A quantification of the non-spherical geometry and accretion of collapsing cores

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ABSTRACT
We present the first detailed classification of the structures of Class 0 cores in a high-resolution simulation of a giant molecular cloud. The simulated cloud contains $10^4 M_\odot$ and produces over 350 cores which allows for meaningful statistics. Cores are classified into three types according to how much they depart from spherical symmetry. We find that three-quarters of the cores are better described as irregular filaments than as spheres. Recent Herschel results have shown that cores are formed within a network of filaments, which we find has had a significant impact on the resulting core geometries. We show that the column densities and ram pressure seen by the protostar are not uniform and generally peak along the axes of the filament. The angular momentum vector of the material in the cores varies both in magnitude and direction, which will cause the rotation vector of the central source to fluctuate during the collapse of the core. In the case of the more massive stars, accretion from the environment outside the original core volume is even more important than that from the core itself. This additional gas is primarily accreted on to the cores along the dense filaments in which the cores are embedded, and the sections of the surfaces of the cores which do not coincide with a filament have very little additional material passing through them. The assumption of spherical symmetry cannot be applied to the majority of collapsing cores, and is never a good description of how stars accrete gas from outside the original core radius. This has ramifications for our understanding of collapsing cores, in particular their line profiles, the effect of radiation upon them and their ability to fragment.

Key words: stars: formation – ISM: clouds – ISM: structure.

1 INTRODUCTION
Understanding the birth of stars from their parent molecular clouds has been a long-standing problem in astrophysics, and over the years it has received considerable attention (e.g. Mac Low & Klessen 2004; McKee & Ostriker 2007). While early investigations used spherical models for the collapse of gas to stellar densities (e.g. Larson 1969; Penston 1969; Shu 1977), it has been known for some time that structure within molecular clouds is both irregular and filamentary (Blitz 1993).

It is observationally well established that molecular clouds are filamentary in nature (e.g. Schneider & Elmegreen 1979; Low et al. 1984; Bally et al. 1987; Loren 1989; Johnstone & Bally 1999). This has been further emphasized in recent results from the Herschel Space Telescope which have revealed that cores are formed within a network of narrow filaments (André et al. 2010; Henning et al. 2010; Men’shchikov et al. 2010; Miville-Deschênes et al. 2010; Ward-Thompson et al. 2010). Additionally, the formation of irregular structures has been a long-standing feature in simulations of turbulent, dynamic star formation. For example, in simulations with turbulence and self-gravity (Klessen 2001; Jappsen et al. 2005; Vázquez-Semadeni et al. 2005; Heitsch et al. 2008; Bate 2009; Walch et al. 2009; Federrath et al. 2010) filaments are a ubiquitous phenomena. Indeed, Burkert & Hartmann (2004) have shown that filaments are a natural consequence of gravitational focussing during the collapse of any mass distribution which departs from circular symmetry.

Filaments are prone to fragmentation and several authors have analysed their stability (Ostriker 1964; Inutsuka & Miyama 1992; Hennebelle 2003). Inutsuka & Miyama (1997) found that quasi-equilibrium filaments fragment into dense cores separated by about

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The simulation

This paper is the latest in a series of papers (Smith, Clark & Bonnell 2009a, hereafter SCB09 and SLB09) that have utilized large simulations of a GMC to study in depth the properties of clustered pre-stellar cores, and the simulation here is the same as that described in SLB09. The smoothed particle hydrodynamics (SPH) method is used to follow the evolution of a $10^4 \, M_\odot$ cloud over 102 free-fall times or $\approx 6.6 \times 10^4$ yr. The cloud resembles a long filament, with a length of 10 pc and a radius of 3 pc. The cloud has a local density gradient such that one end of the cloud is gravitationally bound while the other end of the cloud is unbound, and thus a range of star-forming environments is present. The gas has internal decaying turbulence following a Larson-type $P(k) \sim k^{-4}$ power law that is normalized such that the total kinetic energy balances the total gravitational energy in the cloud at the start of the simulation. Sink particles are used to model sites of star formation (Bate, Bonnell & Price 1995), and have an outer accretion radius of $10^{-3}$ pc and an inner accretion radius of $10^{-4}$ pc. At the outer accretion radius, the gas will be accreted by the sink if it is unequivocally bound to it. Any remaining gas will only be accreted if it reaches the inner accretion radius.

