Slingshot Mechanism for Clusters: Gas Density Regulates Star Density in the Orion Nebula Cluster (M42)

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ABSTRACT
We characterize the stellar and gas volume density, potential, and gravitational field profiles in the central ∼0.5 pc of the Orion Nebula Cluster (ONC), the nearest embedded star cluster (or rather, proto-cluster) hosting massive star formation available for detailed observational scrutiny. We find that the stellar volume density is well characterized by a Plummer profile \[ \rho_{\text{stars}}(r) = 5755 M_\odot pc^{-3} (1 + (r/a)^2)^{-5/2} \]
where \( a = 0.36 \) pc. The gas density follows a cylindrical power law \[ \rho_{\text{gas}}(R) = 25.9 M_\odot / pc^3 (R/pc)^{-1.775} \]. The stellar density profile dominates over the gas density profile inside \( r \sim 1 \) pc. The gravitational field is gas-dominated at all radii, but the contribution to the total field by the stars is nearly equal to that of the gas at \( r \sim a \). This fact alone demonstrates that the proto-cluster cannot be considered a gas-free system or a virialized system dominated by its own gravity. The stellar proto-cluster core is dynamically young, with an age of ∼2-3 Myr, a 1D velocity dispersion of \( \sigma_{\text{obs}} = 2.6 \) km s⁻¹, and a crossing time of ∼0.55 Myr. This timescale is almost identical to the gas filament oscillation timescale estimated recently by Stutz & Gould (2016). This provides strong evidence that the proto-cluster structure is regulated by the gas filament. The proto-cluster structure may be set by tidal forces due to the oscillating filamentary gas potential. Such forces could naturally suppress low density stellar structures on scales \( \gtrsim a \). The analysis presented here leads to a new suggestion that clusters form by an analog of the "slingshot mechanism" previously proposed for stars.

Key words: open clusters and associations: individual: M42 (ONC) - Stars: formation - Infrared: stars - ISM: clouds - Clouds: Individual: Orion A

INTRODUCTION
The Orion Nebula Cluster (ONC, also known as M42) is the nearest site of massive star formation and significant embedded cluster available for detailed observational scrutiny. At a distance of ∼400 pc (e.g., Menten et al. 2007; Sandstrom et al. 2007; Schlafly et al. 2014; Kounkel et al. 2017) it has been the subject of many studies (e.g., Jones & Walker 1988; Hillenbrand & Hartmann 1998; Kroupa et al. 1999; Kroupa 2000; Kroupa et al. 2001; Hartmann & Burkert 2007; Tobin et al. 2009; Megeath et al. 2012, 2016; Meingast et al. 2016; Da Rio et al. 2016; Portegies Zwart 2016) scrutinizing in detail the stellar and protostellar content of the region. Generally, these studies have restricted themselves to the investigation of the stellar content of the cluster for lack of high quality observations that reliably trace the total gas mass distribution, which have only been obtained recently (Stutz & Kainulainen 2015; Stutz & Gould 2016).

The ONC is directly associated with a larger high line-mass gas filament called the Integral Shaped Filament (ISF; Bally et al. 1987; Tatematsu et al. 2008; Stutz & Gould 2016; Kainulainen et al. 2016). The ONC is partially embedded in the high density filament and lies slightly in foreground (e.g., O’Dell 2001; Wen & O’Dell 1995), as is apparent from the continuous distribution of stellar extinctions (S. T. Megeath, private communication 2017). The filament, with a wave-like morphology, has dimensions of ∼7.3 pc in height and a horizontal oscillation semi-amplitude of ∼1.5 pc (Stutz & Gould 2016). The stellar distribution is highly elongated as the stars follow the gas (e.g., Hillenbrand & Hartmann 1998; Da Rio et al. 2014; Megeath et al. 2016; Stutz & Kainulainen 2015; Stutz & Gould 2016). Indeed, significant effort has been dedicated to characterizing the asymmetries in the projected stellar distribution (e.g., Megeath et al. 2016, and references above). Nevertheless, the relationship
between the stellar and gas volume density structures in the central $\sim 0.5$ pc of the ONC has so far remained unexplored. Recently, Stutz & Gould (2016) proposed, based on a high density of observations, that the gas filament in the ISF is oscillating and ejecting young stars (the “Slingshot”, see also Boekholt et al. 2017; Schleicher & Stutz 2017). Given the extremely close association of the ONC stars with the gas filament, this scenario immediately raises the question of whether such filamentary gas oscillations might affect the structure of the embedded stellar cluster. Here we investigate this possibility through analysis of both the stellar (Megeath et al. 2016) and gas (Stutz & Kainulainen 2015; Stutz & Gould 2016) distributions in the center of the ONC.

