1. Introduction

The processes regulating the fragmentation of molecular clouds are still a matter of vigorous discussion and debate. These processes have been studied from an observational point of view at different spatial scales. At large scales (~1 pc) or clump scales, gravoturbulent fragmentation (or thermal Jeans fragmentation) seems to describe the observations well (e.g., Román-Zúñiga et al. 2009; Takahashi et al. 2013; Walker-Smith et al. 2013; Samal et al. 2015; Kainulainen et al. 2016; Sharma et al. 2016; Hacar et al. 2017b), although there are cases where the effects of feedback (Busquet et al. 2016) or large-scale collapse (Csengeri et al. 2017) seem to be important as well. The term "gravoturbulent fragmentation" refers to the fragmentation that takes place in a turbulent and self-gravitating cloud. In these clouds, turbulence generates high-density regions where the Jeans mass decreases and thus fragmentation is favored (e.g., Padoan & Nordlund 2002; Schmeja & Klessen 2004; Hopkins 2013; Gong & Ostriker 2015).

At medium scales (~0.1 pc), fragmentation also seems to be dominated by gravity acting in a turbulent medium (e.g., Teixeira et al. 2016; Kirk et al. 2017). In this respect, Palau et al. (2014, 2015) compile a sample of 19 massive dense cores and study their fragmentation level against different parameters, finding that the fragmentation level seems to be well correlated with the density (within the approximate core size of 0.1 pc), a result consistent with thermal Jeans fragmentation. However, there are also works that show at these scales the mass of the fragments seem to be too high compared to the thermal Jeans mass (e.g., Zhang et al. 2009, 2015; Bontemps et al. 2010; Pillai et al. 2011; Wang et al. 2011, 2014; Lu et al. 2015). This needs to be further investigated with better mass sensitivities (Henshaw et al. 2017) and in relation to the kinematics of the surrounding molecular gas (e.g., Duarte-Cabral et al. 2013).

At even smaller scales (~0.01 pc or ~1000 au), the "fragmentation properties" are usually referred to as "multiplicity properties," and most studies have been carried out toward low-mass star-forming regions. At these scales, new ingredients such as rotational fragmentation (e.g., Chen et al. 2012; Chabrier et al. 2014) or fragmentation of a (pseudo)disk through gravitational instability (e.g., Kratter & Matzner 2006; Tobin et al. 2016) have been proposed to explain the formation of multiple/binary systems. Thus, it is not clear whether the dominant process regulating fragmentation at these small scales is inherited from large scales (as suggested by some observational works, Lee et al. 2015) or whether the aforementioned processes start to be important. At these scales, there is a lack of observations about the fragmentation properties in intermediate- and high-mass star-forming regions at very early stages, but it is quite well established that the multiplicity fraction in high-mass main-sequence stars, as well as the number of companions per system, increases with stellar mass (e.g., Chini et al. 2012; Kraus et al. 2017). Thus, studying the fragmentation/multiplicity properties in deeply embedded intermediate/high-mass star-forming regions should provide clues to the dominant processes determining fragmentation at these scales.

Here we present a study of the fragmentation properties of a region forming intermediate- and low-mass protostars, the Orion Molecular Cloud 1 South (hereafter, OMC-1S). The region lies near the center of the Integral Shaped Filament...
(e.g., Johnstone & Bally 1999; Stutz & Gould 2016), a ∼50′ long filament in the Orion A cloud whose central part harbors the famous Orion-KL and Orion bar regions. The right panel of Figure 1 presents the central 15′ of the Integral Shaped Filament, with OMC-1S highlighted with respect to Orion-KL and the Orion bar. The most recent measurement of the distance has been made by Kounkel et al. (2017), who report 388 pc. OMC-1S has been widely studied using multiple observational techniques, which have revealed a nascent cluster characterized by a large number of spectacular molecular outflows and Herbig–Haro objects (e.g., Smith et al. 2004; Zapata et al. 2005, 2006; Henney et al. 2007). In addition, the outer layers of the OMC-1S region, which are bathed by external irradiation from the surrounding massive stars within the Orion Nebular Cluster (Tahani et al. 2016), also seem to be undergoing global infall (e.g., Hacar et al. 2017a). Therefore, a very active phase of clustered star formation is taking place in OMC-1S, and the region becomes an excellent target for studying fragmentation down to very small scales (≪1000 au). In Section 2, we present the millimeter ALMA and Very Large Array (VLA) observations toward OMC-1S down to spatial scales of ∼40 au for the VLA observations. In Section 3, we describe the main results. In Section 4, we analyze the properties of the fragmenting cores in OMC-1S; in Section 5 we discuss our main findings, and in Section 6 we give the conclusions.

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2. Observations

2.1. ALMA at 1.3 mm

The ALMA Band 6 (1.3 mm) observations were carried out on 2015 May 19 and August 18 as part of the Cycle 2 program 2013.1.01037.S. On May 19, we used 38 of the 12 m antennas, yielding baselines with projected lengths from 21 to 555 m (16–427 kλ), while on August 18 we used 37 antennas also of 12 m, yielding baselines with projected lengths from 43 to 1600 m (33–1230 kλ). Including both epochs, the range of projected baselines covered is 16–1230 kλ, which corresponds to the largest angular scale to which ALMA was sensitive of 5′.7 (following equation (A.5) of Palau et al. 2010). The integration time on-source (OMC-1S) was about 8 minutes in each observation.

