The Physical and Chemical Status of Pre-protostellar Core B68

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ABSTRACT

We have investigated the physical and chemical status of the pre-protostellar core B68. A previous extinction study suggested that the density profile of B68 is remarkably consistent with a Bonnor-Ebert sphere with 2.1 $M_\odot$ at 16 K. We mapped B68 in C$_3$H$_2$, CCS, and NH$_3$ with the Deep Space Network (DSN) 70m telescope at Goldstone. Our results show that the NH$_3$ peak coincides with the dust continuum peak, whereas CCS and C$_3$H$_2$ are offset from the NH$_3$ and dust peaks. The B68 chemical structure is consistent with that seen in other such pre-protostellar cores (L1498, L1544) and is explained by time dependent chemical models that include depletion. We measured the kinetic temperature of B68 with NH$_3$ (1,1) and (2,2) spectra obtained with a DSN 34m telescope. We find that the kinetic temperature of B68 is only 11 K which is significantly lower than that previously assumed. We also derive the non-thermal linewidth in B68, and show that B68 is thermally dominated with little contribution from turbulence support ($<10\%$). We consider a modified Bonnor-Ebert sphere to include effects of turbulence and magnetic fields and use it to constrain the uncertainties in its distance determination. We conclude that the distance to B68 is $\sim 95$pc with a corresponding mass of $\sim 1.0 \ M_\odot$. If some magnetic field is present it can be further away (beyond $\sim 100$pc) and still satisfy the density structure of a Bonnor-Ebert sphere. The sulfur (CS and CCS) and carbon chain (C$_3$H$_2$) molecules are heavily depleted in B68 and do not trace the dense interior region. We see some evidence for depletion of NH$_3$ at the core center roughly on a scale similar to that of N$_2$H$^+$. Our observations do not preclude any instability such as the onset of collapse, or slow contraction, occurring in the center of the core, which cannot be resolved with our beam size ($45''$).

Subject headings: ISM: molecules – ISM: abundances – ISM: globules – ISM: individual (B68) – stars: formation
1. Introduction

What are the initial conditions that give rise to star formation? Understanding the physical and chemical structure of the cores at the pre-collapse stage (“pre-protostellar cores”) is critical for examining models for the core evolution and star formation. Several theoretical models have been proposed for pre-protostellar cores; recently one of these, the Bonnor-Ebert sphere, has been the subject of increased interest. A pre-protostellar core may be described as a hydrostatic isothermal pressure-confined, non-rotating, non-magnetized, self-gravitating sphere – a Bonnor-Ebert sphere (Bonnor 1956; Ebert 1955). If the center to edge density contrast of a Bonnor-Ebert sphere exceeds a critical value, this core is unstable and subject to collapse with small perturbation. The extreme case of such collapsing cores is a singular isothermal sphere with density \( n \propto r^{-2} \), which will collapse in a free-fall time scale (Shu 1977). Recent extinction study by Alves, Lada, & Lada (2001; hereafter ALL2001) suggested that the density profile of B68 is remarkably consistent with a Bonnor-Ebert sphere with 2.1 \( M_\odot \) at 16 K. As turbulence exists prevalently in giant molecular clouds, a Bonnor-Ebert sphere must be formed after turbulence has decayed; however, it is not well understood how this transition occurs and how long it takes for the decay of turbulence. It is, therefore, important to determine observationally the degree of turbulence present in B68. Furthermore, the presence of magnetic fields in some pre-protostellar cores have been detected through dust polarization (Ward-Thompson et al. 2000). If magnetic fields couple to the gas dynamics through the ionized gas component (ambipolar diffusion), magnetic fields could slow down the dynamical collapse of the cores (Ciolek & Mouschovias 1993). These models predict a different physical structure for the density, temperature, magnetic fields, and turbulence, which will determine the dynamics and evolutionary history of the core. Both turbulence and magnetic fields can provide additional support against gravity. Thus, for a given/observed center-to-edge density contrast, the presence of any turbulence and magnetic field can modify the size and hence the mass, for an equivalent Bonnor-Ebert sphere.

The density structure of pre-protostellar cores is obtained through three major approaches: (sub-)millimeter and infrared dust emission (e.g. Shirley et al. 2000; Willacy & Langer 2000), dust extinction from optical and infrared wavelengths (e.g. ALL2001), and molecular gas emission with tracers that do not readily deplete at high density such as NH\(_3\) and N\(_2\)H\(^+\) (e.g. Kuiper et al. 1996; Tafalla et al. 1998). However there are limitations to each of these probes of the core status. The dust is optically thin at submillimeter and far infrared wavelengths and thus can be well mapped. However, the interpretation of the dust emission is sensitive to both temperature and density. The dust extinction obtained with optical and infrared has very high spatial resolution; however, it requires background stars along each line of sight across the core and the derivation of density relies on the assumed gas-to-dust
ratio. Nevertheless when a grid of a large number of stars are observed, as demonstrated by ALL2001 for B68, it can provide a robust estimate of the core size and the relative density profile across the core. The molecular spectral line observations are important probes of core dynamics, which cannot be obtained with dust observations. However they too have limitations as density and dynamical probes because of depletion. Chemical models suggest that most molecules may deplete in the center of the cores as molecules accrete onto dust grains (Rawlings et al. 1992; Bergin & Langer 1997), making H$_2$ column density and mass determinations subject to the assumed depletion factor. NH$_3$ and N$_2$H$^+$ are among the very few molecules whose abundances remain high even when others, e.g., CO, CCS and CS, are heavily depleted.