Previous efforts at simulating open cluster formation have focused mainly on proto-cluster formation within turbulent molecular clouds (e.g., Bate 2009; Fujii & Portegies Zwart 2016). Here, proto-clusters (or embedded clusters) are distinct entities from clusters. Both are defined by concentrations of stars whose gravity is sufficiently strong to influence the stellar dynamics. However, in clusters, the gravity is dominated by the stars whereas in proto-clusters it is dominated by the gas out of which the stars are still forming. With this analysis we provide the essential ingredients necessary for simulating cluster formation conditions in ONC-analogs, in which clusters form on massive dynamical gas filaments. We quantify both the stellar and gas volume density distributions using simple geometric assumptions and discuss the relationship between them. We find that the gas and star gravitational field profiles reach near-equality at $r = a = 0.36$ pc, the softening scale of the stellar density profile. At all other radii the gas dominates the gravitational field. This, combined with the fact that the cluster crossing time is very similar to the estimated timescale for the gas filament motions, strongly suggests that the cluster profile and dynamics are controlled by the gas filament.

## 2 Gas and Stellar Mass Maps

### 2.1 Gas Mass Map

We use the column density map from Stutz & Kainulainen (2015, ; see also Stutz & Gould 2016). This map was derived from the Herschel dust emission data at 160 $\mu$m, 250 $\mu$m, 350 $\mu$m, and 500 $\mu$m. The final resolution of the map is about 20". We refer the reader to Stutz & Kainulainen (2015) for further details.

The Stutz & Kainulainen (2015) N(H) map was corrupted due to saturation in the center of the Orion Nebula Cluster (ONC) over a small elongated region covering less than $1.5' \times 6'$. We correct this defect using the APEX 870 $\mu$m data (e.g., Stanke et al. 2010; Stutz et al. 2013). This correction assumes that: (1) the spatial filtering in the ground-based submillimeter data is negligible across the narrow extent of the Herschel N(H) map artifact (with a maximum width of $\sim 1.5'$); and (2) the 870 $\mu$m emission is optically thin and traces the same dust emission as the Herschel maps. We use the region immediately outside the saturation artifact to scale the 870 $\mu$m data in E-W strips to fill in the missing column density information.

Figure 1 shows the corrected N(H) map of the Integral Shaped Filament (ISF) region, with M42 and the forming star cluster (ONC) located in the center. The grey line in Figure 1 is our recalculated dust ridgeline (for details see Stutz & Gould 2016) based on the corrected N(H) maps, which follows the maximum N(H) as a function of $\delta$. It is interesting to note the spike in the dust ridgeline near $\delta = -5.5^\circ$, caused by discontinuity in the filament that causes the ridgeline to “jump” to the to the nearest N(H) maximum, in this case to the west of the main filament. The filament also appears discontinuous in the high density gas tracer $N_2H^+$ (Tatematsu et al. 2008; Hacar et al. 2017), indicating that while the filament appears approximately like
Figure 2. Star mass map of the ISF. The vertical scale of the figure is 7.3 pc, the horizontal scale is \( \sim 10 \) pc. The \( \times \)-symbol indicates the stellar center of mass of the ONC at \( \alpha = 05:35:17.0, \delta = -05:22:37.95 \). The dust ridgeline is indicated as a dark-grey line. The white box is 0.5 pc \( \times \) 10 pc in size. The large white box is 0.5 pc \( \times \) 10 pc in size while the inner vertical lines indicate radii of 0.5 pc and 2.0 pc.

a single structure, it is in fact being broken apart at this location immediately below the cluster formation site (see discussion).

2.2 Stellar mass map

We use the disk star count map of Orion A based on the Spitzer data analyzed in detail by Megeath et al. (2016) (see also Megeath et al. 2012). Figure 2 shows the stellar mass map. Briefly, in our map each young star is represented by a delta function and then convolved to a 37" beam size (approximately matching the Herschel 500 \( \mu m \) beam). The weight of each delta function is equal to the inverse estimated local incompleteness at the source location. In regions of high nebulosity such as the center of the ONC the completeness correction fails due to the limited amount of information in the images. Therefore Megeath et al. (2016) use the COUP x-ray data (Feigelson et al. 2005) to augment the incomplete Spitzer counts. To accomplish this, Megeath et al. (2016) apply weighting factors to account for two principal effects:

1. The COUP data detect a different source population than the Spitzer data; Spitzer is based on IR excess, while the COUP data are sensitive to all xray emitting stars.

