MODELING THE PHYSICAL STRUCTURE OF THE LOW-DENSITY PRE-PROTOTOSTELLAR CORE LYND'S 1498

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ABSTRACT

Pre-protostellar cores likely represent the incipient stages of low-mass (≈1 M⊙) star formation. Lynds 1498 is a pre-protostellar core (PPC) and was one of the initial objects toward which molecular depletion and differentiation was detected. Despite the considerable scrutiny of L1498, there has not been an extensive study of the density and temperature structure as derived from radiative transfer modeling of dust continuum observations. We present deep SCUBA observations of L1498 at 850 and 450 μm, high-resolution BEARS maps of the N2H+ 1 → 0 transition, Caltech Submillimeter Observatory observations of the N2H+ 3 → 2 transition, and Green Bank Telescope observations of the C3S 4 → 3 transition. We also present a comparison of derived properties between L1498 and nearby PPCs that have been observed at far-infrared and submillimeter wavelengths. The L1498 continuum emission is modeled using a one-dimensional radiative transfer code that self-consistently calculates the temperature distribution and calculates the spectral energy distribution and intensity profiles at 850 and 450 μm. We present a more realistic treatment of PPC heating that varies the strength of the interstellar radiation field (sISRF) and includes attenuation of the ISRF due to dust grains at the outer radius of the core, AV. The best-fit model consists of a Bonner-Ebert sphere with a central density of (1–3) × 104 cm−3, R0 ≈ 0.29 pc, 0.5 ≤ sISRF ≤ 1, AV ≈ 1 mag, and a nearly isothermal temperature profile of ≈10.5 K for OH8 opacities. C3S emission shows a central depletion hole, while N2H+ emission is centrally peaked. We derive a mean N2H+ abundance of 4.0 × 10−10 relative to H2 that is consistent with chemical models for a dynamically young yet chemically evolved source. The observed depletions of C3S and H2CO, the modest N2H+ abundance, and a central density that is an order of magnitude lower than other modeled PPCs suggests that L1498 may be a forming PPC. Our derived temperature and density profile will improve modeling of molecular line observations that will explicate the core’s kinematical and chemical state.

Subject headings: ISM: clouds — ISM: individual (L1498) — stars: formation

1. INTRODUCTION

Pre-protostellar cores (PPCs or starless cores) are thought to represent the initial stages of low-mass (M < few M⊙) star formation. PPCs are identified with dense molecular cores (n ≥ 104 cm−3) that lack evidence for an internal heating source. Their column density is traced by dust continuum emission (Ward-Thompson et al. 1994, 1999; Shirley et al. 2000; Tafalla et al. 2002) and nitrogen-bearing molecular tracers such as NH3 and N2H+ (Myers & Benson 1983; Jijina et al. 1999; Caselli et al. 2002b; Crapsi et al. 2005). It is important to characterize their physical structure (density, temperature, kinematical, and chemical) to constrain the initial conditions of low-mass star formation. It is also important to understand the evolution of the physical structure of PPCs to trace the evolution of a nascent protostar.

Lynds 1498 is a nearby molecular core (D = 140 pc) located in the west-central portion of the Taurus molecular cloud (see Cambrésy 1999). L1498 was classified as a pre-protostellar core by its submillimeter dust emission and lack of an Infrared Astronomical Satellite detection at 100 μm (Ward Thompson et al. 1994). The relatively weak submillimeter dust emission indicated that L1498 was a low-density core.

L1498 has been extensively studied with molecular line observations and using theoretical chemical modeling (Rawlings et al. 2002b; Crapsi et al. 2005).
et al 1992; Taylor et al 1996). L1498 was initially identified kinematically as a core potentially on the verge of protostellar collapse (Zhou et al. 1994). Subsequent molecular line observations have shown dramatic evidence for the freezing of gas-phase molecules onto dust grains (e.g., H₂CO, CS, CCS, and C¹⁴O) (Wang 1994; Lemme et al. 1995; Kuiper et al. 1996; Willacy et al. 1998; Tafalla et al. 2004); as a result, many molecular species cannot reliably trace the densities in the center of the core. Prominent exceptions are the nitrogen-bearing molecules NH₃ and N₂H⁺, which resist depletion (Flower et al. 2005). Even though NH₃ and N₂H⁺ remain in the gas phase in cold, dense molecular cores, the optical depth, gas temperature, and abundance profile must be reliably determined in order to accurately calculate the density structure of the core.

Optically thin dust emission at submillimeter wavelengths is a good tracer of temperature and density since the specific intensity is proportional to the integral of density, opacity, and Planck function along a line of sight,

\[ I_ν = \frac{2\mu m}{c^2} \int_0^{∞} \frac{\kappa_ν(s) m(s)}{\exp[hu/kT(s)] - 1} ds \]  

(Adams 1991; Shirley et al. 2003). Knowledge of the temperature and density structure is essential to a correct interpretation of chemical and kinematic models of L1498. Previous dust continuum studies of PPCs used radiative transfer models to constrain the density and temperature structure of the cores (e.g., Evans et al. 2001; Zucconi et al. 2001; Stamatellos & Whitworth 2004). The density structures are well characterized by Bonner-Ebert (BE) spheres: pressure-bounded, isothermal solutions to the equations of hydrostatic equilibrium that do not include the effects of magnetic fields or turbulence. A general picture of the initial stages of low-mass star formation involves the evolution of a BE sphere from low central density to high central density, perhaps retarded by magnetic pressure, until a central hydrostatic core develops. If we wish to understand the beginning of this process, we must identify and study low-density PPCs.

In this paper we present deep submillimeter maps of L1498 (§ 2.1) with radiative transfer modeling that includes a more sophisticated treatment of the heating of the PPC (§ 3). The results of dust continuum modeling are discussed in § 4. A comparison between the derived properties from dust continuum observations of PPCs that were observed with ISO (Infrared Space Observatory) and SCUBA (Submillimeter Common-User Bolometric Array) is discussed in § 4.1.2. We also present the highest resolution single-dish N₂H⁺ and C₃S maps of L1498 (§§ 2.2 and 2.3) with analysis of variations in the column density, abundance, and velocity (§§ 4.2 and 4.3).

2. OBSERVATIONS

2.1. SCUBA Continuum Observations

2.1.1. Reduction

L1498 was observed simultaneously at 850 and 450 μm with SCUBA on the 15 m James Clerk Maxwell Telescope during the nights of 1998 August 29 and 30. A total of 50 jiggle maps were made toward the source, each map consisting of four 64 point jiggle maps with 256 s of on-source integration time. The total on-source integration time was 3.55 hr. Previous spectral line maps showed that L1498 is extended in a southeast to northwest direction; therefore, the chop angle was set to a constant position angle of 20° with a 120° chop throw to chop perpendicular to the major axis of the core. Nonazimuthal chopping results in a slight reduction in signal-to-noise ratio (S/N) in the map since a symmetrical chopping pattern does not lie at constant air mass. A preliminary map made in 1998 April showed that the source was detected to the edge of a single 64 point jiggle map field of view (2″). Therefore, the map was extended using three offset five-pointing maps, each with 30″ spacing (see Fig. 1a). The five-pointing maps were centered at (0°, 0°), (+30°, −30°), and (−30°, +30°) from the central coordinates of \( \alpha = 4°10'525" \), \( \delta = +25°9'55" \) (J2000.0). The final maps span ±140″ in right ascension and declination.

Each map was reduced using the standard SURF (SCUBA User Reduction Facility) reduction routines (Jenness & Lightfoot 1997). Each 64 point jiggle map was flat-fielded and corrected for chop throw, extinction, and sky noise. The 450 μm images were reduced using a set intensity scale to ensure consistent identification of improper sky-noise subtraction. The telescope pointing was checked every hour. The largest pointing shift was 2″; therefore, the standard pointing offsets from the five-pointing maps were used to shift and add together the individual maps.

Sky dips at 850 and 450 μm were performed every hour during both nights. These sky dips are compared to the opacity measured every 10 minutes at 225 GHz (\( \tau_{CSO} \)) and 350 μm from tippers located at the Caltech Submillimeter Observatory. The \( \tau_{CSO} \) data were only available for the night of August 30. Using the relationship derived by Archibald et al. (2002) between \( \tau_{CSO} \) and the sky-dip–determined opacity at 850 μm (\( \tau_{850} \)), \( \tau_{850} = (3.99 ± 0.02) \tau_{CSO} - (0.004 ± 0.001) \), we found excellent agreement between our sky dips and the scaled 850 μm opacity (Fig. 2). Therefore, we use the scaled \( \tau_{CSO} \) values to correct for the 850 μm opacity in individual jiggle maps on the night of August 30. We linearly interpolated between 850 μm sky dips for the night of August 29.

Since the sky opacity at 350 and 450 μm is very sensitive to short-term variations in atmospheric precipitable water vapor, we used the tipper opacity at 350 μm to monitor the variability of \( \tau_{450} \) between the hourly sky dips. We found an average ratio of \( \tau_{450} \) sky dips to \( \tau_{450} \) sky dips of 0.71 ± 0.07 for both nights. The 450 μm opacity was corrected for each jiggle map using the scaled \( \tau_{450} \) opacity interpolated from the tipper measurements bracketing each jiggle map.

2.1.2. Images

The reduced maps are shown in Figure 1. L1498 was detected at both wavelengths with a peak S/N of 18 and 13 for the 850 and 450 μm maps, respectively. The contours are spaced by 3 σ for both images. The submillimeter images are characterized by an amazingly flat intensity plateau. A 1200 μm continuum map, smoothed to 20″ resolution (Tafalla et al. 2004), is also shown for comparison. The FWHM intensity contour of the 1200, 850, and 450 μm maps are very similar and well fitted by an ellipse with a major axis \( (a) \) of 197″, minor axis \( (b) \) of 108″, and position angle of 122°. The 850 and 450 μm ellipses have similar centroids (+11″, −16″) with an uncertainty of ±4″ with respect to the pointing center (§ 2.1.1). The half-width at half-maximum radius of the core, defined by the geometric mean of the major and minor axes \( [R_{1/2} = (ab)^{1/2}/2, ] \) is 73″. While this radius may be used as a representative size of the core, it is important to realize that the FWHM contour is asymmetric, with an aspect ratio \( (a/b) \) of 1.8. Furthermore, the 1200 and 850 μm maps are non-axysymmetric, with a sharper gradient in the intensity along the northeast edge than the southwest edge.

The ISO map at 170 μm is also shown in Figure 1b (Ward-Thompson et al. 2002). This is the shortest wavelength at which the far-infrared emission has been observed to peak on the core;
Fig. 1.—(a) Jiggle map pointing centers are plotted with the chop direction. The (0, 0) position is $\alpha = 4^h 10^m 52^s, \delta = +25^\circ 9^\prime 55^\prime\prime$ (J2000.0). Contour maps of L1498 at (b) 170 $\mu$m (Ward-Thompson et al. 2002), (c) 450 $\mu$m, (d) 850 $\mu$m, (e) 1200 $\mu$m (Tafalla et al. 2004), and (f) $T(J_1)$ of N$_2$H$^+$ $J = 1 \rightarrow 0$. The contour levels are as follows (lowest contour and contour increment in percentage of the peak flux): N$_2$H$^+$, 17% (3 $\sigma$); 1200 $\mu$m, 20% (3 $\sigma$), increasing by 20%; 850 $\mu$m, 20% (3 $\sigma$), increasing by 20%; 450 $\mu$m, 25% (3 $\sigma$), increasing by 25%; and 170 $\mu$m, 2.0–3.6 Jy pixel$^{-1}$ increasing by 0.2 Jy pixel$^{-1}$. The 170 $\mu$m image is plotted on a scale that is twice as large as the other images.
ISO 90 μm observations detect a more diffuse emission peak approximately 3' south of the submillimeter centroid. The scale of the 170 μm map is ±300", twice the scale in the (sub)millimeter maps. The ISO beam was very large (≈80") at 170 μm; therefore, the map does not show the nonaxisymmetric structure observed on smaller scales at 850 and 1200 μm. The core is elongated, but with a slightly different position angle on larger scales (P.A. ~ 150°). Far-infrared emission is detected on very large scales, up to 300" (42,000 AU) from the centroid of the submillimeter emission.

