MASSIVE QUIESCENT CORES IN ORION: DYNAMICAL STATE REVEALED BY HIGH-RESOLUTION AMMONIA MAPS

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ABSTRACT

We present combined Very Large Array and Green Bank Telescope images of NH$_3$ inversion transitions (1, 1) and (2, 2) toward OMC2 and OMC3. We focus on the relatively quiescent Orion cores, which are away from the Trapezium cluster and have no sign of massive protostars or evolved star formation. The 5" angular resolution and 0.6 km s$^{-1}$ velocity resolution enable us to study the thermal and dynamic state of these cores at $\sim$0.02 pc scales, comparable to or smaller than those of the current dust continuum surveys. We measure temperatures for a total of 30 cores, with average masses of 11 $M_\odot$, radii of 0.039 pc, virial mass ratio $R_{\text{vir}} = 3.9$, and critical mass ratio $R_C = 1.5$. Twelve sources contain Spitzer protostars. The thus defined starless and protostellar subsamples have similar temperature, line width, but different masses, with an average of 7.3 $M_\odot$ for the former and 16 $M_\odot$ for the latter. Compared to other Gould Belt dense cores, more Orion cores have a high gravitational-to-kinetic energy ratio and more cores have a larger than unity critical mass ratio. Orion dense cores have velocity dispersions similar to those of cores in low-mass star-forming regions but larger masses for given size. Some cores appear to have truly supercritical gravitational-to-kinetic energy ratios, even when considering significant observational uncertainties: thermal and non-thermal gas motions alone cannot prevent collapse.

Key words: instrumentation: interferometers – ISM: clouds – ISM: individual objects (Orion) – stars: formation

Online-only material: color figures

1. INTRODUCTION

Stars form in molecular clouds. Within molecular clouds, discrete structures with observable column density contrast, particularly in high-density tracers, with its surroundings are referred to as cores (e.g., Benson & Myers 1989; Ward-Thompson et al. 2007). The relatively high extinction and density of cores make them the likely site for the onset of collapse.

Recent core surveys (e.g., Ikeda et al. 2007; Kőnyves et al. 2010; Sadavoy et al. 2010) are facilitated by focal plane imaging arrays of growing sizes. Although many surveys have large sample size in the hundreds, the majority of these studies are of dust continuum, which tend to focus on core mass function. Direct measurement of cores’ thermal and dynamic structures requires spectra maps of high-density tracers and preferably covers the same spatial dynamic ranges as those of dust emission.

There seems to be an observational dichotomy between low-mass star formation and high-mass star formation. Massive stars are formed exclusively in giant molecular clouds and with higher efficiency. Due to the large distances of most massive star-forming regions, many massive cores are under-resolved, showing signs of star formation well underway, such as H$_2$O masers (Mookerjea et al. 2004) and/or compact H II regions (Reid & Wilson 2005). At about 437 pc (Hirota et al. 2007; Menten et al. 2007), Orion molecular clouds are the closest massive star-forming region with an OB cluster, and thus are particularly suited for studying the early stages of star formation in massive cores and/or under the influence of young massive stars. In a series of papers, we identified “quiescent” Orion clouds/cores (containing no H II region, no IRAS point sources, and at least 1 pc away from the OB cluster) with NH$_3$ and N$_2$H$^+$ with a beam size of about 1" (Li et al. 2003, hereafter Paper I), presented high-resolution 350 $\mu$m images with a beam size of 9" (Li et al. 2007, hereafter Paper II), and revealed that two-thirds of Orion cores have signatures of ongoing dynamic evolution, both outflows and inflows (Velusamy et al. 2008, hereafter Paper III). Based on dust mass and dust core size (Paper II), the majority of the cores are seemingly supercritical, i.e., with no adequate support from thermal pressure, turbulence (c.f. McKee & Tan 2003), or static magnetic field. This is consistent with the majority of the cores being hydrostatically unstable (Paper III), which, however, could not be directly tested due to a lack of high-resolution spectroscopic data.