The simulation has 15.5 million SPH particles on two levels to maximize the numerical resolution in the cores. Regions that underwent star formation and formed sink particles or were subsequently accreted by these sink particles were identified in a lower resolution simulation. These particles were then replaced in the initial conditions with nine lower mass particles, conserving the mass and kinetic energy of the initial conditions, yielding a maximum mass resolution of 0.0167 $M_\odot$. This high resolution is essential in order to sufficiently resolve the cores to study their geometry. The simulation was rerun from the initial conditions with the locally increased mass resolution.

The simulation treats the thermal content of the cloud through a barotropic equation of state ( Larson 2005; Jappsen et al. 2005) and a thermal heating contribution is included to represent radiative feedback from the sinks. The heating from the newly formed stars is approximated by way of a grid of previously computed Monte Carlo radiative transfer models of young stars (Robitaille et al. 2006). A one-dimensional temperature profile was derived from the youngest of these models as a function of stellar mass and distance which gives a very rough estimate of the radiative feedback. If anything, this procedure should overestimate the gas temperatures. Nevertheless, it gives an estimate of the emission expected in regions of the gas surrounding the core is extended in all three dimensions. However, if gas approaches the core along a few very dense flows, it may be more difficult to shut off inflow by radiative processes (e.g. Dale & Bonnell 2008; Krumholz et al. 2009; Peters et al. 2010a,b), and mechanisms such as jets may need to be invoked to finally stop accretion (Wang et al. 2010).

The aims of this paper are therefore twofold. First we aim to quantify how common extreme anisotropies are in the Class 0 cores formed within a high-resolution simulation of a giant molecular cloud (GMC). This should provide robust statistics which can be compared to observations and provide initial conditions for future modelling of core collapse. Further, this paper aims to trace how material originally external to the core approaches the forming protostar and to determine whether accretion on to a core takes place in an inhomogeneous manner.

2 METHOD

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massive star formation. From the Monte Carlo models, the temperature at a distance \( r \) due to the radiative feedback is given by

\[
T(r) = \begin{cases} 
100 \left( \frac{m}{10 M_\odot} \right)^{0.35} \left( \frac{r}{1000 \text{ au}} \right)^{-0.45} \text{ K} & m \leq 10 M_\odot \ \\
100 \left( \frac{m}{10 M_\odot} \right)^{1.11} \left( \frac{r}{1000 \text{ au}} \right)^{-0.5} \text{ K} & m > 10 M_\odot,
\end{cases}
\]

where \( m \) is the mass of the protostar (here assumed equal to the sink particle mass). The gas temperature around the young stars is set to be the maximum of the temperature from either the barotropic equation of state or the radiative feedback. This ensures a maximal effect from the radiation.

### 2.2 Column density surface projections

To study the local environment of the protostars, we make maps of the column density of the core of gas surrounding the sink. These are made from the perspective of the central protostar looking outward. We define the core to be all material within \( R_c = 0.01 \text{ pc} \) of the central sink. In order to ensure that our core sample has a constant volume we do not use a clumpfinding approach. This ensures that differences in the column densities are due to internal density enhancements, and not due to differing radial extents. In SCB09, it was found that the typical radius within which the bound material of a pre-stellar core was contained was \( r = 1.16 \times 10^{-2} \text{ pc} \). Therefore our selected size of 0.01 pc represents the volume which will first collapse. Although the Class 0 classification scheme is based on low-mass young stellar objects, we do form high-mass stars in this simulation. However, as shown in SLB09 there are no high-mass pre-stellar cores in this simulation. Therefore we use the term ‘Class 0’ to refer to all of our collapsing cores.

We use Hammer projections to show the column density surface. In this projection, a point at \((\lambda, \phi)\) on a spherical surface will correspond to position \((x, y)\) on the projected flat surface, according to the transformation:

\[
\begin{align*}
\lambda &= 2 \arctan \left[ \frac{z x}{2(2 z^2 - 1)} \right] \\
\phi &= \arcsin(z y),
\end{align*}
\]

where

\[
z = \sqrt{1 - \left( \frac{1}{4} x \right)^2 - \left( \frac{1}{2} y \right)^2}.
\]

This projection is not conformal, but area is conserved, which is essential for the following calculation of column density.

The first stage to make the Hammer projections is to find the particles within the core volume for every sink just after it has formed. Cores that are within \( 2 R_c \) of an existing sink are rejected. In addition, to ensure that we have sufficient resolution, we only use cores with over 500 SPH particles. This is 10 times higher than our minimum resolution of 50 particles. In practice, the cores generally have \( \sim 1500 \) particles.

