STAR FORMATION AND FEEDBACK: A MOLECULAR OUTFLOW–PRESTELLAR CORE INTERACTION IN L1689N

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ABSTRACT

We present *Herschel*,¹¹ ALMA Compact Array (ACA), and Caltech Submillimeter Observatory observations of the prestellar core in L1689N, which has been suggested to be interacting with a molecular outflow driven by the nearby solar-type protostar IRAS 16293-2422. This source is characterized by some of the highest deuteration levels observed in the interstellar medium. The change in the NH₂D line velocity and width across the core provides clear evidence of an interaction with the outflow, traced by the high-velocity water emission. Quiescent, cold gas characterized by narrow line widths is seen in the NE part of the core, while broader, more disturbed line profiles are seen in the W/SW part. Strong N₂D⁺ and ND₃ emission is detected with ACA extending S/SW from the peak of the single-dish NH₂D emission. The ACA data also reveal the presence a compact dust continuum source with a mean size of ~ 1100 au, a central density of $(1-2) \times 10^7$ cm⁻³, and a mass of 0.2–0.4 $M_{\odot}$. The dust emission peak is displaced $\sim 5''$ to the south with respect to the N₂D⁺ and ND₃ emission, as well as the single-dish dust continuum peak, suggesting that the northern, quiescent part of the core is characterized by spatially extended continuum emission, which is resolved out by the interferometer. We see no clear evidence of fragmentation in this quiescent part of the core, which could lead to a second generation of star formation, although a weak dust continuum source is detected in this region in the ACA data.

Key words: ISM: molecules – stars: formation – submillimeter: ISM – techniques: interferometric – techniques: spectroscopic

1. INTRODUCTION

Low-mass star formation is known to occur exclusively in the shielded interiors of molecular cloud cores, when gravity wrests control from supporting thermal, magnetic, and turbulent pressures and collapse ensues. Over the past 20 years, much effort has been focused on understanding the subsequent stages of star formation, when a central object and a surrounding circumstellar disk are formed and evolve toward a newly formed star and, potentially, its associated planetary system. However, the initiation of this process is among the least understood steps of star formation. Yet it is key to understanding some of its most fundamental aspects, such as the initial mass function, the binarity fraction and its dependence on stellar mass, and the star formation efficiency.

Generally, starless cores are thought to represent this earliest stage of star formation. In one view, magnetically supported clouds develop magnetically critical cores over a long timescale (a few Myr) in a quasi-static fashion through the process of ambipolar diffusion (Shu et al. 1987; Mouschovias et al. 1991). Alternatively, turbulence continuously shreds and twists molecular clouds, forming denser structures—through shocks—that collapse, fragment, or otherwise disappear. In this view,

starless cores are highly dynamical structures that evolve over a few sound-crossing times, i.e., 10 times faster than the ambipolar diffusion timescale (see Ballesteros-Paredes & Hartmann 2007 and references therein). These different scenarios for the formation and evolution of starless cores result in very different three-dimensional (3D) morphological structures and unique dynamic signatures. The environment in which a core forms is also critical to its subsequent evolution. Dense cores in regions of cluster-forming clouds tend to have higher masses and column densities than isolated prestellar cores. The molecular cloud cores in Taurus and Ophiuchus provide a case in point (e.g., Ward-Thompson et al. 2007 and references therein).

Much of our insight into the structure of starless cloud cores comes from observations of millimeter dust emission (Bergin & Tafalla 2007). *Herschel* observations using PACS and SPIRE have shown that cores preferentially form along dense filaments (André et al. 2010; Molinari et al. 2010). The *Herschel* Gould belt survey in particular has discovered a large population of nearby prestellar cores, allowing for the accurate determination of the core mass function (e.g., Könyves et al. 2010; André et al. 2014, but see the recent results of Pagani et al. 2015), which can be compared with model predictions for the IMF produced by the collapse of a turbulent cloud (e.g., Hennebelle & Chabrier 2008, 2009). High angular resolution interferometric continuum studies provide insights

¹¹ *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

into the formation of multiple systems (Maury et al. 2010). However, continuum observations are likely to yield only a partial picture of the cloud structure since coagulation of dust is a key process at the high densities of inner starless cores, and this will change the grain opacity coefficient and effectively “hide” much of the mass of the dust from view (Pagani et al. 2010; Steinacker et al. 2010; Lefèvre et al. 2014, 2016). Moreover, dust studies do not provide direct insight into the dynamics of these cores or their chemistry.