Spectroscopic survey of CO 1–0 (Williams et al. 2003) and CO 3–2 (Takahashi et al. 2008) reveals that part of the Orion molecular cloud, namely, OMC2 and OMC3, contains many molecular outflows. OMC2 and OMC3 have also been mapped in high-density tracers. Using the Nobeyama 45 m telescope, Tatematsu et al. (2008) identified 34 cloud cores in N$_2$H$^+$ 1–0 with a beam width of around 18". Ikeda et al. (2007) studied dense gas in the same region using HCO$^+$, also with Nobeyama. These studies find higher column density for respective tracers compared with low-mass star-forming regions, such as Taurus. NH$_3$ inversion transitions are particularly suited for studying dense cores due to their lack of depletion and their sensitivity to kinetic temperature (Ho & Townes 1983). Wiseman & Ho (1998) obtained NH$_3$ maps of an 8' $\times$ 6' region around Orion-KL using Very Large Array (VLA). The
gas morphology there is dominated by quasi-parallel filaments severely influenced by the energy output of young massive stars.

In this Letter, we present the combined VLA and Green Bank Telescope (GBT) ammonia survey of the cores in OMC2 and OMC3. The spatial resolution of ~5″ and the spectral resolution of 0.6 km s\(^{-1}\) facilitate a detailed examination of the thermal and dynamic states of massive quiescent Orion cores.

2. OBSERVATIONS AND DATA REDUCTION

The VLA observations of OMC2/OMC3 were carried out in the D configuration on 2000 July 29 and September 24. We used the correlator mode 4 to cover the NH\(_3\) \((J,K)=(1,1)\) and \((2,2)\) inversion transitions simultaneously. With a primary beam of about 2″ at the observing frequencies, a total of 20 pointings were used to mosaic the OMC2/3 regions. The correlator was configured to a bandwidth of 3.13 MHz for each transition that was divided into 64 channels, providing a velocity coverage of 40 km s\(^{-1}\) in 0.6 km s\(^{-1}\) channel spacing. We used quasar 3C286 as the flux calibrator and 3C84 or 3C273 as bandpass calibrators. The time-dependent gains were monitored by observing 0539−057 or 0605−085. Visibility data were calibrated in AIPS and exported to MIRIAD for imaging. The 1σ rms in the channel maps, after combining the two observations, is about 8 mJy per spectral channel.

The observations of NH\(_3\) \((1,1)\) and \((2,2)\) transitions with the GBT were taken on 2005 April 6 and 7 in the OTF mode using the receiver Rcvr18-26. The correlator setup had a 200 MHz bandwidth and 0.31 km s\(^{-1}\) velocity resolution (8192 channels). The flat baseline and the wide bandwidth allowed us to use frequency switch with a throw of 12.5 MHz. The spectra were folded and the three-dimensional data cube was resampled to a grid of 12″ spacing and 0.3 km s\(^{-1}\) channel. The resulting GBT spectra have a typical 0.12 K rms noise per channel.

We combine the NH\(_3\) data from the VLA with those from the GBT to recover missing short spacing fluxes in the interferometric data. The combination was performed in the UV domain using MIRIAD, following the procedure outlined in Vogel et al. (1984) and Zhang et al. (2000). The NH\(_3\) emission from the combined image, when convolved to the 30″ GBT beam, recovers more than 80% of the fluxes detected in the GBT data. The integrated intensity of the NH\(_3\) \((1,1)\) line with previously identified continuum sources and a pair of typical spectra are presented in Figure 1.

3. DERIVATION OF KINETIC TEMPERATURE AND VELOCITY DISPERSION

Largely following Ho & Townes (1983), Paper I described a recipe for deriving kinetic temperature from spectrally resolved, modestly blended NH\(_3\) lines (intrinsic line width \(\Delta V \sim 1.0\) km s\(^{-1}\)). In this Letter, we report line width \(\Delta V\) in FWHM. The one-dimensional velocity dispersion \(\sigma\) used in Equations (6), (9), and (10) is related to FWHM as \(\Delta V = \sqrt{8\ln(2)}\sigma\) for a Gaussian. The key step is to obtain the optical depth of the \((1,1)\) line from simultaneously fitting all hyperfine components. As can be seen in Figure 1, the VLA band is not wide enough to fully cover the two outer groups (osg). The combined data set thus only has the main and inner satellite components of the \((1,1)\) transition and has a velocity resolution of 0.6 km s\(^{-1}\). Toward most positions, the intrinsic line width is smaller or approaching channel width. For such under-resolved line, the opacity cannot be easily uniquely fitted.
We developed a more straightforward recipe utilizing two ratios between integrated intensities, which are directly observable,
\[ R_{12} = \frac{\int T_A^{(1,1)}(1,1) d\nu}{\int T_A^{(2,2)}(2,2) d\nu} \]
and
\[ R_{\text{sm}} = \frac{\int T_A^{(1,1)}(1,1) d\nu}{\int T_A^{(mg)}(1,1) d\nu} \].
The rotational temperature can be derived as the following:
\[ T_R = \frac{41.5 \text{ K}}{\ln \left[ 1.06 \times C(1,1) \times R_{12} \right]} \],

where \( C(1,1) \) is a numerical factor determined as
\[ C(1,1) = 0.003 + 2.26 R_{\text{sm}} + 0.00032 e^{5.38 R_{\text{sm}}} \],

which is based on fitting the simulated NH3 (1,1) spectra based on a grid of opacities and line width. The kinetic temperature is then (Paper I)
\[ T_k = 3.67 + 0.307 \times T_R + 0.0357 \times T_R^2 \].