Azimuthally averaged, normalized radial profiles of the 850, 450, and 1200 μm maps were calculated. The images were re-binned to pixels with half-beam spacing (7" at 850 μm and 3.75" at 450 μm) corresponding to the Nyquist sampling limit in the map. The centroid was chosen to be the average of the 850 and 450 μm centroids (+11", -16"). The 1200 μm profile was binned at 10" since the image was smoothed by a 20" Gaussian (Tafalla et al. 2004). The flat intensity plateau has the same extent in all of the profiles.

Since L1498 is a very elongated core, azimuthally averaged profiles will be weighted toward a flatter intensity profile (see Jørgensen et al. 2002). This effect may be quantified by considering the normalized profile within sectors centered on the major and minor axes. If the sector centered on the major axis is chosen with the opening angle given by

$$\theta_{maj} = 2 \tan^{-1}(b/a),$$

where $b/a$ is the ratio of the minor to major axes ($\theta_{min} + \theta_{maj} = \pi$), then the areas of sectors are equal. The azimuthally averaged and sector-averaged profile will be modeled separately in § 3.

### 2.1.3. Calibration and the Spectral Energy Distribution

Uranus and AFGL 618 were observed on August 29 and 30 as flux calibrators and for beam profiles at 850 and 450 μm. The total flux of Uranus was 74.0 Jy at 850 μm and 195.5 Jy at 450 μm. The apparent diameter of Uranus was 3″7, effectively making Uranus a point source at both wavelengths (see Shirley et al. 2000 for an analysis of Uranus’s finite size on the beam size). The flux of AFGL 618 was assumed to be 4.56 ± 0.17 Jy beam^−1 at 850 μm and 11.2 ± 1.4 Jy beam^−1 at 450 μm (SCUBA Secondary Calibrator World Wide Web page^4). Since we are interested in the total flux observed toward L1498, we calibrated the flux in

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4 See http://www.jach.hawaii.edu/JCMT/continuum/calibration/sens/secondary_2004.html.
TABLE 1  
L1498 Spectral Energy Distribution

| $\lambda$ (\(\mu\)m) | $S_\nu$ (Jy) | $\theta$ (arcsec) | Reference |
|-----------------------|-------------|------------------|-----------|
| 90……………….. | ⩽1.0 | 150 | 1 |
| 170……………….. | 10.4 ± 3.2 | 150 | 1* |
| 200……………….. | 15.2 ± 4.8 | 150 | 1* |
| 450……………….. | 0.700 ± 0.080 | 18 | 2 |
| 450……………….. | 2.69 ± 0.59 | 40 | 3 |
| 450……………….. | 14.70 ± 2.42 | 120 | 3* |
| 800……………….. | 0.120 ± 0.018 | 18 | 2 |
| 850……………….. | 0.376 ± 0.021 | 40 | 3 |
| 850……………….. | 2.30 ± 0.08 | 120 | 3* |
| 1100……………….. | 0.035 ± 0.006 | 18 | 2* |
| 1200……………….. | 0.016 ± 0.004 | 12 | 4* |
| 1300……………….. | 0.010 ± 0.003 | 12 | 2* |

* Fluxes used in calculation of $\chi^2_{\text{SED}}$.

Table 1. The uncertainty on the calibration factor was calculated not strong enough to be used for extended beam profiles ($V$ is the total voltage observed within the aperture ($V$), and $\theta$ is the calibration factor. The fluxes for L1498 are included in the source properties in Table 1. The uncertainty on the calibration factor was propagated by the errors using

$$\sigma^2 = S^2 \left[ \frac{(\sigma^2/\nu)^{\text{running avg.}} + (\sigma^2/\nu^2)_{\text{source}} + \sum_{\text{pixels}} A^2 \sigma^2 L}{C^2 V^2} \right],$$

where $S_\nu$ is the flux density (Jy), $C$ is the calibration factor (Jy/V), $V$ is the total voltage observed within the aperture ($V$), and $A_i$ is the area of a pixel included within the aperture.

The SCUBA beam profiles were determined using observations of Uranus at 850 and 450 \(\mu\)m. Uranus was observable only at the beginning of our observing shift and only at high air mass (see $z \approx 2$). The Uranus profile cannot be traced beyond 60\(\mu\)m at 450 \(\mu\)m and beyond 50\(\mu\)m at 450 \(\mu\)m. Unfortunately, AFGL 618 is not strong enough to be used for extended beam profiles ($\theta > 25^\circ$). The Uranus profiles are similar to the average Uranus beam profile determined from maps made in 1998 April (Shirley et al. 2000). Since all of our observations were made during the morning observing shift (1:30–9:30 A.M. HAST), the dish should have cooled sufficiently such that the beam shape is stable. Significant trends were seen in the 1998 April beam maps observed during the morning observing shift; therefore, we feel justified in using the Uranus beam profile for all second-shift observations.

The spectral energy distribution (SED) was constructed from our SCUBA observations and a search of the literature (Table 1). The SED includes previous (sub)millimeter observations by Ward-Thompson et al. (1994), as well as ISO far-infrared observations at 170 and 200 \(\mu\)m (Ward-Thompson et al. 2002). The inclusion of the far-infrared fluxes is extremely important for bracketing the peak of the SED.

2.2. \(N_2\)H$^+$ Observations

2.2.1. BEARS

Lynds 1498 was mapped with BEARS, a 25 beam double-sideband SIS receiver array that operates at 3 mm (Sunada et al. 2000), on 2004 April 26 at the Nobeyama Radio Observatory 45 m telescope. The average beam size within the array is 17.8 at 93.17 GHz (Tatematsu et al. 2004); however, each beam in the array is separated by slightly more than 2$\theta_{\text{WHM}}$ (41'). We observed the source using a dithered 4 × 4 position-switched grid on the sky spaced by 20.55. The array was rotated by ±90' after each dithered map to change relative beam positions with respect to the source. A digital autocorrelator back end with 37.8 kHz resolution ($\approx 0.12$ km s$^{-1}$) was used. BEARS was tuned to the frequency of the strongest hyperfine component (93.1737767 GHz $J_F = 123 \rightarrow 122$; see the Appendix). The resulting \(N_2\)H$^+$ map has 100 spectra separated at nearly full-beam resolution and represents the highest resolution \(N_2\)H$^+$ spectrum obtained toward L1498.

BEARS viewing was consistent across the array with an average $T_{\text{sys}}$ of 220 K. The intensity was calibrated for the receiver sideband ratio by observing the bright high-mass star-forming core, G40.50+2.54, with every beam in the BEARS array and the Nobeyama facility single-sideband S100 receiver. Spectra from the S100 receiver were calibrated on the $T_R$ scale using the standard chop-switch method (Penzias & Burrus 1973). The calibration source was observed twice with the array rotated by 90° to minimize systematic calibration errors. The resulting calibration is good to approximately 20%. The spectra were converted to the $T_R$ scale by assuming that the BEARS side lobes are negligible and using $\eta_{\text{ms}} = 0.51$ (Tatematsu et al. 2004).

Pointing observations were performed every hour using the SiO $v = 1, J = 1 \rightarrow 0$ maser transition toward NML Tau. The largest pointing shifts were 6° with average corrections of 4° and 3° in azimuth and elevation, respectively. The weather was clear with winds typically below 6 m s$^{-1}$ during L1498 observations. Conditions were good for \(N_2\)H$^+$ observations, and the absolute pointing errors are small compared to the BEARS beam size.

The data were baselined, summed, calibrated, and interpolated onto a regular spatial grid using the NewStar$^5$ software package of the Nobeyama Radio Observatory. The reduced maps were written out to the group FITS format (Greisen & Harten 1981) and read into AIPS++. Fitting of the hyperfine components were performed with Glish scripts in AIPS++. The group FITS data cube was also written to a series of ASCII files for calculation of baseline rms and the integrated intensity.

2.2.2. CSO Observations

The \(N_2\)H$^+$ $J = 3 \rightarrow 2$ transition was observed in position-switched mode toward the centroid continuum position of Lynds 1498 with the CSO on the night of 2004 July 24. The 230 GHz double sideband SIS receiver (Kooi et al. 1992) with a 50 MHz AOS back end were used. The average $T_{\text{sys}}$ was approximately 430 K. The spectral resolution was 147 kHz (0.15 km s$^{-1}$) after smoothing to the actual resolution of the spectrometer (three channels). The receiver was tuned to the JPL line catalog frequency, 279.511701 GHz, for \(N_2\)H$^+$ $J = 3 \rightarrow 2$; this frequency is within 160 kHz of a blend containing the strongest hyperfine component (279.5118631 GHz, $J_F = 3 45 \rightarrow 2 34$; L. Dore 2004, private communication).

Pointing and main-beam calibration were performed on Venus. The main-beam efficiency was determined to be $\eta_{\text{mb}} = 0.60 \pm 0.06$ at 279 GHz for a 26'8 beam. The pointing was consistent with a largest pointing shift of less than 3° in both azimuth and zenith angle during the observations. The spectra were

$^5$ See http://www.nro.ac.jp/nro45mrt/NEW45m/NewStar/index.html.
smoothed, baseline, and summed using the CLASS software package (Buisson et al. 2002). L1498 was observed for a total of 10 minutes on-source. The final spectrum has a baseline rms of $\sigma(T_B) = 45$ mK.

2.3. C$_3$S Observations

The C$_3$S $J = 4 \rightarrow 3$ transition at 23.1229820 GHz was mapped using the 100 m Robert C. Byrd Green Bank Telescope (GBT) on the nights of 2005 March 14 and 15. The spectrometer was set up to observe four intermediate frequencies (IFs) with two polarizations at 6.125 kHz resolution (0.079 km s$^{-1}$) using a single beam of the K-band receiver. The four IFs were centered on the C$_3$S $^{33}$S, $^{13}$CCCS, and C$_{13}$CCS $J = 4 \rightarrow 3$ transitions. The observations were frequency switched by $+4$ MHz at a frequency of 4 Hz. Initially, a pointed map was made using a 7 × 5 grid, with 60 s integration time per pointing, spaced at 33" (full-beam spacing) centered on the SCUBA dust continuum centroid position. Three smaller 3 × 3 maps with 1675" spacing were centered at the offsets (0, 0), (+49.5", −16.5"), and (−49.5", +16.5") with respect to the dust continuum centroid.