We select lines of sight from a uniform \((50 \times 100)\) grid on the Hammer surface, in order to ensure equal area sampling. This equates to 3895 lines of sight within the projected elliptical surface. We calculate the density at each point along the line of sight using the standard SPH density equation,

\[
\rho = \sum_{j=1}^{N} m_j W(r - r_j, h),
\]

where \( m_j \) is the mass of the \( j \)th particle, \( W(r - r_j, h) \) is the smoothing kernel and \( N \) is the number of particles within a smoothing length, \( h \). The densities are then integrated along the line of sight to obtain the column density. A ram pressure map of the core can be made in a similar manner, by integrating the product of density and velocity along the line of sight.

### 2.3 Angular covariance

To categorize the column density surfaces, the angular covariance of the high-density gas is calculated for each core projection. The covariance is

\[
\operatorname{cov}(d\theta) = Q(d\theta) - \bar{N}^2,
\]

where \( \bar{N} \) is the mean column density and

\[
Q(d\theta) = \frac{\sum_{i<j} q_{ij}(d\theta_{ij})}{N},
\]

where \( q_{ij} = N_i N_j \) is the product of the column density, \( N_i \), at points \( i \) and \( j \), which have an angular separation in the range \( d\theta \) and \( N \) is the number of pairs \( ij \) separated by \( d\theta \). The covariance is calculated at \( 5^\circ \) intervals, as this allows each bin to be well filled while still sampling the angular range finely enough to see small-scale structure.

If the column density distribution is uniform, then we expect \( \operatorname{cov}(d\theta) \) to be zero everywhere as the column densities will be equal to the average. However, if there is structure in the column density map with a particular angular scale, for example in the form of \( 10^\circ \) wide blobs, then the value of \( \operatorname{cov}(d\theta) \) will be higher at this angular separation as the structure is highly correlated on this scale.

### 3 THE STRUCTURE OF PROTOSTELLAR CORES

#### 3.1 Surface projections

The column density projections of four representative cores are shown in Fig. 1. Core (a) has a fairly uniform column density. However, the other three cores have at least one preferred direction where the column density is higher. This distribution is consistent with the high-density material being distributed along a filament. If the sink particle is situated at the end of the filament, then the column density is higher in the direction of the filament, as in core (b). If the sink particle is located within the filament, then the column density peaks where the filament intersects the core volume and falls off perpendicular to the filament. Cores (c) and (d) represent this situation. Core (c) has a filament which is denser on one side than the other, and core (d) has a filament which is equally dense on both sides, showing that the sink is located at the centre of the filament.

The column density seen by the central sink is almost entirely due to the core itself. Fig. 1 is calculated using only the material within 0.01 pc of the central sink, but when this range was extended to 1.0 pc, there was no significant change in the column density projection. This is because the density of the gas close to the sink is so high, and covers such a large angle, that it completely dominates the column density.

The range of column densities seen by the central sink is shown in Fig. 2 as a percentage of the total core surface area and mass. For the symmetric core (a), nearly all of its area and mass is at column densities below 1 (g cm\(^{-2}\)). However, the column densities reach higher values where there are filaments. The spatial clustering in the column density projection means that a larger proportion of the mass is at higher column densities than a simple average may suggest.
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3.2 Global classifications

That star formation often takes place in filaments is not in itself a new result, although the impact this has on the environment ‘seen’ by the...
protostars is perhaps surprising. However, due to the large number of stars formed in a variety of environments within this simulation, it is possible to quantify how common this is. Obviously it is impractical to show all the column density projections, so the cores are classified according to the shapes of their angular covariance functions. Fig. 3 shows the covariance functions of the four cores shown in Fig. 1. These covariance functions are typical of the entire data set and using these shapes it is possible to classify the cores into three types according to the number of overdensities they contain. T10 have carried out a similar classification on their Class 0 sources, and have independently proposed a very similar scheme.

However before discussing the differences, it is important to note that all the covariance functions are similar in that the greatest variance is always seen at small separations. This reflects the fact that no column density map was completely uniform, and that in every case high column densities were concentrated at a few centrally peaked locations, rather than distributed randomly throughout the core surface.

Type 0 cores have no strong overdensities, and therefore have a covariance function which is close to 0 at all angular separations. Core (a) in Fig. 1 corresponds to this type. We define Type 0 cores as those whose maximum or minimum value departs by less than 0.01 from zero. They have no strong overdensities, and correspond to the cores in fig. 3 of T10.