The phase center for both observations was the same, α(J2000) = 05°35′14″; δ(J2000) = −05°24′00″. The continuum image was obtained by averaging line-free channels from four spectral windows (of 1.875 GHz width) centered at rest frequencies of 233.683 GHz, 231.323 GHz, 219.266 GHz, and 216.875 GHz, which covers a total bandwidth of 7.5 GHz.
The weather conditions were very good and stable with an average precipitable water vapor of 0.8 mm and an average system temperature of 60 K. The ALMA calibration included simultaneous observations of the 183 GHz water line with water vapor radiometers, used to reduce the atmospheric phase noise. Quasars J0541−0541, J0522−364, and J0750+1231 were used to calibrate the bandpass, the flux scale, the atmosphere, and the gain fluctuations.

The data were calibrated, imaged, and analyzed using the Common Astronomy Software Applications (CASA) version 4.7. Imaging of the calibrated visibilities was done using the task CLEAN. We combined the two epochs with the task CONCAT in CASA. The resulting (dynamic-range limited) image rms noise was 0.7 mJy beam$^{-1}$ at an angular resolution of $0.28\times0.22$ with position angle $PA=81.64^\circ$. We also generated an image using only the extended configuration, in order to extract the compact sources. In this case, the rms of the 1.3 mm continuum is 0.45 mJy beam$^{-1}$, and the synthesized beam is $0.022\times0.017$, corresponding to a spatial resolution of $\sim74\text{ au}$ at the distance of OMC-1S, with $PA=73.37^\circ$. Throughout the paper, we will refer to the rms noise of the extended configuration image by $\sigma$. We used the ROBUST parameter of CLEAN in CASA set to 0 for an optimal compromise between angular resolution and sensitivity. The millimeter continuum image obtained for OMC-1S was corrected by the primary beam attenuation. The primary beam at this wavelength had a full width at half maximum of about 27″.

2.2. VLA at 7 mm

The observations were made with the Very Large Array of NRAO$^9$ in the continuum mode at 7 mm (43.34 GHz) during 2004 November 10, under the project code AZ154. The effective bandwidth of the observations was 100 MHz. At this epoch, the VLA was in A configuration, providing baselines covering projected lengths from 0.68 to 36 km (99−5200 kλ). This corresponds to the largest angular scale to which the VLA was sensitive of $0.9^\circ$.

The phase center of the observations was $\alpha(J2000)=05\text{h}35\text{m}14\text{s}$; $\delta(J2000)=-05^\circ24'03''$, very close to the center of the radio cluster reported by Zapata et al. (2004). The absolute amplitude calibrator was J1331+305 (with an adopted flux density of 1.45 Jy) and the phase calibrator was J0541−056 (with a bootstrapped flux density of 1.10 ± 0.09).

The data were acquired and reduced using the recommended VLA procedures for high-frequency data, including the fast-switching mode with a cycle of 120 s. We used the ROBUST parameter of IMAGR in AIPS set to 0. The resulting image had an angular resolution of $0.065\times0.053$ with $PA=-7.73^\circ$, but we smoothed the image to a final circular beam of $0.09^\circ$ in order to be more sensitive to faint and extended structure. The rms noise of the smoothed image is 0.13 mJy beam$^{-1}$. A 7 mm continuum image was also corrected for the primary beam attenuation. The primary beam at this wavelength has a full width at half maximum of about 60″.

9 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

3. Results

In Figure 1 we present the ALMA 1.3 mm continuum emission toward OMC-1S with an angular resolution of $\sim0.025$, corresponding to $\sim100$ au. The strongest millimeter sources detected by ALMA coincide very well with the sources already detected with the Submillimeter Array (see, e.g., Figure 1 of Zapata et al. 2005), but the ALMA image, about two orders of magnitude deeper, reveals additionally a number of faint point-like sources as well as a striking extended emission around the strong millimeter sources. We identify three main filamentary structures, plus three additional sources to the north of the image, which do not seem to belong to any filamentary structure. Two of the main filaments lie in the central part of the image, with the eastern one (hereafter, the “Eastern Filament”) elongated in the east–west direction, and the western one (the “Western Filament”) elongated in the north–south direction. The third filament, which is the most prominent one, lies about 10″ to the south (hereafter, the “Southern Filament”) and is also elongated in the east–west direction.

In order to extract the point and fainter sources detected by ALMA, we generated an image using only the extended configuration data. In Figures 2–5 we show a zoom of the ALMA image of Figure 1 on the four different regions/ filaments identified in this figure. We identified 31 compact sources above a 12$\sigma$ threshold$^{10}$ (white contour in the figures; in this identification, we did not take into account those sources whose 12$\sigma$ contour encompasses an area smaller than half of the beam, so that we avoid artifacts or peaks of noise). For the case of N1 and SF5, which are the strongest and most extended millimeter sources in the region, we identified subcomponents (using only the extended configuration data) by fitting 2D Gaussians and inspecting the residuals: if the residuals lie above the 12$\sigma$ detection threshold, we required the inclusion of an additional Gaussian. Among the 31 identified sources, 11 sources belong to the Southern Filament (named SF1 to SF6, with SF3, SF4, SF5, and SF6 consisting of several components); nine sources belong to the Eastern Filament (named EF1 to EF7, with EF5 consisting of three components), six sources belong to the northern region (N1 to N3, with N1 consisting of three components and N2 consisting of two), and five sources belong to the Western Filament (named WF1 to WF3, with WF2 consisting of three components). The Eastern Filament seems to have two “arms,” the northern arm including EF1, EF2, and EF3, and the southern arm including EF4 and EF5, with EF6 and EF7 being sources common to both arms. Since EF4 and EF5 are interconnected by extended emission that reaches EF6 and EF2 (see Figures 1 and 3), it seems reasonable to think that the two arms should have a common origin.