2. The Spitzer data are incomplete due to nebulosity (see above).

In order to account for these effects and match the two data-sets, Megeath et al. (2016) compare the nebulosity-corrected Spitzer counts to the COUP surface densities in the region of overlap where both the Spitzer and COUP incompleteness are minimized (that is, outside of the core of the ONC) to scale the COUP profile to the Spitzer counts. In the regions where the Spitzer data do not provide complete information, the scaled COUP counts are used. This analysis is described in detail in Megeath et al. (2016). The total number of stars with disks across Orion A is 5265. The total number of stars within the box centered on the ONC (see Fig. 2) is 1031. The Spitzer and COUP counts can in principle be used without a nebulosity correction, and the resulting mass distribution differences are discussed below.

To convert the young star count map into a total stellar mass map we must assume two quantities: 1.) a mean stellar mass of 0.5 \( M_\odot \) (Kroupa et al. 2001), and 2.) a disk fraction
of 0.75 (Megeath et al. 2016). Figure 2 shows the projected stellar mass distribution of the ISF. Ideally, we would base the conversion from star counts to stellar mass on empirically observed quantities, such as direct measurements of the IMF. Da Rio et al. (2012) measure the ONC IMF over a region covering about 30'×30'. Based on various evolutionary tracks they measure the (model dependent) characteristic mass (the peak IMF mass) to be about 0.3 $M_\odot$ (see their Table 4). As they note, this relatively high characteristic value is driven by their finding that the low mass population is deficient compared to other regions. They argue that incompleteness at low masses is not driving this result. Such values would correspond to somewhat higher mean stellar masses than those assumed here. Nevertheless, given the status of the current observational evidence, our assumed mean stellar mass is justified. Furthermore, our basic ONC results are not affected by small shifts in the assumed mean stellar mass as these will not change the shape of the fitted density profile (see below). Our disk fraction assumption of 0.75 is analyzed in detail in Megeath et al. (2016). We refer the reader to that work (specifically Sect. 2.2) for discussion on the derivation of the disk fraction. We note that Getman et al. (2014) argue for a higher disk fraction in the center of the ONC. However, small shifts in the ONC results do not affect our results (see below). Here we follow Megeath et al. (2016) and assume a single average disk fraction throughout our map. This approach works well in regions dominated by disk stars, such as the ONC.

3 STELLAR MASS DISTRIBUTION OF THE ISF

We begin by analyzing the stellar mass distribution as a function of $\delta$ and projected radial distance ($w$) from the gas ridgeline in Figure 3. The highly non-uniform stellar mass distribution is evident, and peaks approximately in the central region of the ONC where it is difficult to differentiate between a spherical symmetry and an elongated (elliptical) structure. Vertical dashed lines indicate the extent of the main structural components of the ONC: a clear stellar cluster core with $r<0.7$ pc and a more extended but lower density "halo" extending to about $r=2.0$ pc. The total stellar mass associated with the ISF is about $2200 M_\odot$. The cluster mass within $r=0.7$, 2.0 pc is about 1300, 2000 $M_\odot$.

Figure 4. Stellar mass inside projected radii for elliptical (solid line, 2:1 axis ratio with long axis oriented North-South) and circular apertures (dotted line). Here the "radius" of the ellipse corresponds to the minor axis of the elliptical aperture. Vertical dashed lines indicate the extent of the main structural components of the ONC: a clear stellar cluster core with $r<0.7$ pc and a more extended but lower density "halo" extending to about $r=2.0$ pc. The total stellar mass associated with the ISF is about $2200 M_\odot$. The cluster mass within $r=0.7$, 2.0 pc is about 1300, 2000 $M_\odot$.

4. There are $\sim900 M_\odot$ of stars outside $r=0.7$ pc, distributed in a lower density stellar "halo".

5. These "halo stars" have a distribution that surrounds the main central cluster, but follows the gas filament (i.e., is highly elongated).

