CB 17: INFERRING THE DYNAMICAL HISTORY OF A PRESTELLAR CORE WITH CHEMODYNAMICAL MODELS

YA. PAVLYUCHENKOV
Max Planck Institute for Astronomy (MPIA), Königstuhl 17, D-69117 Heidelberg, Germany; payyar@mpia.de

D. WIEBE
Institute of Astronomy of the Russian Academy of Sciences (INASAN), 48 Pyatnitskaya Street, 119017 Moscow, Russia; dwiebe@inasan.ru

AND

R. LAUNHARDT AND TH. HENNING
Max Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany; rlau@mpia.de, henning@mpia.de

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ABSTRACT

We present a detailed theoretical study of the isolated Bok globule CB 17 (L1389) based on spectral maps of CS, HCO\(^+\), C\(^{18}\)O, C\(^{34}\)S, and H\(^{13}\)CO\(^+\) lines. The intensity of the external UV field, the probability for molecules to stick onto dust grains, the core age, the infall, and rotation velocity all significantly affect the molecular line spectra. We demonstrate that these parameters are well constrained when results of the modeling are compared to observations in multiple lines of sight through the core. We use a detailed chemical model to compute the time-dependent abundances in a number of locations within the core. Both static and dynamically evolving cloud configurations are considered. These abundances are then used to simulate the spectral maps. We developed a general criterion that allows us to quantify the difference between observed and simulated spectral maps. By minimizing this difference, we isolate the model that represents a good approximation to the core chemical and kinematic structure. The chemical age of the core is about 2 Myr, while the most probable effective sticking probability value is 0.3–0.5. The spatial distribution of intensities and self-absorption features of optically thick lines is indicative of attenuated UV radiation of the core. The line asymmetry pattern in CB 17 is reproduced by a combination of infall, rotation, and turbulent motions with velocities of \(\sim0.05\), \(\sim0.1\), and \(\sim0.1\) km s\(^{-1}\), respectively. These parameters correspond to energy ratios \(E_{\text{rot}}/E_{\text{grav}} \approx 0.03\), \(E_{\text{turb}}/E_{\text{grav}} \approx 0.8\), and \(E_{\text{grav}}/E_{\text{grav}} \approx 0.05\) (the rotation parameters are determined for \(i = 90^\circ\)). Based on the angular momentum value, we argue that the core is going to fragment, i.e., to form a binary (multiple) system.

Subject headings: astrochemistry — ISM: individual (CB 17) — ISM: molecules — line: profiles — stars: formation

1. INTRODUCTION

Of all the diverse steps of the star formation process, the prestellar stage is supposed to be the most quiescent phase. Starless cores are nearly isothermal, have more or less regular shapes, and lack prominent kinematic features such as disks and outflows. Among those cores, Bok globules are especially attractive for studies, as they are relatively isolated from a confusing surrounding material and thus represent “clean” examples of the prestellar chemical and dynamical evolution. Numerous embedded and isolated starless cores have been subjects of chemical and kinematic studies during recent years. As we generally want to know if these cores are going to become stars eventually or, in other words, if they are not only starless but really prestellar, these studies are mainly directed toward the search for infall signatures. A commonly used collapse indicator is the characteristic blue-red line asymmetry of optically thick lines (Evans 1999). Usually, the central spectrum of a core is used to demonstrate that this asymmetry is present.

However, if one wants to investigate the kinematics in more detail, it is necessary to observe and to analyze spectra at locations offset from the center of a core. One-dimensional spectral cuts or two-dimensional spectral maps are employed in various ways. Spectral maps for several molecules have allowed Tafalla et al. (1998) to detect an extended infall in the now famous L1544 prestellar core. This study was followed by Williams et al. (1999), who used N\(_2\)H\(^+\) spectral maps to investigate the infall in the very center of the core. Mapping surveys for infall motions in a number of starless cores have been carried out by Gregersen & Evans (2000) in lines of HCO\(^+\) and by Lee et al. (2001) in lines of CS, CO, and N\(_2\)H\(^+\).

Another goal of investigating spectral maps is the study of rotation of starless cores, in which both red and blue asymmetric line profiles are present; e.g., Kane & Clemens (1997) have studied the rotation in 15 starless Bok globules based on CO maps, while Pavlyuchenkov & Shustov (2004) have used HCO\(^+\) spectral maps, obtained by Gregersen & Evans (2000), to determine the average rotation speed (as well as the shape and the infall speed) for the L1544 core. Pavlyuchenkov & Shustov (2004) assumed that the core collapses from the initial rigid rotation state so that its total angular momentum remains constant. The spatial separation of red and blue asymmetric HCO\(^+\) line profiles in the maps of the L1689B prestellar core has been reproduced with a three-dimensional molecular line radiation transfer model by Redman et al. (2004). They showed that the asymmetry in this core can be explained under the assumption of solid-body rotation in the core center. At a later evolutionary stage, the rotation and infall profiles for the very young protostar IRAM 04191 have been determined by Belloche et al. (2002) from CS spectral maps.

A more comprehensive analysis of spectral maps is also possible. Lada et al. (2003) interpreted the alternating asymmetry pattern in CS spectral lines observed in B68 as a signature of simultaneous inward and outward motions having both radial and nonradial modes. Tafalla et al. (2004) performed a similar
study of the L1498 and 1517B prestellar cores. Using $^{15}$N$_2$H$^+$ and NH$_3$ spectral maps they investigated velocity gradients across the core faces and found them indicative of a velocity pattern more complicated than just infall or rotation. They suggested that this pattern is associated with asymmetric gas motions resulting from residual core collapse. These results indicate clearly that, given the overall quest for infall in starless cores, great care must be taken to avoid confusion between infall and other bulk motions. They also stressed that detailed kinematic information on starless cores is necessary to draw any conclusion about their dynamical and evolutionary state.

The spectral maps are not the only ingredient needed for an analysis of the starless core kinematics. To serve this purpose they have to be complemented by some knowledge of the core chemical composition. The uniform abundances of tracer molecules over the core are now confidently rejected on both observational (e.g., Tafalla et al. 2002) and theoretical (Rawlings & Yates 2001) grounds. It is now customary to reproduce observations with some simplified representation of a radial abundance profile (e.g., a step function). However, Lee et al. (2005) showed that simple empirical distributions may not be good indicators of the real chemical structure in collapsing cores. But if they would be, these simple distributions do not contain information about the dynamical and chemical history of the core. Rawlings & Yates (2001) argued that only multiple line-of-sight observations coupled to detailed chemical models are able to shed light on prestellar evolution.

This is the approach we adopt here, using detailed spectral maps in a number of transitions for the CB 17 core. This core is located at the southeast edge of a small, isolated, and slightly elongated globule at a distance of about 300 pc. Several authors have studied its chemical composition, but the most extensive investigation has been performed by Turner and coauthors (Turner 1995, 1996; Turner et al. 1997, 1998). They argued that the chemical composition of this core is in many respects unusual, with overabundant HCO$^+$, N$_2$H$^+$, HC$_3$N, and some other species. However, it must be noted that their study has been focused on small translucent clouds. When compared to other dense cores, the CB 17 core shows typical column densities of N$_2$H$^+$ (Benson et al. 1998; Caselli et al. 2002) and ammonia (Lemme et al. 1996).

Using molecular line maps, we study in this paper abundances of CO, HCO$^+$, and CS as a function of distance from the core center. We choose a detailed chemical model to compute the time-dependent abundances at a number of locations within the core, assuming its spherical symmetry. Both static and dynamically evolving configurations are considered. These abundances are then used to simulate the spectral maps that are directly compared to the observed line profiles.

