Wiseman & Ho 1998; Gómez et al. 2003; Sánchez-Monge et al. 2013; see also Palau et al. 2014). VLA beams are typically ≤5 arcsec, and the minimum angular scales filtered out by the interferometer are ≥35 arcsec (estimated following appendix in Palau et al. 2010, and using a minimum baseline of 35 m). The latter corresponds to ∼0.3 pc (for typical distances of the regions in the sample), slightly larger than the field of view of 0.1 pc that we are studying. Thus, with these VLA NH3 data we are recovering most of the emission at the spatial scales we are studying, with an angular resolution good enough (∼5 arcsec) to resolve typical sizes of massive dense cores (e.g., Sánchez-Monge et al. 2013). The NH3(1,1) hyperfine structure was fitted and hyperfine ‘observed’ FWHM line widths, Δνobs, were inferred for each core. We note that we took special care to make the sample as uniform as possible and we measured the NH3(1,1) line width in all cases by using the ‘nh3(1,1) method’ in the CLASS package of the GILDAS software, on the spectrum resulting from averaging the NH3(1,1) emission over the central region of ∼0.1 pc of diameter of the dense core where we study the fragmentation level. In two sources (I22134 and DR21-OH) we fitted two velocity components. From these line widths we calculated the observed velocity dispersions as σνobs = Δνobs/(8 ln2)1/2.

The values of the compiled observed velocity dispersions from NH3(1,1) VLA data are listed in Table 1 and the spectra with the corresponding fits to the hyperfine structure are shown in Appendix A.

Because in some cases the VLA NH3(1,1) emission...
Table 1. Modeled properties of the massive dense cores and compiled observational velocity dispersions

| Source         | $N_{mm}$ | $M_{0.1pc}$ | $n_0_{1pc}$ | $T_{0.1pc}$ | $\sigma_{NH_3}^{obs}$ | $\sigma_{NH_3}^{nth}$ | $N_{NH_3}$ | $\sigma_{NH_3}^{obs}$ | $\sigma_{NH_3}^{nth}$ | $M_{N_2H^+}$ | $\sigma_{N_2H^+}^{obs}$ | $\sigma_{N_2H^+}^{nth}$ | $M_{N_2H^+}$ |
|----------------|----------|-------------|-------------|-------------|----------------------|----------------------|------------|----------------------|----------------------|------------|----------------------|----------------------|------------|
| 1-IC1396N      | 4        | 11          | 3.6         | 25          | 0.47                 | 0.45                 | 2.6        | 0.59                 | 0.59                 | 3.4        |                      |                      |            |
| 2-I22198       | 1.5      | 11          | 3.6         | 26          | 0.47                 | 0.45                 | 2.6        | 0.59                 | 0.59                 | 3.4        |                      |                      |            |
| 3-N2071-1      | 4        | 17          | 5.7         | 24          | 0.44                 | 0.43                 | 2.5        | –                    | –                    | –          | –                    | –                    | –          |
| 4-N7129-2      | 1        | 11          | 3.6         | 35          | –                    | –                    | –          | 0.59                 | 0.59                 | 2.8        |                      |                      |            |
| 5-CB3-mm       | 2        | 15          | 5.2         | 40          | –                    | –                    | –          | 0.73                 | 0.72                 | 3.3        |                      |                      |            |
| 6-I22172N      | 3        | 9           | 3.2         | 48          | 0.59                 | 0.58                 | 2.4        | 0.87                 | 0.86                 | 3.6        |                      |                      |            |
| 7-OMC-1S       | 9        | 38          | 13          | 49          | 1.11                 | 1.10                 | 4.5        | 0.90                 | 0.89                 | 3.7        |                      |                      |            |
| 8-AS1415      | 7        | 39          | 13          | 47          | 1.61                 | 1.61                 | 6.8        | 1.09                 | 1.08                 | 4.6        |                      |                      |            |
| 9-I05358NNE    | 4        | 27          | 9.1         | 35          | 0.72                 | 0.71                 | 3.5        | 1.07                 | 1.07                 | 5.3        |                      |                      |            |
| 10-I20126      | 1        | 14          | 4.8         | 68          | 2.00                 | 1.99                 | 7.0        | 0.85                 | 0.84                 | 2.9        |                      |                      |            |
| 11-I22134      | 3.5      | 10          | 3.2         | 50          | 0.71                 | 0.70                 | 2.8        | 0.62                 | 0.61                 | 2.5        |                      |                      |            |
| 12-HH80-81     | 3        | 12          | 4.2         | 66          | 0.74                 | 0.72                 | 2.6        | –                    | –                    | –          | –                    | –                    | –          |
| 13-W3IR55      | 3.5      | 12          | 4.0         | 138         | 0.87                 | 0.84                 | 2.1        | 1.18                 | 1.17                 | 2.9        |                      |                      |            |
| 14-A2591       | 1.5      | 16          | 5.2         | 147         | 0.68                 | 0.62                 | 1.5        | –                    | –                    | –          | –                    | –                    | –          |