Type 1 cores have a steeper fall-off in their covariance function, and the covariance does not become greater than zero again at large angular scales. Core (b) is an example of this type. Physically, this type of covariance function represents a core with one strong overdensity. Type 1 cores correspond to the cores in fig. 2 of T10.

Type 2 cores also have a steep fall-off in their covariance function. However, at larger angular separations the covariance becomes greater than zero again. This reflects the fact that in these cores there is more than one strong accretion stream. Moreover the covariance function has a minimum at 90° and a second maximum at 180°, which strongly suggests a filamentary geometry. Cores (c) and (d) are both examples of this type. Type 2 cores correspond to the cores in fig. 1 of T10.

Table 2 shows the number of cores assigned to each classification and their percentage of the total number. Three-quarters of the cores are dominated by an irregular filament, and therefore this geometry represents the most common initial state of a collapsing core in the molecular cloud. It is clear that in the majority of cases, the dense cores still strongly retain the geometry of the filament in which they are formed. This can be understood as during the collapse of the filaments there is no internal pressure support that can slow the collapse sufficiently for a spherical core to form.

The cores have distinct differences in their mass and column densities, as shown in Table 3. The filaments concentrate more mass in the cores, and allow them to have a greater range in column density across their structure. The cores which are in the middle of a filament have the largest masses and column densities. The distribution of column densities is highly skewed, as shown earlier in Fig. 2, and a high-density tail of column densities means that the range in column densities is larger than the average itself.

### 3.3 Radial profiles

While the core surface projections are highly anisotropic, the averaged radial profiles are still consistent with previous work since as the cores are collapsing objects, they are centrally condensed, and their density profile decreases outward according to a power law.

To confirm this, we fitted the power law $\rho \propto r^{-n}$ to the volume-averaged density profiles and obtain values for the exponent $n$ for each core. Table 4 shows the average power-law exponent, $n$, fitted to the radial profiles of the entire core population in various ranges. Within the core volume ($r < R_c$), the volume-averaged profile

| Type | Avg. mass | Avg. density | Avg. density range |
|------|-----------|--------------|--------------------|
| 0    | 0.429     | 0.427        | 0.605              |
| 1    | 0.946     | 0.713        | 3.246              |
| 2    | 1.594     | 1.108        | 7.712              |

Table 3. The average masses and column densities of the cores.

Table 4. The mean power-law exponent $n$ of the volume-averaged radial density profiles of the cores, fitted over two different ranges of radii. The standard deviation of $n$ is also listed.

| Fitted range | $n$ | $\sigma$ |
|--------------|-----|----------|
| $r < 0.01$ pc| 2.04| 0.38     |
| $r < 0.1$ pc | 1.57| 0.26     |

Figure 3. Covariance functions for the four representative cores displayed earlier. The key shows the classification of each core. Type 0 cores have a relatively flat covariance function with no large over-densities. Type 1 cores have a decreasing covariance function and have one large overdensity. Type 2 cores have a double-peaked covariance function and have two large overdensities.
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Figure 4. Volume-averaged radial density profiles (left) and projected column density profiles along an arbitrary viewing angle (right) for the four representative cores. The red vertical line shows our fiducial core radius $R_c = 0.01$ pc. Note that the column density profiles will change depending on the viewing angle.

has an exponent of $n = 2.04 \pm 0.38$, consistent with the $n = 2$ that is expected from the dynamic collapse of an isothermal sphere (Larson 1969; Penston 1969). Fig. 4 shows the volume weighted density profiles and the column density projections for the four representative cores. As shown by Ballesteros-Paredes et al. (2003) and Hartmann (2004), core density profiles are artificially smoothed by two effects. First, by taking an azimuthal angle average as shown in the volume-averaged density profiles of Fig. 4, and secondly by projection effects as shown in the column density projections in the right-hand panel. Thus a smooth power law is obtained from complex structure.

Observationally, it is extremely hard to probe the $r = 0.01$ pc scales just discussed, and so we also show the slopes fitted to radii of $r \leq 0.1$ pc in Table 4. The mean power-law exponent in this case is $n = 1.57 \pm 0.26$, which is close to the $n = 1.5$ value expected for a freely falling envelope (Young et al. 2003). Shirley, Evans & Rawlings (2002) and Young et al. (2003) carried out radiative transfer modelling of Class 0 and Class I sources and found that they were best explained by a mean radial profile with $n \sim 1.6$. Enoch et al. (2008) measured power-law profiles for protostellar cores in Perseus, Serpens and Ophiuchus and deduced exponents of $n = 1.3–1.5$. The radial profiles of our cores are therefore in good agreement with previous theories and observations, despite their asymmetrical nature.