The attempt to reproduce the observed state of the core as an outcome of the time- and depth-dependent chemical model is hampered by the presence of many unknown or poorly known parameters. At first sight, it may seem they can be adjusted almost arbitrarily to get the best agreement with observations. However, this is not exactly the case when multiple lines of sight are analyzed. The most important parameters for the chemical model are the probability $S$ for species to stick to dust grains and the intensity $G$ of the UV field that illuminates the core, as they control abundances in the inner and outer regions of a core, respectively. Two remarks should be made about these parameters. First, the sticking probability $S$ represents an effective value, which is valid as long as there are no desorption mechanisms other than those considered in the paper (thermal desorption, cosmic-ray desorption, and photodesorption). In the case where some pow-
Static Model
- Fixed density profile
- Time-dependent chemistry
- Radiation transfer (1D)

Dynamical Model without Rotation
- Evolving density profile
- Time-dependent chemistry
- Radiation transfer (1D)

Dynamical Model with Rotation
- Orientation & Angular Momentum
- Radiation transfer (2D)

Fig. 1.—Flowchart of the technique used in the paper.

In the following, we describe both the static and nonstatic models in detail, together with the adopted models of the chemical evolution and the line radiation transfer. A criterion is presented that is used to compare modeled and observed spectral line maps. For this comparison, we consider the optically thin transitions $\mathrm{C}_3\mathrm{S}$ (2–1), $\mathrm{HCO}^+$ (1–0), and $\mathrm{C}\,^{18}\mathrm{O}$ (2–1) as well as line maps. Rather than for the outer regions, all spectra of a given line were combined and resampled on a regular spatial and frequency grid using a Gaussian beam of half-power beamwidth (HPBW) and channel width listed in Table 1. The reference position (0, 0) for all data and maps in this paper is R.A. = 04$^h$00$^m$32$^s$90, decl. = 56$^\circ$47$'$52$''$0 (B1950.0). These observations represent part of an extensive study of the CB 17 core in many molecules and transitions, which will be described in full detail in another paper (R. Launhardt et al. 2006, in preparation).

To compare models and observations we need to define velocity shift for modeled spectra, i.e., $V_{\text{LSR}}$, which represents velocity of a model core with respect to an observer. Obviously, this value should be the same for all the studied lines. However, the Gaussian fit to the observed profiles toward the center of the core produces different $V_{\text{LSR}}$ values for various lines (between $-4.59$ and $-4.73$ km s$^{-1}$; Table 1). Within the framework of our approach we cannot explain this scatter of $V_{\text{LSR}}$ values for central profiles. On the other hand, differences in observed $V_{\text{LSR}}$ values may be caused not by a presumably complex structure of the core but rather by somewhat incorrect values of rest frequencies for the studied transitions.

For simplicity, in our calculations we adopt $V_{\text{LSR}} = -4.7$ km s$^{-1}$ for $\mathrm{HCO}^+$(1–0), $\mathrm{CS}$ (2–1), and $\mathrm{C}^{18}\mathrm{O}$; and $V_{\text{LSR}} = -4.6$ km s$^{-1}$ for $\mathrm{H}^{13}\mathrm{CO}^+$(1–0) and $\mathrm{C}^{34}\mathrm{S}$ (2–1).
microturbulent velocity, $V_{\text{turb}}$, which is taken to be 0.15 km s$^{-1}$ over the entire core in order to reproduce the observed line width.

2.1.2. Collapsing Core

The static model does not provide a complete description of a typical starless core, as many such cores (including CB 17) show clear signs of internal dynamics. Molecular abundances certainly do not only depend on the core density and chemical age but rather represent the result of its entire previous chemodynamical evolution. This is why almost all recent chemical studies of prestellar cores are coupled in some way or another to dynamical models (e.g., Shematovich et al. 2003; Aikawa et al. 2005; Lee et al. 2005; Flower et al. 2005). In this paper we do not stick to any particular dynamical solution. Instead we choose a phenomenological approach that allows us to describe the core evolution with only a few parameters.

As in the static model, we assume that the nonuniform (“N”) density distribution (eq. [1]) represents the current, observed state of the core. In this configuration, the model core is divided into 48 concentric shells of equal width, having radii $R_N^i$. In the initial uniform (“U”) state the model core is spherically symmetric and has the constant initial density $n_U = 5 \times 10^3$ cm$^{-3}$ (Fig. 2), which is close to the typical gas density in the vicinity of the core. Our results are not sensitive to small variations of this parameter. Locations of shell boundaries in the U configuration are determined by the requirement that each shell has the same mass as in the final state, i.e., the initial radius of each shell $R_U^i$ is uniquely defined by the assumed $n_U$. The timescale for the evolution of the system, needed for configuration U to evolve to configuration N, is $t_0$. At any moment $t$ the location of the $i$th shell is defined by

$$R_i(t) = R_U^i - W_i \left( \frac{t}{t_0} \right)^\delta,$$

where $W_i$ is defined by the condition $R_i(t_0) = R_N^i$, so that $W_i = R_U^i - R_N^i$. Using equation (2), we compute the density of each shell as a function of time and use this in the chemical model. The radial velocity of shell $i$ at time $t_0$ is

$$V_i(t_0) = -\delta \frac{W_i}{t_0}.$$

Thus, the velocity only depends on the $\delta/t_0$ ratio, provided the initial density is fixed. The power-law index $\delta$ in equation (2) allows us to describe different regimes of the core collapse without going into details of an underlying physical model.

As an example, in Figure 3 we show plots for the central density evolution and the radial velocity profiles in models with...
$t_0 = 10^6$ yr and various values of $\delta$. A nearly linear growth of the central density corresponds to $\delta = 0.1$. At smaller $\delta$, density accumulation decelerates with time; at $\delta > 0.1$ the density first stays almost constant, but then grows faster and faster. The static model corresponds to $\delta = 0$.

This model is similar in concept to other generalized prescriptions given, e.g., by Whitworth & Ward-Thompson (2001) or Myers (2005). It is also close (for $\delta \approx 2$) to the destabilized Bonnor-Ebert sphere collapse model used by Aikawa et al. (2005), which is also shown in Figure 3. The velocity profile in our model is shallower and shows less tendency to peak at the near-core region. This is caused by a different choice of initial conditions, specifically, by the uniform initial density distribution.

This prescription for the core contraction may not satisfy the momentum equation strictly and is therefore potentially inconsistent. However, our intention here is more to demonstrate that it is possible in principle to distinguish different regimes of the core evolution using observations of molecular lines, rather than to give support to some self-consistent solution. Also, the dynamics of prestellar cores can be influenced by magnetic fields and/or turbulence, so that the simplest form of momentum equation for spherical isothermal collapse may not be satisfied anyway. Using this approach, it may be possible to find the extent to which the momentum conservation in collapsing cores is affected by non-thermal supporting factors.

2.1.3. Collapsing Core with Rotation

Even though the rotation of starless cores does not influence their (early) dynamical evolution, it affects molecular line profiles. The CB 17 core is likely to have a significant angular momentum, which shows up as an alternating asymmetry pattern across the core face.

We include rotation into the phenomenological model, assuming that a toroidal element $dV_1$ of a shell (Fig. 2), initially located at a distance $a_U$ from the rotation axis, moves during collapse so that its angular momentum is conserved, i.e., that the momentum is not redistributed over the core. This is a good approximation as long as there is no magnetic braking or turbulent momentum transport. We assume that the core initially rotates as a solid body with the angular velocity $\Omega$, so the azimuthal velocity at $t_0$ is

$$V_\phi = \frac{\Omega a_U^2}{a_N},$$

where $a_U$ and $a_N$ are radii of a toroidal element in configurations U and N. Each of the 48 shells is subdivided into 32 angular cells. This model is used in the following to estimate the angular momentum of the CB 17 core and to derive its spatial orientation.