The raw frequency-switched spectra were folded and calibrated on the $T_B$ scale using the DISH software package within AIPS++. The data were then written to ASCII files where opacity corrections were applied ($T_B$) and RR and LL polarizations were summed with 1/$\alpha_{\text{baseline}}$ weighting. The opacity at 23.1 GHz was determined using the weather model of R. Maddalena (2005, private communication), which averages the precipitable H$_2$O measurements from three nearby towns (Elkins, Hot Springs, and Lewisburg, West Virginia). The average zenith opacity was $\tau_{72.1} = 0.049 \pm 0.002$ on March 14 and $\tau_{72.5} = 0.106 \pm 0.002$ on March 15 during the observations. Final conversion to the $T_{mb}$ scale was achieved using position-switched scans of the quasars 3C 48 and 3C 286. Unfortunately, the aperture efficiency was not properly determined at 23.1 GHz on March 14; therefore, we have linearly interpolated from measurements made at 9 GHz (Langston et al. 2004) and 46 GHz (2005 March 18) to find $n_{\text{H$_2$}} = 0.54 \pm 0.11$. The GBT has an active surface that mitigates variations in the aperture efficiency with elevation and temperature. We have applied a 20% systematic uncertainty to account for these effects. The main-beam efficiency is then $\beta_{\text{mb}} = 0.74 \pm 0.15$. The $T_{mb}$ temperature scale may be compared with observations on the $T_B$ scale if the side-lobe pickup is negligible (see Rohlfs & Wilson 2000, p. 194); this is a reasonable assumption for the K-band receiver on the GBT.

Pointing and focusing were performed once per hour. The sky was clear and the wind was less than 4 m s$^{-1}$ on both March 14 and March 15 during the observations. Since the observations were performed at nighttime, the temperature variation was small ($\Delta T < 1.9^\circ$C). The pointing and focus were very stable with a largest pointing shift of $7\arcsec$.

3. MODELS

3.1. One-dimensional Continuum Radiative Transfer

The dust continuum observations are modeled using the one-dimensional radiative transfer code CSDUST3 (Egan et al. 1988), which self-consistently calculates the temperature distribution for a given density distribution, dust opacity, and interstellar radiation field (ISRF). CSDUST3 simulates anisotropic scattering, which may affect the temperature distribution in the outer regions of the core, a feature that is not present in the radiative transfer code of Ivezic et al. (1999). Once the temperature distribution has been calculated, the intensity profiles at 850 and 450 $\mu$m are created by convolving the model intensity profiles with the measured beam shape and simulating chopping. The model SED is also calculated and compared to the observed fluxes. Simultaneous modeling of the intensity profiles and SED result in nearly orthogonal constraints on the shape of the density profile and the total mass for a given opacity choice (see Shirley et al. 2002). The modeling procedure for PPCs is described in more detail in Evans et al. (2001).

We use a family of BE spheres (Ebert 1955; Bonnor 1956) to attempt to fit the L1498 observations since BE spheres were used by Evans et al. (2001) to successfully fit submillimeter continuum observations of other PPCs. BE sphere are solutions to the pressure-bounded equations of hydrostatic equilibrium that ignore the effects of magnetic fields and turbulence. The BE density profile is flat in the inner regions and asymptotically approaches $r^{-2}$ in the outer regions. The size of the flat density plateau decreases as the central density of the BE sphere increases (density FWHM = $R(\frac{1}{2}n_c) \sim 1/(n_c)^{1/2}$; Chandrasekhar & Wares 1949). The temperature structures are characterized by decreasing dust temperature from outside to inside due to extinction of heating radiation from the ISRF. The temperature gradient from outside to inside increases for more centrally condensed BE spheres. Isothermal BE spheres may be parametrized by a single variable, the central density $(n_c)$ for a fixed temperature (10 K). Evans et al. (2001) showed that nonspherical correction to the shape of the BE profile was negligible for profiles used to describe PPCs. Isothermal BE spheres are calculated with central densities ranging from log $n_c = 3.5$ to log $n_c = 7.0$. Since L1498 is embedded within a larger molecular cloud with $A_V \approx$ 1–3 mag (Cambresy 1999), the power-law portion of the BE profile is not continued below $10^3$ cm$^{-3}$.

Since PPCs lack an internal source, the heating is from the ISRF. The spectrum of the ISRF is derived from COBE (Cosmic Background Explorer) data (Black 1994) with ultraviolet wavelength constructed using an empirical description of the radiation field that reproduces the ISRF of Draine (1978; see van Dishoeck 1988). This spectrum is the same as used in the models of Evans et al. (2001). The shape of the ISRF spectrum may be modified by two effects: the intensity of the ISRF (UV to far-infrared) varies at different locations throughout the Galaxy; and the short-wavelength intensity of the ISRF (UV to near-infrared) may be modified by dust extinction (see Fig. 3). The scaling of the intensity is parameterized by $s_{\text{ISRF}}$, while the amount of dust extinction at the core’s outer radius is parameterized by $A_V$. We use dust opacities appropriate for the general interstellar medium (ISM) (graphite- and silicate-based grains; Draine & Lee 1984) to modify the ISRF spectrum. The combination of scaling the ISRF and extinction at the outer core radius is a more realistic description of the incident intensity than has been used in previous models of PPCs.

The reprocessing of the ISRF is strongly affected by the dust opacity within the core. We model the emission using eight different opacity models (see Table 2 and Fig. 3). The opacities of Ossenkopf & Henning (1994) are derived from models of grains that have coagulated for $10^5$ yr and that have acquired varied depths of ice via gas adsorption: OH2 no-ice mantles, OH5 thin ice mantles, and OH8 thick ice mantles (cols. [2], [5], and [8], respectively of Table 5 of Ossenkopf & Henning 1994). The opacities of Mathis et al. (1983) are derived from an empirical fit to dust properties. We also test the opacities of Weingartner & Draine (2001), which describe silicate and
Fig. 3.—Top: Specific intensity of the ISRF with variations in $s_{\text{surf}}$ and $A_v$. Bottom: The dust mass opacities (total gas + dust mass) used in dust models. A $M_{\text{gas}}/M_{\text{dust}} = 100$ was assumed.

| Table 2: Dust Opacity Properties |
|----------------------------------|
| Model Name | Description | $\beta_{\text{sub-mm}}$ | $\kappa_v(850)$ | Reference |
|------------|-------------|-----------------|----------------|-----------|
| Draine-Lee | Silicates + carbonaceous grains | 2.0 | 0.003 | 1 |
| WD3        | Silicate + carbonaceous + PAH ISM fit | 1.8 | 0.005 | 2 |
| WD4        | Silicate + carbonaceous + PAH ISM fit | 1.6 | 0.006 | 2 |
| Pollack1   | Silicates + organic C | 2.2 | 0.004 | 3 |
| MMP        | Empirical fit to ISM | 2.3 | 0.030 | 4 |
| OH2        | Coagulated for $10^5$ yr, no ice mantles | 1.3 | 0.034 | 5 |
| OH3        | Coagulated for $10^5$ yr, thin ice mantles | 1.8 | 0.018 | 5 |
| OH4        | Coagulated for $10^5$ yr, thick ice mantles | 1.9 | 0.022 | 5 |

* Here $\kappa \sim \nu^\beta$, where $\beta_{\text{sub-mm}}$ is determined by a linear regression over $\nu \in [350 \ \mu \text{m}, 1300 \ \mu \text{m}]$.

References.—(1) Draine & Lee 1984; (2) Weingartner & Draine 2001; (3) Pollack et al. 1994; (4) Mathis et al. 1983; (5) Ossenkopf & Henning (1994).
graphite grains, including a population of small grains and polycyclic aromatic hydrocarbons (PAHs), appropriate for the ISM. The opacities of Pollack (1994) describe an alternative grain composition based on silicate grains (olivine and orthopyroxene), iron compounds (troilite and metallic iron), and various organic C compounds. The mass opacity at 850 \(\mu\)m, \(\kappa_m(850)\), varies by more than 1 order of magnitude between the opacity models (Table 2). A constant opacity with radius (\(R^{2/3}\)) is assumed throughout the core.

### 3.2. L1498 Model

A total of 770 radiative transfer models were run that vary \(n_c\), \(R_o\), \(s_{isrf}\), \(A_V\), and \(\kappa_V\). For each model, the reduced \(\chi^2\), given by

\[
\chi^2_r = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{\chi^2_{obs,i} - \chi^2_{mod,i}}{\sigma_{obs,i}^2} \right)^2,
\]

was calculated for the 850 and 450 normalized intensity profiles and for the SED. A \(\chi^2\) is also calculated for the flux in a 120\(^\prime\) aperture at 850 \(\mu\)m. The best-fit models are determined by finding the intersection of the sets of \(\chi^2_r\) for each quantity within the typical range \(\chi^2_r \in [0, 1]\). Since the error bars of the intensity profiles include azimuthal variations, as well as intensity uncertainties, and since the error bars of the SED include an estimate of systematic uncertainty, it is possible that \(\chi^2_r < 1\).

The first grid of models varies \(n_c\) and \(R_o\), for \(s_{isrf} = 1, A_V = 1\), and OH5 opacities (see Fig. 4, top row). The best-fit model to the azimuthally averaged, normalized intensity profiles is \(n_c = 1 \times 10^4\) cm\(^{-3}\). If we recalculate the \(\chi^2_{mod}(850)\) using the sector-averaged, normalized intensity profiles, then a wider range of central densities fit, \(n_c = 1+2.0 \times 10^4\) cm\(^{-3}\) (see Fig. 5d, dashed profiles). The best-fit central density does not strongly depend on the size of the outer radius; radii from 30,000 to 60,000 AU are well fitted. Since emission is clearly detected 100\(^\prime\) from the core.

![Fig. 4.— Color-coded \(\chi^2_r\) are plotted for the radiative transfer model grid for OH5 dust; \(\chi^2_{mod}(850)\) and \(\chi^2_{mod}(450)\) are plotted for a grid of \(n_c\) and \(R_o\) (top row); \(\chi^2_{SED}\) (middle row) and \(\chi^2_{S(850)}\) (bottom row) are plotted for grids of \(s_{isrf}\) and \(A_V\) with outer radii of 20,000, 40,000, and 60,000 AU. Note that red points represent the best-fit \(\chi^2_r\).](image-url)
center of the SCUBA maps, $R_o$ must be greater than 15,000 AU. Furthermore, the ISO 170 $\mu$m image (Ward-Thompson et al. 2002) detects dust emission at radii greater than 200" (28,000 AU) from the center; therefore, the best-fit model $R_o$ are consistent with submillimeter and far-infrared observations.

Since the SCUBA continuum centroid and 1.2 mm continuum peaks are different by 31", we have also compared the dust model intensity profiles to azimuthally averaged intensity profiles centered at the 1.2 mm peak. The best-fit model is $n_c = (1-3) \times 10^4$ cm$^{-3}$ BE spheres. This agreement with the best-fit models toward the SCUBA centroid position is a result of L1498’s very flat submillimeter intensity profile, which does not vary strongly with different central positions within $\pm 30"$ of the SCUBA continuum centroid (see Fig. 1).

The second grid of models varies $s_{\text{surf}}$ and $A_V$ for the $n_c = 1 \times 10^4$ BE sphere, $R_o = 20,000, 40,000,$ and 60,000 AU, and the different opacity models. The $s_{\text{surf}}$ and $A_V$ are varied on non-linear grids with values between [0.2, 10] and [0.1, 10], respectively. The middle and bottom rows of Figure 4 display $\chi^2(S_{850})$ for OH5 dust opacities. Changing $s_{\text{surf}}$ and $A_V$ has a negligible effect on the best-fit normalized intensity profiles; the $n_c = 1 \times 10^4$ BE sphere is the best fit for all opacity models.

Previous dust continuum models relied only upon submillimeter fluxes to constrain the heating properties of the ISRF. However, $\chi^2(S_{850})$ alone does not strongly constrain $s_{\text{surf}}$ and $A_V$ (Fig. 5, bottom row); a wide range of values provide good fits. When we include the complete SED, the $s_{\text{surf}}$ is constrained to be $\leq 2$ for the best-fit models (Fig. 5, middle row).