a $M_{0.1pc}$ is the mass inside a region of 0.1 pc of diameter computed according: $M_{0.1pc} = M(R = 0.05pc) = 4\pi r_0^2 \rho_0^{1.5}$, where $r_0$, $\rho_0$ are the density and temperature power law, the reference radius adopted to be 1000 AU, and the density at the reference radius (given in Table 1 of Palau et al. 2014); $n_0_{1pc}$ and $T_{0.1pc}$ correspond to average density and temperature inside a region of 0.1 pc of diameter.

b $T_{0.1pc}$ is estimated as $T_{R0} = \left(\frac{\nu H}{\nu_0 H(r)}\right)^{2/3} dr$, where $\nu H$ and $\rho H(r)$ were calculated as power laws of the form $T(r) = T_0(r/r_0)^{-b}$ and $\rho(r) = \rho_0(r/r_0)^{-a}$, with $T_0$, $\rho_0$, and $b$ being the values at the reference radius $r_0$ of 1000 AU. $T_0$, $\rho_0$, $a$, and $b$ are calculated in Table 1 of Palau et al. (2014). The final expression is $T_{R0} = \left(\frac{T_0}{\nu_0 H(r_0)}\right)^{2/3}$.

c $\sigma_{NH_3}^{obs}$ and $\sigma_{NH_3}^{nth}$ are calculated from the measured FWHM line width, $\Delta v_{obs}$, as $\sigma_{NH_3}^{obs} = \Delta v_{obs}/(8\ln 2)^{1/2}$. $\sigma_{NH_3}^{nth} = \sigma_{NH_3}^{obs}/(\nu_0 H(r_0))^{1/2}$.

d Marginal detection of the NH$_3$(1,1) line, not taken into account in the analysis of this work.

References: IC1396N: Alonso-Albi et al. (2010); I22198: Sánchez-Monge et al. (2013); Fontani et al. (2011); NGC2071-1: Zhou et al. (1990); NGC7129-2: Fuente et al. (2005); CB3-mm: Alonso-Albi et al. (2010); I22172N: Sánchez-Monge et al. (2013); Fontani et al. (2006); OMC-1S: Wiseman & Ho (1998); Tatematsu et al. (2008); A5142: Sánchez-Monge et al. (2013); Fontani et al. (2011); 105358NNE: Sánchez-Monge et al. (2013); Fontani et al. (2011); I20126: Sánchez-Monge et al. (2013); Fontani et al. (2006); I22134: Sánchez-Monge et al. (2013); Fontani et al. (2015); HH80-81: Gómez et al. (2003); W3IR55: Tieftrunk et al. (1998); Gerner et al. (2014); A2591: Torrelles et al. (1989); Cyg-N53: VLA archive; Bontemps et al. (2010); Cyg-N12: Bontemps et al. (2010); Cyg-N63: Bontemps et al. (2010); Cyg-N48: Mangum et al. (1992); Bontemps et al. (2010); DR21-OH: Mangum et al. (1992).