2.2. Chemical Model

The model for the chemical evolution of the core is described by Wiebe et al. (2003) and Semenov et al. (2004). We refer the reader to these papers for more details. Here only the main features of the model are summarized. The model is a time-dependent chemical model that includes gas-phase reactions as well as the freezing out of molecules onto dust grains and their desorption back to the gas phase. For simplicity, all grains are assumed to have the same radius of 10$^{-5}$ cm. Surface reactions are not taken into account in the current study.

Gas-phase reactions are taken from the UMIST95 rate file (Millar et al. 1997). We consider the evolution of species containing H, He, C, N, O, Mg, Na, Fe, S, and Si atoms. For the cosmic rate ionization rate the standard value of $1.3 \times 10^{-17}$ s$^{-1}$ is assumed. The UV flux for photoreaction rates is expressed by the $G$ factor measured in units of the average interstellar flux (Draine 1978). We are aware that the spectrum of the radiation field in star-forming regions may differ quite significantly from the average interstellar spectrum. The relative “hardness” of a spectrum affects the photoreaction rates. However, the study of this effect is beyond the scope of the present paper. The CB 17 core is quite isolated, so that there are no young massive stars nearby and no obscuring molecular cloud is present. Thus, the spectrum of the radiation field should be similar to that of the interstellar field.

The density profile evolves with time. This is why the extinction is a function of time too, and is evaluated as

$$A_V(r, t) = N_H(r, t)/1.59 \times 10^{21} \text{ cm}^{-2},$$

where

$$N_H(r, t) = \int_r^R n(H) \, dr$$

is the column density of hydrogen nuclei measured from the core boundary $R$ to a point at the radius $r$. H$_2$ self- and mutual shielding of CO and H$_2$ are taken into account using the results obtained by Lee et al. (1996). No attempt is made to account for the thermal balance in the medium. The model core is assumed to be isothermal at 10 K. This assumption breaks down at the core edge where the gas is heated by UV radiation. However, this moderate heating would not affect the chemical reaction rates significantly. The same is true for the desorption from grains, as this region is dominated by photodesorption.

Neutral species other than H$_2$ and He are assumed to stick to dust grains with the same probability $S$, which is one of the parameters of our study. In addition to photodesorption, thermal desorption and cosmic-ray-induced desorption are taken into account. Desorption energies are taken from Hasegawa & Herbst (1993).

At $t = 0$ all elements are present in atomic form with the only exception of hydrogen, which is entirely bound in H$_2$ molecules initially. The “low metal” initial abundance set from Wiebe et al. (2003) is used. The entire core is chemically uniform initially. After the onset of collapse, in the adopted Lagrangian description each gas parcel moves and evolves independently, with the density varying according to the adopted dynamical prescription.

In our study we vary two parameters for the chemical model, namely, the strength of the external UV field $G$ and the sticking probability $S$, which regulate the abundances of species in the outer envelope and in the core center, respectively.

As a test of the model, we compare it to results obtained by Aikawa et al. (2005). The closest match to their model with $\alpha = 1.1$ (see Aikawa et al. [2005] for details) and central density of $3 \times 10^6$ cm$^{-3}$ is given by our dynamical model with $\delta \approx 2$ (Fig. 3). For this comparison, we set $G = 1, S = 1, A_V = 3$ mag at the core edge and included surface reactions. Also, the branching ratio for the N$_2$H$^+$ dissociative recombination from Geppert et al. (2004) is taken into account. In Table 2 we compare column densities from this calculations to those given in Table 2 by Aikawa et al. (2005). We present both straight column densities from this calculations to those given in Table 2 by Aikawa et al. (2005).
2.3. Radiative Transfer Model

The radiative transfer modeling is based on the solution of the radiative transfer (RT) equation coupled with balance equations for molecular level populations. We solve this system with the one-dimensional/two-dimensional non-LTE code URAN(IA) developed by Pavlyuchenkov & Shustov (2004). This code partly uses the scheme originally proposed and implemented in the available one-dimensional code RATRAN (Hogerheijde & van der Tak 2000).

Here we only summarize the general concept of the URAN(IA) code. The iterative algorithm is the following. First, initial molecular level populations and a set of photon random paths through the model space are defined. With these quantities, the specific intensities \( I_i \) are computed for each cell by the explicit integration of the RT equation along the predefined photon paths \( n_i \). Then, \( n_i \) and \( I_i \) are used to calculate the mean line intensity \( J \) in each cell for all transitions. The computed mean intensities are used in the next iteration step to refine the level populations by solving balance equations in all model cells. To accelerate the convergence of the entire procedure for optically thick lines, additional internal subiterations are applied to bring into agreement the internal mean intensity of the line and the corresponding level populations in each cell. After the final molecular level populations are obtained, we repeat the calculations, but with another set of predefined random photon paths in order to estimate a typical error in the computed values. In our simulations, relative errors in the level populations are not larger than 1%. Finally, the resulting level populations are used to calculate excitation temperatures, which are further transformed into synthetic beam-convolved single-dish spectra.

### TABLE 2

| Species       | Aikawa et al. (2005) | This Work | This Work (With Convolution) |
|---------------|----------------------|-----------|-----------------------------|
| CO............ | 1.9(17)              | 6.3(16)   | 7.1(16)                     |
| HCO+........... | 2.9(13)              | 1.2(13)   | 1.3(13)                     |
| HCN........... | 8.0(14)              | 3.6(14)   | 2.3(14)                     |
| HC\(_3\)N....... | 5.8(12)              | 4.7(13)   | 3.9(13)                     |
| NH\(_3\)....... | 7.8(15)              | 4.1(15)   | 1.5(15)                     |
| N\(_2\)H\(^+\)...... | 1.8(13)              | 8.4(13)   | 2.8(13)                     |
| CS.............. | 1.0(13)              | 4.5(13)   | 4.5(13)                     |
| C\(_2\)S....... | 6.9(11)              | 2.2(12)   | 2.3(12)                     |
| C\(_3\)H\(_2\)....... | 8.7(12)              | 3.9(13)   | 3.6(13)                     |

2.4. Evaluation of the Model Quality

The selection of criteria for a quantitative comparison of modeled and observed spectral maps represents an important step but is a rather complicated problem. In a detailed analysis we would need to take into account a (dis)agreement of the various features and characteristics of the spectra, such as intensities, widths, asymmetries, shifts, dips, and regularities in the spatial distributions. These features can be either analyzed separately or incorporated into a common criterion with different weights. Using different features and criteria, based on them, we can assess different aspects of the consistency between the model and observations.

One of the commonly used techniques to check the model is to compare distributions of observed and modeled integral line intensities over the core. This allows us to judge how well a model reproduces the spatial distribution of the total energy that is emitted in a given transition, reflecting not only the total molecular content (and excitation conditions) but also the molecular distributions within the core.

Of course, minimization of this value does not guarantee the consistency between modeled and observed kinematic properties of the source because it does not account directly for widths, shifts, and asymmetries that reflect the velocity field. To estimate if the model reproduces the kinematic structure, e.g., rotation of the core, one can compare the distributions of the mean velocities. In turn, such a comparison does not take into account the consistency of the line intensities.