Submillimeter and millimeter continuum maps of pre-protostellar cores have shown that the typical intensity profile of pre-protostellar cores is flat at the inner region and steepens toward the edge (Ward-Thompson et al. 1994; Ward-Thompson, Motte, & Andre 1999, Willacy & Langer 2000). If the temperature gradient in the cores is negligible, the intensity profile can be treated as a column density profile. Such profiles are consistent with the predicted signature of Bonnor-Ebert spheres (Ward-Thompson 2002), but they are also qualitatively consistent with the ambipolar diffusion model (Ciolek & Basu 2000).

B68 is an isolated quiescent Bok Globule near the Ophiucus complex. Its nearly spherical geometry makes it a good candidate for comparison between observations and theoretical models (which are primarily spherically symmetric). The importance of B68 is that it may be a core on the verge of collapse. ALL2001 derive the radial extinction profile of B68 from the optical and near infrared photometry of background stars, and the profile is remarkably consistent with a 16 K isothermal Bonnor-Ebert sphere with a mass of 2.1 M$_\odot$ (assuming a distance of 125 pc) which is slightly over the critical mass. Their result on the center-to-edge density contrast implies that B68 can adequately be supported by the thermal pressure without the support from turbulence and/or magnetic fields before the dynamical collapse takes place. As the best candidate of a Bonnor-Ebert sphere to date, B68 has attracted great attention recently. Langer & Willacy (2001) used the ISO 200 $\mu$m and 160 $\mu$m data and obtained a density profile that can be fitted by a series of power laws with exponents -1.2, -2, and -4, going from center to edge, which is similar to the density profile of other pre-protostellar cores. Recently the submillimeter dust continuum has been mapped at 450 and 850 $\mu$m with SCUBA (Visser, Richer, & Chandler 2002). However, to date, the extinction data of ALL2001 has the highest spatial resolution (3") and provides a robust density profile and estimate for its angular size.

Knowledge of the distance to the core (to estimate the size and mass) and temperature (to estimate the thermal pressure) are critical to characterize the true status of B68 as a
prestellar core. Hotzel et al. (2002) obtain T~8K from the excitation analysis of CO lines and suggest that the previous temperature measurement from Bourke et al. (1995) contains calibration or calculation errors. In a later paper, Hotzel, Harju, & Juvela (2002) also derived a kinetic temperature of 10±1.2 K from the less depleted NH$_3$. Here, we present spectral line maps of B68 in C$_3$H$_2$, CCS, and NH$_3$ to characterize its chemical status and to derive the temperature and turbulence in the core. Our results when combined with the density structure derived from extinction data (ALL2001) provide stringent constraints on the distance (and thus, linear size and mass) to the B68 core.

2. Observations

We made single-dish maps of B68 in C$_3$H$_2$, CCS, and NH$_3$ lines between January and July 2002 using NASA’s Deep Space Network (DSN) 70 m antenna at Goldstone. We mapped B68 over ~4′×4′ region with Nyquist sampling every 25″ around the nominal center position from Benson & Myers (1989) at R.A.(1950)=17$^h$19$^m$36$^s$, Dec.(1950)=−23°47′13″. The maps were made with a K-band HEMT receiver tunable between 18–26 GHz. The spectra of these lines were taken with the two-million-channel Wide Band Spectral Analyzer (WBSA; Quirk et al. 1988). We co-added 256 adjacent channels in real time to produce a 8192 point spectrum with 5 kHz spectral resolution and high signal-to-noise ratio. We also used a DSN 34m antenna and the WBSA to obtain the spectra of NH$_3$ (1,1) and (2,2) lines simultaneously in order to derive the kinetic temperature of B68. The spectrum were taken at (0′25, 0′25) offset from the nominal center of B68 so that the 34 m beam includes most of the NH$_3$ emission. A CCS $J_N = 2_1 \rightarrow 1_0$ spectrum was also obtained with the DSN 34m at (0′25, 0′25) to determine the non-thermal linewidth. In Table 1 we list the observed transitions and their spatial and spectral resolutions.

3. Results

3.1. Chemical Differentiation

Figure 1 shows our DSN 70m maps of C$_3$H$_2$, NH$_3$, and CCS. The NH$_3$ map shows a centrally peaked distribution with the maximum close to the nominal center. By contrast, C$_3$H$_2$ and CCS both have their strongest peaks to the northeast of the NH$_3$ peak and their intensity decreases towards the southwest of the NH$_3$ peak. The C$_3$H$_2$ map shows a low level emission along the southwest edge. CCS has another strong peak at the southeast extension of B68. The JCMT dust continuum maps of B68 at 850μm (Visser, Richer, & Chandler 2002)
and CS emission (Lada et al. 2003) also show a distinct peak at the southeast extension, indicating this extension could be a separate core.