might be affected by the passage of an outflow (e.g., the NH$_3$(1,1) line width of IRAS 20126+4104 is larger along the direction of the outflow, see Fig. B1 of Sánchez-Monge et al. 2013), we additionally compiled data from a different dense gas tracer, N$_2$H$^+$(1–0), observed using a single-dish telescope (IRAM30m in 99% of all cases except for OMC-1S, for which Nobeyama 45m was used). This is a reasonable approach to avoid contamination because the outflow is typically compact and thus its emission should be diluted in the single-dish beam. The N$_2$H$^+$(1–0) data were compiled from the literature (Fuente et al. 2005; Fontani et al. 2006, 2011, 2015; Tatematsu et al. 2008; Alonso-Albi et al. 2010; Bontemps et al. 2010; Gerner et al. 2014), and its hyperfine structure was fitted using the CLASS package of the GILDAS software. The IRAM30m Telescope provides a beam of ~ 26 arcsec at the frequency of N$_2$H$^+$(1–0), comparable to the spatial scale at which the massive dense cores are being studied (0.1 pc, at the typical distances of the cores of our sample), and about a factor of 5 larger than the VLA beam. By using the same method outlined above for NH$_3$(1,1) we inferred the observed velocity dispersions for N$_2$H$^+$(1–0), listed in Table 1 and the spectra and fits are shown in Appendix A. The observed N$_2$H$^+$(1–0) velocity dispersions range from 0.6 to 1.2 km s$^{-1}$, a narrower range than that of the velocity dispersions inferred from VLA NH$_3$ data (ranging from 0.5
to 2.0 km s\(^{-1}\)), as expected (because of the outflow contamination of the NH\(_3\) VLA data).

3 RESULTS AND ANALYSIS

3.1 Fragmentation level vs. density and velocity dispersions

The compiled observed velocity dispersions of NH\(_3\)(1,1) and N\(_2\)H\(^+\)(1–0) together with the modeling of the temperature structure of the massive dense cores (Palau et al. 2014) allowed us to separate the thermal from the non-thermal contribution of the observed velocity dispersion. We estimated the thermal component of the velocity dispersion, \(\sigma_{\text{th}}\), from \(\sqrt{k_B T/(\mu m_H)}\), with \(k_B\) the Boltzmann constant, \(\mu\) the molecular weight (17 for NH\(_3\), 29 for N\(_2\)H\(^+\)), \(m_H\) the mass of the hydrogen atom, and \(T\) the temperature of the region, which was adopted from the average density-weighted temperature inside a region of 0.1 pc of diameter (the same region where we assessed the fragmentation level). This average temperature is estimated from the density and temperature power-laws modelled by Palau et al. (2014, see notes of Table 1 for further details) for each core. The non-thermal component was estimated by using \(\sigma_{\text{nth}} = \sqrt{\sigma_{\text{obs}}^2 - \sigma_{\text{th}}^2}\). Then, the total (thermal + non-thermal) velocity dispersion is calculated by adding quadratically the thermal and non-thermal components, using for the thermal component a molecular weight of 2.3, which corresponds to the sound speed and thus: \(\sigma_{\text{tot}} = \sqrt{\sigma_{\text{th}}^2 + \sigma_{\text{nth}}^2}\). The Mach number \(M\) is calculated as \(\sigma_{\text{tot}}/c_s\), with \(\sigma_{\text{tot}}^2 = \sqrt{3}\sigma_{\text{th}}\sigma_{\text{nth}}\). The resulting Mach numbers range from \(\sim 2\) to 7.