The only dust opacity models that provide satisfactory fits to $I_{850}, S_{850},$ and the SED are the Ossenkopf & Henning opacities. None of the model $\chi^2(S_{850})$ for WD3, WD4, Pollack 1, or Draine-Lea opacities are below 6. These models underestimate the fluxes observed at far-infrared through millimeter wavelengths for the $1 \times 10^4$ cm$^{-3}$ BE sphere. This is not surprising since the mass opacity at 850 $\mu$m for these models is 3–8 times smaller than the mass opacity of OH8 dust. Furthermore, Ossenkopf & Henning opacities for grains with ice mantles (OH5 and OH8) provide better fits to $S_{850}$ and the SED than grains without ice mantles (OH2). The OH2 opacities tend to overestimate $S_{850}$ while underestimating the far-infrared fluxes. It is encouraging that the dust opacities for grains with ice mantles provide the best fits since these models are qualitatively consistent with a physical model of L1498 that accounts for the observed gas depletion of species such as CO, H$_2$CO, CS, and CCS.

![Fig. 5.—(a) Dust temperature profile, (b) SED, (c) $I_{850}$ profile, and (d) $I_{450}$ profile for the best-fit models. The Uranus beam profile is shown in the 850 and 450 $\mu$m profile. The sector-average radial profiles at 850 $\mu$m are plotted as dashed-lines in panel d. A distance of 140 pc is assumed (Loinard et al. 2005).](image_url)
The best-fit models from all of the model grids are listed in Table 3 and shown in Figure 5. The models fall into two categories: OH5 opacities with $s_{\text{surf}} \in [1, 2]$ and $A_V \in [4, 8]$; and OH8 and OH5 opacities with $s_{\text{surf}} \in [0.5, 1]$ and $A_V \in [0.5, 2]$. The fluxes and intensity profiles are well fitted at all wavelengths except 1.2 mm for all of the models. All of the best-fit models have an outer radius of 60,000 AU (0.29 pc). Since a large outer radius is preferred, it seems unlikely that the high-$A_V$ models are physical. An optical extinction map of the Taurus molecular cloud limits the large-scale extinction around L1498 to $A_V \lesssim 3$ mag (Cambrésy 1999). Indeed, for $A_V = 6$, the column density of material outside $R_0$ would be $N_{\text{HI}} \approx 1 \times 10^{22}$ cm$^{-2}$; this value is larger than the column density derived from a 1 $\times$ 10$^4$ cm$^{-3}$ BE sphere with $R_0 = 60,000$ AU. We prefer the low-$A_V$ models as the best, most physical fit.

All of the best-fit models are characterized by dust temperatures between 10 and 11.1 K (Fig. 5a). The low-$A_V$, OH5 and OH8 models have temperature gradients of $0.3 < \Delta T_{[0.9]} < 0.5$. These are nearly isothermal temperature profiles compared to previous models of PPCs ($\Delta T_{[0.9]} > 1$ K; e.g., Evans et al. 2001). The low density of L1498 combined with the inclusion of dust attenuation at the outer radius results in the nearly isothermal temperature profiles.

### TABLE 3

**Best-Fit Models**

| $\log n_\text{s}$ (cm$^{-3}$) | $R_0$ (10$^4$ AU) | $s_{\text{surf}}$ | $A_V$ (mag) | $\chi^2_{(T_{\text{bol}})}$ | $\chi^2_{(S_{850})}$ | $\chi^2_{(\text{SED})}$ |
|-----------------------------|------------------|------------------|-------------|------------------|------------------|------------------|
| 4.0.................. | 60.................. | 0.5.................. | 1.0$^a$ OH8 | 0.67.................. | 0.12.................. | 0.84.................. |
| 4.0.................. | 60.................. | 0.5.................. | 4.0 OH5 | 0.52.................. | 0.10.................. | 0.90.................. |
| 4.0.................. | 60.................. | 0.5.................. | 2.0 OH5 | 0.52.................. | 0.26.................. | 0.88.................. |
| 4.0.................. | 60.................. | 0.5.................. | 2.0 OH5 | 0.66.................. | 0.28.................. | 0.90.................. |
| 4.0.................. | 60.................. | 0.5.................. | 1.0 OH5 | 0.68.................. | 0.35.................. | 0.90.................. |
| 4.0.................. | 60.................. | 2.0 .................. | 8.0 OH5 | 0.52.................. | 0.46.................. | 0.97.................. |

*Note.—* Models for which $\chi^2_{(T_{\text{bol}})} \in [0, 1]$ $\cap$ $\chi^2_{(S_{850})} \in [0, 1]$ $\cap$ $\chi^2_{(\text{SED})} \in [0, 1]$.

* Model is consistent with Cambrésy (1999) optical extinction constraint that $A_V \lesssim 3$ mag.

### 4. ANALYSIS

#### 4.1. Derived Properties from Continuum Observations

##### 4.1.1. L1498

The bolometric luminosity was calculated by integrating under the SED of L1498 (Table 1) and is 0.12 $\pm$ 0.02 $L_\odot$, low for a PPC, but not the lowest reported luminosity (see Table 4). The bolometric temperature, the temperature of a blackbody with the same mean frequency as the observed SED (Chen et al. 1995), is 13.9 $\pm$ 3.1 K. This is one of the lowest bolometric temperatures reported for a PPC (see Table 4).

We calculate the mass from the flux at 850 $\mu$m in a 120$''$ aperture and assuming a constant density, isothermal dust temperature, and optically thin emission using

$$M_D(T_d) = \frac{S_{850} D^2}{2 \pi r_{\text{ap}}^2 k_{\nu} T_d^2} \left( \exp \left( \frac{\hbar \nu}{k T_d} \right) - 1 \right).$$

Based on one-dimensional dust radiative transfer models, a dust temperature of 10.5 $\pm$ 0.5 K is used for L1498. The resulting dust mass, $M_D(10.5 \text{ K}) = 0.67 \pm 0.16 \ M_\odot$, for an average of OH5 and OH8 opacities [$\tau_{850} = 0.020 \pm 0.002 \text{ cm}^2 \text{ g}^{-1}$].

### TABLE 4

**Properties of Nearby PPCs Observed with ISOPHOT$^a$ and SCUBA**

| Source | Reference | $D$ (pc) | $a \times b$ (AU x AU) | $R_{1/2}$ (AU) | $L_{\text{bol}}$ (L$_\odot$) | $L_{\text{bol}}/L_{\text{sub-mm}}$ | $T_{\text{bol}}$ (K) | $M_D(10.5 \text{ K})$ (M$_\odot$) |
|--------|-----------|-----------|-----------------------|---------------|---------------------|--------------------------|-----------------|-------------------------------|
| L1498 | 04 10 53.3 | +25 09 39 | 1                     | 140           | 27600 $\times$ 15000 | 10170 1.8 0.12 (0.02) 5 (2) 13.9 (3.2) 0.67 | 15.1 (3.3) 0.67 |
| L1517B | 04 55 18.1 | +30 37 48 | 3                     | 140           | 11600 $\times$ 9700 | 5300 1.2 0.06 (0.01) 18 (9) 15.2 (3.5) 0.67 |
| L1512 | 05 04 08.2 | +32 43 20 | 2                     | 140           | 19000 $\times$ 8500 | 6350 2.2 0.10 (0.02) 7 (4) 15.2 (4.0) 0.53 |
| L1544 | 05 04 17.1 | +25 10 48 | 2                     | 140           | 19000 $\times$ 5700 | 3940 1.9 0.15 (0.02) 5 (2) 13.9 (3.2) 1.06 |
| L183 | 15 54 08.5 | -02 52 32 | 3                     | 150           | 11400 $\times$ 6200 | 4200 1.8 0.09 (0.01) 13 (3) 15.6 (2.5) 0.89 |
| L1709A | 16 30 50.4 | -23 42 05 | 3                     | 125           | 15800 $\times$ 10500 | 6440 1.5 0.09 (0.02) 15.4 (4.9) 0.98 |
| L1689B | 16 34 49.2 | -23 48 07 | 3                     | 125           | 9600 $\times$ 7700 | 4300 1.3 0.13 (0.02) 7 (1) 15.9 (3.7) 0.74 |
| L63 | 16 50 14.4 | -18 06 17 | 3                     | 160           | 12400 $\times$ 7800 | 4920 1.6 0.20 (0.04) 21 (2) 16.4 (5.3) 1.15 |
| B68 | 17 22 39.0 | -23 49 57 | 4                     | 95            | 9500 $\times$ 7500 | 5530 1.3 0.05 (0.02) 5 (2) 14.5 (3.5) 0.50 |
| B133 | 19 06 08.0 | -06 52 52 | 2                     | 200           | 14900 $\times$ 12100 | 6710 1.2 0.37 (0.06) 9 (2) 15.9 (4.0) 1.22 |

*Note.—* Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$ ISOPHOT fluxes from Ward-Thompson et al. (2002).

$^b$ SCUBA 850 $\mu$m continuum FWHM contour centroid in J2000.0 coordinates.

References—(1) This paper; (2) Shirley et al. 2000; (3) CADC SCUBA archive; (4) Bianchi et al. 2003; Lai et al. 2003.
The errors in $M_D$ are propagated from $S_\nu$, $T_d$, and $\tau_c(850)$. L1498’s dust mass is consistent with and slightly lower than previously observed pre-protostellar cores ([$M_D(10.5)$] = 0.9 ± 0.3 $M_\odot$; Table 4).

We also calculate the aperture-averaged column density from the 850 $\mu$m fluxes using

$$N_{H_2} = \frac{2S_\nu c^2}{h\nu^3 \mu m_{H_2} \pi \theta^2_{ap}} \left[ \exp \left( \frac{h\nu}{kT_d} \right) - 1 \right].$$

The column density at the SCUBA continuum centroid is (1.25 ± 0.71) $\times 10^{22}$ cm$^{-3}$ in a $17\arcsec$6 aperture, where errors are propagated in $S_\nu$, $T_d$, and $\tau_c$. This aperture size matches the BEARS beam size, allowing a direct comparison between dust and N$_2$H$^+$ column density (§4.1.2). The column density corresponds to a visual extinction of $A_V = 13$ mag (Whittet 2003). This extinction is comparable to the peak extinction observed using near-infrared extinction mapping toward the low-density PPC, Coalsack G2 ($A_V = 11.5$ mag; Lada et al. 2004). Modeling of the Coalsack G2 extinction profile indicates a peak density of $\approx 10^4$ cm$^{-3}$, corroborating the low density derived for L1498 from our radiative transfer models.

Dust opacities tend to follow a single power law with frequency at submillimeter wavelengths ($\kappa_\nu \propto \nu^{\beta}$, $\lambda \in [350, 1300]$ $\mu$m). The observed dust emissivity index, $\beta$, for a core observed at 850 and 450 $\mu$m is given by

$$\beta(T_d) = \frac{\log(S_{450}/S_{850})}{\log(S_{850}/S_{450})} - 3 + \frac{\log[(\exp(h\nu_{850}/kT_d) - 1)/(\exp(h\nu_{450}/kT_d) - 1)]}{\log(850/450)},$$

where the term in square brackets is the spectral index between 450 and 850 $\mu$m, $\alpha_{450/850}$, and the term in curly braces is the correction for failure of the Rayleigh-Jeans approximation. Assuming a dust temperature of $10.5 \pm 0.5$ K, we find $\alpha_{450/850} = 2.91 \pm 0.61$ and $\beta = 2.44 \pm 0.62$. The spectral index is higher than all of the PPCs observed by Shirley et al. (2000) except for the two cores associated with L1689A. The $\beta$ is larger than the theoretical $\beta$ for dust opacities used in modeling but is consistent, within errors, with all of the dust opacity models except OH2 and WD4 (see Table 2). While OH5 and OH8 opacities give good fits, within error bars, to the $\beta$, they consistently under-estimate the flux at 450 $\mu$m while matching the 850 $\mu$m flux. Sub-millimeter measurements of $\alpha$ and $\beta$ do not discriminate well between opacity models; radiative transfer modeling of the complete SED is a better discriminator.