In Table 1 we give the position, peak intensity, flux density, deconvolved size, and $PA$ of the 31 identified millimeter sources, after performing 2D Gaussian fits (with the task IMFIT in CASA) using the extended+compact configuration image (Figure 1). In the table, we also provide an estimate of the mass of gas and dust for each millimeter source, using the flux

10 The ALMA array is so sensitive that it detects a lot of extended emission in OMC-1S. Because of this, some secondary lobes of the dirty beam cannot be properly removed with the cleaning process. Those secondary lobes reach the 12$\sigma$ contour in some cases, as is the case for the Southern Filament and the northern part of N2. 12$\sigma$ is the threshold where the secondary lobes are reduced to sizes smaller than the beam size.
density given in column 5 of Table 1, and assuming a dust temperature of 25 K and a dust (+gas) mass opacity coefficient at 1.3 mm of 0.00899 cm$^2$ g$^{-1}$ (column 6 of Table 1 of Ossenkopf & Henning 1994, corresponding to agglomerated dust grains with thin ice mantles at densities of 10$^6$ cm$^{-3}$). The dust temperature is estimated from observations of the NH$_3$(1,1) and (2,2) transitions by Wiseman & Ho (1998) in the Orion-KL and OMC-1S regions, and assuming that gas and dust are thermalized in the dense cores. These authors provide an image of the ratio of NH$_3$(2,2) to (1,1) integrated intensities, and for OMC-1S the ratio ranges from 0.5 to 1, corresponding to rotational temperatures from 18 to 33 K (for opacities of the NH$_3$(1,1) transition around 1, Table 2 of Wiseman & Ho 1998). Thus, we adopt an average temperature of 25 K for all the millimeter sources. Although some of the millimeter sources might be slightly more evolved than others (see Section 4) we adopt the same dust temperature because no big variations are expected given the embedded nature of the OMC-1S region (e.g., Sánchez-Monge et al. 2013). We estimated an uncertainty in the masses due to an uncertainty in the dust opacity of a factor of about two. The derived masses range from 0.02 to 1.5 $M_\odot$.

Using the 7 mm data from the VLA in its most extended configuration, we can further study the substructure of the ALMA sources down to 0$''$09 or 40 au. We identified those 7 mm sources above the 5$\sigma$ threshold. The VLA 7 mm 5$\sigma$ detections correspond to a 1.3 mm intensity of $\sim$18 mJy beam$^{-1}$, assuming a spectral index of 2. Thus, the ALMA sources fainter than this threshold could not have been detected by the VLA at 7 mm. The small panels of Figures 2–5 present a zoom of the ALMA sources (above $\sim$18 mJy) on a color scale, with the 7 mm continuum emission overplotted in black contours. As can be seen in Figure 2, the ALMA sources N3 and N1b have clear counterparts at 7 mm. In the Eastern Filament, sources EF1, EF2, and EF6 also have 7 mm counterparts (Figure 3), similar to WF2b and WF3 in the Western Filament (Figure 4). Finally, in the Southern Filament, SF2, SF3b, SF5, and SF6b have 7 mm counterparts above the 5$\sigma$ threshold (Figure 5). After comparison of the 7 mm emission among the different regions/filaments, it is obvious that while the 7 mm counterparts in the northern region, Eastern Filament and Western Filament are single sources, an important fraction of the ALMA sources in the Southern Filament split up into several sources at 7 mm.

Table 2 summarizes the properties of the identified 7 mm sources: their peak position, peak intensity, and flux density (integrated inside the 2.5$\sigma$ contour). In the table, we also give the peak intensity of the 1.3 cm emission from Zapata et al. (2004). Using these values, and taking into account the positive spectral indices inferred by Zapata et al. (2004) for the 1.3 cm counterparts, a non-negligible part of the 7 mm emission could
be contributed by the free–free emission detected at longer wavelengths. Therefore, we cannot determine from this information alone whether the 7 mm emission comes mainly from free–free or thermal dust emission, and we refrain from estimating masses of gas and dust using the 7 mm emission.

4. Analysis

4.1. Typical Separations between the ALMA Sources

In this section we aim to study the spatial distribution of the ALMA sources. For this, we first calculated the angular separations, \( \theta \), from each source to every other one in Table 1 using the R.A., Decl. coordinates. Figure 6 (top) presents the histogram of separations between the ALMA sources. As can be seen from the figure, the peak of the histogram is at \( \log 2.35 \), corresponding to 6240 au. This indicates that the three main filaments in OMC-1S are separated by approximately the same projected distance (as can be seen from Figure 1), which would naturally imply that the most common separation between ALMA sources is the typical distance between the filaments. The second peak in the histogram is around \( \log 2.95 \), or 1570 au, which corresponds to the typical separation between the sources within a filament (this will be further analyzed below).

Second, we calculated the mean surface density of companions (MSDC), \( \Sigma_0 \), for the sources listed in Table 1. The MSDC has been widely used to investigate the transition from pairs to groups in distinct scenarios that include young star clusters and dense cores (Gómez et al. 1993; Bate et al. 1998; Kraus & Hillenbrand 2008; Román-Zúñiga et al. 2010; Tafalla & Hacar 2015). In the diagram of \( \Sigma_0 \) versus \( \theta \), the binary and clustering regimes present a steep negative slope, while a uniform distribution of sources would present a flat slope (e.g., Bate et al. 1998; Hartmann 2002; Kraus & Hillenbrand 2008).