In Fig. 1 we plot the number of millimetre sources within a field of view of 0.1 pc in diameter, \(N_{\text{mm}}\) (a proxy to the fragmentation level), as function of (a) the core density within a region of 0.1 pc of diameter (modelled in Palau et al. 2014) —upper panel—, and (b) the non-thermal velocity dispersion measured from NH\(_3\)(1,1) (interferometric data) —middle panel—, and from N\(_2\)H\(^+\)(1–0) (single-dish data) —lower panel—. The figure shows that, while there is a correlation between \(N_{\text{mm}}\) and the density within 0.1 pc (correlation coefficient: 0.89), there is no clear trend between \(N_{\text{mm}}\) and the velocity dispersion measured with NH\(_3\) (correlation coefficient: 0.27), nor with N\(_2\)H\(^+\) (correlation coefficient: 0.35). This suggests that the velocity dispersion of the massive dense cores might not be a crucial ingredient in determining the fragmentation level.

3.2 Fragmentation level vs ‘turbulent’ Jeans number

To further compare the role of the physical properties of the cores (density, temperature, velocity dispersion) in determining the fragmentation, we estimated the expected number of fragments under different assumptions for the gravitationally unstable mass, to which, for convenience, we continue referring as a ‘Jeans’ mass in general. First, we have searched for a correlation between the observed fragmentation level \(N_{\text{mm}}\) and the expected number of fragments in a turbulent support scenario (e.g., Mac Low & Klessen 2004). Thus, we have computed the expected mass of the fragments by assuming that the critical ‘Jeans’ mass is determined by non-thermal (‘turbulent’) support, and given by (e.g., Pillai et al. 2011):

\[
\left(\frac{M_{\text{Jeans}}}{M_\odot}\right) = 1.578 \left[\frac{\sigma_{\text{nth}}}{0.188 \text{ km s}^{-1}}\right] \left[\frac{n}{10^5 \text{ cm}^{-3}}\right]^{-1/2}.
\]

Then, the number of expected fragments, \(N_{\text{Jeans}}\), is estimated from the ratio of the mass of the core inside a region of 0.1 pc of diameter, \(M_{\text{0.1pc}}\), and the Jeans mass, \(M_{\text{Jeans}}\):
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Figure 2. ‘Fragmentation level’ (N_{\text{mm}}) vs Jeans number. **Top panels:** Jeans number calculated using the velocity dispersions estimated from NH$_3$, as explained in Section 3.2. **Middle panels:** idem but using the velocity dispersions estimated from N$_2$H$^+$ (Section 3.2). **Bottom panels:** Jeans number calculated considering only thermal support, calculated either using a fixed temperature of 20 K for all the cores (panel ‘g’), or the temperature inferred from the core modelling presented in Palau et al. (2014; panels ‘h’ and ‘i’; see Section 3.3). In all panels, the Jeans number is calculated using the average density inside a region of 0.1 pc of diameter (as explained in the table notes of Table 1; see also Palau et al. 2014), except for panels on the right, where the average density has been multiplied by the square of the Mach number (following Mac Low & Klessen 2004). In all panels, the dotted black line represents the one-to-one relation, for a core formation efficiency (CFE) of unity. For ‘g’ and ‘h’ panels, the red dashed line represents the indicated CFE value (12–34%).

$$N_{\text{Jeans}} = \frac{M_{0.1pc}}{M_{\text{Jeans}}}.$$  \hspace{1cm} (2)

The result is presented in Figs. 2h and 2i (for NH$_3$(1,1) and N$_2$H$^+$(1–0), respectively).

We also estimated the Jeans mass including both thermal and non-thermal support:

$$\left[ \frac{M_{\text{tot,Jeans}}}{M_{\odot}} \right] = 1.578 \left[ \frac{\sigma_{1D,\text{tot}}}{0.188 \text{ km s}^{-1}} \right]^3 \left[ \frac{n_{\text{cm}^{-3}}}{10^5} \right]^{-1/2}.$$  \hspace{1cm} (3)