In particular, we emphasize that in the center of the cluster, at radii $\lesssim0.5$ pc, Figure 4 shows that the departures from circular symmetry are minimal. That is, the differences between the elliptical and circular apertures in the cumula-
Figure 5. Cumulative distributions of gas (top) and stellar (bottom) mass within various projected separations $w$ from the dust column density ridgeline for the ISF. The cumulative distributions start at the southern boundary of the ISF (Dec = $-5.9^\circ$). The separate cumulative distributions for the east ($-w < x < 0$) and west ($0 < x < +w$) are shown in different line types. For ease of comparison (and clarity) these are multiplied by two. The vertical black line indicates the $\delta$ of the stellar center of the ONC. The relative mass profiles are small, reaching 27% at $r = 0.5$ pc. These differences are small compared to the overall variations in the density profile (see below). Thus the assumption of spherical symmetry is reasonable.

4 ONC GAS AND STAR VOLUME DENSITY, GRAVITATIONAL POTENTIAL, AND GRAVITATIONAL FIELD

It is clear from Figure 5 that the gas (top panel) and stellar mass (bottom panel) distributions are radically different. The ISF stars exhibit a large mass concentration in the center of the gas filament in the ONC (e.g., Megeath et al. 2016). This stands in contrast to the gas mass distribution, which is very close to uniform along the ISF, as Stutz & Gould (2016) showed. In addition, this figure shows that the correction to the saturated portion of the Herschel N(H) image has a negligible effect on the gas mass distribution profiles of the ISF (see Figure 4 of Stutz & Gould 2016 for the ISF mass distributions without the APEX 870 $\mu$m correction). We note that previous works have characterized the projected stellar surface density distributions of the ONC (Megeath et al. 2016, ; see also Gutermuth et al. 2015, 2009 for methodology) and show that the stellar distribution has departures from circular symmetry on scales $\gtrsim 0.5$ pc. Here we adopt the approximation of spherical symmetry in the case of the stars in order to execute a simple volume density analysis. This assumption is valid on small scales near the stellar cluster core, and not on larger scales as has been previously shown (see above references). Thus, Figures 4 and 5 motivate scrutinizing a narrow range in $\delta$ within which...
the stellar mass distribution is far more concentrated and a circular (or spherical) approximation is reasonable.

To this end we analyze the cumulative gas and stellar mass distributions centered on the ONC star cluster, shown in Figure 6. Here we analyze a much smaller range in $\delta$ of 0.5 pc, indicated with boxes in Figures 1 and 2. Both the gas and star mass distributions are calculated relative to the dust ridgeline (see above and Stutz & Gould 2016). The top panel of Figure 6 shows the gas mass distribution over the center of the ONC, while the bottom panel shows the stellar mass distribution. From this figure we can see that the cumulative gas mass increases relatively smoothly across the 0.5 pc extent of the ONC region that we are scrutinizing, although not as smoothly as for the ISF as whole (see Figure 5 and Stutz & Gould 2016). Meanwhile, the stellar mass distribution exhibits significant curvature associated with underlying circular (or spherical) structure of the cluster.

Taking advantage of the simple geometry implied by the two distributions (cylindrical for gas and spherical for stars) we construct mass per unit length profiles for both, shown in Figure 7. Here, the projected mass per unit length ($M/L$) profiles are integrated over a height $\delta = 0.5$ pc centered on the region of highest projected stellar density, the center of the ONC. In practice this represents the $M/L$ profile over a thin “orange slice” centered on the equatorial plane of the stellar cluster. This thin slice approach allows us to analyze the gas and star distributions in the direction perpendicular to the gas filament using simple geometric considerations. In particular, this approach allows us to ignore the more complex geometry of the star distribution on larger scales, where elongation along the gas filament precludes an accurate analysis using spherical or azimuthal averaging.

4.1 ONC Gas

Assuming cylindrical geometry, the gas distribution follows a power law of the form

$$\lambda(w) = K \left( \frac{w}{\text{pc}} \right)^\gamma; \quad K = 866 \frac{M_\odot}{\text{pc}}, \quad \gamma = 0.225.$$  (1)

Here $w$ is the projected radius as observed on the plane of the sky (or the impact parameter to the dust ridgeline). This power law has a different normalization and index than that of the ISF filament as a whole\(^1\) (Stutz & Gould 2016). We discuss this difference below. Such a power law line mass distribution can be easily converted to a gas volume density profile assuming cylindrical symmetry following Eqn. 5 of Stutz & Gould (2016):

$$\rho(R) = 25.9 \frac{M_\odot}{\text{pc}} \left( \frac{R}{\text{pc}} \right)^{\gamma-2}.$$  (2)