The full recipe is given in J. Kauffmann et al. (2013, in preparation) and is generally applicable to a wide range of conditions in opacities, channel width, and intrinsic line width. In the observed line width range, the dependence of \( C(1,1) \) on line width is small. The uncertainty in derived kinetic temperature is then calculated using a Monte Carlo approach (Paper I). For pixels with (2,2) detection, the representative 1σ uncertainty is about 1–2 K for emission peaks and between 2 K and 5 K for diffuse areas. Except for about 1.5% of scattered pixels, the derived temperatures are between 10 K and 30 K. When there is no detection of the (2,2) line, we derive an upper limit to kinetic temperatures \( T_k^{u} \) assuming 3σ(2,2) intensity.

Figure 2 shows the derived temperatures overlaid with the dust continuum and dust cores. The temperatures generally drop while moving the dust cores inward, consistent with Paper I at a coarser spatial grid. A quantitative analysis of the thermal structure of the whole region will be presented in J. Kauffmann et al. (2013, in preparation).

For every dense core, velocity dispersions are derived from spectra averaged over the ellipses reported by Nutter & Ward-Thompson (2007). The low velocity resolution of 0.62 km s\(^{-1}\) complicates the calculation of velocity dispersions. We first identify main group channels with signal-to-noise ratios \((S/N) > 3\). If more than one such channel is found, a dispersion \( \sigma_{\text{data}} \) is calculated, in which channels are weighted by their intensity; if a single channel is found, an upper dispersion limit of 0.26 km s\(^{-1}\) (channel width) is adopted. The intrinsic dispersion of the (1,1) main group is then subtracted to obtain
\[ \sigma_{\text{obs}} = [\sigma_{\text{data}}^2 - (0.2 \text{ km s}^{-1})^2]^{1/2} \]. A numerical experiment was performed based on simulated Gaussian lines with noise. For our observed core-averaged S/N of 13–43 and typical dispersion of <0.4 km s\(^{-1}\), using only channels with S/N > 3 results in an underestimation of the intrinsic line dispersion by about 5%. This is negligible considering that we have used an upper limit for single-channel detections.

4. DYNAMIC STATE OF CORES

For a full coverage of all OMC2 and OMC3 cores, we use the SCUBA survey of Orion by Nutter & Ward-Thompson (2007,
The pixels have derived temperature lower than 20 K. We therefore assumed a temperature of 20 K was assumed in N07. In our map, 74% of the flux is lower in N07 than in Ossenkopf & Henning (1994). This comes mainly from the assumption of dust opacity, which is thought to be about 10%. The uncertainty in the determination of dust mass and temperature comes mainly from the assumption of dust opacity, which is thought to be about 10%. The uncertainty in the determination of dust mass and temperature is smaller than the observed ratio, (Myers et al. 1991; Li 2002), and so the intrinsic axis ratio, in equilibrium (Bonnor 1956). Dense cores are likely prolate gravitating structures in virial equilibrium fulfill |

\[ E \propto \frac{1}{r} \frac{1}{F} \left( \alpha \beta \frac{GM^2}{r} \right) \]

for a radius \( r \), where \( \beta = \arcsin e/e \) is the geometry factor determined by eccentricity \( e = \sqrt{1 - f^2} \), \( \alpha = (1 - a/3)/(1 - 2a/5) \) for a power-law density profile \( \rho \propto r^{-a} \), and \( G \) is the constant of gravity. We adopt \( a = 1.6 \) for an isothermal cloud in equilibrium (Bonnor 1956). Dense cores are likely prolate (Myers et al. 1991; Li 2002), and so the intrinsic axis ratio, \( f \), is smaller than the observed ratio, \( f_{\text{obs}} \), due to projection. We substitute

\[ f = \frac{2}{\sqrt{5}} f_{\text{obs}} F_1(0.5, 0.5, -0.5, 1.5, 1, -f_{\text{obs}}^2) \]

for the most likely value for a prolate ellipsoid (Fall & Frend 1983), where \( F_1 \) is the Appell hypergeometric function of the first kind.