(Figs. 2b and 2e), and including only non-thermal support but taking into account that large-scale supersonic flows compress the gas and generate higher densities (Mac Low & Klessen 2004):

$$\left[ \frac{M_{\text{conv,flows,Jeans}}}{M_{\odot}} \right] = 1.578 \left[ \frac{\sigma_{1D,\text{nth}}}{0.188 \text{ km s}^{-1}} \right]^3 \left[ \frac{n_{\text{cm}^{-3}} M^2}{10^5} \right]^{-1/2},$$  \hspace{1cm} (4)

sphericity, a basic assumption of the core modelling of Palau et al. (2014).
3.3 Fragmentation level vs thermal Jeans number

Given the poor correlations found between the observed number of fragments and the expected number of fragments in case of turbulent support, we considered only thermal support (no contribution from ‘turbulence’), and estimated the Jeans mass as

\[
\frac{M_{\text{Jeans}}}{M_\odot} = 0.6285 \left[ \frac{T}{10^2 \text{K}} \right]^{3/2} \left[ \frac{n}{10^6 \text{cm}^{-3}} \right]^{-1/2}.
\] (5)

This was done using two different assumptions for the temperature. First, we used a fixed temperature of \(\sim 20\) K, as a first approximation to the ‘initial’ (i.e., before being heated by the protostellar feedback) temperature of the dense core (e.g., Sánchez-Monge et al. 2013). Second, we used the average temperature estimated for each core within a region of 0.1 pc of diameter, \(T_\text{ave}\) (ranging from 25 to 150 K, Table 1). This assumption should give an upper limit to the temperature at the time when fragmentation took place.

The results are plotted in Fig. 2g,h. Fig. 2k shows a correlation of \(N_{\text{num}}\) and \(N_{\text{Jeans}}\), with a slope of 0.60 \pm 0.14, clearly larger and closer to 1 than the slope obtained for the turbulence-supported case (\(\sim 0.2\), Table 2). In this panel, the temperature is fixed for all the cores and equal to 20 K. The data are clearly offset with respect to the one-to-one relation (dotted black line), which can be explained if only a percentage of the total mass of the core is converted into compact fragments. We define the Core Formation Efficiency (CFE) as the fraction of mass of a dense core found in compact fragments (as in Bontemps et al. 2010), and in this case:

\[
N_{\text{Jeans}} = \frac{M_{\text{th,nor}} \cdot \text{CFE}}{M_{\text{Jeans}}}.
\] (6)

Thus, we fitted a line with slope 1 (dashed red line in Fig. 2k) and the offset should be a first approximation to the CFE. By doing this for the dataset of Fig. 2k we found a CFE of 12%, with a correlation coefficient of 0.70.

We additionally estimated \(N_{\text{Jeans}}\) using the different average temperatures inferred for each core (Table 1), and the result is shown in Fig. 2h. This approach again yields a correlation between \(N_{\text{num}}\) and \(N_{\text{Jeans}}\) with slope closer to 1 compared to the turbulence-supported case, but in general \(N_{\text{Jeans}}\) is smaller (compared to the previous case of fixed temperature equal to 20 K), because the Jeans masses are larger due to the higher adopted temperatures, and hence the inferred CFE is larger as well. There are two cores (cores 13 and 14) for which the average temperature inside a region of 0.1 pc of diameter, of \(\sim 100\) K, is significantly higher than that of the other cores. These two cores are also the most luminous ones (bolometric luminosity \(\sim 10^3 L_\odot\)) and are seen to depart significantly from the trend defined by the other cores, most likely because the modelled temperature is already affected by stellar feedback and overestimates the actual temperature at the time of fragmentation.

The effect of using such a high temperature is to predict too small a number of fragments (too small \(N_{\text{Jeans}}\)), and therefore we did not take these two cores into account to infer the CFE in this case. We thus obtained a correlation coefficient of 0.66, and a CFE of 34%. This value is fully consistent with the independent direct measurements of the CFE by Bontemps et al. (2010) and Palau et al. (2013), who estimated this quantity by dividing the total mass in compact fragments (detected with an interferometer in an extended configuration) by the mass of the core (measured with a single-dish). Our inferred CFEs are also similar to those found by Louvet et al. (2014) in the W43-MM1 region.