4.1.2. Comparison with Nearby PPCs

The properties of L1498 may be placed in context by comparing to other PPCs that have been observed with ISO and SCUBA. Table 4 lists observed and derived properties of 10 nearby ($D < 200$ pc) sources. Including the 170 $\mu$m ISOPHOT flux gives at least one flux point on the Wien side of the SED, resulting in a more accurate calculation of $L_{bol}$. Each source SED contains at least three flux points (170, 200, and 850 $\mu$m). We also analyzed the SCUBA 850 $\mu$m images for each source. All of the SCUBA observations are published except for three cores, L183, L1709A, and L63, which were obtained from the CADC SCUBA archive. The reduction procedure for these cores is identical to that described in §2. We have calculated the size, aspect ratio, bolometric luminosity, standard evolutionary indicators ($T_{bol}$ and $L_{bol}/L_{sub-mm}$), and the dust-determined mass from the 850 $\mu$m flux. This is a small sample but probably representative of nearby PPCs. The CADC SCUBA archive contains many more observations of PPCs; however, far-infrared observations are needed to calculate $L_{bol}$.

L1498 is the largest nearby PPC in the sample by 50% and nearly twice as large as the average core size. L1498 also has one of the lowest masses (0.67 $M_\odot$) of the sample. This is consistent with the interpretation that L1498 is a low-density core with a uniquely flat intensity profile. In contrast, the average nearby PPC is a core with 0.14 $L_\odot$, 0.8 $M_\odot$, and elongated ($(a/b) = 1.6$) with a mean radius of 6000 AU.

PPCs are clearly separated from Class 0 sources on a $T_{bol}$ versus $L_{bol}/L_{sub-mm}$ diagram (Fig. 6). All of the PPCs have low $T_{bol} < 20$ K and $L_{bol}/L_{sub-mm} < 25$, whereas the observed Class 0 sources all have $T_{bol} > 20$ K. $T_{bol}$ and $L_{bol}/L_{sub-mm}$ for PPCs do not correlate. This is not surprising since these evolutionary indicators are strongly influenced by the strength of the ISRF; this is an environmental effect not directly related to the evolutionary state of the core. A better scheme for characterizing the evolutionary state of PPCs would be the comparison of the dynamical maturity determined from radiative transfer models ($n_c$) and the chemical state of molecules that are abundant at different times. For instance, comparisons of [CCS]/[N$_2$H$^+$], comparisons of [N$_2$D$^+$]/[N$_2$H$^+$], and the depletion fraction ($f_D$) of C$^{18}$O and H$_2$CO are promising candidates. The evolutionary state of L1498 is discussed in §4.3.

4.2. Derived Properties from N$_2$H$^+$ Observations

The seven hyperfine lines of N$_2$H$^+$ $J = 1 \rightarrow 0$ were well detected over an extent of $\pm 80''$ in the map (Fig. 1f). The peak $T_d$ in the map is coincident with the continuum centroid (Fig. 7a). We can estimate the effective density needed to excite an easily observable 1 K N$_2$H$^+$ line (see Table 1 of Evans 1999). The
The critical density of the $J = 1 \rightarrow 0$ transition is $n_{\text{crit}} = 3.8 \times 10^5$ cm$^{-3}$ (collision rates determined from Turner 1995). By analogy with HCO$^+$, the resulting effective density (corrected for optically thin hyperfine structure) is $n_e \approx 2 \times 10^4$ cm$^{-3}$, consistent with the derived central density.

The integrated intensity is calculated by integrating over the seven hyperfine components. The $T(A)$ at the continuum centroid is also the peak in the $N_2H^+$ map, $T(A) = 3.92 \pm 0.48$ K km s$^{-1}$. The FWHM integrated intensity contour agrees very well with the FWHM continuum contour in size and position angle. The $N_2H^+$ emission appears to trace the general shape of the continuum emission but does not peak as sharply along the northeastern ridge as is seen in the 850 $\mu$m and, especially, the 1200 $\mu$m images.

The hyperfine structure was fit with seven Gaussian functions, constrained by the hyperfine transition velocities (see Appendix), using the profile fitter task in AIPS++. The average line width was calculated to be $0.22 \pm 0.02$ km s$^{-1}$ over the map using the isolated hyperfine component ($J_F = 1 \rightarrow 0$). This line width is slightly smaller than the line width of $0.28$ km s$^{-1}$ found by Caselli et al. (2002) using the Five College Radio Astronomy Observatory (FCRAO). The nonthermal contribution to the line width is $\Delta v_{\text{nt}} = 0.13$ km s$^{-1}$. A plot of the line width versus radius (Fig. 7b) indicates that the line width does not vary significantly out to 15,000 AU ($\approx 110''$). Therefore, the average gas motions in L1498 have low turbulence and are similar throughout the core. This result agrees with the $\Delta v$-$r$ relationship toward other PPCs in Taurus observed with BEARS (Tatematsu et al. 2004).

We calculate the virial mass using the Doppler line width and assuming an isothermal dust temperature,

$$M_{\text{vir}} = \frac{(6R_{\text{flat}} + 9R_{1/2})}{8G \ln 2} \left[ \frac{kT_{\text{iso}}}{\mu m_{\text{H}}^2} + \frac{\Delta v^2}{8 \ln 2} - \frac{kT_{\text{iso}}}{m_{\text{amu}} m_{\text{H}}} \right].$$ (8)

For a more accurate calculation, we split the radial profile into two sections. The first corresponds to $R \leq R_{\text{flat}}$ (the radius at...
which $n = 0.9n_{cr}$, which is approximated by a constant density. For a $1 \times 10^4$ cm$^{-3}$ BE sphere, $R_{th}$ is 520 AU. Within the second section, $R_{th} \leq R \leq R_1$, the density can be approximated by an inverse power law with $r^{-2}$ ($R_1/2 = 10,200$ AU; § 2.1.2). The term in square brackets converts the observed $N_2H^+$ line width to a three-dimensional velocity dispersion (Shirley et al. 2002). Using the $\Delta v$ determined above, we find $M_{ex} = 0.84 \pm 0.21 M_\odot$ with errors propagated in $R_1/2$, $T_{th}$, and $\Delta v$. This mass agrees with the mass derived from dust continuum emission (§ 4.1.1), indicating that L1498 is likely a bound core and that the best-fit OppenKopf & Henning dust opacities are appropriate.

The $N_2H^+ J = 1 \rightarrow 0$ transition is observed to have moderate optical depths toward low-mass cores (e.g., Tatematsu et al. 2004; Crapsi et al. 2005); therefore, we must calculate the optical depth at each position in the map to derive the column density. For position-switched observations, theoretically we observe the quantity $T_R = |J_i(T_{ex}) - J_i(T_{bg})| [1 - \exp (-\gamma)]$, where $J_i(T) = (h\nu/k) / \exp(h\nu/kT) - 1$. This $T_R$ is related to the actual observed quantity, $T_{\lambda}$, through source-beam coupling and the efficiency of the antenna (including spillover and atmospheric attenuation; see Kutner & Ulrich 1981). Since the hyperfine lines lie close together in frequency ($\Delta \nu < 4.65$ MHz), we assume that the proportionals for each line are constant (Keto et al. 2004). Therefore, we find the optical depth in the strongest hyperfine component ($\tau_m$, $J - F = 1 23 \rightarrow 1 12$) by taking ratios of the observed antenna temperatures of the $i$th hyperfine component to the strongest hyperfine component,

$$
\frac{T^\ast_{\lambda}(m)}{T^\ast_{\lambda}(m)} = \frac{1 - e^{-\tau_m}}{1 - e^{-\tau_0}},
$$

where $R_i$ is the ratio of relative strengths of the hyperfine lines to the strongest line. $R_i$ is calculated in the Appendix.

The average optical depth in the strongest hyperfine line, $\langle \tau_m \rangle$, was calculated using four of the six observed line ratios and equation (9). Two of the lines ($J - F = 1 12 \rightarrow 0 12$ and $1 10 \rightarrow 0 11$) consistently gave lower ($\tau_m$) and higher ($\tau_m$) by factors of 0.4 and 2.0, respectively. This may be due to anomalous hyperfine excitation, an effect that has been observed toward other PPCs (Caselli et al. 1995; Turner 2001). An optical depth was determined for 47 positions with suitable S/N. The optical depth is not affected by line blending since the line width is 0.22 km s$^{-1}$ (see Appendix). Since each hyperfine line has a different optical depth, then correcting the column density using only $\tau_m$ would underestimate the column density. We define the average tau by averaging the theoretical hyperfine ratios for the seven observed transitions ($\gamma = \sum R_i \tau_{m} / (27/49) \tau_{m}$. The average optical depth in the map is $\langle \tau_{map} \rangle = 0.83 \pm 0.54$, indicating that the $N_2H^+ J = 1 \rightarrow 0$ transition is moderately optically thick over most of the map. As an example, the SCUBA continuum centroid position has an optical depth of $\langle \gamma \rangle = 1.11 \pm 0.61$, resulting in a correction for optical depth to the column density of $\langle \tau \rangle / (1 - e^{-\langle \tau \rangle}) = 1.66^{+0.43}_{-0.38}$.

The total column density for $N_2H^+$ is (see Goldsmith & Langer 1999)

$$
N_{N_2H^+} = \frac{3kQ(T_{ex}) \exp(E_u/kT_{ex})}{8\pi^3 \mu_i^2 J_u} \frac{\langle \gamma \rangle}{1 - e^{-\langle \tau \rangle}} \int \frac{T^\ast_{\lambda}}{\eta_{mb}} dv_i,
$$

where $Q(T_{ex})$ is the rotational partition function and $\mu = 3.4$ D (Green et al. 1974) is the dipole moment. We assume an excitation temperature of 10 $\pm$ 5 K. Errors in $N_{N_2H^+}$ are propagated for $T_{ex}$, $\gamma$, and $I(T^\ast_2)$. The peak column density is $(8.3 \pm 3.4) \times 10^{12}$ cm$^{-2}$ with an average column density of $(3.5 \pm 2.1) \times 10^{12}$ cm$^{-2}$. The peak column density agrees remarkably well with the calculation of Caselli et al. (2002a) for lower resolution FCRAO 15 m $N_2H^+$ observations toward L1498 [(8 $\pm$ 4) \times 10^{12}$ cm$^{-2}$] and the intermediate resolution IRAM 30 m observations of Crapsi et al. (2005; (7.1 $\pm$ 0.7) \times 10^{12}$ cm$^{-2}$).

We calculate the abundance, $X_{N_2H^+}(R) = N_{N_2H^+}(R) / N_{H_2}(R)$, by comparing the $N_2H^+$ column density to the beam-averaged column density determined from the 850 $\mu$m dust continuum map (eq. [6]). The average column density in the map is $X_{N_2H^+}(\text{map}) = (4.0 \pm 3.7) \times 10^{-6}$ relative to $H_2$. This column density agrees very well with the early-time abundances of the coupled dynamical-chemical models of Lee et al. (2004) for quasi-statically evolving PPCs (§ 4.3). The abundance shows no significant variations with radius out to 15,000 AU, although the errors on the abundance are sizable (Fig. 7d). Radiative transfer models of the $N_2H^+$ emission should assume a constant abundance of $\approx 4 \times 10^{-10}$.