Following the prescription by Simon (1997), we took the angular separations \( \theta \) and grouped them in annuli of 0.1 dex within \(-6 < \log \theta < 0\). Then, \( \Sigma_0 \) is computed as the number of elements in each annulus, \( N_0(\theta) \), divided by the area, normalized by the total number of elements. The MSDC is equivalent, in this way, to the two-point correlation function (TPCF), \( W_\theta \), that compares the value of \( \Sigma_0 \) with a uniform, random distribution of points in an area of the same size as our field (\( A_m = 10^{-4} \) deg\(^2\)). If \( N_r \) is the number of randomly distributed points that fall in each of our annuli, then

\[
W_\theta = \frac{N_p}{N_r} - 1.
\]

To determine \( N_r \), we averaged the output from \( 5 \times 10^4 \) drawings using a simple Monte Carlo routine. Then,

\[
\Sigma_0(TPCF) = \left( \frac{N_p}{A_m} \right)(1 + W_\theta)
\]

can be compared directly to the value of \( \Sigma_0 \) estimated from direct counting in the annular bins.

The results of this calculation are shown in Figure 6 (bottom). The figure shows that \( \Sigma_0 \) is anticorrelated to \( \theta \) from \(-4.5 < \log \theta < -3.4 \) (about 44–556 au), then the distribution appears to flatten out to \( \log \theta \approx -3 \) (about 1397 au), followed by another short fall from \(-3 \) to \(-2.7 \) and a flattening or small bump from \(-2.7 \) to \(-2.5 \). The values of the MSDC and the TPCF are very consistent down to this last value, but above it the function shows an abrupt decrease, indicating where the angular separation reaches the field size. Two aspects are remarkable: one is that the linear fit in the range \(-4.5 < \log \theta < -3.4 \), or 44–556 au, has a well defined slope of \(-1.05 \), consistent with ordered
breaks are marked with vertical dashed lines in Figure 6. For example, a break in the regime dominated by the distribution of binaries might be indicated by a slope change, with respect to the slope near the size of cores that fragment and lead to the formation of binary systems. The size of cores that fragment and lead to the formation of binary systems,

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In the previous section a particular spatial scale associated with the size of binary and multiple systems was found at \( \sim 556 \) au. We use such a spatial scale here to define a "core," as the grouping of those millimeter sources for which the distance between each member of the group and at least one other member is \( < 556 \) au. To illustrate this more clearly, in the Appendix we present the ALMA images with circles of radius 556 au centered on each ALMA source listed in Table 1. From those figures, it is straightforward to see which sources are separated by \( < 556 \) au, and thus which sources would belong to the same "core" (marked in the figure with the same color code). Because our data indeed present an excess of source surface density at such a scale, the cores are well defined and do not extend indefinitely through a filament. According to our definition, cores are structures of \( \sim 1100 \) au in diameter that might harbor one single millimeter source or several millimeter sources. By doing this, we identified 19 cores, listed in Table 3.

4.2. Cores Defined as Groups of ALMA Sources

In the previous section a particular spatial scale associated with the size of binary and multiple systems was found at \( \sim 556 \) au. We use such a spatial scale here to define a "core," as the grouping of those millimeter sources for which the distance between each member of the group and at least one other member is \( < 556 \) au. To illustrate this more clearly, in the Appendix we present the ALMA images with circles of radius 556 au centered on each ALMA source listed in Table 1. From those figures, it is straightforward to see which sources are separated by \( < 556 \) au, and thus which sources would belong to the same "core" (marked in the figure with the same color code). Because our data indeed present an excess of source surface density at such a scale, the cores are well defined and do not extend indefinitely through a filament. According to our definition, cores are structures of \( \sim 1100 \) au in diameter that might harbor one single millimeter source or several millimeter sources. By doing this, we identified 19 cores, listed in Table 3.
1.3 mm and the same assumptions as in Table 1; the average of the positions of the ALMA sources belonging to the same core (Table 3), and estimated the average (standard deviation) separation between cores within each filament: 1310 (460) au for the Eastern Filament, 1280(300) au for the Western Filament, and 1140(350) au for the Southern Filament. These average separations are consistent with the secondary peak at 1570 au of the histogram of separations shown in Figure 6 (top).

4.3. Fragmentation Level versus Density

The ALMA and VLA observations have revealed the structure of the millimeter emission in OMC-1S, at spatial scales spanning almost two orders of magnitude, from 2200 au (corresponding to the largest angular scale of the ALMA data) down to ∼40 au (corresponding to the angular resolution of the VLA data). This allowed us to identify three extended filamentary structures, with 19 cores embedded in them, as well as further sources within these cores.

In the following, we define the “fragmentation level” of each core as the number of closed contours above the detection threshold at each wavelength (12σ at 1.3 mm and 5σ at 7 mm), within a region of 1100 au in diameter, as this is approximately the core size. This is similar to the definition used by Palau et al. (2013, 2014, 2015), but in these works the fragmentation was assessed within a region of 0.1 pc, while in the present work we assess the fragmentation in a region about one order of magnitude smaller. In the case of no closed contours but the single Gaussian fit clearly requiring an additional Gaussian (see Section 3), we counted each Gaussian as a separate source (this is the case for N1 and SF5 in the ALMA data). In the cases where the ALMA source has a clear 7 mm counterpart, we have counted them as one single source. Our VLA+ALMA data set allows us to study the fragmentation properties in OMC-1S down to spatial resolutions of ∼40 au and for mass sensitivities of ∼0.05 M☉ (estimated using a flux density of 18 mJy at 1.3 mm and the same assumptions as in Table 1; the flux density threshold corresponds to the extrapolation of the 7 mm sensitivity to 1.3 mm, see Section 3). For this reason, the fragmentation in those cores whose peak intensity is below 18 mJy has not been studied down to 40 au but to 74 au, and thus its fragmentation level is considered as a lower limit. This is the case for six out of the 19 cores.