We have considered the cores as if they were spheres in order to compare to the literature. However, it should be noted that for a perfectly cylindrical, non-magnetized filament, a constant density profile is expected along the major axis of the filament and a steep $\rho \propto x^{-4}$ density profile along the minor axis (Ostriker 1964; Hennebelle 2003; Tilley & Pudritz 2003).

The radial velocity profiles of the cores are shown in Fig. 5. The central regions of all the cores are collapsing supersonically on to the sink particle. The sound speed for a molecular gas at 10 K is of the order of 0.2 km s$^{-1}$, meaning that the flow in the cores is only mildly supersonic. However, we are unable to accurately resolve scales of less than 0.001 pc due to the sink particle. Moreover, the sudden steepening seen in the velocity profile at the centre may be due to the inability to accurately follow the pressure gradient across the sink particle, which would lead to an artificial increase in the acceleration. The central infall velocity predicted by the Larson–Penston model is $-3.3 c_s$. However, as Hunter (1977) has shown, this value is rarely approached apart from at the very central regions of numerical simulations. Ogino, Tomisaka & Nakamura (1999) carried out simulations of collapsing profiles and found that the radial velocity profiles were in good agreement with the $v \propto r^{-1/2}$ profile expected. Our profiles are not so simple, due to the more complex geometry, but like the spherical isothermal collapse models, they do collapse more quickly at the centre.

A key factor determining the evolution of the cores is the evolution of their angular momentum. In Fig. 6, we show the angular momentum profiles of two of the cores and their environments. The relative magnitude of the three components of the angular
Figure 6. Radial profiles of specific angular momentum for cores (b) (top) and (d) (bottom). The left-hand panels show the specific angular momentum and its three components in the central core, and the right-hand panels show the specific angular momentum and its three components in the surrounding gas, out to a distance of 0.1 pc. The relative magnitude of the angular momentum components alters radially, meaning that the angular momentum vector of the core will be constantly shifting as it accretes new material.

momentum vector changes radially outward, meaning that the angular momentum vector of the core will shift as the core accretes new material. Discs formed in the centre of these cores will shift in orientation as new material is accreted. The specific angular momentum inside the cores is of the order of $10^{20}$ cm$^2$ s$^{-1}$ and is smaller and more homologous than that outside ($j \approx 10^{21} - 10^{22}$ cm$^2$ s$^{-1}$), where the environment is supersonically turbulent and there are multiple structures. The specific angular momentum decreases radially towards the centre of the collapsing cores due to gravitational torques, as discussed by Jappsen & Klessen (2004). The observed angular momentum for the cores will therefore be sensitive to the physical size scale probed by the observations.

As an illustrative example, Figs 7 and 8 show the radial velocity and a column density projection for the wider environment of the filamentary core (d). In Fig. 7 there is a second strong signature of collapse at radii outside the core. This is a common occurrence in our core sample, and represents the wider collapse of the region within which the core is located. This infalling material can also be accreted by the central sink, and in the case of massive stars constitutes the majority of the final sink mass (see SLB09). The geometry of the material involved in this secondary stage of accretion is discussed in Section 4.1. This widespread infall is a clear indicator of the dynamic nature of the core’s formation process, and it would not be seen in a singular isothermal sphere type collapse, where outside the rarefaction wave the gas is hydrostatic. Fig. 8 shows a column density projection centred on core (d). The filament within which the core is situated is clearly visible and it is surrounded by a complex morphology of cores and filaments.

In conclusion, the radial behaviour of the collapsing cores is in good agreement with previous models. The core structure can therefore be thought of as a superposition of two effects. First, there is the high-density peak and steep radial decrease in mean density due
4 ACCRETION ON TO THE CORE

4.1 Geometry of accreted gas

Generally low-mass and high-mass sinks have different accretion histories. Typically low-mass sinks only have accretion from within their core as outlined in the previous section. However, the growth of higher mass sinks is dominated by a secondary stage of accretion; the accretion of additional infalling material from outside the original core radius. We shall now examine whether this additional material is also inhomogeneously distributed.