The $N_2H^+ J = 3 \rightarrow 2$ transition was not detected toward the continuum centroid position with a 1$\sigma$ ($T^\ast_2$) baseline rms of 45 mK (Fig. 7c); however, Crapsi et al. (2005) report a detection with the IRAM 30 m toward the 1.2 mm continuum peak position ($T^\ast_2 = 380 \pm 53$ mK; see inset in Fig. 7c).

This is puzzling since the $J = 1 \rightarrow 0$ BEARS map shows no enhancement toward that position. It is possible that the 1.2 mm continuum peak represents the true density peak of L1498. A high-resolution, oversampled map of the $N_2H^+ J = 3 \rightarrow 2$ emission is needed to resolve this discrepancy. The exact location of the density peak will be important for molecular line radiative transfer modeling, but does not affect the conclusions from dust continuum modeling (§ 3.2).

The L1498 $N_2H^+$ observations will be modeled, along with other PPCs, in a future paper.

4.3. Derived Properties from C$_3$S Observations

The $C_3S J = 4 \rightarrow 3$ line was strongly detected toward L1498 (Fig. 8) and the emission follows the same double-peaked pattern as previous observations of CS and CCS (Fig. 1 of Willacy et al. 1998). The line intensity is strongest in the southeastern peak ($T^\ast_2 = 1.64 \pm 0.35$ K) at $v = 4.10^{+0.569}_{-0.6} \pm 25^9 22^25$ (J2000.0). Since the $C_3$S emission has an intensity saddle at the SCUBA dust continuum centroid, it is another excellent example of strong chemical differentiation in L1498. The southeastern $C_3$S peak does not exactly correspond to the Willacy et al. (1998) CS or CCS peak, but instead lies between them and closer to the CS peak. Combination of the GBT observations with higher resolution observations (e.g., VLA) would improve the peak position and may confirm slight chemical differentiation between all of the observed sulfur-carbon chain molecules.

The $C_3$S $J = 4 \rightarrow 3$ line width was measured using the Gaussian fitting routine is AIPS++ toward 42 positions in the map with detections greater than 3 $\sigma$. The average line width is $\Delta v = 0.21 \pm 0.03$ km s$^{-1}$, consistent with the $N_2H^+$ line width. No significant variation of $\Delta v$ is also seen for $C_3$S with radius (Fig. 8b).

The column density of $C_3$S was estimated using the same method as for $N_2H^+$ (eq. [10]). We estimate the optical depth of the $C_3$S $J = 4 \rightarrow 3$ with 10 minute observations at the southeastern peak position of three isotopologues. The detection of $C_3^{13}$S $J = 4 \rightarrow 3$ [Fig. 8c; $T^\ast_2(C_3S) / T^\ast_2(C_3^{13}S) = 19.7 \pm 3.1$] and lack of a significant detection ($>3 \sigma$) of $^{13}$CCS or $^{13}$CCS
J = 4 → 3, indicates, for the standard ISM isotope ratios of $^{32}\text{S}/^{34}\text{S} = 22$ and $^{12}\text{C}/^{13}\text{C} = 77$ (Wilson & Rood 1994), that the C$_3$S emission is consistent with being optically thin. The peak column density is $N_{\text{C}_3\text{S}} = (5.0 \pm 1.8) \times 10^{12}$ cm$^{-2}$ and is less than a factor of 2 less than the peak CCS column density determined by Wolkovitch et al. (1997; $8.7 \times 10^{12}$ cm$^{-2}$).

The abundance of C$_3$S was calculated by comparing the C$_3$S column density to the column density derived from the 850 μm map in 33″ apertures. Since the C$_3$S emission is very asymmetrical, we plot the abundance versus radius in the major-axis sector ($\pm 2.12$) in Figure 8d. Negative radii refer to positions southeast of the dust continuum centroid. The depletion of C$_3$S is clearly visible, with enhanced abundances by factors of 4.8 and 2.3 at the two C$_3$S intensity peaks. The abundance is largest in the southeast peak ($X_{\text{C}_3\text{S}} = (4.5 \pm 2.4) \times 10^{-11}$). The abundance peaks are symmetrically located at a radius of 9500 AU from the dust continuum centroid position. This radius set a limit for the depletion radius of C$_3$S, corresponding to a density of $(0.8-1.5) \times 10^4$ cm$^{-3}$ for the best-fit BE spheres. Since the abundance pattern of C$_3$S is similar to smaller sulfur-carbon chain molecules (e.g., CS and C$_2$S), the southeastern C$_3$S peak of L1498 would be an excellent site to search for larger sulfur-carbon chain molecules such as C$_4$S and C$_5$S (Gordon et al. 2001).

4.4. Interpretation of Density Structure

Radiative transfer modeling of submillimeter images combined with far-infrared and millimeter photometry indicate that L1498 is a low-density, nearly isothermal PPC, with a low strength of the ISRF and dust opacities appropriate for coagulated, icy grains. The central density of $(1.3-5) \times 10^4$ cm$^{-3}$ is the among lowest central densities reported for PPCs, similar to Coalsack G2 (Lada et al. 2004). This density range agrees with the densities determined by Langer & Willacy (2001) from analysis of ISO observations of L1498 [(1.2-5.5) $\times 10^4$ cm$^{-3}$ with lower densities more appropriate for larger core radii]. However, our modeling results differ substantially from the analytical model of Tafalla et al. (2004), which fits the radial profile of L1498 at 1.2 mm with
a function of the form \( n(r) = n_0/[1 + (r/R_{1/2})^p] \) and assumes an isothermal dust temperature profile of \( T_d(r) = 10 \, \text{K} \). Tafalla et al. find a central density of \( 9.5 \times 10^4 \, \text{cm}^{-3} \), 3 times larger than the maximal BE central density in our models. There are a few discrepancies that may account for this difference. Tafalla et al. assume a dust opacity of \( 5 \times 10^{-3} \, \text{cm}^2 \, \text{g}^{-1} \) at 1.2 mm that is a factor of 2 smaller than OH5 opacities (1.02 \( \times 10^{-3} \, \text{cm}^2 \, \text{g}^{-1} \)). Since the column density is inversely proportional to the opacity, the Tafalla et al. opacity would result in a factor of 2 larger central density. This does not account for the full difference between the results. The Tafalla et al. centroid position is located at the peak of the nonaxisymmetry, which is much more pronounced at 1.2 mm than at submillimeter wavelengths. Tafalla et al. calculate a column density of (3–4) \( \times 10^{22} \, \text{cm}^{-2} \), a factor of 3 higher than our column density determined at 850 \( \mu \text{m} \). For all of the best-fit radiative transfer models, the 1.2 mm flux is always underestimated, while the other six fluxes (170, 200, 450, 850, 1100, and 1300 \( \mu \text{m} \)) are fitted within the error bars. The 1.2 mm flux point appears to be anomalously high. It is possible that calibration uncertainties may account for the remaining difference.

The low density implies that L1498 is dynamically young. Indeed, L1498 may be in a stable hydrostatic state. One measure of stability of BE spheres is the density gradient between inside and outside of the core. If the density contrast exceeds 14.3, then the BE sphere is in an unstable equilibrium (see Foster & Chevalier 1993). A lower density limit of \( 10^3 \, \text{cm}^{-3} \) was assumed for the core in the radiative transfer models. This lower limit was chosen to be larger than the average density in a molecular cloud (\( 10^2 \, \text{cm}^{-3} \)) since L1498 is situated within an extended condensation of \( 1 \sim 3 \, A_p \) in the Taurus-Auriga molecular cloud (see Cambrésy 1999). The average solution (\( 1 \times 10^4 \, \text{cm}^{-3} \)) is stable, but this results depends sensitively on the density at the outer radius. For the maximal central density (\( 3 \times 10^4 \, \text{cm}^{-3} \)), the density contrast is 30 and the core is unstable. Unfortunately, we cannot strongly constrain the density contrast since the submillimeter observations are insensitive to structure outside the chop distance (120\( \circ \), or 16,800 AU).

A more quantitative way to test the stability is to directly compare the Jeans mass with the mass of the BE sphere. The Jeans mass for \( T = 10.5 \, \text{K} \) and \( n = 10^4 \, \text{cm}^{-3} \) is \( M_J \approx 18T^{3/2}n^{-1/2} = 5.7 \, M_\odot \) (Spitzer 1978), while the \( 1 \times 10^4 \, \text{cm}^{-3} \) BE sphere has a mass of \( M_{\text{BE}} \approx 1.15(T/10 \, \text{K})(P_\nu/10^5 \, \text{K} \, \text{cm}^{-3})^{-1/2} = 3.6 \, M_\odot \) (Bonnor 1956). The BE mass is within a factor of 2 of the Jeans mass, but \( M_{\text{BE}} < M_J \). If we use the 3 \( \times 10^4 \, \text{cm}^{-3} \) BE sphere, then the mass is comparable to the Jeans mass \( M_J = 3.3 \, M_\odot \). This mass comparison is consistent with L1498 being a core that is marginally stable to gravitational collapse.

While L1498 may be dynamically unevolved, it appears to be chemically evolved. Species such as H$_2$CO, CS, CCS, and C$_2$S (e.g., Willacy et al. 1998; Tafalla et al. 2004; Young et al. 2004; § 4.3) are depleted toward the center of the core. We can estimate the depletion timescale from the rate equation given in Rawlings et al. (1992). For a depletion fraction, \( f_D \), the adsorption timescale of a neutral molecular species, \( i \), is given by

\[
 t_{\text{adsorp}}(i) = \frac{1.38 \times 10^9 \ln (1/f_D)m_i^{1/2}}{nS_iT_i^{1/2}} \, \text{yr},
\]

where \( m_i \) is the molecular mass in amu and \( S_i \) is the sticking coefficient (see also Charnley et al. 2001). For example, H$_2$CO has been observed to be severely depleted toward L1498 over a large spatial extent (Wang 1994; Young et al. 2004). The adsorption timescale is \( t_{\text{adsorp}}(\text{H}_2\text{CO}) \approx 5.5 \times 10^5 \, \text{yr} \) for \( f_D = 1/10, \ S_i = 1, \) and \( T = 10.5 \, \text{K} \) in the absence of other formation or destruction mechanisms. In reality, many chemical effects may affect this timescale. Two of the first molecules to be depleted are CCS and C$_2$S. Comparisons with detailed coupled dynamical-chemical models indicate that the CCS becomes depleted on timescales of a few \( 10^5 \, \text{yr} \) (e.g., Li et al. 2002; Aikawa et al. 2003; Lee et al. 2004).

A chemical age of a few \( 10^5 \, \text{yr} \) is consistent with the observed abundance of N$_2$H$^+$ (Aikawa et al. 2003; Lee et al. 2004). N$_2$H$^+$ is considered a “late-time” species since it is primarily destroyed in the gas phase by CO and its abundance increases after CO is significantly adsorbed (although dissociative recombination may also be important at low densities; see Geppert et al. 2004). Detailed chemical models indicate that this abundance increase occurs after \( \approx 10^5 \, \text{yr} \) (e.g., Aikawa et al. 2003). Clearly, L1498 must be have been in a stable or very slowly evolving configuration for at least \( 10^5 \, \text{yr} \) to display the extreme molecular depletion and modest N$_2$H$^+$ abundance that is observed.