In this paper the quality of the spectra fit is evaluated with the general criterion,

\[
SP = \frac{1}{J_{\text{obs}} + J_{\text{mod}}} \sum_{k=1}^{N_{\text{chan}}} \sum_{i=1}^{N_{\text{chan}}} \left| I_k^i_{\text{obs}} - I_k^i_{\text{mod}} \right| \Delta v_i. \tag{5}
\]

The inner sum is the absolute difference between observed and modeled spectra at map position \( k \), \( I_k^i_{\text{obs}} \) and \( I_k^i_{\text{mod}} \) are observed and theoretical intensities in velocity channel \( i \), \( N_{\text{chan}} \) is the number of velocity channels, \( \Delta v_i \) is the channel width, and \( J_{\text{obs}} \) and \( J_{\text{mod}} \) are the observed and modeled intensities integrated over the frequency and over the map:

\[
J = \sum_{k=1}^{N_{\text{chan}}} \sum_{i=1}^{N_{\text{chan}}} I_k^i \Delta v_i. \tag{6}
\]

SP is normalized so that \( 0 \leq SP \leq 1 \).

To illustrate the behavior of this criterion, we consider the case of a single spectrum, when both observed and modeled line profiles are rectangular with equal width \( \Delta v \) and position \( v_0 \), but with different intensities. In this case SP is equal to

\[
SP = \frac{|J_{\text{obs}} - J_{\text{mod}}|}{J_{\text{obs}} + J_{\text{mod}}}. \tag{7}
\]

The value of SP as a function of \( J_{\text{obs}}/J_{\text{mod}} \) is shown in Figure 4. In the log scale this function is symmetric relative to the point

![Fig. 4.—SP criterion as a function of \( J_{\text{obs}}/J_{\text{mod}} \) for rectangular profiles.](attachment:image.png)
$J_{\text{obs}}/J_{\text{mod}} = 1$, where SP = 0. If intensities differ by a factor of 2, then SP $\approx 0.4$, while an order-of-magnitude difference gives SP $\approx 0.8$.

SP thus describes the normalized deviation between modeled and observed line intensities averaged over all velocity channels and all map positions. On the other hand, SP no longer contains any information about the specific cause of a disagreement between the model and the observations.

3. RESULTS FOR THE STATIC MODEL

Here we consider three important parameters of the static model, namely, the total chemical evolution time $t_0$, the sticking probability $S$, and the strength of the external UV field $G$. Regarding these quantities as free parameters, we fit the observed spectra, considering the three-dimensional parametric space of models with $0 < S < 1$, $0 < G < 1$, and $0.2 < t_0 < 2.0$ Myr, and calculated 330 models in total.

For each of these models, we calculate molecular abundances as a function of radius. Then, distributions of molecular abundances are used as input data for the RT model. As a result of the RT simulations, we obtain distributions of level populations over the core for molecules of interest, which are further transformed into spectral maps. All the synthetic line profiles in the map are convolved with Gaussian beams and shifted in accordance with the observed $V_{\text{LSR}}$ position. Line profiles are calculated for those locations in the map where they have been observed. Finally, the SP criterion is checked for each model.

3.1. Overview of the Core Chemical Structure

Radial distributions of CO, CS, and HCO$^+$ abundances for the static model at $t = 0.2$ and 2.0 Myr are shown in Figure 5. The overall chemical structure of the core is very similar to that obtained by Lee et al. (2005; cf. the Fig. 9 abundances for $t = 0$ in their model). The evolution of the CO abundance is quite simple. In the $S = 0$ case (just gas-phase chemistry) $\chi(\text{CO})$ is almost constant all over the core, being nearly equal to the total carbon abundance. The nonzero sticking probability leads to a noticeable CO freezeout in the core and to a minor CO depletion in the envelope. In the case with UV illumination, CO molecules in the envelope are almost totally dissociated.

The HCO$^+$ abundance is not very sensitive to the actual $S$-value. The only parameter that can be more or less reliably constrained with observations of HCO$^+$ is $G$.

The CS abundance depends on all three parameters. The location of the dip in the radial CS profile, appearing in UV-illuminated models, coincides with the region of enhanced CO abundances, which decrease the number of carbon atoms available for CS formation.

The discussed behavior is not strongly time dependent, being only slightly more pronounced at later times of the chemical evolution. We should note that the same general features are shared by dynamical models, which justify our usage of line profiles in the static model as a guide for possible ranges of $S$ and $G$.

3.1.1. Note on N-bearing Species

Before we analyze the CO, CS, and HCO$^+$ data, we discuss briefly our ability to match the other available observations, specifically, the data on N-bearing species that are not the main subject of the current study. The column density of N$_2$H$^+$ has been determined by Benson et al. (1998) and Caselli et al. (2002) to be $3-5 \times 10^{12}$ cm$^{-2}$. The column density of NH$_3$ is about $8 \times 10^{14}$ cm$^{-2}$ (Lemme et al. 1996; Jijina et al. 1999). Our values, compiled in Table 2, are somewhat higher for both molecules.

Currently, our ability to treat these molecules with URAN(IA) is limited because of the poor knowledge of hyperfine transition parameters. We modeled the N$_2$H$^+$ (1–0) profile, neglecting its hyperfine structure, and obtained antenna temperatures of the order of 0.4–0.6 K, similar to what is observed. We also performed an approximate modeling of the HCN (1–0) line and compared the result with the profile obtained by Turner et al. (1997). We are able to reproduce the antenna temperature and main features of the profile, in the sense that both the $F = 2-1$ and 1–1 transitions are self-absorbed, while the $F = 1-0$ transition is not self-absorbed. The intensity ratios in our model are different from those in Turner et al. (1997). Molecular data from Schöier et al. (2005) are used for this analysis.

3.2. Optically Thin Lines

We first analyze optically thin transitions that probe the total molecular content of the core. In order to show the fitting results in a compact way, we present them as $ts$-diagrams, which are two-dimensional plots of SP-values for various $t_0$ and $S$ parameters at a fixed $G$-value. The $ts$-diagrams for optically thin transitions of C$^{18}$O, H$^{13}$CO$^+$, and C$^{34}$S are shown in Figure 6.

All panels in Figure 6 indicate that values of $S$ close to zero are ruled out. Higher sticking efficiencies are not favored in the analysis of the C$^{18}$O and H$^{13}$CO$^+$ transitions. However, it must be kept in mind that the range of SP is not very large for these transitions. This means that conclusions from their analysis must be taken with care.

The C$^{34}$S lines appear to be more robust discriminators between the model parameters. On the $ts$-diagram we clearly see the hyperbolic zone of best fitting with a significant range of $0.22 < \text{SP} < 0.95$. As might have been expected, smaller SP-values become appropriate as $t_0$ increases, as a lower sticking rate is compensated by a longer timescale.

In general, there are combinations of the studied parameters that provide a good agreement with observations, with SP-values
being less than 0.3 for all the optically thin transitions simultaneously. This corresponds to differences in the line intensities by a factor of 2. All the considered optically thin lines are not very sensitive to variations of the UV field. Indeed, they are mostly formed in the inner part of the core where the UV field is attenuated by the envelope.

### 3.3. Optically Thick Lines

Although the static model is quite successful in reproducing the observed optically thin line profiles, this should not be over-interpreted. Both the observed and modeled optically thin lines are nearly Gaussian in shape. The width of the theoretical profiles is defined by the adopted value of the microturbulent velocity. In our study this velocity is chosen to be 0.15 km s\(^{-1}\) in order to fit the observed line widths. Thus, for optically thin lines the quality of the fit in a static model depends mainly on the column density.

On the other hand, optically thick transitions are mostly sensitive to the conditions in the envelope, which makes them promising tracers of the external UV field. In our study, we consider the optically thick transitions of CS and HCO\(^+\). The \(ts\)-diagrams for these transitions are shown in Figure 7.