Following Stutz & Gould (2016) we also obtain the enclosed gas line density $\Lambda(R)$, acceleration $a(R)$, and the gravitational potential profiles:

$$\Lambda(R) = f(\gamma)\lambda(R) = 0.83\lambda(R) = 723 \frac{M_\odot}{\text{pc}} \left( \frac{R}{\text{pc}} \right)^\gamma,$$  (3)

$$a(R) = 2G\lambda/r = 6.2 \text{ km s}^{-1}\text{Myr}^{-1} \left( \frac{R}{\text{pc}} \right)^{\gamma-1},$$  (4)

and

$$\Phi(R) = \eta(\gamma)G\lambda(R) = 27.6 \text{ (km s}^{-1})^2 \left( \frac{R}{\text{pc}} \right)^\gamma.$$  (5)

Here, $f(\gamma)$ and $\eta(\gamma)$ are defined in Stutz & Gould (2016), and have values of 0.834 and 7.418 respectively for $\gamma = 0.225$.

4.2 ONC stars

Assuming spherical symmetry in the stellar core, we determine the stellar volume density using a model of the form

$$\Sigma_v(b) \propto (1 + (b/a)^2)^{-\beta}$$  (6)

to analyze the projected stellar $M/L$ profile (Fig. 7). This is a generalized form of the projected surface density of a Plummer profile; a value of $\beta = 2$ gives the familiar Plummer profile (Plummer 1911; Binney & Tremaine 2008), which has a well defined density-potential pair, and is commonly used to characterize star cluster profiles (e.g. Portegies Zwart et al. 2010; Bianchini et al. 2017). In Figure 8 we show various $M/L$ curves for different values of both $\beta$ and $a$. The best match to the observed stellar distribution is given by $\beta = 2$ and $a = 0.36$ pc. All models in Figure 8 are normalized at large radii ($r = 1$ pc with $M_{\text{slice}}/L = 1285 M_\odot$/pc, see below). The normalization at small radii then strongly discriminates against most models. No model fits the data perfectly. In particular, those that fit well at intermediate projected radii are slightly too low at very small projected radii. Two models appear to fit the data at intermediate radii, $(\beta, a) = (2.0, 0.36 \text{ pc})$ and $(\beta, a) = (2.5, 0.44 \text{ pc})$. Since

\(^1\) Stutz & Gould (2016) measure values of $K = 385 M_\odot$ pc\(^{-1}\) and $\gamma = 3/8$ (see their Eqn. 4) for the ISF as a whole.
Figure 8. Model fits to the stellar mass distribution in Fig. 7 using equation 6. The best-fit model to the stellar distribution corresponds the red-dashed line, that is, to \( a = 0.36 \) pc and \( \beta = 2 \) (i.e., a Plummer profile). Here we adopt \( M_{\text{slice}}/L = 1285 \, M_{\odot}/pc \) at \( r = 1 \) pc as the total mass per unit length for the fit (see text). The dot-dashed line corresponds to the Spitzer star counts when ignoring the effects of nebulosity (see text and Megeath et al. 2016).

\((\beta, a) = (2.0, 0.36 \text{pc})\) fits at the intermediate radii almost perfectly and is closer to the data at small radii, we adopt this model as a good analytic representation of the stellar profile.

From simple analytic analysis, we show in Appendix A that for the case of \( \beta = 2 \), we obtain a relation between \( M/L \) measured in a thin slice and the volume density profile, where

\[
\rho_s(r) = K (1 + (r/a)^2)^{-\gamma}; \quad \gamma = \beta + 0.5, \tag{7}
\]

and

\[
K = \frac{3}{2\pi a^2} \frac{M_{\text{slice}}}{L} \sqrt{1 + (L/2a)^2}. \tag{8}
\]

Here, \( M_{\text{slice}}/L = 1285 \, M_{\odot}/pc \) is the value of the stellar \( M/L \) measured from Figure 8 at \( r = 1 \) pc.