The dust opacities that best fitted the L1498 SED were Ossenkopf & Henning (1994) opacities for grains that had coagulated for \( 10^5 \, \text{yr} \) and accreted ice mantles (OH5 and OH8). These opacities have also successfully fitted the SEDs of low-mass embedded protostars (e.g., Shirley et al. 2002) and high-mass embedded protostars (e.g., Mueller et al. 2002). The OH opacities are qualitatively consistent with the observed molecular depletion and the chemical timescale for L1498; however, the coagulation simulation of OH5 and OH8 assumes a density of \( n_{\text{h}_2} = 10^6 \, \text{cm}^{-3} \) sustained for \( 10^5 \, \text{yr} \) (see Ossenkopf 1993). This density is substantially higher than the density derived from dust continuum models; therefore, the OH5 and OH8 opacities may not be based on an accurate representation of fluffy aggregation of grains in low-density PPCs.

How do you create a dynamically young yet chemically evolved core? If L1498 is in an unstable equilibrium, it cannot have been in that state for a long period of time since the free-fall time for a \( (1 \sim 3) \times 10^4 \, \text{cm}^{-3} \) BE sphere, \( t_{\text{ff}} = (3\pi/8Gm_{\text{h}_2}n)^{1/2} \) (Spitzer 1978), is approximately \( (3 \sim 1.7) \times 10^5 \, \text{yr} \). Clearly, L1498 has not yet collapsed and displays chemical differentiation that requires a similar timescale. L1498 must have been static or slowly collapsing for more than \( 10^5 \, \text{yr} \). While magnetic fields may also play a significant role in cloud support and evolution for dynamically nascent PPCs (e.g., Mouschovias & Spitzer 1976; Li et al. 2002), in the case of L1498, they are not necessary for support of the cloud (since \( M_{\text{BE}} < \rho_\odot \approx M_J \)). Nevertheless, we can estimate the strength of the B-field required for equipartition of magnetic, gravitational, and kinetic energy. The strength of this B-field is given by \( B \approx 0.51n^{1/2}\Delta v m_{\text{h}_2}(\text{km s}^{-1}) = 8.7 \, \mu\text{G} \) (Lada et al. 2004). This is a small magnetic field compared with Zeeman measurements of the CCS \( J = 3 \rightarrow 2 \) transition, which provide a rough estimate of the line-of-sight field strength of \( 48 \pm 31 \, \mu\text{G} \) (Levin et al. 2001). If L1498 becomes massive enough to be unstable to gravitational collapse, then the magnetic field appears to be strong enough to support L1498, in which case the timescale for collapse is controlled by the ambipolar diffusion timescale until the core becomes magnetically supercritical.

Recent molecular line studies of PPCs in the Taurus-Auriga molecular cloud have identified cores (e.g., L1521B and L1521E) that appear to be dynamically and chemically young (Hirota et al. 2002, 2004; Tafalla & Santiago 2004). The signature of chemical youth is strongly peaked sulfur-bearing carbon chain molecules (e.g., CCS and C$_2$S), weak NH$_3$ and N$_2$H$^+$ emission, and low molecular depletion of C$^{18}$O. Confirmation of the chemical and dynamical youth of these cores requires a detailed comparison
between submillimeter dust continuum emission and high-resolution observations of CCS or C$_3$S. These objects, along with L1498, L1512 ($n_c = 10^5$ cm$^{-3}$), and L1544 ($n_c = 10^6$ cm$^{-3}$) may represent an evolutionary sequence in Taurus-Auriga in which chemical maturity is reached first and then dynamical evolution occurs (see Fig. 9).

An important caveat is that our one-dimensional modeling has ignored the observed nonaxisymmetry in L1498. The dust continuum emission peaks along the northeast ridge and not at the FWHM centroid. This effect is most pronounced in the 1.2 mm but is also detected at 850 $\mu$m. Other PPCs (e.g., L1544 and L63) also display clear nonaxisymmetries. The spherical BE model is limited and unable to describe this structure. A full three-dimensional radiative transfer modeling is needed to probe the structure of the nonaxisymmetry (e.g., Doty et al. 2004). Also, since the 90 $\mu$m ISO image (Ward-Thompson et al. 2002) shows a clear gradient across the image, there is evidence that the ISRF asymmetrically heats L1498 (also see Langer & Willacy 2001). Three-dimensional models could explore triaxial, BE-like model with a spatially varying ISRF compared to fully nonaxisymmetric density distributions (see Gonçalves et al. 2004). Encouragingly, a comparison between three-dimensional models and one-dimensional models of L1544 indicate that the one-dimensional models are an acceptable fit to the average physical structure (Doty et al. 2004).

5. CONCLUSION

We have presented deep SCUBA observations, BEARS and CSO N$_2$H$^+$ observations, and GBT C$_3$S observations of the pre-protostellar core Lynds 1498. Radiative transfer modeling of the submillimeter intensity profiles and the complete SED were performed. Our main conclusions are as follows.

L1498 is characterized by a low-density BE sphere with central density of $(1-3) \times 10^4$ cm$^{-3}$ and outer radius greater than 40,000 AU. The SED is best fitted with Ossenkopf & Henning opacities for coagulated grains with thick and thin ice mantles (OH8 and OH5 opacities). A more realistic treatment of the ISRF was used that includes variations in the strength of the incident specific intensity and extinction due to dust grains at the outer radius of the core. L1498 is a potentially stable ($M_{BE} < M_J$), magnetically subcritical core that appears to be dynamically young. These results do not change if the 1.2 mm continuum peak is used for the radial intensity profiles instead of the SCUBA continuum centroid.

Observations of the depletion of species such as C$_3$S and H$_2$CO indicate L1498 is chemically evolved ($t > 10^5$ yr). The modest N$_2$H$^+$ abundance is also consistent with a chemically evolved source. The best-fit Ossenkopf & Henning opacities are consistent with this timescale, although the Ossenkopf coagulation models assume a higher density than is observed toward L1498. The N$_2$H$^+$ and C$_3$S line width do not vary significantly with radius out to 15,000 AU. The N$_2$H$^+$ abundance also does not vary significantly with radius, while the C$_3$S abundance indicates significant depletion toward the center of L1498.

Comparisons of L1498 with nearby PPCs that have also been observed at far-infrared and submillimeter wavelengths indicate that L1498 is larger than average, less luminous than average, and less massive than average. The standard evolutionary indicators used for low-mass protostars, $T_{bol}$ and $L_{bol}/L_{sub-mm}$, do not correlate for PPCs. All of the PPCs in this sample are characterized by $T_{bol} < 20$ K and $L_{bol}/L_{sub-mm} < 25$.

The temperature and density structure derived from one-dimensional models may now be used in more realistic models of molecular line emission. Future studies of PPCs require high-resolution far-infrared observations coupled with three-dimensional radiative transfer modeling of multiple wavelengths. Instruments such as HAWC (High-resolution Airborne Wide Bandwidth Camera) on SOFIA (Stratospheric Observatory for Infrared Astronomy) and the launch of the Herschel Space Observatory will provide the needed high-resolution far-infrared observations.

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APPENDIX

HYPERFINE LEVELS OF N$_2$H$^+ J = 1 \rightarrow 0$

Since every nucleus in the N$_2$H$^+$ molecules has nonzero nuclear spin, N$_2$H$^+$ has a very rich hyperfine spectrum that can be exploited to probe the physical conditions in star-forming regions. In this appendix, we summarize the hyperfine splitting of the ground state rotational transition of N$_2$H$^+$.

The hyperfine splitting (in order of importance) is due to (1) an electric quadrupole interaction due to the outer nitrogen; (2) an electric quadrupole interaction due to the inner nitrogen; (3) a magnetic dipole interaction due to the outer nitrogen; (4) a magnetic dipole interaction due to the inner nitrogen; (5) a magnetic dipole interaction due to the hydrogen nucleus; and (6) spin-spin interactions between the nuclei. The final two effects are ignored in calculations of hyperfine splitting for astronomical sources since the observed line width is $>0.1$ km s$^{-1}$ ($>31$ kHz) and the hyperfine coupling constants are small (see Caselli et al. 1995).

There are 15 electric dipole allowed transitions for N$_2$H$^+$ $J = 1 \rightarrow 0$ in the $|J F F_a F_i F_i |$ basis ($|\Delta J = -1, \Delta F_1 = 0 \pm 1, \Delta F = 0 \pm 1, 0 \rightarrow 0$). The 15 transitions are listed in Table 5; however, since in practice the $J = 0$ level is not split, degenerate transitions are collected together into the seven observed transitions. We adopt the standard notation from Caselli et al. (1995) for the transition labels.

It is convenient to calculate the ratio of relative strengths, $R_i$, of the hyperfine levels for calculations of optical depth and column density ($\S$ 4.2). The relative strengths, $s_j$, are determined using irreducible tensor methods (Gordy & Cook 1984) and are defined such that the sum of the relative strength of the electric dipole allowed transitions are equal to 1 (see Rudolph 1968). The ratio of relative strengths for the N$_2$H$^+$ $J = 1 \rightarrow 0$ transitions in the $|J F_1 F \rangle$ basis are given by

$$R_i(1 F'_i F'' \rightarrow 0 F_1 F) = \sum_{\text{allowed}} 3 \left\{ \frac{1}{7} \left[ \frac{1}{10} F_1 \right] \right\}^2 \left\{ \frac{1}{1} F'_i \right\}^2 \prod_{F_1 = F'_i F_i F''} (2 F_i + 1), \quad (A1)$$

where the $6$-$j$ symbols needed in equation (A1) may be found in Table 5 of Edmonds (1974). The ratios must be summed over the degenerate transitions from the same $J = 1 F'_i F''$ level (Table 5).

It is necessary to calculate the dependence of $R_i$ on the line width for closely spaced hyperfine lines (see Turner 2001). We have performed this calculation for the N$_2$H$^+$ $J = 1 \rightarrow 0$ transitions, assuming that each hyperfine component is Gaussian:

$$R_i(\Delta \nu) = \frac{\sum_{j=1}^{7} s_j \exp\{-4 \ln 2[v_j - v_i^2/\Delta v^2]\}}{\sum_{j=1}^{7} s_j \exp\{-4 \ln 2[v_j^2/\Delta v^2]\}}. \quad (A2)$$

The results are shown in Figure 10. For sources with $\Delta \nu \leq 0.3$ km s$^{-1}$, the theoretical hyperfine ratios are sufficient. This is the case for L1498. However, for N$_2$H$^+$ observations of sources with broader line widths, the line width–corrected $R_i$ should be used.

| TABLE 5 |
| N$_2$H$^+ J = 1 \rightarrow 0$ HYPERFINE TRANSITIONS |

| $J' F'_i F'' \rightarrow J F_1 F$ | $s_j$ | $J'' F'_i F'' \rightarrow J F_1 F''$ | $\nu$ (GHz) | $\Delta \nu$ (km s$^{-1}$) | $R_i$ |
|-----------------|-----|-----------------|------|-----------------|-----|
| 1 0 → 0 1 1............. | 1/27 | 1 1 0 → 0 1 1 | 93.1716200 | +6.944 | 1/7 |
| 1 1 0 → 0 1 2............. | 3/10 | 1 1 2 → 0 1 2 | 93.1719168 | +5.988 | 5/7 |
| 1 1 1 → 0 1 1............. | 1/10 | 1 1 1 → 0 1 2 | 93.1737767 | +0.000 | 1 |
| 1 1 1 → 0 1 2............. | 1/10 | 1 1 2 → 0 1 1 | 93.1743796 | +0.956 | 7/7 |
| 1 2 0 → 0 1 2............. | 5/10 | 1 2 0 → 0 1 2 | 93.1720533 | +5.549 | 3/7 |
| 1 2 0 → 0 1 3............. | 5/10 | 1 2 0 → 0 1 3 | 93.1737767 | +0.000 | 1 |
| 1 2 1 → 0 1 2............. | 1/10 | 1 2 1 → 0 1 2 | 93.1739666 | -0.611 | 3/7 |
| 1 2 1 → 0 1 3............. | 5/10 | 1 2 1 → 0 1 3 | 93.1762650 | -8.011 | 3/7 |
| 1 0 0 → 0 1 2............. | 1/8 | 1 0 0 → 0 1 2 | 93.1762650 | -8.011 | 3/7 |
| 1 0 0 → 0 1 3............. | 1/8 | 1 0 0 → 0 1 3 | 93.1762650 | -8.011 | 3/7 |

* Standard notation.
Fig. 10.—Variation of the ratio of relative strengths for $N_2H^+ J = 1 \rightarrow 0$ hyperfine lines with line width. The theoretical ratios are valid for $\Delta v \leq 0.3 \text{ km s}^{-1}$.