Likewise, molecular observations are also generally known to provide a biased view of starless cores. This reflects the condensation of species onto ice mantles at high densities. There are two exceptions to this general rule. First, for reasons that are not fully understood, nitrogen-bearing species, ammonia in particular, do not seem to participate in this freeze out (Tafalla et al. 2002; Crapsi et al. 2007). Deuterated species form the second exception (see the recent review by Ceccarelli et al. 2014). The high deuteration of gas-phase species is, in effect, a result of the freeze out and the coincidental disappearance of ortho- H_2 from the gas phase, without which no deuteration would happen (Pagani et al. 1992, 2009; Flower et al. 2006). This drives up the gas-phase abundance and fractionation of H_3^+ . The high fractionation of this species is then passed on through ion-molecule chemistry, to the few molecules remaining in the gas phase (Roberts & Millar 2000). These chemical aspects can be used to our advantage to study prestellar cores. We note that some deuterated species, such as formaldehyde or water, are formed and deuterated primarily through grain-surface chemistry in icy mantles (Ceccarelli et al. 2014). These molecules can then be thermally or photo-desorbed in active environments, such as molecular hot cores, outflows, or shocks. Of the two key deuterated species studied here, N_2D^+ is believed to be formed in cold, dense, CO-depleted regions through gas-phase chemistry driven by H_3^+ and its deuterated isotopologues. Ammonia deuteration is also straightforward to understand in the framework of gas-phase processes (Roueff et al. 2005). However, recent laboratory experiments (Fedoseev et al. 2015) suggest that ammonia and its deuterated isotopologues may also be formed thorough successive additions of hydrogen and deuterium atoms to nitrogen atoms in CO-rich interstellar ice analogs, which are efficient at temperatures below 15 K.

High spectral resolution investigations of the velocity field in central regions of cold, dense cores are invaluable for disentangling rotation and collapse (Belloche et al. 2002), providing excellent constraints on fragmentation and formation of disks, which are critically dependent on the magnetic field (Hennebelle & Fromang 2007; Hennebelle & Teyssier 2007). This requires, however, that suitable molecular tracers be chosen. The fundamental submillimeter lines of ammonia isotopologues have critical densities of the order of 10^6 cm^{-3} and, with simple hyperfine patterns, are excellent tracers of dense gas at the onset of star formation (Lis et al. 2002b, 2006), providing information complementary to H_2D^+ (van der Tak et al. 2005; Vastel et al. 2006, 2012; Caselli et al. 2008). The interferometric study of Crapsi et al. (2007) has shown a very high $\text{NH}_2\text{D}/\text{NH}_3$ fractionation ratio in the central region of L1544, $\sim 0.5 \pm 0.2$ which demonstrates the persistence of deuterated ammonia molecules at very high densities ($\sim 2 \times 10^6 \text{ cm}^{-3}$), and low temperatures ($\sim 10 \text{ K}$). Very high deuteration ratios have also been reported in other molecules (e.g., $\text{N}_2\text{D}^+/\text{N}_2\text{H}^+ = 0.7 \pm 0.2$ in L183; Pagani et al. 2007;

see the recent review of Ceccarelli et al. 2014). Nevertheless, lines of deuterated isotopologues of ammonia, with their simple hyperfine patterns, fulfill all of the requirements for being optimum tracers of cold, dense cores.

Herschel has enabled for the first time systematic studies of the fundamental submillimeter lines of NH_3 and NH_2D in prestellar cores. The long-term goals of this study are threefold: (a) to firmly establish the utility of ammonia isotopologues as tracers of dense, cold gas at the onset of star formation as postulated by Lis et al. (2006, 2008); (b) to determine the morphology and velocity structure of an example prestellar core, the processes that drive the evolution in this earliest stage of star formation and that control such important aspects as core fragmentation, and the resulting initial mass function and binarity fraction of protostars; (c) to improve our understanding of the chemical and physical processes that control gas-grain interaction, freeze out, and mantle ejection in dense cloud cores, including when/why species freeze out, and of deuterium fractionation. These processes are of key interest for the chemistry of regions of star formation, and hence the supply of volatiles in planet-forming environments, likely including the early solar nebula.