Finally, we calculated the Jeans mass considering that turbulence is only producing regions of higher density, but not providing support against gravity (with the latter being only thermal, e.g., Padoan & Nordlund 2002):

\[
\frac{M_{\text{conv,flows-th}}}{M_\odot} = 0.6285 \left[ \frac{T}{10^2 \text{K}} \right]^{3/2} \left[ \frac{n \cdot M^2}{10^6 \text{cm}^{-3}} \right]^{-1/2}.
\] (7)

(Fig. 2h: blue symbols correspond to \(N_{\text{H}}^2\) data).

Overall, the best correlation between \(N_{\text{num}}\) and \(N_{\text{Jeans}}\) is found for the case of pure thermal support adopting a temperature of \(\sim 20\) K for all the cores. In addition, also for this case the slope in the \(N_{\text{num}}\) vs \(N_{\text{Jeans}}\) relation is closest to 1 (see Table 2).

| Support                      | correl coeff | slope      |
|------------------------------|--------------|------------|
| thermal at fixed T=20K       | 0.72         | 0.60 ± 0.14|
| thermal varying T\(^a\)     | 0.66         | 0.50 ± 0.15|
| turbulent \(\text{NH}_2(1,1)\) VLA\(^b\) | 0.24     | 0.14 ± 0.18|
| turbulent \(\text{N}_2\text{H}^+(1-0)\) single-dish\(^b\) | 0.23 | 0.22 ± 0.25|

\(^a\) Core temperature estimated from the modelled temperature profile by Palau et al. (2014), by calculating the density-weighted average temperature inside a region of 0.1 pc of diameter (see Table 1 for further details). Cores 13 and 14 are not included in the fit because their temperature is clearly overestimated (see text).

\(^b\) Fits are performed for the relations in Figs. 2a and 2d, which correspond to \(N_{\text{Jeans}}\) estimated using the non-thermal velocity dispersion given in Table 1.

3.4 Fragment masses

We have estimated the masses of the fragments identified in each massive dense core by assuming the temperature at
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4 DISCUSSION AND CONCLUSIONS

In the present work we have investigated which process, turbulence or gravity, is controlling the fragmentation level of massive dense cores at ~ 0.1 pc scales. We have used a sample of 19 massive cores, previously presented in Palau et al. (2013) and Palau et al. (2014), to show that the fragmentation of these objects seems to be controlled mainly by thermal Jeans fragmentation. Specifically, we have shown that the fragmentation level, \( N_{\text{num}} \) —measured as the number of compact fragments within a core—, presents a significantly better correlation with the core density than with its non-thermal velocity dispersion. Correspondingly, we have shown that \( N_{\text{num}} \) correlates linearly with the number of fragments expected from simple thermal Jeans fragmentation, with core formation efficiencies, CFE, ranging from 12% to 34%, while, instead, assuming turbulence-dominated fragmentation, the majority of the cores should not fragment, contrary to what is observed. Finally, we have given hints that the masses of most of the fragments in our sample seem to be of the order of the Jeans mass calculated considering only pure thermal support.

4.1 Comparison to previous works

It is important to point out that our results are not inconsistent with those of Zhang et al. (2009), Pillai et al. (2011), Wang et al. (2011, 2014), and Lu et al. (2015). Those authors concluded that the fragments within massive cores of infrared-dark clouds have masses significantly larger than the thermal Jeans mass, and consistent with the turbulent Jeans mass instead. However, in most of these clouds, this could be related to a sensitivity and spatial resolution issue due to the large distance of these infrared-dark clouds (ranging from 3.3 to 7.4 kpc). For example, in four (out of six) of those clouds, the mass sensitivity is \( > 2 M_\odot \) (above the Jeans mass) and the spatial resolution is \( > 5000 \) AU, while the massive dense cores studied here are observed with mass sensitivities \( < 1 M_\odot \), and spatial resolutions \( \sim 1000 \) AU.