REFERENCES

Adams, F. C. 1991, ApJ, 382, 544
Alkawa, Y., Ohashi, N., & Herbst, E. 2003, ApJ, 593, 906
Archibald, E. N., et al. 2002, MNRAS, 336, 1
Bianchi, S., González, J. Albrecht, M., Caselli, P., Chini, R., Galli, D., & Walmsley, M. 2003; A&A, 399, L43
Black, J. H. 1994, in ASP Conf. Ser. 58, The First Symposium on the Infrared Circus and Diffuse Interstellar Clouds, ed. R. M. Cutri & W. B. Latter (San Francisco: ASP), 355
Bonnor, W. B. 1956, MNRAS, 116, 351
Buisson, G., Desbats, L., Duvert, G., Forveille, T., Gras, R., Guilloteau, S., Lucas, R., & Valiron, P. 2002, Continuum and Line Analysis Single-Dish System Manual (IRAM: Grenoble)
Cambresy, L. 1999, A&A, 345, 965
Caselli, P., Benson, P. J., Myers, P. C., & Tafalla, M. 2002a, ApJ, 572, 238
Caselli, P., Myers, P. C., & Thaddeus, P. 1995, ApJ, 455, L77
Caselli, P., Walmsley, C. M., Zucconi, A., Tafalla, M., Dore, L., & Myers, P. C. 2002b, ApJ, 565, 344
Chandrasekhar, S., & Wannier, P. G. 1949, ApJ, 109, 551
Charnley, S. B., Rodgers, S. D., & Ehrenfreund, P. 2001, A&A, 378, 1024
Chen, H. Myers, P. C., Ladd, E. F., & Wood, D. O. S. 1995, ApJ, 445, 377
Craspi, A., Caselli, P., Walmsley, C. M., Myers, P. C., Tafalla, M., Lee, C. W., & Bourke, T. L. 2005, ApJ, 619, 379
Doty, S. D., Everett, S. E., Shirley, Y. L., Evans, N. J., II, & Palotti, M. L. 2004, MNRAS, submitted
Draine, B. T. 1978, ApJS, 36, 595
Draine, B. T., & Lee H. M. 1984, ApJ, 285, 89
Ebert, R. 1955, Z. Astrophys., 37, 217
Edmonds, A. R. 1974, Angular Momentum in Quantum Mechanics (3rd ed.; Princeton: Princeton Univ. Press)
Egan, M. P., Leung, C. M., & Spagna, G. F. 1988, Comput. Phys. Commun., 48, 271
Evans, N. J., II, 1999, ARA&A, 37, 311
Evans, N. J., II, Rawlings, J. M. C., Shirley, Y. L., & Mundy, L. G. 2001, ApJ, 557, 193
Flower, D. R., Pineau des Forêts, G., & Walmsley, C. M. 2005, A&A, 436, 933
Foster, P. N., & Chevalier, R. A. 1993, ApJ, 416, 303
Hirota, T., Ito, T., & Yamamoto, S. 2002, ApJ, 565, 359
Hirota, T., Maczawa, H., & Yamamoto, S. 2004, ApJ, 617, 399
Geppert, W. D., et al. 2004, ApJ, 609, 459
Goldsmith, P. F., & Langer, W. D. 1999, ApJ, 517, 209
González, J., Galli, D., & Walmsley, M. 2004, A&A, 415, 617
Gordon, V. D., McCarthy, M. C., Apponi, A. J., & Thaddeus, P. 2001, ApJS, 134, 311
Gordy, W., & Cook, R. L. 1984, Microwave Molecular Spectroscopy (3rd ed.; New York: Wiley), chap. 15
Green, S., Montgomery Jr., J. A., & Thaddeus, P. 1974, ApJ, 193, L89
Greisen, E., & Harten 1981, A&AS, 44, 371
Ivezic, Z., Enckova, M., & Elitzur M. 1999, User Manual for DUSTY (Univ. Kentucky Internal Rep.)
Jennings, T. L., & Leftwich J. F. 1997, SURF-SCUBA User Reduction Facility Ver. 1.1 User’s Manual, Starlink User Note 216 (Hilo: Joint Astronomy Centre)
Jijina, J., Myers, P. C., & Adams 1999, ApJS, 125, 161
Jørgensen, J. K., Schöier, F. L., & van Dishoeck, E. F. 2002, A&A, 398, 908
Keto, E., Rybicki, G. B., Bergin, E. A., & Plume, R. 2004, ApJ, 613, 355
Kooi, J. W., Chan, M., Phillips, T. G., Bumble, B., & Leduc, H. G. 1992, IEEE Trans. Microwaves Theror. Tech., 40, 812
Kuiper, T. B. H., Langer, W. D., & Velusamy, T. 1996, ApJ, 468, 761
Kutner, M. L., & Ulrich, B. L. 1981, ApJ, 250, 341
Lada, C. J., Huard, T. L., Crews, L. J., & Alves, J. F. 2004, ApJ, 610, 303
Lai, S.-P., Velusamy, T., Langer, W. D., & Kupier, T. B. 2003, ApJ, 126, 311
Langer, W. D., & Willacy, K. 2001, ApJ, 557, 714
Langston, G., Braat, J., Ghigo, F., Maddalena, R., Minter, T., & O’Neal, K. 2004, GBT Commissioning Memo 24
Lee, J.-E., Bergin, E. A., & Evans, N. J., II, 2004, ApJ, 617, 360
Lemme, C., Walmsley, C. M., Wilson, T. L., & Muters, D. 1995, A&A, 302, 509
Levin, S. M., Langer, W. D., Velusamy, T., Kuiper, T. B. H., & Crutcher, R. M. 2001, ApJ, 555, 850
Li, Z.-Y., Shematovich, V. I., Wiebe, D. S., & Shustov, B. M. 2002, ApJ, 569, 792
Loinard, L., Mioduszewski, Rodriguez, L. F., Gonzalez, R. A., Rodriguez, M. I., & Torres, R. M. 2005, ApJ, 619, L179
Mathis, J. S., Mezger, P. G., & Panagia, N. 1983, A&A, 128, 212
Mouschovias, T. C., & Spitzer, L., Jr 1976, ApJ, 210, 326
Müller, H. S. P., Thorwirth, S., Roth, D. A., & Winnewisser, G. 2001, A&A, 370, L49
Müller, K., Kuiper, T. B. H., Shirley, Y. L., Evans, N. J., II, & Jacobson, H. R. 2002, ApJS, 143, 469
Myers, P. C., & Benson, P. J. 1983, ApJ, 266, 309
Ossenkopf, V. 1993, A&A, 280, 617
Ossenkopf, V., & Henning, Th. 1994, A&A, 291, 943
Penzias, A. A., & Burrus, C. A. 1973, ARA&A, 11, 51
Pollack, J. B., Hollenbach, D., Beckwith, S., Simonelli, D. P., Roush, T., & Fong, W. 1994, ApJ, 421, 615
Rawlings, J. M. C., Hartquist, T. W., Menten, K. M., & Williams, D. A. 1992, MNRAS, 255, 471
Rohlfis, K., & Wilson T. L. 2000, Tools of Radio Astronomy (Berlin: Springer)
Rudolph, H. D. 1968, Z. Naturforsch, 23, 540
Shirley, Y. L., Evans, N. J., II, & Rawling, J. M. C. 2002, ApJ, 575, 337
Shirley, Y. L., Evans, N. J., Rawling, J. M. C., & Gregersen, E. M. 2000, ApJS, 131, 249
Shirley Y. L., Mueller, K. E., Young, C. H., Evans, N. J., II. 2003, in ASP Conf. Ser. 287, Galactic Star Formation across the Stellar Mass Spectrum, ed. J. M. De Buizer (San Francisco: ASP), 298
Spitzer, L., Jr. 1978, Physical Processes in the Interstellar Medium (New York: Wiley), 287
Stamatellos, D., & Whitworth, A. P. 2004, preprint (astro-ph/0406549)
Sunada, K., Yamaguchi, N., Kuno, S., Okumura, S., Nakai, N., & Ukita, N. 2000, in ASP Conf. Ser. 217, Imaging at Radio through Submillimeter Wavelengths, ed. J. G. Mangum & S. J. E. Radford (San Francisco: ASP), 19
Tafalla, M., Myers, P. C., Caselli, P., Walmsley, C. M., & Comito, C. 2002, ApJ, 569, 815
———. 2004, A&A, 416, 191
Tafalla, M., & Santiago, J. 2004, A&A, 414, L53
Tatematsu, K., Umemoto, T., Kandori, R., & Sekimoto, Y. 2004, ApJ, 606, 333
Taylor, S. D., Morata, O., & Williams, D. A. 1996, A&A, 313, 269
Turner, B. E. 1995, ApJ, 449, 635
———. 2001, ApJS, 136, 579
van Dishoeck, E. F. 1988, Rate Coefficients in Astrochemistry, ed. T. L. Millar & D. A. Williams (Dordrecht: Kluwer), 49
Wang, Y. 1994, Ph.D. thesis, Univ. Texas
Ward-Thompson, D., André, P., & Kirk, J. M. 2002, MNRAS, 329, 257
Ward-Thompson, D., Motte, F., & André, P. 1999, MNRAS, 305, 143
Ward-Thompson, D., Scott, P. F., Hills, R. E., & André, P. 1994, MNRAS, 268, 276
Weingartner, J. C., & Draine, B. T. 2001, ApJ, 548, 296
Whittet, D. C. B. 2003, Dust in the Galactic Environment (2nd ed.; Philadelphia: IOP), 11
Willacy, K., Langer, W. D., & Velusamy, T. 1998, ApJ, 507, L171
Wilson, T. L., & Rood R. 1994, ARA&A, 32, 191
Wolfkovich, D., Langer, W. D., Goldsmith, P. F., & Heyer, M. 1997, ApJ, 477, 241
Young, C. H., Shirley, Y. L., Evans, N. J., II, & Rawlings, J. M. C. 2003, ApJS, 145, 111
Young, K. E., Lee, J.-E., Evans, N. J., II, Goldsmith, P. F., & Doty, S. 2004, ApJ, 614, 252
Zhou, S., Evans, N. J., II, Wang, Y., Peng, R., & Lo, K. Y. 1994, ApJ, 433, 131
Zucconi, A., Walmsley, C. M., & Galli, D. 2001, A&A, 376, 650