As expected, both the HCO\(^+\) and CS diagrams are sensitive to variations of the UV radiation. In the case of no UV field (left), molecules survive in the envelope and produce emission over a broad range of impact parameters. In addition, enhancement

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**Fig. 6.**—Values of SP criterion (\(ts\)-diagrams) for optically thin transitions of C\(^{18}\)O (top), H\(^{13}\)CO\(^+\) (middle), and C\(^{18}\)S (bottom). Smaller values (lighter colors) correspond to better agreement. Columns differ by \(G\)-values, indicated on top of each panel. The gradient scales on the right side of the first plot in each row are appropriate for all plots in the row.
of the molecules in the envelope leads to prominent dips in the profiles of optically thick lines. In contrast, a strong UV field, $G = 1$ (right), destroys molecules in the outer parts of the core, leading to more centrally peaked distributions of the integral intensity and to weaker self-absorption dips. Both effects worsen the agreement between observed and synthetic maps.

To demonstrate the influence of the UV field on the spectra, we show observed and theoretical spectral maps of CS (2–1) in Figure 8. For the static model with no UV radiation, $S = 0.6$ and $t = 0.8$ Myr CS line profiles have nearly the same intensity at all positions and self-absorption dips, which are much deeper than in the observed spectra. The synthetic intensities of the model with strong UV field, $S = 0.6$, and $t = 0.4$ Myr decrease rapidly toward the edge of the core. The self-absorption dips become shallower than in the model without the UV field.

According to Figure 7, the model with attenuated UV radiation ($G = 0.1$) seems to be most appropriate. It must be noted that it would be impossible to constrain the effect of the UV field using a central spectrum alone. One may argue that the excess intensity of the CS (2–1) line in the zero-UV model can be mediated by an adjustment of the sulfur abundance, which is not well constrained observationally. We computed two additional series of models with zero UV intensity and sulfur abundance decreased by factors of 3 and 10, respectively, relative to our standard value. These models showed that a lower initial sulfur abundance leads to an overall decrease of S-bearing species in the core. This results in a better agreement for the central spectrum. However, the gradual decrease of the CS line intensity toward the outer boundary of the core can only be reproduced in models with some UV illumination.

Although the modeled optically thick lines have the expected double-peaked shape, these peaks are equal in height, contradicting the observed asymmetry. In order to describe this asymmetry, we must move from the static model toward a dynamical model. From Figures 6 and 7 it is obvious that the sticking efficiency is not well constrained in the static model. Therefore, the only parameter we fix in dynamical models is the strength of the UV field ($G = 0.1$).

We also do not consider $t_0 < 0.4$ Myr values, as they do not fit both the optically thin and optically thick lines. This seemingly minor limitation has an important implication for our dynamical models. The asymmetry of the central spectrum mentioned in the previous paragraph implies that the CB 17 core undergoes an infall with a velocity of $\sim 0.05–0.1$ km s$^{-1}$. In the adopted prescription and for $t_0 > 0.4$ Myr, such velocities are only possible with $\delta \geq 0.5$.

4. RESULTS FOR THE DYNAMICAL MODEL

As described in \S 2.1.2, the dynamical history of the core is represented by two parameters, which are the evolutionary time $t_0$ and the power-law index $\delta$. In the following, we investigate the sensitivity of molecular spectral maps to these parameters, at the same time searching for combinations of $t_0$ and $\delta$ that give the best agreement between observed and modeled CB 17 maps.

Ideally, in order to find the “best-fit” parameters for the CB 17 core one should vary $G$, $S$, $t_0$, and $\delta$ simultaneously. However, the primary goal of this paper is rather to show the general effect of the selected parameters. Therefore, we fix $G$ to a value of 0.1 as determined from the static models, but vary $S$ together with the dynamical parameters $t_0$ and $\delta$. 

Fig. 7.— Values of SP for the optically thick transitions of HCO$^+$ (top) and CS (bottom). Smaller values (lighter squares) correspond to better agreement. Columns differ by $G$-values indicated on the top of each panel.
In the dynamical modeling yet another parameter has to be considered. In the static configuration we assumed the microturbulent velocity $V_{\text{turb}}$ to be 0.15 km s$^{-1}$. This value is needed to reproduce the line width in the static model, and as such it hardly leaves any room for a systematic velocity field. On the other hand, the central line asymmetry clearly shows that there is a non-zero infall velocity in the CB 17 core. This seems to imply that $V_{\text{turb}}$ is to be varied along with the other parameters. On the other hand, it obviously makes no sense to consider those values of $V_{\text{turb}}$ that, in combination with the systematic velocity, would result in line widths that are too large or too small.

To minimize the needless effort, we adopted the following approach. For each combination of $\delta$ and $t_0$ we select $V_{\text{turb}}$ to get the line width of about 0.15 km s$^{-1}$, so that the differences between theory and observations are only caused by disagreements in the line intensity and in the relative heights of blue and red peaks in optically thick lines.

4.1. Collapsing Core without Rotation

In purely collapsing models we only compare our results to the central spectrum of CB 17 to avoid confusion with the effects of rotation. Results of the modeling are presented in Figure 9. We show SP-values for three values of $\delta$ (0.5, 1.0, and 1.5), vary $t_0$ between 0.4 and 4 Myr, and $S$ between 0 and 1. Only results for CS lines are given, as other molecules demonstrate much less sensitivity for the discussed parameters.

Figure 9 does not show any significant differences to the static model (see Figs. 6 and 7, bottom). In models with increasing $\delta$ the best-fit region shifts toward later times, which is expected, as larger $\delta$-values lengthen the “less dense” stage of core evolution. It seems that we have the same dilemma as in the static case, being unable to distinguish between large $S$ and large $t_0$. However, if we look at numeric SP-values within the hyperbolic area, we see that the best-fit model for the CS transition (which is most sensitive to the infall velocity) corresponds to $S = 0.2 - 0.3$ for all three $\delta$-values.

The theoretical line profiles show that the agreement is still not perfect, even in the best-fit region. In some cases the line widths are different; in other cases the ratio between blue and red peaks is not the same as observed. The line width can be further adjusted with a more appropriate choice of $V_{\text{turb}}$. Thus, to split the contribution of the line width and the peak asymmetry in a “residual” disagreement, we consider an additional criterion, which is just the difference between the observed and the theoretical blue-to-red peak intensity ratios. Contours in the bottom row of Figure 9 indicate models with the best agreement between theory and observations both in terms of the overall profile shape and the profile asymmetry. The combined selection procedure leads to the model parameters summarized in Table 3. Minimum SP-values are selected only among locations within contours. The best-fit models are somewhat different for CS and $C^{34}$S.

The data in Table 3 indicate that the sticking probability has an effective value of about 0.3, while the age of the core is larger than 1 Myr and probably less than 2.5 Myr. All presented SP-values are smaller than in the corresponding static model. However, it must be kept in mind that these numbers are not directly comparable, as they are computed for the central spectrum only in the case of the dynamical model, while in the static model SP-values are calculated for the whole map.

The difference between SP-values computed for various $\delta$ is small for $C^{34}$S and only marginal for CS. However, both transitions show a minor preference toward the model with $\delta = 1.0$. In § 4.2 this model is used as an input for the two-dimensional model. We emphasize that in the general case one may have to vary $V_{\text{turb}}$ along with the other parameters.