In Figure 2 we show an overlay of the NH$_3$ map with the N$_2$H$^+$ map obtained at the IRAM 30m telescope (Bergin et al. 2002) and the 200 $\mu$m dust emission obtained with ISO (Langer & Willacy 2001). We found that the NH$_3$ peak coincides with the dust continuum peak and is located between the two N$_2$H$^+$ peaks in the IRAM map. This result is consistent with the expectation of the chemical models that NH$_3$ and N$_2$H$^+$ are relatively more abundant in high density regions than other molecules. The double peak of N$_2$H$^+$ has been interpreted to indicate that even N$_2$H$^+$ depletes in the region with $A_v > 25$mag. A similar depletion of NH$_3$ could take place in the center of B68, but is not spatially resolved with our observations.

### 3.2. Kinetic Temperature

At low temperatures, where collisional excitation dominates, the rotation temperature of NH$_3$ can be estimated from the intensity ratio of the (1,1) and (2,2) lines $T_{22}/T_{11}$ and the optical depth of the (1,1) main line $\tau_{11}$ (Ho & Townes 1983):

$$T_r = -41.5/\ln \left(\frac{-0.282}{\tau_{11}} \ln \left(1 - \frac{T_{22}}{T_{11}} \times (1 - e^{-\tau_{11}})\right)\right)$$  \hspace{1cm} (1)

We fitted our 34m NH$_3$ (1,1) and (2,2) hyperfine lines using the Continuum and Line Analysis Simple Software (CLASS), and obtained $T_{22}/T_{11} = 0.20 \pm 0.04$K and $\tau_{11} = 2.5 \pm 0.2$. From Eq(1), we derived $T_r = 10.9 \pm 0.8$K (Lai et al. 2002). Figure 4 show how the uncertainty in the estimate of $T_r$ varies with $T_{22}/T_{11}$ and $\tau_{11}$. The rotation temperature slightly underestimates the kinetic temperature $T_k$ in dark clouds (Walmsley & Ungerechts 1983), but it approaches the kinetic temperature when $T_k \rightarrow 10$K. We adopt $T_k = 11$K in further calculations. Independently, Hotzel, Harju, & Juvela (2002) also measured a kinetic temperature of 10±1.2K in B68 from NH$_3$ observations using the Effelsberg 100m telescope.

### 3.3. Non-thermal linewidth

The non-thermal linewidth (FWHM), $\Delta v_{nth}$, can be estimated from $\Delta v_{obs}^2 = \Delta v_{th}^2 + \Delta v_{nth}^2$. The observed linewidth $\Delta v_{obs}$ can be obtained from the spectral line data. The thermal linewidth $\Delta v_{th} = \sqrt{(8 \ln 2)kT_k/\mu m_H}$ ($\mu$ is the atomic weight and $m_H$ is the mass of a hydrogen atom) can be calculated with the kinetic temperature determined in §3.2. We derived $\Delta v_{nth}$ from NH$_3$ and CCS separately. The multiple line fitting of NH$_3$ gives a reliable
determination of the observed linewidth. The CCS molecule has a large atomic weight, and hence a narrower thermal linewidth. We derived for both NH$_3$ and CCS $\Delta v_{nth} \sim 0.14\text{ km s}^{-1}$ (Table 2). These values are consistent with that observed from C$^{18}$O line widths ($\Delta v_{nth} \sim 0.18\text{ km s}^{-1}$) by Lada et al. (2003). The $\Delta v_{nth}$, interpreted as that due to turbulence, is small – of the order of $0.3 \times \Delta v_{th}(\text{H}_2)$.

3.4. Column Density

We calculate the column density of NH$_3$, CCS, and C$_3$H$_2$ under the assumption of LTE at two positions, one at the NH$_3$ peak and one at the CCS peak, in order to compare our results to the chemical evolution models. The derived column densities are listed in Table 3.

The NH$_3$(1,1) hyperfine lines allow us to obtain the antenna temperature $T_A$ and the optical depth $\tau$ directly; therefore, we can derive the excitation temperature $T_{ex}$ of NH$_3$ from the radiative transfer equation

$$T_B = T_A/\eta = (T_{ex} - T_{bg})(1 - e^{-\tau}),$$

(2)

where $T_B$ is the brightness temperature, $T_{bg} = 2.7K$ is the cosmic background temperature, and $\eta \sim 0.7$ is the main beam efficiency of the DSN 70 m antenna. The column density of NH$_3$ can be estimated with the knowledge of the excitation temperature $T_{ex}$, the line width $\Delta v$ and the main group opacity of the (1,1) line $\tau_{11}$ by the usual assumption that only metastable levels are populated (Harju, Walmsley, & Wouterloot 1993), therefore

$$N(\text{NH}_3) = 1.6 \times 10^{13} \Delta v \tau_{11} \frac{\exp(h\nu/kT_{ex}) + 1}{\exp(h\nu/kT_{ex}) - 1} \left( \frac{1}{3} e^{23.4/T_r} + \frac{5}{3} e^{-41.5/T_r} + \frac{14}{3} e^{-101.5/T_r} + \ldots \right) \text{ cm}^{-2}$$

(3)

where $T_r$ is the rotation temperature derived in §3.2. We assume $T_r$ is constant across the core.