To answer this question, we use a modification of the previous Hammer projection technique. As the SPH method is Lagrangian, it is possible to flag each individual gas particle that becomes accreted by a sink. We take a shell at the boundary of the core, and track the positions at which flagged particles from the external environment pass through the shell. We do this over a period of $2 \times 10^4$ yr (which is about the mean dynamical time of the bound pre-stellar cores found in SCB09) and then make Hammer projections of the integrated density on the shell in a similar manner to before. Figs 9 and 10 show the resulting ‘accretion surfaces’ of material which passes through shells at $r = R_c = 0.01$ pc and $r = 0.1$ pc around the representative cores over the time interval. We do not specify the absolute values on this surface as it is merely a way of visualizing the direction at which accreted material approaches the core. It is not a real density.

The cores in Fig. 9 show differing amounts of additional accreted material passing through the core surface at $r = R_c$. For instance, core (a) has almost no additional accretion from its external environment, but core (b) has a large amount. The distribution of accreted material is again highly anisotropic, and shows a resemblance to the column density distribution in Fig. 1. Accreted material from the environment is therefore entering the core along the high column density filaments.

Fig. 10 shows how the accreted material enters the larger environment of the core at $r = 0.1$ pc. The distributions of accreted material through the shells at $r = R_c$ and $r = 0.1$ pc are different for several reasons. First, most of the material passing through the shell at $r = 0.1$ pc does not reach the inner shell in the time period considered here, and so is not included in Fig. 9. Secondly, the external molecular cloud structure is clumpy, with many voids that contain little gas, and which do not contribute to the accretion flow. Thirdly, the flow of material towards the cores is not necessarily purely radial. Instead, the accreted material often flows along the path of the high-density filaments. Fig. 10 shows that the additional accreted material is coming preferentially from just a few directions and large sections of the surface have no accreted material passing through them.

To get a more conceptual view of how the accretion is proceeding, let us examine the representative cores in more detail. Core (a) has very little accretion from its environment and becomes a low-mass star ($0.63 \, M_\odot$). Core (b) undergoes a significant amount of accretion from its environment and at the end of the simulation has a mass of $11.52 \, M_\odot$. It has a large amount of material passing through the $r = 0.1$ pc surface from a variety of directions. However, once again some directions contribute more than others. Core (c) is a clear example of accretion along a filament. Core (d) is also accreting along a filament, but most of the accreted material comes from close to the sink.

We carry out a similar analysis to the covariance function analysis used in Section 3.2 and classify the accretion surfaces of the entire core sample. In this case, we found it more useful to use the...
function $Q(d\theta)$ to classify the surfaces, rather than the covariance $\text{cov}(d\theta)$, as the ‘accretion density’ that we are dealing with here is not a real quantity, and so it makes sense to use a dimensionless function. By normalizing $Q(d\theta)$ by its maximum value, it is possible to make a fair comparison between the cores, regardless of how much they accrete. The class definitions are very similar to those used previously. For Type 0 cores, $Q(d\theta)$ remains almost flat, with deviations no larger than 20 per cent, while for Type 1 cores, it decreases monotonically as we move away from zero angular separation. For Type 2 cores, $Q(d\theta)$ shows a double-peaked structure. The sample of cores is smaller in this case, as the requirement of following the accretion for $2 \times 10^4$ yr means that cores which form close to the end of the simulation must be excluded. The accretion surfaces which the gas external to the core flows through are even more irregular than the column density projections, and almost all the cores have multiple angles from which they receive no additional material.

Fig. 11 shows $Q(d\theta)$ for the accretion surfaces of the representative cores at the $r = 0.1$ pc shell. There are two key differences with the core column density covariance functions shown in Fig. 5. First, the contrast is much larger than before. This is because there are areas of the accretion surface which are completely devoid of additional accreted gas, and hence produce zero correlation. Secondly, the functions are more irregular, owing to the irregular distribution of the accreted material. Table 5 shows the classifications of the accretion surfaces for the entire core population. An almost negligible fraction of the cores have uniform, spherical accretion surfaces. The majority of the accreted material comes from just one or two directions, and in the case of the $r = 0.1$ pc shell, it is almost all coming from just one direction.

In summary, the individual cores have different accretion behaviours, but they all share the property of non-axisymmetry. This is unsurprising, as it is well known that the larger scale structure in molecular clouds is complex and filamentary, and as the accreted material is drawn from this distribution, the accretion flows on to the sink must also be irregular. Accretion on to cores from the external molecular cloud environment is primarily along the filaments in which the cores are embedded. Therefore the angular
momentum being added to the protostellar discs from the environment is typically unbalanced.