In Table 3, we list the 19 ALMA cores and their fragmentation level within 1100 au. From that table, it is obvious that all of the cores in the Southern Filament present a fragmentation level higher than all the cores in the Eastern Filament (we are not taking into account here the cores for which we only have lower limits to the fragmentation level). To quantify whether the differences in fragmentation between the Southern and Eastern Filaments are significant, we calculated the probability of drawing three “ones” (fragmentation level of the three cores in the Eastern Filament) from a Gaussian distribution with mean and standard deviation equal to those of the Southern Filament, which are 3.200 and 1.095, respectively. This yields a probability of drawing one “one” of 0.041. Then, the probability of drawing three ones as in the Eastern Filament is ∼0.0071%, which is really small. This indicates that the fragmentation level in the Southern Filament is significantly higher than in the Eastern Filament.

An ingredient that could be playing a role in the early fragmentation of the cores is their density structure. This was studied by Palau et al. (2014), who found that the fragmentation level in a sample of massive dense cores of >0.1 pc seems to be tightly related to the density of the core within a diameter of 0.1 pc, which in turn depends on the density profile and the central density of the core. With this in mind, we used an approximate method to test the effect of the density structure of the core in our data, assuming that the temperature structure does not change significantly from one core to another and thus that the differences in the intensity profiles mainly reflect the differences in density profiles. For each core, we estimated the mass (in the ALMA image including the extended and compact configurations, and following the same assumptions as in Section 3) enclosed within a given diameter, which we take to be 1100 au, and then converted this into density. By doing this, if the density profile is rather flat we will obtain a high mass within the given diameter, while if the density profile is highly concentrated, the mass within the same diameter will be smaller (assuming similar central densities). In Figure 7 (top) we plot the fragmentation level of each core against the density within 1100 au. The figure shows that the higher the density, the higher the fragmentation level.11 Actually, the average density within 1100 au for the fragmenting cores is 36 × 10^-3 cm^-3, while the average density within 1100 au for the non-fragmenting cores is about a factor of 4 smaller, 9.3 × 10^-3 cm^-3.

4.4. Fragmentation Level versus Evolutionary Stage

We have explored the possibility that the high fragmentation in the Southern Filament is related to the density of each core, and we find indications of a trend between fragmentation and density. Another factor that could also determine the fragmentation level is the evolutionary stage. Recent studies in the literature are suggestive of a trend whereby multiplicity...
fraction decreases with evolutionary stage, from Class 0 to Class I (e.g., Connelley et al. 2008; Chen et al. 2013; Duchêne & Kraus 2013; Tobin et al. 2016). Such a trend is expected if fragmentation takes place bound to the gas potential and the potential is dominated by one central object, naturally leading to a decrease in distance between the fragments (e.g., Sadavoy & Stahler 2017). It is also expected from dynamical evolution, since three-body interactions tend to destroy wide binary systems (e.g., Kroupa et al. 1999; Kaczmarek et al. 2011; Duchêne & Kraus 2013; Li et al. 2016).

To explore this possibility, the most appropriate method would be to construct the spectral energy distribution (SED) for each core. However, to do this we would need mid-infrared and far-infrared information for each core at an angular resolution better than ~2″, and this is not available for the ALMA cores in OMC-1S. We crossed our list of cores with the Orion Spitzer and Herschel catalogs of Megeath et al. (2012) and Furlan et al. (2016), and only found identified Spitzer/IRAC point sources corresponding to N3 and WF2b, and no sources in Spitzer/MIPS or Herschel/PACS catalogs. The sources N3 and WF2b are also detected in the mid-infrared observations of Smith et al. (2004), together with EF1, EF6, and WF3. With a total of four cores with mid-infrared detections, it is definitely not possible to study any trend of fragmentation with SED properties. Instead, we have collected data for all the cores at different wavelengths, so that we may have a rough and very approximate idea of the possible evolutionary stage of each core.

On the one hand, in Figure 8 we present a CAHA Ks image of the OMC-1S region. To obtain this near-infrared image, we used the Calar Alto Public Archive and downloaded a set of near-infrared images taken between 2011 December 13 and 15, with the OMEGA-2000 Camera on the 3.5 m telescope at Calar Alto Observatory. We processed the raw images along with a set of proper calibration files using our reduction pipelines, in a sequence similar to that described by Román-Zúñiga et al. (2015). As can be seen in the figure, some of the ALMA cores (overplotted in blue contours) are detected in the infrared, and these are mainly located in the Western and Eastern Filaments.

In addition, we searched for Chandra X-ray counterparts to the ALMA cores (Rivilla et al. 2013). Finally, we also studied the 1.3 cm emission associated with the cores, following Zapata et al. (2004), together with their respective spectral indices. We summarize all these properties in Table 3 and Figure 8.