Consider objects with vanishing magnetic field strength that are not confined by external pressure. In this case, self-gravitating structures in virial equilibrium fulfill \( |\mathcal{G}| = 2\mathcal{E} \), where \( \mathcal{E} = 3/2 \cdot M \sigma^2 \) is the internal kinetic energy (McKee &...
For given \( \sigma \) and \( r \), objects with mass \( M > M_{\text{vir}} \) are bound, i.e., too massive to be in virial equilibrium, where

\[
M_{\text{vir}} = \frac{5}{\alpha \beta} \frac{\sigma^2 r}{G}
\]

is the virial mass. We can quantify this balance via the virial mass ratio,

\[
R_{\text{vir}} = \frac{M}{M_{\text{vir}}}. \tag{7}
\]

We find that 25 of 30 cores (i.e., 83%; Figure 3 and Table 1) have \( R_{\text{vir}} > 1 \), 13 cores (43%) fulfill \( R_{\text{vir}} > 3 \). The two most extreme cores fulfill \( R_{\text{vir}} \gg 18 \). Following this analysis, most cores are bound by gravity and unstable to collapse. The fraction of unstable cores remains significant even when significant observational uncertainties are considered (Section 4.3).

4.2. Stability and Critical Mass

Now consider the additional impact of external pressure and the internal magnetic field. The critical mass \( M_c \) is defined as the maximum mass that can be stably supported by internal velocity dispersion and magnetic pressure. The two effects can be considered separately and then combined in a simple approximation

\[
M_c = M_J + M_\Phi, \tag{8}
\]

which is accurate to within 5% compared to the more rigorous calculations (McKee 1989).

The Jeans mass for a non-magnetic isothermal cloud (Bonnor 1956; McKee & Zweibel 1992) is

\[
M_J = 1.182 \frac{\sigma^4}{G^{3/2} r_c^{1/2}}. \tag{9}
\]

The external pressure term can be estimated as

\[
P_c = n_c \mu m_{\text{H}} \sigma_c^2, \tag{10}
\]

where the mean molecular weight \( \mu \) relative to \( n(\text{H}_2) \) is 2.8 (Kauffmann et al. 2008) and \( m_{\text{H}} \) is the proton mass. If we consider tracers of more diffuse gas in this region, such as \(^{13}\text{CO}\), the line width is around 1.5 km s\(^{-1}\) (Melnick et al. 2011). We therefore adopt \( \sigma_c > 1 \) km s\(^{-1}\). The intercloud density \( n_c \) is not well known. Radiative transfer analysis of \(^{13}\text{CO}\) and C\(^{18}\)O in this region (Li 2002) shows that the densities are a few times \( 10^4 \) cm\(^{-3}\) in the relatively diffuse area. We thus adopt \( n_c > 10^4 \) cm\(^{-3}\). Correspondingly, the Jeans mass thus derived will be a conservative upper limit.

The maximum mass that can be supported by a steady \( B \) field alone is

\[
M_\Phi = c_\Phi \frac{\pi B^2 r_c}{G}, \tag{11}
\]

where \( c_\Phi \approx 0.12 \) is given by numerical simulations (Mouschovias & Spitzer 1976; Tomisaka et al. 1988). Crutcher et al. (1999) detect the Zeeman effect in the CN 3 mm line near Orion BN/KL. The field strength is derived to be 0.19 mG or 0.36 mG, based on different fitting schemes. This is larger than the \( B \sim 0\text{–}0.027 \) mG measured in dark clouds (Crutcher 1999). Given the proximity of BN/KL to active star formation, the large \( B \) could be explained by rapid collapses’ freezing magnetic flux into high-density regions along the line of sight. We thus take a smaller, nominal \( B = 0.1 \) mG for the quiescent Orion cores.

Analogous to Equation (7), we define the “critical mass ratio” for our quantitative analysis,

\[
R_c = \frac{M}{M_c}. \tag{12}
\]

We find that 14 out of 30 (47%) cores have \( R_c > 1 \), and 6 cores (20%) reside at \( R_c > 2 \). Note that these ratios are quite uncertain: uncertainties in velocity dispersions have a significant impact, since \( M_J \propto \sigma^4 \), and \( B \) is uncertain by fractions of an order of magnitude. Independent of these uncertainties, the observed values of \( R_c \) show that the inclusion of magnetic support reduces the number of supercritical cores. Given the uncertainties involved, we cannot examine whether cores are magnetically supercritical.