The column density of CCS can be derived from

$$N(\text{CCS}) = 5.1 \times 10^{11} \tau \Delta v U \frac{\exp(E_u/kT_{ex})}{\exp(h\nu/kT_{ex} - 1)} \text{ cm}^{-2}$$

(4)

where $E_u$ is the energy level of the upper state and $U$ is the partition function (Suzuki et al. 1992). The excitation temperature of CCS is unknown, because we only have one transition. Wolkovitch et al. (1997) has done excitation analysis with three CCS transitions for L1498 and TMC-1D, and the kinetic temperature for these two cores is 7–10K. Suzuki et al. (1992) derive an excitation temperature of 5 K for a number of quiescent dark cores. Therefore,
we assume $T_{ex} \sim 5 - 10$ K and the partition function $U$ is 24-62 for the lowest 76 rotational transitions.

For $C_3H_2$ we use the approach of Bell et al. (1988),

$$N(C_3H_2) = 1.98 \times 10^{-20} \frac{\tau \nu^2 \Delta \nu Q \exp(E_J/kT_{ex})}{A_{J'J} g_{J'J} [1 - \exp(-h\nu/kT_{ex})]} \text{ cm}^{-2}$$  \hspace{1cm} (5)

where $\nu$ is the frequency of the line in Hz, $\Delta \nu$ is the FWHM in Hz, $E_J = 2.352K$ is the energy of lower level, and the Einstein constant $A_{J'J} = 4.02 \times 10^{-7}$ s$^{-1}$. The partition function Q is calculated from $Q = (5.34/\sigma) \times (T_{ex}^3/ABC)^{1/2}$, where $A=35.092596$ GHz, $B=32.212931$ GHz, $C=16.749315$ GHz, and $\sigma = 2$ for $C_3H_2$ (Thaddeus, Vrtilek, & Gottlieb 1985). We also assume the excitation temperature is in the range of 5–10K.

4. Discussion

4.1. Modified Bonnor-Ebert Sphere

A Bonnor-Ebert sphere is a hydrostatic self-gravitating isothermal core solely supported by its thermal pressure. The density profile of a Bonnor-Ebert sphere is characterized by only one parameter, the dimensionless radius parameter $\xi_{max}$,

$$\xi_{max} = (R/a)\sqrt{\frac{4\pi G \rho_c}{}}$$  \hspace{1cm} (6)

where R is the core radius, $\rho_c = mn_c$ is the central density, $a = \sqrt{kT/m}$ is the isothermal sound speed, and $m$ is the mean molecular weight. ALL2001 demonstrate that the density profile of B68 inferred from extinction is remarkably consistent with that of a Bonnor-Ebert sphere with $\xi_{max} = 6.9$. However the results of our observations show that (1) B68 is colder than what ALL2001 assumed ($T_k = 11$K rather than 16K), and (2) thermal support dominates over turbulence, but that turbulent energy is present. The lower temperature will only affect the scaling of the density profile, but not the interpretation of the nature of B68 as a Bonner-Ebert sphere. We discuss how our observations constrain the parameters in $\xi_{max}$, and hence the distance and the mass of B68. We also consider an empirically modified Bonnor-Ebert sphere that includes turbulent and magnetic support.

The density profile of the Bonnor-Ebert sphere can be used to constrain the distance and the mass of B68 with a temperature measurement. The distance to B68 itself is not well determined. B68 is spatially close to the Ophiuchus complex, and the distance to the Ophiuchus complex is between 80 and 170 pc with a central value of 125 pc (de Geus et al. 1989). ALL2001 have adopted 125pc in their modeling. Hotzel et al. (2002) have presented
detailed discussion on the physical quantities of a Bonnor-Ebert sphere and have derived a mass of 0.7 \( M_\odot \) and a distance of 80pc using \( T_k = 8 \) K from CO observations. Here we shorten the derivation of Hotzel et al. (2002) and directly calculate the distance and the mass of B68, using dimensional analysis of the three observed quantities from the extinction data which are invariant to temperature \( T \) and distance \( D \): the dimensionless radius parameter \( \xi_{\text{max}} \), the angular diameter \( \theta \), and the the central column density \( N_c \). We can express

\[
\frac{\xi_{\text{max}}}{\theta} = m \ D \sqrt{\frac{4\pi G n_c}{k T}}. \tag{7}
\]