After compiling all these data for the ALMA cores, we tentatively assigned an evolutionary stage for each core. We assigned the stage of Class 0/1 for the most embedded sources, and Class 1/II for the more evolved objects probably having only a faint envelope. Intermediate cases would be assigned the Class I stage. We based our classification on the following criteria: (i) near-infrared emission and X-ray emission are usually associated with young stellar objects dominated by a disk (no envelope, e.g., Rivilla et al. 2013; Povich et al. 2016),

12 At the small spatial scales where we have studied fragmentation (~500 au radius), one could refer to sources belonging to the same core as forming a “multiple system.” However, from our data alone it is not possible to ensure the protostellar nature of all the detected millimeter sources, nor is it possible to study whether the sources belonging to each core are gravitationally bound or not. For these reasons, we refrain from calling our study a “multiplicity study” and prefer to call it a “fragmentation study.”

13 http://www.caha.es/caha-public-archives.html

14 In a nutshell, our pipelines consist of IRAF and Fortran routines that provided a two-pass sky subtraction reduction, centroid-corrected dither registering, a <0.2″ rms astrometric solution, as well as aperture and PSF photometry catalogs for all detectable sources.
and detection in at least one of these signposts plus association with HH objects (no molecular outflows) would suggest a Class I/II nature; (ii) if a source is detected in all the signposts of Table 3, with the outflow being molecular, we consider it to be in an intermediate stage (i.e., Class I); (iii) sources driving molecular outflows (traced by SO, CO, or water masers) and being associated with thermal centimeter emission (positive spectral index between 3.6 and 1.3 cm, Zapata et al. 2004), with no detection in the infrared or X-rays, are typically deeply embedded sources (e.g., Liu et al. 2014; Pech et al. 2016), suggesting a Class 0/I nature; (iv) if a source has not been detected in any of the signposts listed in Table 3, we consider it to be deeply embedded (i.e., Class 0/I), since the extreme compact nature of the dust emission suggests that at least a hydrostatic core should have already been formed.

In Figure 7 (bottom) we plot the fragmentation level against this tentative evolutionary stage, which could be suggestive of a decreasing trend. However, it should be kept in mind that the statistics used to build Figure 7 (bottom) are extremely poor (essentially because most of the sources seem to be in the Class 0/I stage), and that in the earliest stage there is a wide spread of fragmentation levels: from the lowest possible (around one source) up to the highest (five sources). Therefore, to draw firmer conclusions regarding a possible trend between the fragmentation level and evolutionary stage, better statistics especially in the later stages should be compiled.

5. Discussion

In the previous section we studied the fragmentation level of the OMC-1S cores, and showed that most of the cores of the Southern Filament present a higher fragmentation level than the cores of the Eastern filament. We studied whether this could be related to the evolutionary stage of the cores but cannot draw any conclusion because most of the cores seem to be in a similar, deeply embedded, evolutionary stage, with only four cores out of 19 having hints of being in later evolutionary stages. Thus, it remains to be understood which process sets the pristine fragmentation level of a core. OMC-1S is an excellent region in which to study this because of the high number of cores detected with ALMA, and because most of these cores seem to harbor young stellar objects at very early evolutionary stages (Table 3).

There are several processes that have been proposed in the literature to play a role in setting the pristine fragmentation of a core, such as magnetic fields (e.g., Boss 2004; Vázquez-Semadeni et al. 2005; Commerçon et al. 2011; Hennebelle et al. 2011; Fontani et al. 2016), turbulent support (e.g., Zhang et al. 2009, 2015; Pillai et al. 2011; Wang et al. 2011, 2014; Lu et al. 2015), or the rotational-to-gravitational energy (e.g., Lim et al. 2016; Arreaga-García 2017). Recently, Palau et al. (2014, 2015) have studied the aforementioned processes in a sample of 19 massive dense cores and found that the fragmentation level within cores of 0.1 pc is best correlated with the density structure of the cores, rather than with the non-thermal velocity dispersion (Palau et al. 2015) or even the rotational-to-gravitational energy (Palau et al. 2014). Interestingly, Lee et al. (2015) also find no clear correlation of the fragmentation level with non-thermal velocity dispersion or rotational-to-gravitational energy in L1448N, but a good correlation of higher fragmentation with density. Other recent observational works supporting the crucial role of the density in the star formation history of the cores are those of Samal et al. (2015), Sharma et al. (2016), and Figueira et al. (2017). All these works