The most puzzling clouds are G28.34+0.06 P1 (Zhang et al. 2015), and the Snake (G11.11−0.12 P6, Wang et al. 2014). In these two clouds, observed down to subsolar mass sensitivities, there seems to be a lack of low-mass fragments, suggesting that the bulk of low-mass fragments have not formed yet at such earlier stages, or that the low-mass fragments form outside the core and follow the global collapse.
of the cloud. However, other recent multiwavelength studies focused on the stellar content of infrared-dark clouds show that most of the protostars formed in these clouds are of low-mass ($< 2 M_\odot$; e.g., Samal et al. 2015), and thus this needs to be further investigated. Our study, carried out toward a sample of 19 regions more evolved than those in infrared-dark clouds, shows that most of the fragments detected in our sample are of low mass, and consistent with the thermal Jeans mass, indicating that at these stages the low-mass fragments do already exist. If the lack of low-mass fragments in infrared-dark clouds is confirmed in future observations, our data suggest that the duration of the stage when the low-mass fragments are formed is quite short. This is consistent with the extremely non-linear nature of the gravitational collapse (see, e.g., Fig. 1 (bottom-left) of Toalá, Vázquez-Semadeni, & Gómez 2012, and Fig. 1 of Zamora-Avilés & Vázquez-Semadeni 2014).

Finally, while it is possible that, in order to form the most massive fragments, additional compression mechanisms besides gravity may be necessary, the bulk of the fragmentation process in cores actively forming stars seems to be dominated by gravity rather than by turbulence. This is consistent with recent claims that the bulk of the non-thermal motions in clouds and cores may be dominated by infall rather than by random turbulence (e.g., Vázquez-Semadeni et al. 2008, Schneider et al. 2010, Ballesteros-Paredes et al. 2011a, Peretto et al. 2013, González-Samaniego et al. 2014; see also the review by Vázquez-Semadeni 2015).

### 4.2 Physical implications

Our results suggest that $N_{\text{th}}$ does not seem to depend significantly on the internal supersonic motions of the core, and are thus contrary to the widespread notion that support against gravity is necessary and that turbulence is the main physical process providing it and causing the fragmentation of molecular clouds. Since non-thermal supersonic motions are indeed observed in massive dense cores, but they do not seem to be random enough to act as a pressure against gravity, we propose that the observed ‘turbulence’ cannot be used to define a ‘turbulent-Jeans’ mass.

Although turbulence may very well play a crucial role in the formation of the seeds of what eventually will grow as cores, as demonstrated by the early evolution of molecular clouds in numerical simulations (e.g., Clark & Bonnell 2005; Vázquez-Semadeni et al. 2007, Heitsch & Hartmann 2008), one possible interpretation of our results is that the fragmentation process in star-forming regions is controlled mainly by gravitational contraction and the ensuing reduction in the thermal Jeans mass as the density increases during the collapse. Thus, a possibility is that the non-thermal motions are dominated by infall, produced by the gravitational contraction (e.g., Ballesteros-Paredes et al. 2011a). Indeed, analysis of the dense regions in simulations of driven, isothermal turbulence, indicate that the overdensities tend to have velocity fields with a net negative divergence (i.e. a convergence), rather than being completely random with zero or positive net divergence, as would be necessary for the bulk motions to exert a ‘turbulent pressure’ capable of opposing the self-gravity of the overdensities (Vázquez-Semadeni, et al. 2008, González-Samaniego et al. 2014). Another possibility is that the non-thermal motions are strongly affected by stellar feedback, but in this case the effect on the clouds may be disruptive rather than supportive (Colín et al. 2013).

If the non-thermal motions in the clumps and cores do not exert a turbulent pressure capable of providing support against the self-gravity of the structures, then molecular cloud models based on the competition between gravity and turbulent support should be revisited (McKee & Tan 2003, Hennebelle & Chabrier 2008, Hennebelle & Chabrier 2011, Hopkins 2012). Clearly, a detailed comparison with simulations is needed to understand the origin of the non-thermal motions in massive dense cores and their role in the fragmentation process of molecular clouds.