Because \( \xi_{\text{max}} \) and \( \theta \) are fixed by observations, from Eq(7) the number density at the center \( n_c \propto D^{-2} T \). Furthermore, \( n_c \) is also related to the column density \( N_c = \int n \ ds = K n_c D \theta \), where \( K \) is a constant which depends only on the shape of the density profile characterized by \( \xi_{\text{max}} \). Because the central column density \( N_c \) is fixed by observation,

\[
n_c = \frac{N_c}{K D \theta} \propto D^{-1}. \tag{8}
\]

Since \( n_c \propto D^{-2} T \) and also \( \propto D^{-1} \), we find \( D^{-1} T \) is a constant. Therefore, the temperature measurement can be used to constrain the distance. ALL2001 assumed \( D=125 \)pc and \( T=16 \) K, to derive a model consistent with \( \xi_{\text{max}} = 6.9 \) and \( M = 2.1 \ M_\odot \). With our measured temperature of 11 K, B68 would have to be at a closer distance \( \sim 85 \) pc with a mass of \( \sim 1.0 \ M_\odot \) for the same \( \xi_{\text{max}} \). This would place B68 on the near side of the Ophiuchus complex.

The isothermal Bonnor-Ebert sphere is supported purely by thermal pressure and does not include effects of turbulence or magnetic fields. Turbulence and magnetic fields have been observed in some pre-protostellar cores and therefore they may provide significant support to the core stability. We present an empirical modification to the Bonnor-Ebert sphere that includes the turbulence and magnetic field support while preserving a Bonnor-Ebert sphere-like density profile consistent with the observed \( \xi_{\text{max}} \). Though empirical, such a representation is useful for a qualitative study of the core properties.

The observed turbulence in B68 (reported in this paper) provides additional support to the core. We can incorporate the turbulent support by replacing the temperature in Eq(7) with an effective temperature \( T_{\text{eff}} \) that includes both thermal and the turbulent pressures: \( T_{\text{eff}} = T_k + T_{\text{turb}} \), where \( T_{\text{turb}} \) is obtained from the turbulence velocity width, \( \Delta v_{\text{nth}}^2 = (8 \ln 2) k T_{\text{turb}} / m \). We can now modify Eq(7) as

\[
\frac{\xi_{\text{max}}}{\theta} = m \ D \sqrt{\frac{4\pi G n_c}{k T_k + \frac{m \Delta v_{\text{nth}}^2}{8 \ln 2}}}. \tag{9}
\]

We use Eqs(8) & (9) and the observed \( T_k \) and \( \Delta v_{\text{nth}}^2 \) to constrain the distance of B68 to be 85–100pc, as shown in Figure 5a.
Eq(9) can be modified further to include a magnetic pressure term. However, in order to preserve the Bonner-Ebert-like density profile, this modification is possible only in cases where the magnetic pressure also varies radially as the thermal pressure. That is, magnetic pressure \( P(r) \sim n(r) \). Coincidentally, theoretical models of an axially symmetric isothermal core with magnetic flux freezing give \( B \sim n^{1/2} \) (Fiedler & Mouschovias 1993), therefore magnetic pressure \( B^2/8 \pi \sim n \). Zeeman observations in molecular clouds also support such a scaling law (Crutcher 1999). Therefore, we can rewrite Eq(9) to include magnetic field support with \( T_{\text{eff}} = T_k + T_{\text{turb}} + T_{\text{mag}} \), where \( T_{\text{mag}} \) is the equivalent temperature corresponding to the magnetic pressure, \( B^2 \). For simplicity, we express \( T_{\text{mag}} \) in terms of magnetic pressure using the average magnetic field \( \bar{B} \) and the average density \( \bar{n} \). We obtain the following relation between \( \xi_{\text{max}} \) and the kinetic temperature \( T \), distance \( D \), central density \( n_c \), turbulent velocity width \( v_{\text{nth}} \), and magnetic field strength \( B \).

\[
\frac{\xi_{\text{max}}}{\theta} = m D \sqrt{\frac{4 \pi G n_c}{kT + \frac{m \Delta v_{\text{nth}}^2}{8 \ln 2} + \frac{B^2}{12 \pi \bar{n}}}}.
\] (10)

Though Eq(10) is valid only under certain conditions (when \( B \) scales as \( n^{1/2} \)) it is useful to show the dependence of the observed parameters on the physical conditions in the core. We use Eq(10) to constrain the linear size (or its distance) for B68 as a function of kinetic temperature, turbulence, and magnetic field strengths as shown in Figure 5. For any given choice of turbulence with no magnetic fields, the distance and temperature along the lines shown in Figure 5a represent stable cores that can be described with Bonner-Ebert density profiles, while those above and below represent supercritical and subcritical cores respectively. The shaded area in Figure 5a marks the best estimate for distance consistent with our measurements of temperature and turbulence when magnetic support is ignored. Figure 5b shows the distance, for which B68 will be static, as a function of increasing magnetic field derived using Eqs(10) & (8). (The temperature and turbulence widths are fixed at the observed value of 11K and \( \Delta v_{\text{nth}} = 0.3 \Delta v_{\text{th}} \).) Because \( n_c \) and \( \bar{n} \) are both proportional to \( D^{-1} \), as long as \( \xi_{\text{max}} \) and \( N_c \) are fixed, the distance can be derived for any given \( \bar{B} \). Figure 5b indicates that if B68 is at distances beyond \( \sim 100 \) pc, then it can remain a stable core only if magnetic fields are present. However, under the flux freezing condition, the magnetic field should be responsible for the excitation of the non-thermal linewidths. The observed 0.14 km s\(^{-1} \) non-thermal linewidths only gives \( B \sim 5 - 10 \mu \) G for density of \( 1 - 3 \times 10^4 \) cm\(^{-3} \).