The final volume density profile of the stars is

\[
\rho_s(r) = 5755 \, M_{\odot}/pc^3 (1 + (r/a)^2)^{-5/2}. \tag{9}
\]

The corresponding gravitational acceleration and potential profiles are

\[
a_s(r) = 37.3 \, \text{km s}^{-1}\text{Myr}^{-1} (1 + (r/a)^2)^{-3/2}r/a, \tag{10}
\]

and

\[
\Phi_s(r) = -13.4 \, (\text{km s}^{-1})^2(1 + (r/a)^2)^{-1/2}. \tag{11}
\]

The mass and density profiles are consistent with previous investigations into the density structure as a whole, for which e.g., Da Rio et al. (2014) find that a slope of \( \gamma \sim 2.2 \) for the volume density profile. In agreement with Hillenbrand & Hartmann (1998), we find an inner flattening of the core density profile. Below \( r \sim 0.36 \) pc the stellar surface
what follows we use the fully corrected profiles.

essential for obtaining accurate stellar profiles. Therefore in
would not be affected. However, the nebulosity correction is
the parameters for the shape of the volume density profile
profile for the mass profile based on the maps neglect-
M/L comparison to Megeath et al. (2016), in Figure 8 we show the
depend on the overall normalization of the
M/L terms of the density profile, the values of
bution that would continue into the center of the cluster. In
density flattens, and is inconsistent with a power-law distri-
while the gravitational field due to the gas dominates everywhere
r consequent to the cluster. The gas then has a causal relationship to
radius, both smaller and larger.

We estimate the cluster crossing time $t_{cross} = 2a/\sigma_{obs} \sim 0.55$ Myr, where $a = 0.36$ pc and $\sigma_{obs} = 2.6$ km s$^{-1}$. We measure a velocity dispersion for the stars of $\sigma_{obs} = 2.6$ km s$^{-1}$ from the APOGEE data (e.g., Stutz & Gould 2016; Da Rio et al. 2016). Then we must estimate the size of the cluster, i.e. the radius of a sphere containing the stars having a velocity $\sim 2.6$ km s$^{-1}$. This can be obtained from the data, for example from Figure 9 where we can es-
characteristic radius (containing most of the stars) as 2a. If the lifetime of the ONC is $\sim$2-3 Myr (Da Rio et al. 2016), then the core is about 4-6 crossing times young. On
this relatively short timescale we do not expect significant internal evolution to have taken place in the cluster. Fur-
therefore, Stutz & Gould (2016) estimate the timescales of
the gas filament motion of $\sim 0.6$ Myr, which is very similar
to the cluster $t_{cross}$.

The ensemble of evidence presented here strongly sug-
gests that the cluster profile and dynamics are controlled by
the gas filament. First, the gravitational field is everywhere
dominated by the gas. This fact alone, established here for
the first time, demonstrates that the stellar cluster cannot be
considered a virialized system dominated by its own gravity.
Second, the transition from cluster core to halo (at softening
radius $a$) occurs at exactly the point that the cluster gravity
would begin to dominate that of the gas. This indicates that
the gas potential somehow limits the growth of the cluster
core. That is, the structural parameters of the star cluster
might be determined by the gas filament. Third, the internal
cluster timescale is the same as the oscillation timescale of
the filament, which is measured on spatial scales that are an
order of magnitude larger than the cluster.

The coincidence of timescales, together with the fact
that the filament oscillations are clearly independent of the
cluster, implies that it is these oscillations that are driving
the internal dynamics of the cluster. The driver for the gas
oscillations is rooted in the interaction between the magnetic
field and gravity of the gas filament. That is, the magnetic
field is not felt by the stars, they move independently, only
affected by gravity, both their own and that of the gas. Yet
the gas does feel the magnetic field. The gas is distributed in
a $\sim 7$ pc long filament which is much larger and more
massive than the star cluster, and which has a wave-like
morphology (and kinematics) that indicates that the gas is
oscillating, as proposed by Stutz & Gould (2016). In this
picture, the gas oscillations are determined by the interac-
tion of the magnetic field and the gravitational potential of
the gas (which completely dominates over the potential of
the stars, except in a small region near $r = a$ in the cen-
ter of the ONC). The gas then has a causal relationship to

5 DISCUSSION AND CONCLUSIONS

In Figure 9 we show the volume density profiles for the gas
(black curve) and stars (grey curves). One of the most strik-
ing features of this diagram is that the stellar density sur-
passes the gas inside $r \sim 1$ pc, but outside the system is gas
dominated. In Figure 10 we show the corresponding gravi-
tational field profiles for the gas, stars, and total. The stars
contribute a maximum to the field at $r/a \sim 0.8$ ($\sim 0.3$ pc),
and have about equal contribution as the gas near $r/a \sim 1.1$
($\sim 0.45$ pc). That is, the stars contribute most significantly
to the field at $r \sim a$, while the gas dominates at all other
radii, both smaller and larger.