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APPENDIX A: NH$_3$ AND N$_2$H$^+$ SPECTRA

In this appendix, we present the NH$_3$(1,1) and N$_2$H$^+$(1–0) spectra used in this work to estimate the non-thermal line widths for each massive dense core. The spectra, together with the hyperfine fits done using the CLASS program of GILDAS, are presented in Figs. A1 and A2 and result from a compilation of data already published (see Section 2 for references) or reduced from the VLA archives.

APPENDIX B: NEW DENSITY AND TEMPERATURE DETERMINATION FOR IRAS 22198+6336

In Palau et al. (2014) the original images of IRAS 22198+6336 (122198) published by Jenness et al. (1995) using the JCMT were not available, and the images were digitized. The images are now available and we have re-done the fit, with the additional difference (with respect to Palau et al. 2014) that the main beams assumed here were 7 and 14 arcsec at 450 and 850 µm, respectively, with no consideration of error beams. The results are presented in Fig. B1 and Table B1.
Figure A1. VLA NH$_3$(1,1) spectra averaged over a region of $\sim 0.1$ pc of diameter, where the fragmentation has been assessed. Red lines correspond to the CLASS fits to the hyperfine structure, from which the line width given in Table 1 has been inferred. For regions I22134 and DR21-OH, two velocity components have been used.

Table B1. Best-fit parameters to the radial intensity profiles and Spectral Energy Distribution of IRAS 22198+6336 (I22198), and inferred properties (updated after Palau et al. 2014)

| Source   | $\beta^a$ | $T_0^a$ (K) | $\rho_0^a$ ($\times 10^{-17}$ g cm$^{-3}$) | $p^a$ | $\chi_r^a$ | $q^b$ | $r_{10 K}^b$ (pc) | $r_{\text{max}}^b$ (pc) | $M_{\text{obs}}^b$ ($M_\odot$) | $\Sigma_{0.1 \text{pc}}^b$ (g cm$^{-2}$) | $n_{0.1 \text{pc}}^b$ ($\times 10^5$ cm$^{-3}$) |
|----------|-----------|-------------|-------------------------------------------|-------|-------------|------|----------------|----------------|----------------|----------------|----------------|
| I22198   | 1.16 ± 0.22 | 44 ± 4      | 3.4 ± 0.4                                 | 1.75 ± 0.03 | 0.580       | 0.39 | 0.22          | 0.31           | 115            | 0.29           | 3.6            |

$^a$ Free parameter fitted by the model: $\beta$ is the dust emissivity index; $T_0$ and $\rho_0$ are the temperature and density at the reference radius, 1000 AU; $p$ is the density power law index; $\chi_r$ is the reduced $\chi$ as defined in equation (6) of Palau et al. (2014).

$^b$ Parameters inferred (not fitted) from the modeling, $q$ is the temperature power-law index, and $r_{10 K}$ is the radius of the core where the temperature has dropped down to $\sim 10$ K; $r_{\text{max}}$ is the radius at the assumed ‘ambient’ density of 5000 cm$^{-3}$; $M_{\text{obs}}$ is the mass computed analytically from the model integrating until the radius where the density profile could be measured for each source. $\Sigma_{0.1 \text{pc}}$ and $n_{0.1 \text{pc}}$ are the surface density and density inside a region of 0.1 pc of diameter.
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Figure A2. Single-dish $\text{N}_2\text{H}^+ (1-0)$ spectra averaged over a region of $\sim 0.1$ pc of diameter, where the fragmentation has been assessed. Blue lines correspond to the CLASS fits to the hyperfine structure, from which the line width given in Table 1 has been inferred.
Figure B1. New fit (after Palau et al. 2014) to the radial intensity profiles and Spectral Energy Distribution of IRAS 22198+6336 (I22198) after using original JCMT data of Jenness et al. (1995) work.