We conclude that the Bonner-Ebert-like density profile does not necessarily rule out the existence of the turbulence and magnetic fields, although their contributions are small in the case of B68. The fact that B68 is dominated largely by thermal support suggests that the turbulence and the magnetic flux have been dissipated and the core could be on
the verge of the collapse. The observed $\xi_{\text{max}} = 6.9$ is slightly larger than the critical value $6.5$, which means the core is static but unstable, thus the gravitational collapse could occur with small perturbation. Therefore, it is possible that B68 is slightly supercritical and could be undergoing slow contraction. The most well-known collapsing core L1544 has similar size and mass to B68 and its collapse velocity is $\gtrsim 0.1$ km s$^{-1}$ (Lai & Crutcher 2000). If B68 collapses with a velocity of the same order of magnitude, the collapse motion should have been detected with our spectral resolution ($\sim 0.06$ km s$^{-1}$). However, if B68 has just initiated collapse, which in the standard Shu inside-out scenario originates in the center, we may not be able to spatially resolve the collapse with the beam size in our maps. With the spatial resolution of the IRAM 30m observations Lada et al. (2003) have suggested that the outer layers of the B68 core have small amplitude non-radial oscillations or pulsations about an equilibrium configuration. Higher spatial and spectral resolutions line observations will be needed to determine if B68 has initiated collapse deep in the center.

### 4.2. Depletion and Chemical Differentiation in B68

The observed depletion of molecular species in dense cold cloud cores is broadly consistent with time dependent chemical modeling (c.f. Bergin and Langer 1997). The well defined density structure (Bonnor Ebert sphere) of B68 makes it a unique core to study the chemical structure and evolution of dense starless cores. Bergin et al (2002) have found two orders of magnitude decrease in the C$^{18}$O abundance across the core, from low ($A_v < 2$mag) to high ($A_v > 20$mag) density regions. Even N$_2$H$^+$, which is believed to be a non-depleting molecular probe shows a decrease in abundance by factor of 2 between the low density ($A_v < 3$mag) and high density ($A_v > 20$mag) regions. Di Francesco et al. (2002) found that all the molecules (CO, CS, HCO$^+$, H$_2$CO, C$_3$H$_2$, N$_2$H$^+$, NH$_3$) have lower abundances in B68 than in other cloud cores. However, only a few molecules have been mapped in detail, CO, CS, and N$_2$H$^+$ (Bergin et al. 2002; Hotzel et al. 2002; Lada et al. 2003). Our data include fully sampled spectral line intensity maps of three additional species NH$_3$, C$_3$H$_2$ and CCS. While NH$_3$ emission shows an enhancement near the extinction peak, CCS and C$_3$H$_2$ emissions show emission peaks away from the center with distinctly low emission at the extinction peak. As seen in Figure 1, the CCS and C$_3$H$_2$ emission peaks appear well outside the brightest N$_2$H$^+$ and NH$_3$ emission. The CCS and C$_3$H$_2$ emissions seem to trace only the outer low density regions of the core. Our results suggest that CCS and C$_3$H$_2$ are severely depleted at the core center. Both species show a strong asymmetry about the center roughly along the northeast to southwest direction. The CS emission (Lada et al. 2003) also shows somewhat similar asymmetry, and the intensity map of CCS emission is broadly consistent with that of CS. The strong CCS emission to the southeast of the core is coincident with
the strongest CS emission. The relative intensities of their emissions at the extinction peak suggest that CCS is more severely depleted than CS. Such difference between CCS and CS is consistent with the predictions of the depletion models of Bergin and Langer (1997) that CCS depletion occurs before CS. We conclude that CCS, CS and C\textsubscript{3}H\textsubscript{2} do not trace the core center. But they trace the chemistry in the outer layers of B68. The chemical gradients traced by these molecules may be the result of the local conditions such as the UV penetration. Indeed the extinction map (ALL2001) shows a sharper boundary to the the east and northeast, coincident with the strongest CCS emission. Lada et al. (2003) have suggested that B68 might have undergone interaction with the Loop I supernova bubble. Interestingly the center of this bubble is located to the southwest of B68. It is not unlikely that some of the asymmetries in the chemical structure as traced by CCS and C\textsubscript{3}H\textsubscript{2} resulted from such an interaction.