4.2. Collapsing Core with Rotation

Finally, we now include rotation in the dynamical description of the core, the RT problem becoming two-dimensional. In our model (§ 2.1.3), the rotation of the core is characterized by the initial angular velocity $\Omega$. To simulate observations, we also have to specify the orientation of the core with respect to the observer, which is defined by the inclination angle $i$ and the position angle (P.A.). We assume that the core is observed edge-on ($i = 90^\circ$) in order to get an estimate of the minimum value of its angular
momentum. No attempt is being made to reproduce the inclination angle, as within the framework of a spherically symmetric model we are not able to distinguish between rapid rotation and low inclination. We tried several other values for $i$ and found that variations of excitation conditions due to different rotation velocity profiles in the CB 17 model are not strong enough to produce noticeable differences in observed spectra. It would be possible to determine $i$, using a more realistic dynamical model that would provide independent information on the core rotation. Also, we note that it may be possible to estimate $i$ independently for elongated cores from geometric reasoning.

The two parameters that are varied to get the best agreement with observations are the initial angular velocity $\Omega$ and the P.A., which is defined as the angle between the projection of the core rotation axis on the sky and the direction to the north.

The simulation is made in the following way. The chemical structure of the core and its radial velocity field are taken from the best-fit one-dimensional dynamical model with the parameters $\delta = 1.0$ and $t_0 = 1.6$ Myr. For the given $\Omega$-value we generate azimuthal velocities according to equation (4). These velocities are combined with the infall velocities to get the two-dimensional velocity field. This field is then used to solve the two-dimensional radiation transfer equation. Having specified the P.A., we calculate the convolved spectral map, which is further compared to the observed map using the SP criterion.

Results of this comparison are shown in Figure 10. Obviously, when there is no rotation, the model shows no sensitivity to the P.A. value. As we increase $\Omega$, both the optically thin and optically thick transitions show a clear preference to a P.A. value of $250^\circ$–$300^\circ$. It is interesting to note that the sensitivity of the model to the P.A. increases when we adopt $\Omega$-values that are greater than allowed observationally.

When the P.A. is specified incorrectly, both transitions indicate that the model with pure infall agrees better with the observations than the model with infall and rotation (SP-values increase from left to right in Fig. 10). For P.A. $\approx 270^\circ$, SP-values have minima at $V_{\text{ini}} = 0.13$ km s$^{-1}$ for the C$^{34}$S line, and at a somewhat smaller value of $V_{\text{ini}} = 0.07$ km s$^{-1}$ for the CS line. The disagreement is probably caused by a higher rotation velocity closer to the core center (where the C$^{34}$S line is generated) than our model predicts. This can be further adjusted by adopting a different initial rotation velocity distribution. However, it must be noted that the optically thick CS line is in general less sensitive to $\Omega$ variations, which is indicated by the smaller SP range. This implies that optically thin lines are better rotation indicators, at least when the SP criterion or another similar width-sensitive criterion is used.

We note that the lowest SP-values in the model with infall and rotation are actually higher than the corresponding values for the static model. This is caused by the values for $V_{\text{turb}}$ adopted in the dynamical model. Because we did not try to vary $V_{\text{turb}}$ along with the other parameters, the widths of some theoretical profiles do not quite fit those of their observed counterparts. This results in higher SP-values.

Finally, in Figures 11 and 12 we show the convolved spectral maps of the CS (2–1), C$^{34}$S (2–1), HCO$^+$ (1–0), H$^{13}$CO$^+$ (1–0),

| $\delta$ | $t_0$ (Myr) | $S$ | SP (CS) | SP (C$^{34}$S) |
|----------|-------------|-----|--------|----------------|
| 0.5............ | 1.0–1.2     | 0.3–0.4 | 0.153   | 0.208          |
| 1.0............ | 1.6–1.8     | 0.3  | 0.152   | 0.187          |
| 1.5............ | 2.2–2.4     | 0.3  | 0.154   | 0.190          |

Fig. 9.—Values of SP for the optically thin C$^{34}$S transition (top) and the optically thick CS transition (bottom). Columns differ by $\delta$-values of 0.5 (left), 1.0 (middle), and 1.5 (right). Best-fit regions, selected by the blue-to-red peak intensity ratio, are shown by solid contours in the bottom row.
and C$^{18}$O (2–1) lines for the best-fit two-dimensional model (Table 4). In all the modeled optically thin transitions, shifts of the observed lines are reproduced quite successfully. Furthermore, the modeled optically thick CS profiles follow the asymmetry of the observed spectra, with blueshifted profiles in the bottom left corner and nearly equal peak intensities in the upper part of the map. The consistency between the shapes of the theoretical and observed HCO$^+$ profiles is less impressive. However, the theoretical line intensities are close to the observed ones, and the asymmetry is well reproduced in the central part of the map. The fit is worse in the upper part of the map, where there is some disagreement in the CS profiles as well. Given the overall consistency between maps of optically thin and optically thick lines, we believe this residual disagreement originates in the core structure, which is certainly more complicated than the assumed spherical symmetry. It is also possible that there are some small-scale motions within the core that are not well described by the microturbulence model (like the motions discussed for B68 and L1489; see § 1).

In general, all the modeled maps do reproduce the spatial distributions of line intensities, except the C$^{18}$O (2–1) intensity, which is approximately 1.5–2 times greater than that observed. The C$^{18}$O overabundance is present in the static model as well and seems to follow from the adopted relatively low S-value, which is supposed to provide the best agreement for CS lines. The top panels in Figure 6 indicate that regardless of UV intensity values $S > 0.5$ are preferred from the point of view of the C$^{18}$O abundance.

Some further adjustment of the CO abundance can be made with a variation in the cosmic-ray ionization rate. However, there is a more natural explanation. In our study we assume that the C$^{18}$O/C$^{18}$O ratio is constant and equal to 490, which is just the $^{16}$O/$^{18}$O ratio. Due to the chemical fractionation the ratio C$^{13}$O/C$^{18}$O can vary by a factor of a few (Federman et al. 2003). Specifically, the isotope-selective photodestruction of CO molecules may decrease the abundance of the isotopomer with the less abundant isotope (Bally & Langer 1982). Importantly, the fractionation apparently affects the C$^{13}$O/C$^{18}$O ratio stronger than the $^{12}$CO/$^{13}$CO ratio (Chu & Watson 1983; Federman et al. 2003), which would explain why we have the intensity disagreement in the C$^{18}$O lines, but not in the H$^{13}$CO$^+$ lines.

**5. DISCUSSION**

This paper represents an attempt to develop a technique that allows us to get as much information as possible from the spectral maps of a starless core. The technique is outlined in Figure 1. As an example, we used the CB 17 core, for which we have detailed observational data. This core appears to be quite young, having a chemical age of about 2 Myr. It is tempting to put it into an evolutionary sequence with other starless cores. Taking the central density as an indicator of the dynamical evolution, we have to assume that CB 17 is quite evolved, as it is almost as dense as L1544. From the point of view of the central depletion CB 17 appears to be less evolved. There is some depletion in its center, which is indicated by high SP-values for models with $S = 0$. In best-fit static models (e.g., $t_0 = 1$ Myr, $S = 0.4$) the CO molecule is depleted by a factor of 40 in the core center, and the CS molecule is depleted by a similar factor. However, this depletion is not very obvious in the CS column density distribution and is not seen at all in the CO column density distribution. This explains why the central holes are not seen in the observed maps of optically thin transitions of C$^{34}$S and C$^{18}$O. Within the classification scheme suggested by Lee et al. (2003) and Shirley et al. (2005), the CB 17 core is evolved dynamically and moderately evolved chemically.