density flattens, and is inconsistent with a power-law distri-
bution that would continue into the center of the cluster. In
terms of the density profile, the values of $\beta$ and $a$ do not
depend on the overall normalization of the $M/L$ profile. For
comparison to Megeath et al. (2016), in Figure 8 we show the
$M/L$ profile for the mass profile based on the maps neglect-
ing the nebulosity correction (see Section 2). The shape of
the $M/L$ profile is the same, but the normalization is a factor
of 1.7 lower, with a value of $M_{hss}/L = 746.7 M_\odot$/pc. Thus,
the parameters for the shape of the volume density profile
would not be affected. However, the nebulosity correction is
essential for obtaining accurate stellar profiles. Therefore in
what follows we use the fully corrected profiles.
the stellar cluster, whereby the gas oscillations imprint on
the stellar cluster structure through changes in the grav-
titational field (felt by the cluster) which are caused by the
accelerating gas filament. To second order, the density en-
hancement of the stars in the center of the ONC might affect
the oscillation, but based on the star to gas mass ratios in
the region, this effect is not dominant. The gas filament,
both its gravitational-magnetic oscillations and the gravita-
tional tides that it generates, naturally explain all three of
the above elements.

The first key point is tides represent the differential ac-
celeration on a particle relative to the center of mass of
a system that is moving through an external potential. If
the cluster were sitting in a non-accelerating external po-
tential, there would be no tides: the particles (stars) would
simply reorganize themselves according to the external po-
tential and their own velocity dispersion (somewhat modi-
fied by their self-potential, which is subdominant). On the
other hand, if the gas filament is accelerating due to non-
gravitational (i.e., magnetic) forces, then the cluster (which
is only subject to gravitational forces) will always be mov-
ing relative to the gas and so will be subject to tides. In this
way, the filament potential sets the structural parameters of
the ONC. These tides will then automatically suppress low
density structures, such as the outskirts of the cluster (for
spherical analogs see Lammers et al. 2005; Gieles & Renaud
2016; Renaud et al. 2011).

As shown by Stutz & Gould (2016), the stars are born
(as protostars) on the filament and have essentially zero ve-
clocity relative to the filament. That is, the specific kinetic
energy of the protostars is $\sim 6$ times smaller than that of
the stars. On the other hand, the stellar velocity disper-
sion is comparable to the velocity amplitude of filament os-
cillations, which is one of the pieces of evidence that led
Stutz & Gould (2016) to conclude that the stars were being
ejected from the filament as they mechanically decoupled
from the gas. This ejection mechanism naturally explains
why the cluster has a core: the core is populated by stars
that have been ejected (and fall into the potential well of the
cluster) over a range of velocities and positions as the fila-
ment oscillates. Moreover, this naturally explains why the
ter core just at the point that the cluster's gravity is be-
ginning to dominate? Again, the key lies in the filament's
oscillations. As long as the nascent proto-cluster remains a
basically passive accumulation of stars, its collective impact
on the filament likewise remains minimal. But to the ex-
tent that the cluster becomes self-gravitating and capable
of following its own inertial orbit, it begins to impact the
gas flows within the filament as the filament oscillates away
from it. Indeed, there is some evidence from the extinction
measurements (e.g., O'dell 2001; Wen & O'dell 1995) that
the cluster center is currently displaced from (somewhat in
front of) the gas filament.

This picture gives insight not just into the past history
of the ONC, but also its future. Just as individual proto-
stars separate from the filament at the moment when their
self-gravity enables them to marginally decouple mechan-
ically from the gas, so the ONC proto-cluster as a whole
will separate from the filament as it becomes marginally
self-gravitating and can decouple gravitationally from the
filament. In the case of the individual protostars, their exit
from the filament initiates the next phase of their evolution
as disk-bearing stars that have been cut off from external
gas accretion. The proto-cluster’s exit likewise initiates a
new phase of life as a nascent cluster that is cut off from the
aggregation of new stars.