The NH\textsubscript{3} emission is resolved and not strongly centrally peaked as would be expected for the density structure of B68 core. This suggests that NH\textsubscript{3} too is somewhat depleted in the center. In Table 3 we compare the column densities for NH\textsubscript{3}, CCS and C\textsubscript{3}H\textsubscript{2} at two positions: at the NH\textsubscript{3} peak and the CCS peak. The column densities for CCS and C\textsubscript{3}H\textsubscript{2} have uncertainties of order 2–3 due to assumed T\textsubscript{ex}. Nevertheless the column densities in Table 3 show, roughly, that NH\textsubscript{3} has a shallower depletion (by about factor 2) than CCS and C\textsubscript{3}H\textsubscript{2} (> factor 3). The large beam size of the maps does not resolve fully the emissions at the two positions (CCS and NH\textsubscript{3} peaks) and therefore, the CCS and C\textsubscript{3}H\textsubscript{2} column densities at the NH\textsubscript{3} peak are rough upper limits. Furthermore, the excitation analysis for NH\textsubscript{3} is more reliable than for the others. (Using the hyperfine lines of NH\textsubscript{3} provides a good estimate of the optical depth). The NH\textsubscript{3} results are consistent with depletion on an angular scale and magnitude similar to that of N\textsubscript{2}H\textsuperscript{+}, as suggested by Bergin et al. (2002).

Since CCS is an early time molecule and NH\textsubscript{3} is abundant at a later stage, the column density ratio of CCS and NH\textsubscript{3} has been suggested as a possible indicator for cloud evolutionary time (Suzuki et al. 1992; Bergin & Langer 1997). As the evolutionary status of B68 has been established to be a likely pre-protostellar core on the verge of collapse, in Table 4 we compare its N(CCS)/N(NH\textsubscript{3}) to two other well-studied pre-protostellar cores, L1498 and L1544. A comparison of the column densities and core sizes indicates that B68 has the lowest CCS and NH\textsubscript{3} abundances, in agreement with the general conclusion of Di Francesco et al. (2002) that in B68 the molecular abundances are lower than those in dense clouds. Among these three cores, L1544 is the most evolved core, because the collapse motion has been directly observed (Tafalla et al. 1998; Lai & Crutcher 2000). L1498 could be younger than B68, because CCS is more widely distributed in L1498 than in B68. From the values of N(CCS)/N(NH\textsubscript{3}) listed in Table 3, B68 appears to be in an intermediate stage between L1498 and L1544 in core evolution.
5. Conclusion

B68 has been suggested to be a pre-protostellar core that can be described as a Bonnor-Ebert sphere at 16 K. Our DSN 70m maps show that B68 resembles the chemically differentiated structure seen in other pre-protostellar cores; the NH$_3$ peak coincides with the dust continuum peak, whereas CCS and C$_3$H$_2$ are offset from the NH$_3$ peak. We derive a kinetic temperature $\sim 11$ K in B68 from NH$_3$ (1,1) and (2,2) observations and turbulence of $\Delta v_{nth} = 0.3\Delta v_{th}$. Here we derive an empirical formulation for a modified Bonnor-Ebert sphere that includes turbulent, and magnetic pressures, and allows us to constrain the distance to B68 using the observed kinetic temperature and turbulence. We estimate the distance to B68 to be $\sim 95$ pc, on the near side of $\rho$ Oph, with a corresponding core mass of $\sim 1.0$ $M_\odot$. The sulfur species CCS and carbon chain molecule C$_3$H$_2$ are heavily depleted in B68 and do not trace the dense interior region. We show some evidence for depletion of NH$_3$ at the core center roughly on a scale similar to that of N$_2$H$^+$.

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REFERENCES


[40] Ebert, R. 1955, Zeitschrift Astrophysics, 37, 217


AAS TeX macros v5.0.
Fig. 1.— DSN 70 m maps of C$_3$H$_2$, NH$_3$, and CCS in B68 overlaid on the Palomar Optical Sky Survey image. The contours are 10, 30, 50, 70, and 90% of the peak integrated antenna temperature, which are 0.23, 0.25, and 0.084 K km s$^{-1}$ for C$_3$H$_2$, NH$_3$, and CCS, respectively. The (0,0) position corresponds to R.A.(1950)=17$^h$19$^m$36$^s$, Dec.(1950)=−23°47′13″. The plus symbol indicates the extinction peak.

Fig. 2.— Comparison of DSN 70m NH$_3$ map with IRAM 30m N$_2$H$^+$ map (Left; Bergin et al. 2002) and 200μm dust emission (Right; Langer & Willacy 2001).
Fig. 3.— DSN 34m NH$_3$ (1,1) and (2,2) spectra of B68.

Fig. 4.— Determination of the rotational Temperature, $T_r$. 
Fig. 5.— (a) Distance (Left axis) constrained by temperature for magnetic field $B=0$ (see Eqs. 8 & 10 in the text). The turbulence levels are indicated. The broken lines correspond to the uncertainty ($1\sigma$) in the observed temperature and turbulence. The shaded area represents the best estimates for the distance. The corresponding linear size is given on the right axis.