Within the framework of the adopted dynamical formalism we note that ages greater than ~0.5 Myr and infall speeds of order 0.05 km s$^{-1}$ are required. This implies $\delta > 0.5$ (the kinematic difference between the considered $\delta$-values of 0.5, 1.0, and 1.5 is less significant). In this collapse regime the central density first stays almost constant and then undergoes a stage of a very fast growth. This conclusion is further illustrated by the comparison of the derived chemical age, $t_{\text{chem}}$ $\approx$ 2 Myr, to the CB 17 free-fall timescale, $t_{\text{ff}}$ $\approx$ 0.4 Myr, which is 5 times smaller than $t_{\text{chem}}$. So, formally we can conclude that the core has evolved more or less quasi-statically for ~10$^6$ yr, then quickly lost stability and started to collapse. It seems reasonable just from mass
conservation considerations that this is the appropriate scenario for a dense, collapsing, and chemically mature core. The scenario is similar to that favored by Shematovich et al. (2003) and considered by Lee et al. (2004). The quasi-static evolution of the starless core can result from the magnetic field support being gradually lost due to the ambipolar diffusion. On the other hand, Aikawa et al. (2005) and Keto & Field (2005) showed that quasi-static evolution of prestellar cores can be explained by the assumption that the initial condition for contraction represents a destabilized Bonnor-Ebert sphere.

Fig. 11.—Spectral maps for the best-fit CB 17 model. Shown are optically thin transitions: C$^{18}$S (top), H$^{13}$CO$^+$ (middle), and C$^{18}$O (bottom).

Table 4

| Parameter               | Value   |
|-------------------------|---------|
| Chemical age            | $\sim$2 Myr |
| The UV field            | 0.1 G   |
| Effective sticking probability | 0.3    |
| $\delta$                | 1.0     |
| $V_{rot}$               | 0.1 km s$^{-1}$ |
| $V_{\text{fall}}$       | 0.05 km s$^{-1}$ |
| $V_{\text{tan}}$        | 0.1 km s$^{-1}$ |
| P.A.                    | 250°    |

Fig. 12.—Same as in Fig. 11, but for optically thick transitions: CS (top) and HCO$^+$ (bottom).
The estimated CB 17 age of 2 Myr may have implications for current theories of the star formation. For example, it is greater than the typical lifetime of dense cores found in gravoturbulent simulations (Vázquez-Semadeni et al. 2005) and the observationally estimated lifetimes of submillimeter cores studied by Kirk et al. (2005). So, one may ask how solid this estimate is. It must be noted from the static model that even if the core has spent the entire lifetime at constant central density of \( n(H_2) = 5 \times 10^5 \) cm\(^{-3}\), its chemical age is not less than 1 Myr. To make a more sound estimate, which takes into account the density variations, we need to rely on our dynamical models. It is seen from Table 3 that, based on SP(C\(^{34}\)S) values, we can put “error bars” to the age estimate, so that it is \( 2 \pm 0.4 \) Myr. But it must be kept in mind that this estimate is dependent on the adopted initial conditions. Therefore, it is of vital importance to constrain these conditions via models of the very early stages of prestellar core formation and evolution. Also, the dynamical history of CB 17 can be refined with the same analysis applied to a more complicated dynamical model, which we plan to do in a forthcoming study.

Alternating asymmetry patterns in the CB 17 core, i.e., changing blue-to-red asymmetry of optically thick lines and shifts of optically thin lines, indicate that the CB 17 core rotates with an estimated azimuthal velocity of about 0.1 km s\(^{-1}\). More precisely, the model core rotates differentially with a maximum rotation velocity of 0.13 km s\(^{-1}\) at 7000 AU from the core center. The corresponding angular momentum of the core can be estimated as

\[
J = \frac{2}{3} M (R^{1/2}) \Omega \approx 2 \times 10^{56} \text{ g cm}^2 \text{ s}^{-1}.
\]

Because of our assumption that the core is observed edge-on, this is the minimum angular momentum the core can have. Its value corresponds to the specific angular momentum of 1.6 \( \times 10^{21} \) cm\(^2\) s\(^{-1}\), which is too high for a single star and somewhat higher than a corresponding value for a star with a disk (e.g., Ohashi et al. 1997). On the other hand, it is close to specific angular momenta of binary T Tau stars (Simon et al. 1995). So, it seems that CB 17 is going to fragment into at least two prestellar cores.

A possible drawback in using phenomenological descriptions is the possibility that the resulting model may be characterized by a combination of parameters that are mutually incompatible, such as infall in a model where the thermal pressure exceeds the gravitational pressure. In order to check if our best-fit two-dimensional model (Table 4) is physically consistent, we computed the gravitational force, the centrifugal force, and the pressure gradient as functions of radius. The analysis confirms our conclusion that the core is marginally gravitationally unstable as the gravitational force exceeds (in absolute value) the sum of forces, which counteract the collapse, by about 50%. In the inner part of the core the critical rotation velocity that would provide enough centrifugal support against collapse is only slightly higher than the velocity inferred from our study. This agrees with the very low infall velocity and demonstrates that in the inner parts of prestellar cores the rotation can be an important factor of core dynamics. The derived kinematic structure of the CB 17 core corresponds to energy ratios \( E_{\text{rad}}/E_{\text{grav}} \approx 0.03 \), \( E_{\text{therm}}/E_{\text{grav}} \approx 0.8 \), and \( E_{\text{nuc}}/E_{\text{grav}} \approx 0.05 \).

Our conclusions are affected to a certain degree by the choice of the probe molecules. All the lines we consider actually trace more the envelope of the core than its central region. Even optically thin lines of C\(^{18}\)O, H\(^{3}\)CO\(^+\), and C\(^{34}\)S are not good probes of the very center of the core because these species are depleted there. Deuterated and N-bearing species are more promising tracers of the inner core (e.g., van der Tak et al. 2005). Inspection of our chemical results shows that cyanopolyynes are especially sensitive not only to the age of an object, but also to the collapse regime. However, the analysis of cyanopolyyne lines with the proposed technique is not straightforward, as it requires a more complicated approach to the radiation transfer modeling. Another possible limitation of our model is the neglect of UV heating. CB 17 and other similar globules are often cometary shaped, suggestive of some outflow from the heated surface. Thus, UV irradiation affects not only the chemical, but also the thermal and the kinematic structure of the core. This is a promising topic for a more sophisticated dynamical model.

In this paper, we applied the “global” SP criterion, which provides an estimate for the overall agreement between theoretical and observed spectra. However, as mentioned earlier, there are different features of real spectra that can be analyzed separately. For example, the depth of the self-absorption dip of optically thick lines is a good indicator of the UV field strength, while a good measure of the core rotation is given by relative shifts of optically thin lines. In the latter case the right thing to do is to compare the line-center positions and not the overall profile shapes. The optically thin line intensities are sensitive to the molecule column density, the blue-red asymmetry depends on the infall speed, and so forth. In this sense the global criterion is not the best choice, as it has equally bad (large) values for a line that is wider than the observed one (easily adjusted with \( V_{\text{turb}} \); noncritical) as well as for a line that is shifted relative to the observed one (indicative of the wrong rotation model and/or the \( V_{\text{LSR}} \) velocity; critical). On the other hand, when applied with care, an SP-type criterion provides a useful global error control. The global criterion is a good starting point and must be refined in a later analysis. On the other hand, sometimes it can be complemented with more refined criteria that allows us to study certain aspects of the model in detail or just to save the computational effort.

6. CONCLUSIONS

In this paper, we present a chemodynamical pilot study of the isolated Bok globule CB 17 (L1389) based on the spectral maps of CS (2–1), C\(^{13}\)S (2–1), HCO\(^+\) (1–0), H\(^{13}\)CO\(^+\) (1–0), and C\(^{18}\)O (2–1) lines. A phenomenological model of a prestellar core evolution combined with time-dependent chemistry and a radiative transfer simulation of molecular lines is used to reconstruct the chemical and kinematic structure of this core as well as to study the influence of various physical factors on molecular line profiles. The main conclusions of the paper are as follows.