Table 2

Parameters of the Sources Detected with the VLA at 7 mm in OMC-1S

| Source | Position* | Position2 | $L_{\nu}^{7\text{mm}}$ (mJy beam$^{-1}$) | $S_{\nu}^{7\text{mm}}$ (mJy) | $I_{\nu}^{1.3\text{cm}}$ (mJy beam$^{-1}$) |
|--------|-----------|-----------|---------------------------------|----------------------------|---------------------------------|
| N1b    | 05:35:13.709 | 05:23.46.88 | 1.91                            | 17.2                        | 0.59                            |
| N3     | 05:35:14.392 | 05:23.50.82 | 1.88                            | 5.19                         | 0.78                            |
| EF1    | 05:35:15.876 | 05:23.57.22 | 1.65                            | 2.30                         | 0.55                            |
| EF2    | 05:35:14.135 | 05:23.56.68 | 1.14                            | 1.49                         | 0.85                            |
| EF6    | 05:35:14.536 | 05:23.56.02 | 0.76                            | 2.03                         | <0.21                           |
| WF2b   | 05:35:13.571 | 05:23.55.80 | 1.32                            | 1.75                         | 0.57                            |
| WF3    | 05:35:13.558 | 05:23.59.07 | 2.47                            | 5.37                         | 1.00                            |
| SF2aa  | 05:35:13.203 | 05:24.12.62 | 0.80                            | 4.06                         | 0.26                            |
| SF2ab  | 05:35:13.206 | 05:24.12.54 | 0.85                            | ...                          | <0.21                           |
| SF3ba  | 05:35:13.405 | 05:24.11.33 | 1.14                            | 4.13                         | 0.78                            |
| SF3bb  | 05:35:13.411 | 05:24.11.23 | 1.27                            | ...                          | 0.78                            |
| SF5aa  | 05:35:13.737 | 05:24.07.76 | 0.93                            | 13.1                         | 0.15                            |
| SF5ab  | 05:35:13.742 | 05:24.07.82 | 0.96                            | ...                          | 0.15                            |
| SF5ac  | 05:35:13.742 | 05:24.07.76 | 0.84                            | ...                          | <0.21                           |
| SF5ad  | 05:35:13.746 | 05:24.07.57 | 0.69                            | ...                          | <0.21                           |
| SF6ba  | 05:35:13.928 | 05:24.09.41 | 1.09                            | 2.43                         | 0.42                            |
| SF6bb  | 05:35:13.933 | 05:24.09.47 | 0.96                            | ...                          | 0.42                            |

Notes.

* Position of the peak intensity, peak intensity, and flux density integrated within the 2.5σ contour. Uncertainty in the peak intensity is the rms noise of the image, 0.13 mJy beam$^{-1}$.

b Peak intensity at 1.3 cm from Zapata et al. (2004). For non-detections, an upper limit of 3σ is given. For SF3b, SF5, and SF6b the position of the peak of the emission at 1.3 cm lies exactly in between the 7 mm positions of SF3ba and SF3bb, SF5aa and SF5ab, and SF6ba and SF6bb. Thus, we tentatively assigned half of the 0.13 mJy beam$^{-1}$ to each of these 7 mm sources.

c The flux density integrated within the 2.5σ contour includes both “a” and “b” sources for SF2, SF3b, and SF6b, and “aa,” “ab,” “ac,” and “ad” sources for SF5.
favor pure thermal Jeans fragmentation, because in this case, the higher the density of the core, the smaller the Jeans mass and thus the higher number of fragments expected. In the previous section we have studied this in OMC-1S, and find again an increasing trend of higher fragmentation with density within 1100 au, very consistent with the previous works but now at scales about one order of magnitude smaller.

If Jeans fragmentation is at work, we should find sources with a mass comparable to the Jeans mass and separations comparable to the Jeans length. If we take an average density within 1100 au for the fragmenting cores of about \(\sim 36 \times 10^7\) cm\(^{-3}\) (Section 4.3), and a temperature of 25 K, the Jeans mass is \(\sim 0.04\) \(M_\odot\) (following Palau et al. 2015) while the Jeans length is 360 au (following Bontemps et al. 2010). For our ALMA data, the mass sensitivity is 0.018 \(M_\odot\) (for the 12\(\sigma\) detection threshold), fully sensitive to the Jeans mass, and for the VLA data the mass sensitivity is \(\sim 0.2\) \(M_\odot\) (for the 5\(\sigma\) detection threshold and in the case of thermal dust emission). Similarly, the Jeans length is fully resolved by our ALMA and VLA data (\(\sim 100\) au). Among the 31 sources detected with ALMA, almost half of them have masses below \(\sim 0.1\) \(M_\odot\) (Table 1), only a factor of 2.5 larger than the Jeans mass. And we should still keep in mind that the masses reported in Table 1 should be an upper limit to the true mass of the source because we have calculated the masses using the flux density, and thus including extended emission around the sources, which in most cases implies a flux density a factor of 3–10 larger.

Regarding the Jeans length, this is consistent with the spatial scale of the binary regime found in our ALMA data from the MSDC analysis presented in Section 4.1, of \(\sim 550\) au. We can also compare the typical separations of cores along the filaments in OMC-1S to the Jeans length expected for an isothermal, infinite, self-gravitating filament, \(3.94\frac{c_s^2}{G\Sigma_0}\) (Larson 1985, Hartmann 2002), where \(c_s\) is the sound speed, \(G\) the gravitational constant, and \(\Sigma_0\) the surface density of the filament. Assuming a temperature of 25 K and a surface density around 2 g cm\(^{-2}\) (corresponding to the cores in Table 3 with smaller densities), the Jeans length is 1780 au. This is in full agreement with the measured separations of cores.
along the filaments, ranging from 1100 to 1300 au, and the secondary peak of the histogram of separations, 1570 au, and it is only slightly smaller than the second break on the MSDC curve, 2800 au. It should be kept in mind that the observed separations have not been corrected for projection effects and that these are lower limits. Therefore, both the Jeans mass and the Jeans length seem to be in reasonable agreement with thermal Jeans fragmentation.

This suggests two-level Jeans-like fragmentation, as found by Teixeira et al. (2016) in the northern filament of the Orion Molecular Cloud 1. These authors study the role of turbulence and magnetic field and find that they cannot explain the observed Jeans lengths, and suggest that thermal Jeans fragmentation is taking place simultaneously with the local collapse of the clumps. Although the spatial scales where Teixeira et al. (2016) find fragmentation, 2500 and 12,400 au, are larger than the scales studied in this work, the fact that two-level fragmentation is found in both nearby regions suggests that hierarchical fragmentation is a normal process at least in the Orion molecular clouds. This is also supported by a recent work studying fragmentation in the Integral Shaped Filament down to ~1000 au, where a hierarchical, two-mode fragmentation is also found (Kainulainen et al. 2017).