(b) Distance constrained by magnetic fields. Here we use the observed core temperature ($11\text{K}$) and turbulence $\Delta v_{nth} = 0.3 \Delta v_{th}$.
Table 1: Observations and Resolutions

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Transition</th>
<th>Frequency (MHz)</th>
<th>Antenna</th>
<th>HPBW (arcsec)</th>
<th>Velocity Resolution (km s$^{-1}$)</th>
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<tbody>
<tr>
<td>C$_3$H$_2$</td>
<td>$J_{K-}K_+ = 1_{0,0} \rightarrow 1_{0,1}$</td>
<td>18343.145</td>
<td>DSN 70 m</td>
<td>45</td>
<td>0.080</td>
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<td>CCS</td>
<td>$J_N = 2_1 \rightarrow 1_0$</td>
<td>22344.033</td>
<td>DSN 70 m</td>
<td>45</td>
<td>0.066</td>
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<tr>
<td>CCS</td>
<td>$J_N = 2_1 \rightarrow 1_0$</td>
<td>22344.033</td>
<td>DSN 34 m</td>
<td>90</td>
<td>0.066</td>
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<tr>
<td>NH$_3$</td>
<td>$J, K = 1, 1$</td>
<td>23694.495</td>
<td>DSN 70 m</td>
<td>45</td>
<td>0.062</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>$J, K = 1, 1$</td>
<td>23694.495</td>
<td>DSN 34 m</td>
<td>90</td>
<td>0.062</td>
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<tr>
<td>NH$_3$</td>
<td>$J, K = 2, 2$</td>
<td>23722.633</td>
<td>DSN 34 m</td>
<td>90</td>
<td>0.062</td>
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Table 2: Linewidths of NH$_3$ and CCS

<table>
<thead>
<tr>
<th></th>
<th>NH$_3$(1,1)</th>
<th>CCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{LSR}$ (km s$^{-1}$)</td>
<td>3.35±0.01</td>
<td>3.36±0.02</td>
</tr>
<tr>
<td>$\Delta v_{obs}$ (km s$^{-1}$)</td>
<td>0.22±0.01</td>
<td>0.17±0.03</td>
</tr>
<tr>
<td>$\Delta v_{th}$ (11K)</td>
<td>0.17</td>
<td>0.094</td>
</tr>
<tr>
<td>$\Delta v_{nth}$</td>
<td>0.14±0.01</td>
<td>0.14±0.03</td>
</tr>
</tbody>
</table>

Table 3: Column densities at two positions

<table>
<thead>
<tr>
<th>Position</th>
<th>$N$(NH$_3$) ($10^{14}$ cm$^{-2}$)</th>
<th>$N$(CCS)$^a$ ($10^{12}$ cm$^{-2}$)</th>
<th>$N$(C$_3$H$_2$)$^a$ ($10^{12}$ cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH$_3$ peak (0',0')</td>
<td>1.9</td>
<td>1–1.5</td>
<td>0.8–3.3</td>
</tr>
<tr>
<td>CCS peak (0'.28,0'.7)</td>
<td>3.1</td>
<td>2.1–5.5</td>
<td>2.4–10</td>
</tr>
</tbody>
</table>

$^a$ - the lower and upper limits of the column density for CCS and C$_3$H$_2$ are correspond to the assumed $T_{ex} = 5$ and 10 K, respectively. For NH$_3$, $T_{ex}$ derived from the spectral line data were used.
Table 4: Comparison of L1498, B68, and L154

<table>
<thead>
<tr>
<th></th>
<th>L1498</th>
<th>B68</th>
<th>L1544</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N(\text{CCS}) , (10^{12} \text{ cm}^{-2})$</td>
<td>$6.5^{(1)}$</td>
<td>$1$–$1.5$</td>
<td>$1$–$4^{(3)}$</td>
</tr>
<tr>
<td>$N(\text{NH}_3) , (10^{14} \text{ cm}^{-2})$</td>
<td>$8^{(2)}$</td>
<td>$2$</td>
<td>$10^{(2)}$</td>
</tr>
<tr>
<td>$\frac{N(\text{CCS})}{N(\text{NH}_3)}$</td>
<td>$0.008$</td>
<td>$0.005$–$0.0075$</td>
<td>$0.001$–$0.004$</td>
</tr>
<tr>
<td>Size (pc)</td>
<td>$0.07 \times 0.16$</td>
<td>$0.12$</td>
<td>$0.06 \times 0.12$</td>
</tr>
<tr>
<td>$T_k$ (K)</td>
<td>$7$–$10^{(1)}$</td>
<td>$11$</td>
<td>$10^{(2)}$</td>
</tr>
<tr>
<td>$\Delta v_{nth}$ (km s$^{-1}$)</td>
<td>$0.18$–$0.21^{(4)}$</td>
<td>$0.14$</td>
<td>$0.25^{(2)}$</td>
</tr>
<tr>
<td>$E_{nth}$ $E_{nth}$</td>
<td>$0.12$–$0.13$</td>
<td>$0.09$</td>
<td>$0.32$</td>
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</table>