4.3. Discussion: Is Orion Special?

Our data suggest mass ratios \( R_{\text{vir}} > 3 \) for 43% of the Orion cores studied here. This is different from other clouds in solar neighborhood within \( \sim 500 \) pc. In Perseus, Foster et al. (2009) and Kirk et al. (2007) find an equivalent \( R_{\text{vir}} \lesssim 3 \). In Ophiuchus, André et al. (2007) imply \( R_{\text{vir}} \lesssim 1 \) based on their Table 4 after adopting the dust opacity used here. For SCUBA-identified Gould Belt cores, Sadavoy et al. (2010) find that only 20 out of 354 cores have \( M/M_J > 2 \) (again adjusting dust opacities, and excluding their Orion data to avoid overlap). Their \( M_J \) represents a purely thermal Jeans mass, which means that these cores will have an even smaller mass ratio using our definitions.

The observed \( R_{\text{vir}} \) in Orion may be similar to those found in high-mass star-forming regions, e.g., the two clouds studied by Pillai et al. (2011). Although direct comparison is difficult due to the much larger distance of other high-mass star-forming regions.

The calculations differ slightly between studies, e.g., in the factors \( \alpha, \beta \), and dust opacities. These differences alone cannot explain the larger mass ratios observed in Orion. Thus, compared to other surveys, our result that >40% of Orion cores have \( R_{\text{vir}} > 3 \) is significant. It appears that the gravitational binding...
of Orion dense cores is stronger than for cores in other Gould Belt clouds. The analysis executed here suffers from a variety of uncertainties. First, the dust opacity might be larger than adopted here. An opacity increase by a factor two, e.g., would reduce $R_{\text{vir}}$ and $R_C$ by the same factor. Uncertainties in the velocity dispersion enter as $R_{\text{vir}} \propto \sigma^{-2}$ and $R_C \propto \sigma^{-4}$. It is plausible that such uncertainties bias the mass ratios toward larger values, and that the true fraction of supercritical cores is smaller than derived here. Still, we stress that some cores with high virial mass ratios seem to be genuinely supercritical when excluding magnetic fields: uncertainties alone are, e.g., unlikely to lead to $R_{\text{vir}} > 18$ for the two most extreme cores. Such large mass ratios are not seen in low-mass star-forming regions.

Inspection suggests that the velocity dispersion of Orion cores does not exceed those of the cores in other regions studied by Kirk et al. (2007), André et al. (2007), and Foster et al. (2009). The higher values of $R_{\text{vir}}$ and $R_C$ of Orion cores are thus not due to different velocity field, but higher masses. Such higher masses are indeed found in this Orion sample. Kauffmann & Pillai (2010) suggest that Ophiuchus and Perseus dense cores have a size-dependent limit:

$$m_{\lim}(r) = 870 M_\odot (r/pc)^{3.33},$$  \hspace{1cm} (13)

above which high-mass star formation occurs. We find 12 cores (40%) above this threshold. Within the Gould Belt, Orion cores are unusually massive, which apparently results in unusually strong gravitational binding.

5. CONCLUSIONS

We have mapped OMC2 and OMC3 in NH$_3$ (1, 1) and (2, 2) with both VLA and GBT. The combined single dish plus interferometric data provide a rare detailed look into the thermal and dynamic properties of a collection of massive quiescent cores. Our main results are the following.

1. We obtain good temperature measurement for 30 dust cores. The median core temperature is 17K. The typical uncertainty for derived temperature of each pixel is about 2 K.

2. A total of 25 cores (83%) are gravitationally bound ($R_{\text{vir}} > 1$) with respect to their kinetic energy: 13 cores (43%) achieve $R_{\text{vir}} > 3$, and $R_{\text{vir}} \gtrsim 18$ is found for two cores. 14 cores have $R_C > 1$. In many cores, thermal and non-thermal gas motions alone cannot prevent collapse, even when including observational uncertainties. Strong magnetic fields >500 $\mu$G would be needed to render cores subcritical.

3. Compared to other clouds in the Gould Belt, Orion dense cores are unusually tightly bound (i.e., have large $R_{\text{vir}}$). This follows when compensating for differences in the observational strategy, and is thus to first order independent of observational uncertainties. The unusually strong binding in Orion appears to result from unusually high dense core masses for given size.

In summary, this sample of Orion cores appears to contain a substantial fraction of supercritical cores. They will evolve rapidly and either collapse or fragment soon.

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