1. We present a promising approach that allows us to derive the chemical and kinematic structure of a prestellar core from its spectral maps. We analyze both optically thick and optically thin lines, center and off-center positions, and various species and transitions. We show that even when this detailed information is available, it is not trivial to construct a consistent core model.

2. Among the considered molecules, CS and its isotopomer C\(^{34}\)S turned out to be most sensitive species to variations in model parameters and can be used to reconstruct the dynamical history of prestellar cores. As the effects of the age and sticking probability (S) are quite similar for this molecule, it is desirable to have more qualitative information on the S-value.

3. UV irradiation is an important factor affecting the chemistry and, correspondingly, line profiles in prestellar cores even when the strength of UV field is much smaller than the average interstellar value. The attenuated UV field (\( G = 0.1 \)) is needed to...
explain distributions of intensities and self-absorption features of the observed CB 17 spectral maps. Optically thick lines tracing the envelope are mostly sensitive to the UV field.

4. The chemical age of the core is about 2 Myr. All the considered species (CO, HCO\(^+\), and CS) are depleted in the inner core, but the degree of depletion is still not high enough to show up in the integrated intensity maps. This allows us to classify this core as evolved dynamically and moderately evolved chemically. The best-fit sticking probability value for the core is \(S = 0.3 \pm 0.5\). This is an effective value that may be higher if we miss some important desorption mechanism.

5. The changing asymmetry pattern of the optically thick line profiles over the cloud surface as well as shifts of the optically thin lines are both indicative of a complex kinematic structure of the core. We argue that the observed maps are reasonably well reproduced by a model with slow infall (0.05 km s\(^{-1}\)), differential rotation (0.1 km s\(^{-1}\)), and microturbulence (0.1 km s\(^{-1}\)). From the derived angular momentum, we conclude that CB 17 is likely to fragment and to form a binary (multiple) star.

6. While being artificial in nature, our phenomenological approach allows us to reveal crucial parameters that must be considered in attempts to compare observations with results of more sophisticated physical models based on combined MHD, chemical, and radiative transfer simulations.

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REFERENCES
Aikawa, Y., Herbst, E., Roberts, H., & Caselli, P. 2005, ApJ, 620, 330
Bally, J., & Langer, W. D. 1982, ApJ, 255, 143
Belloche, A., Andrè, P., Despois, D., & Blinder, S. 2002, A&A, 393, 927
Benson, P. J., Caselli, P., & Myers, P. C. 1998, ApJ, 506, 743
Caselli, P., Benson, P. J., Myers, P. C., & Tafalla, M. 2002, ApJ, 572, 238
Chu, Y.-H., & Watson, W. D. 1983, ApJ, 267, 151
Caselli, P., Benson, P. J., Myers, P. C., & Tafalla, M. 2002, ApJ, 572, 238
Draine, B. T. 1978, ApJS, 36, 595
Evans, N. J., II. 1999, ARA&A, 37, 311
Federman, S. R., Lambert, D. L., SHEffer, Y., Cardelli, J. A., Andersson, B.-G., van Dishoeck, E. F., & Zsargó, J. 2003, ApJ, 591, 986
Flower, D. R., Pineau des Forets, G., & Walmsley, C. M. 2005, A&A, 436, 933
Gregersen, E. M., & Evans, N. J., II. 2000, ApJ, 538, 260
Hogerheijde, M. R., Caselli, P., & Ceccarelli, C. 2005, A&A, 439, 195
Hogerheijde, M. R., & van der Tak, F. S. 2000, A&A, 362, 697
Jijina, J., Myers, P. C., & Adams, F. C. 1999, ApJS, 125, 161
Kane, B. D., & Clemens, D. P. 1997, ApJ, 488, 317
Keto, E., & Field, G. 2005, ApJ, 635, 1151
Lee, J.-E., Bergin, E. A., Alves, J. F., & Huard, T. L. 2003, ApJ, 586, 286
Lee, C. W., Myers, P. C., & Tafalla, M. 2001, ApJS, 136, 703
Lee, H.-H., Herbst, E., Pineau des Forets, G., Roueff, E., & Le Bourlot, J. 1996, A&A, 311, 690
Lee, J.-E., Evans, E. A., & Evans, N. J., II. 2004, ApJ, 617, 360
Lee, J.-E., Evans, N. J., II, & Bergin, E. A. 2005, ApJ, 631, 351
Lee, J.-E., Evans, N. J., II, Shirley, Y. L., & Tatematsu, K. 2003, ApJ, 583, 789
Lada, C. J., Bergin, E. A., & Alves, J. F. 1998, ApJ, 499, 225
Lada, C. J., Bergin, E. A., & Alves, J. F. 1998, ApJ, 513, 302
Lee, J.-E., Bergin, E. A., & Tafalla, M. 2004, ApJ, 617, 360
Lee, J.-E., Evans, N. J., II, & Bergin, E. A. 2005, ApJ, 631, 351
Lee, J.-E., Evans, N. J., II, Shirley, Y. L., & Tatematsu, K. 2003, ApJ, 583, 789
Lee, J.-E., Evans, N. J., II, Shirley, Y. L., & Tatematsu, K. 2003, ApJ, 631, 351
Lee, J.-E., Farquhar, P. A., & Willacy, K. 1997, A&A, 312, 585
Myers, P. 2005, ApJ, 623, 280
Ohashi, N., Hayashi, M., Ho, P. T. P., Momose, M., Tamura, M., Hirano, N., & Sargent, A. I. 1997, ApJ, 488, 317
Pavlyuchenkov, Ya. N., & Shustov, B. M. 2004, Astron. Rep., 48, 315
Rawlings, J. M. C., & Yates, J. A. 2001, MNRAS, 326, 1423
Redman, M. P., Kato, E., Rawlings, J. M. C., & Williams, D. A. 2004, MNRAS, 352, 1365
Schöier, F. L., van der Tak, F. S., van Dishoeck, E. F., & Black, J. H. 2005, A&A, 432, 369
Semenov, D., Wiebe, D., &Henning, Th. 2004, A&A, 417, 93
Shematovich, V. I., Wiebe, D. S., Shustov, B. M., & Li, Z.-Y. 2003, ApJ, 588, 894
Shirley, Y. L., Nordhaus, M. K., Gruveich, J. M., Evans, N. J., II, Rawlings, J. M. C., & Tatematsu, K. 2005, ApJ, 632, 982
Simon, M., et al. 1995, ApJ, 443, 625
Tafalla, M., Marrone, D., Myers, P. C., Caselli, P., Bachiller, R. & Benson, P. J. 1998, ApJ, 504, 900
Tafalla, M., Myers, P. C., Caselli, P., & Walmsley, C. M. 2004, A&A, 416, 191
Tafalla, M., Myers, P. C., Caselli, P., Walmsley, C. M., & Comito, C. 2002, ApJ, 569, 815
Turner, B. E. 1995, ApJ, 449, 635
———. 1996, ApJ, 468, 694
Turner, B. E., Lee, H.-H., & Herbst, E. 1998, ApJS, 115, 91
Turner, B. E., Pirogov, L., & Mihm, Y. C. 1997, ApJ, 483, 235
van der Tak, F. F. S., Caselli, P., & Ceccarelli, C. 2005, A&A, 439, 195
Vázquez-Semadeni, E., Kim, J., Shadmehri, M., & Ballesteros-Paredes, J. 2005, ApJ, 618, 344
Whitworth, A. P., & Ward-Thompson, D. 2001, ApJ, 547, 317
Wiebe, D., Semenov, D., & Henning, Th. 2003, A&A, 399, 197
Williams, J. P., Myers, P. C., Wilner, D. J., & di Francesco, J. 1999, ApJ, 513, L61