### 4.2 Final sink masses

The final outcome of the accretion process also varies between the types of cores. Fig. 12 shows histograms of the masses of the central sinks formed from each type of core at two snapshots in time. The right-hand panel shows the sink masses at one dynamical time ($4.7 \times 10^5$ yr) and the left-hand panel at the end of the simulation ($6.6 \times 10^5$ yr). The thermal feedback in this simulation is unable to prevent accretion (see future papers for a full discussion) so we cannot ascertain the final sink mass reliably. However, it is clear that the filamentary cores have been more successful at gaining additional mass from outside the core region. The entirety of the high-mass end of the sink mass distribution in Fig. 12 is formed from Type 1 or Type 2 cores.

There are two possible reasons for this difference in sink masses. First, the filamentary cores are predominantly formed in denser, more clustered regions in which there is more gas outside the core available for accretion. Secondly, as shown in the Section 4.1, the Types 1 and 2 cores are part of larger external filamentary accretion streams along which additional mass is channelled towards the sink. The filamentary nature of molecular clouds therefore contributes directly to the assembly of stellar masses.

### 5 DISCUSSION

We have classified the surroundings of sink particles in an SPH simulation of a GMC, and discovered that in three-quarters of cases the cores depart significantly from spherical symmetry. Furthermore, accretion on to these cores from the environment is even more asymmetric and takes place primarily along filaments. Traditionally, spherical models have been used to describe star formation, and so in this section we qualitatively discuss some of the implications of non-axisymmetry.

#### 5.1 Detecting infall

The classical signature of collapse is a double-peaked line profile which is shifted to the blue (Evans 1999). This is what would be expected from a spherical cloud undergoing inside-out collapse. A static envelope produces the main self-absorption dip in the line, the back of the cloud collapsing towards the observer produces the blue peak and the front of the cloud collapsing away from the observer produces the red peak. Our Type 0 cores are close to spherical and should have line profiles close to this expected result.

Now consider filamentary geometry, as in the case of Type 2 cores. Along a collapsing filament, the same arguments hold, and the expected double-peaked line profile should be produced. However, when perpendicular to the filament, the line profile may differ. Moreover, for the case of the Type 1 cores, where there is only one strong overdensity, the line profile may entirely lack a strong blue or red peak.

Therefore, from simple dimensional arguments we can estimate how common departures from a blue-skewed, double-peaked line profile will be. About one-third of the cores are Type 1 (33.7 per cent) and 42.1 per cent of the cores are Type 2, and for the latter there is a roughly two in three chance that we will be looking perpendicular to the filament axis. Therefore, conservatively, we would expect $0.337 + 2/3 \times 0.421 \simeq 60$ per cent of cores which are collapsing to depart from the standard line profile. We hope to investigate this more fully in future work, in which we will use radiative transfer modelling of our cores to examine how line profiles change with viewing angle.

In surveys of both protostellar and pre-stellar cores, there is an overabundance of blue line asymmetries over red asymmetries, which suggests that most objects are characterized by collapse. However, there are relatively few unambiguous examples of the expected blueshifted line profiles (e.g. Gregersen et al. 1997; Lee, Myers & Tafalla 1999; Andrè et al. 2007; Chen et al. 2010). The high fraction of filamentary cores seen in this study provides a possible explanation for this.

#### 5.2 Preventing accretion

At present, it is hard to carry out detailed radiative transfer modelling within clustered cores, and generally cores are modelled individually. The Bonnor–Ebert sphere, perhaps with some turbulence injected, is a traditional choice of initial conditions. However, our collapsing cores depart significantly from this geometry, which may have sizable implications for the final results.

In the case of massive stars, there are several current efforts to model radiative effects on core environments (e.g. Yorke & Sonnhalter 2002; Krumholz et al. 2009; Kuiper et al. 2010; Peters et al. 2010b). Kahn (1974) showed that for spherically symmetric accretion, radiation pressure will halt accretion before truly massive stars can form. Recently Krumholz et al. (2009) showed in an
initially spherically symmetric calculation that instabilities on the surface of a radiation-filled bubble surrounding the protostar create self-shielding filaments of gas which continue to channel material on to the disc. Similar results are seen when ionizing radiation is included in the models (Peters et al. 2010a). The cores in our simulation (which are the precursors of both low- and high-mass stars) contain dense filaments and streams from their first formation, and therefore accretion can continue unimpeded throughout. Generally, the geometries of the collapsing cores studied here encourage the escape of radiation, as most of the core surface area is at low column densities, which radiation can pass through easily. The radiation is likely to simply pass around the concentrated filaments of high column density, high inward pressure gas, allowing accretion to proceed unimpeded through these filaments.