In a richer environment than Orion, perhaps several
such marginally bound nascent clusters would merge to form
a truly self-gravitating system. This will not be the fate of
the ONC, however. Rather, because it will exit the filament
when it is only marginally self-gravitating, it will lose a large
fraction of its stars and become a shadow of its former self,
similar to NGC 1977 and NGC 1981. In the still more distant
future, less than 10 Myr, the ONC will likely completely dis-
perse, similar to the fate of the clusters that formed before
NGC 1981 as the gap opened up between the Orion A and
Orion B filaments.
Future numerical simulations coupling oscillating filaments to N-body dynamics (Boekholt et al. 2017, Matus Carrillo et al., in prep.) of star clusters will stringently test this hypothesis. Furthermore, ALMA observations of the number and distribution of protostars within the ONC will provide essential observational constraints on the origin of the stars populating the cluster.

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APPENDIX A: FROM AN M/L TO A VOLUME DENSITY

We assume polytrope density and projected density profiles of the form

$$\rho(r) \equiv K(1 + (r/a)^2)^{-\beta}; \quad \Sigma(b) \equiv C(1 + (b/a)^2)^{-\beta}.$$ 

Here,

$$\Sigma(b) = \int_{\infty}^{\infty} dz \rho(\sqrt{a^2 + b^2}) = 2 \int_{0}^{\infty} dz K((a^2 + b^2)/(a^2 + z^2/a^2))^{-\gamma} \equiv 2(1 + (b/a)^2)^{-\gamma} \int_{0}^{\infty} dz K(1 + z^2/(a^2 + b^2))^{-\gamma} = 2(1 + (b/a)^2)^{-\gamma} \int_{0}^{\infty} dz K(1 + z^2/(a^2 + b^2))^{-\gamma} = 2K(1 + (b/a)^2)^{-\gamma + 0.5} \int_{0}^{\infty} dx (1 + x^2)^{-\gamma}. $$

So, $$\beta = \gamma - 0.5 \quad \text{and} \quad C = 2K a \int_{0}^{\infty} dx (1 + x^2)^{-\gamma}$$

where for $$\gamma = 5/2$$ is $$0.5(-1/2)/((\gamma - 3/2))/((\gamma - 1))! = 0.5(-1/2)/((\gamma - 3/2))/((\gamma - 1))! = 2/3.$$ That is, $$C = (4/3)aK.$$
Now consider an “orange slice”, of infinitesimal width, but offset from the center by $q$:
\[
\lambda(q) = \int_{-\infty}^{\infty} dy \Sigma(\sqrt{q^2 + y^2}) = 2 \int_{0}^{\infty} dy C(((q^2 + y^2)/a^2)^{-\beta})
\]
Then, using exactly the same algebraic steps as above
\[
\lambda(q) = \kappa(1 + (q/a)^2)^{-\delta}
\]
where $\delta = \beta - 0.5$ and $\kappa = Ca(-1/2)!((\beta - 3/2)!/((\beta - 1)!$.

Finally, the total mass in a thick slice within $\pm L/2$ of the center is
\[
M_{\text{slice}} = 2 \int_{-\infty}^{\infty} dq \kappa(1 + (q/a)^2)^{-\beta} = 2 \kappa a \int_{0}^{\tan^{-1}(L/2a)} d\theta \cos^{2\beta - 2} \theta
\]
\[
= 2Ka^3 \left(\frac{1}{L^2}\right) \frac{1}{2} (\tan^{-1}(L/2a)) = 2Ka^3 \frac{1}{2} \sec^{-1}(L/2a) = \frac{1}{\sqrt{1 + (2a/L)^2}}.
\]

That is,
\[
M_{\text{slice}} = 4\pi K a^3 \frac{1}{3 \sqrt{1 + (2a/L)^2}}.
\]

Note that for the special case of $L = \infty$, we recover the standard formula for the cluster mass. For the special case of a thin slice (which was previously considered) we get
\[
M_{\text{slice}} = 2\pi Ka^2 L/3, \text{ i.e., proportional to } L.
\]

Motivated by this “$M/L$” form, we can write the general case as
\[
M_{\text{slice}} = \frac{2\pi Ka^2 L}{3} \frac{1}{\sqrt{1 + (L/2a)^2}}.
\]

From this, we can see that for the particular case of $(L, a) = (0.5, 0.36)$ pc, the “adjustment factor” relative to the previous “thin slice” reasoning is $1/\sqrt{1 + (0.5/0.72)^2} = 0.82$.

The net result is that for our parameters, $\beta = 2.0$, $a = 0.36$ pc, $L = 0.5$ pc,
\[
K = \frac{M_{\text{slice}}}{L} \frac{1}{\sqrt{1 + (L/2a)^2}} = 4.48 \frac{M_{\text{slice}}}{\text{pc}^2 L}.
\]

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