We would like to remark, however, that, although it seems that the fragmentation properties in OMC-1S can be explained through pure thermal Jeans fragmentation, a recent work studying multiplicity in the Perseus cloud finds that systems with separations of around ~200 au should have formed through disk fragmentation, while systems with separations >1000 au should have formed through thermal fragmentation (e.g., Tobin et al. 2016). However, this behavior seems to be different from that in the Taurus cloud (Kraus et al. 2011), and should not necessarily apply to Orion. For the case of Orion, fragmentation has been studied on spatial scales larger than 1000 au and does not cover the “disk fragmentation” domain (e.g., Kainulainen et al. 2017), preventing us from drawing conclusions regarding this model. Thus the mechanism of formation of the closest systems in OMC-1S (such as SF2, SF5, SF6) should be studied in more detail in order to test the disk fragmentation scenario for these cases.

Finally, a note regarding nomenclature. There is currently some confusion in the literature with the nomenclature used to describe the fragmentation processes, especially those including the role of turbulence. For example, some authors call “turbulent fragmentation” the process yielding fragments with masses larger than the thermal Jeans mass, i.e., the Jeans masses are estimated using the Jeans criterion but replacing the factor related to temperature by a
factor related to the non-thermal line width (Equations (2), (4), and (5) of Palau et al. 2015). This approach presents some limitations: in particular, the non-thermal line width could be due to processes different from internal turbulence (e.g., infall). The data presented in this work can be reproduced without this turbulent support and thus there is no need to invoke turbulent support at these small scales (∼1000 au). There are also a number of authors who refer to “gravoturbulent fragmentation” as the fragmentation taking place in a self-gravitating turbulent medium, where the density is determined by the enhancements created by turbulence (e.g., Padoan & Nordlund 2002; Fisher 2004; Goodwin et al. 2004; Schmeja & Klessen 2004; Hennebelle & Chabrier 2008; Offner et al. 2010; Kirk et al. 2017). In this scenario, the estimation of the Jeans mass is reduced to a pure thermal Jeans mass at the scales we consider in this study. Our data are thus fully consistent with this gravoturbulent fragmentation, which we call here “pure thermal Jeans fragmentation.”

6. Conclusions

With the aim of studying the fragmentation properties down to spatial scales of multiple systems, we conducted 1.3 mm ALMA observations toward OMC-1S, with an angular resolution of ∼0′′2, corresponding to spatial scales of ∼74 au, and a sensitivity two orders of magnitude better than previous works. In addition, these observations have been complemented with 7 mm VLA observations at ∼0′′1 angular resolution. Our main conclusions can be summarized as follows.

1. The deep 1.3 mm ALMA continuum image reveals three filamentary structures in OMC-1S (the Eastern, Western, and Southern Filaments) and 31 millimeter continuum sources, most of them embedded within the filaments. The complementary but less sensitive 7 mm observations reveal further substructure within the strongest ALMA sources. This is particularly important in the Southern Filament, where almost all the ALMA cores split up into several sources.

2. An MSDC analysis suggests that there are two characteristic spatial scales in OMC-1S: one at 556 au and the other at 2800 au, indicative of a two-level fragmentation process. We used the first spatial scale to define the boundary of “cores” within filaments, and find 19 cores, which consist of groups of several millimeter sources or single sources.

3. Taking into account both the ALMA and VLA data, a fragmentation level has been assigned to each “core.” There is a correlation of fragmentation level with the density of the core within 1100 au, as found in previous works studying fragmentation at spatial scales one order of magnitude larger, suggesting that fragmentation at the earliest stages and within spatial scales of ∼1100 au is following a thermal Jeans process.

4. Finally, by compiling near-infrared, X-ray, centimeter, and outflow information for all the ALMA cores, a tentative evolutionary stage is assigned to each core. However, because most of the sources are found to be deeply embedded, no clear conclusions can be drawn regarding a possible trend of fragmentation level with evolutionary stage.

In summary, considering that the fragmentation level within 1100 au can be regarded as a first approach to the multiplicity of the core, the deep ALMA data presented here, together with the VLA data, seem to suggest that multiple systems with
separations \( > 40 \) au are formed through the same mechanisms that govern the fragmentation process at larger scales. This result deserves further investigation in order to disentangle the role of disk fragmentation in the formation of multiple systems in OMC-1S, something that definitely requires kinematic information from molecular gas tracers.

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Appendix

In Figures 9–12 in this Appendix we present the identification of each core from the ALMA data, as a result from the

**Figure 9.** Cores N1, N2, and N3 identified in the Northern region. Plus signs correspond to the positions of the ALMA sources (listed in Table 1), and the circles mark the distance of 556 au with respect to each source.

**Figure 10.** Cores EF1 to EF7 identified in the Eastern Filament. Plus signs correspond to the positions of the ALMA sources (listed in Table 1), and the circles mark the distance of 556 au with respect to each source.
Figure 11. Cores WF1, WF2, and WF3 identified in the Western Filament. Plus signs correspond to the positions of the ALMA sources (listed in Table 1), and the circles mark the distance of 556 au with respect to each source.

Figure 12. Cores SF1 to SF6 identified in the Southern Filament. Plus signs correspond to the positions of the ALMA sources (listed in Table 1), and the circles mark the distance of 556 au with respect to each source.