The accretion on to the core from the external molecular cloud environment is also through irregular filaments. Again, this will make it harder to shut off accretion as a uniform radiation field will likely prove too weak to stop the densely collimated inflows. Wang et al. (2010) recently modelled the effects of feedback from protostellar jets and found that these could possibly reduce the accretion through filaments.

5.3 Binary formation and angular momentum

The irregular inflows seen here have implications for the stability of the collapsing cores. Even small departures from spherical symmetry make cores more liable to fragment (Bonnell & Bastien 1992; Burkert & Bodenheimer 1993; Bodenheimer 1995). Moreover, the flow of material on to the disc will be irregular, which increases the likelihood of disc fragmentation and encourages binary formation. In the studies of core fragmentation with the effects of ideal magnetohydrodynamics (MHD) included (Hennebelle & Fromang 2008; Hennebelle & Teyssier 2008) there is some difficulty in producing binaries at all. These authors suggest that one way to overcome this barrier would be if the angular momentum transferred to the core was unbalanced, which would encourage fragmentation. The angular momentum vector of the gas surrounding our sink particle varies in direction and magnitude and therefore the angular momentum of the core will be constantly changing as it collapses (Jappsen & Klessen 2004).

5.4 Outstanding issues

This work considers hydrodynamic collapse and neglects magnetic fields. Magnetic pressure slows gravitational collapse (Strittmatter 1966; Mouschovias & Spitzer 1976; Heitsch, Mac Low & Klessen 2001), and therefore there may be more time for structures to become homogenized. However, uniform magnetic fields also introduce a preferred axis of collapse, which would exacerbate the anisotropies in the collapsing cores. It is unclear which of these effects will be more significant, or whether they would to some extent cancel out.

MHD calculations of molecular clouds have studied the morphologies of clumps and cores with magnetic fields (Li et al. 2004; Tilley & Pudritz 2007), and found they were also filamentary and irregular. This suggests that the addition of magnetic fields would not substantially alter our results. MHD codes are grid based, and require adaptive mesh refinement in order to match the dynamical range of SPH, which enables us to resolve scales of 10 pc down to a few 100 au. It is this property which has allowed us to both generate a large data set of cores, and to probe their structure on the smallest scales. There have been valiant attempts to introduce magnetic fields into SPH (Price & Bate 2008; Price 2010), but as yet there are no large-scale simulations of an entire molecular cloud, as would be needed to robustly assemble enough cores for a statistical analysis.

Our simulation also lacks full radiative transfer, and instead uses a crude heating prescription. This is almost certainly wrong, particularly as it assumes spherical symmetry, which we have just shown to be a poor assumption. However, this heating prescription, if anything, overestimates the heating from the protostars, and therefore is likely to support the core and smooth its structure. Without this prescription, our cores would be even more filamentary. We include it in this analysis as there will be a supporting force from the radiative transfer, and it is better to overestimate it than underestimate it.

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6 CONCLUSIONS

We have classified the structures of Class 0 cores in a large SPH simulation of a GMC. We define the cores as the material within $r = 0.01\,\text{pc}$ of the sink when it first forms. Our main conclusions are as follows.

(i) The density distribution in collapsing cores is highly non-axisymmetric.

(ii) Three-quarters of cores are better described by filamentary geometries than by spherical ones.

(iii) The density profiles decrease radially according to a power law, and are consistent with observations and previous studies of collapse.

(iv) The angular momentum vector of a core and its surrounding gas varies with radius, and so the inclination of protostellar discs formed within the cores will alter with time.

(v) The cores have mildly supersonic infall velocities at their centre.

(vi) Accretion on to the central protostar can be broken into two phases. First, the original core is accreted, and then, in the case of higher mass stars, infalling material from outside the original core radius is accreted.

(vii) Additional accreted material from the wider molecular cloud environment primarily flows towards the cores along the dense filaments in which the cores are embedded.

(viii) Protostars formed in filamentary cores obtain a higher final mass from accretion.

Due to the non-axisymmetric nature of the cores, the line profiles of collapsing cores are likely to be more complex than spherical models suggest. It will be harder to slow down, or prevent core accretion through feedback, as most of the surface of the cores is at low column densities, allowing radiation to escape (Dale & Bonnell 2008), but a significant fraction of the infalling mass has high column density and inward pressure. The asymmetric nature of the cores will also make them more vulnerable to fragmentation and binary formation.

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