In this paper, we present extensive single-dish and interferometric observations of L1689N, a nearby (120 pc; Loinard et al. 2008) dark cloud located in the ρ Ophiuchi complex which harbors one of the best-studied solar-type protostars, IRAS 16293-2422 (hereafter IRAS 16293). The nearby protostellar core, sometimes referred to as I16293E, has previously been suggested to be interacting with the blue lobe of one of the outflows driven by IRAS 16293 (Wootten & Loren 1987; Lis et al. 2002a; Stark et al. 2004). This region is thus an excellent laboratory in which to study the effects of stellar feedback on the physics and chemistry of the surrounding interstellar medium (ISM). In addition to *Herschel* observations, we have obtained interferometric observations of the $970 \mu\text{m}$ dust continuum, ND_3 and N_2D^+ line emission using the ALMA Compact Array (ACA), as well as maps of several deuterated molecular tracers using the Caltech Submillimeter Observatory (CSO). The observational results are presented in Section 3, followed by a discussion in Section 4, and a summary in Section 5.

2. OBSERVATIONS

The observations of the fundamental rotational transitions of NH_2D , NH_3 , and o- H_2O in L1689N presented here¹² were carried out in 2012 February–September using the Band 1 receivers of the Heterodyne Instrument for the Far-Infrared (HIFI; de Graauw et al. 2010) on the *Herschel Space Observatory* (Pilbratt et al. 2010). Both the WBS and HRS spectrometers were used in parallel. The WBS provides full coverage of the 4 GHz intermediate frequency (IF) band in the upper and lower sidebands with a 1.1 MHz resolution (0.59 km s^{-1} at 557 GHz), while the HRS provides higher spectral resolution spectra of selected lines of interest (spectral resolution of 0.12 MHz or 0.07 km s^{-1} at 492 GHz). For mapping observations ($\sim 180'' \times 190''$ for water, $70'' \times 90''$ for NH_2D), the HIFI OTF observing mode was used, while the frequency-switching mode was used for deeper, pointed

¹² *Herschel* OBSIDs: 1342238591–38592, 38650, 50470, 51430; open time program *Ammonia as a Tracer of the Earliest Stages of Star Formation*, OT1_dlis_2, OT2_dlis_3.

Table 1
Herschel, ACA, and CSO Observations of L1689N

Species	Frequency (GHz)	Transition	E_u (K)
<i>Herschel</i>			
p-NH ₂ D	494.45455	1 _{1,0} -0 _{0,0} (0a-0s)	23.7
o-H ₂ O	556.93599	1 _{1,0} -1 _{0,1}	61.0
o-NH ₃	572.49816	1 ₀ -0 ₀ (0s-0a)	27.5
SO	558.08764	12 ₁₃ -11 ₁₂	194.4
SO	559.31952	13 ₁₃ -12 ₁₂	201.1
SO	560.17865	14 ₁₃ -13 ₁₂	192.7
ALMA Compact Array			
N ₂ D ⁺	308.42227	4-3	37.0
CH ₃ OH	309.29040	5 _{1,4} -5 _{0,5} A - +	49.7
SO	309.50244	2 ₂ -2 ₁	19.3
ND ₃	309.90949	1 ₀ -0 ₀ (0a-0s)	14.9
Continuum	309.963	...	...
Continuum	353.949	...	...
Caltech Submillimeter Observatory			
DCO ⁺	216.11258	3-2	10.4
DCN	217.23854	3-2	10.4
DNC	228.91048	3-2	11.0
N ₂ D ⁺	231.32183	3-2	11.1
HCN	265.88643	3-2	12.8
HCO ⁺	267.55763	3-2	12.8
HNC	271.98114	3-2	13.1
N ₂ H ⁺	279.51175	3-2	13.4

observations. The data have been processed through the standard HIFI data reduction pipeline using HIPE version 10.0 (Ott 2010) and the resulting spectra were subsequently reduced using the GILDAS CLASS¹³ software package. The FWHM HIFI beam size is $\sim 44''$ at 492 GHz and $38''$ at 557 GHz, and the main-beam efficiency is 76% (Roelfsema et al. 2012). The frequencies and quantum numbers of the transitions observed are listed in Table 1.

ALMA observations were obtained within two frequency settings (science goals): one near 310 GHz and a second near 340 GHz. The spectral lines discussed in the present manuscript correspond to the 310 GHz frequency setting and are summarized in Table 1. A 10 pointing mosaic covering a $\sim 65'' \times 80''$ region was observed on 7 occasions during 2014 January–April, using 11 7 m antennas of the Morita Array component of ALMA in Cycle 1. At each point of the mosaic, 15 minutes of data were collected for a sensitivity of 0.41 Jy/beam in a 0.1 km s^{-1} channel. Four spectral windows were observed near 309 GHz, with varying spectral resolution. The N₂D⁺ $J = 4-3$ line was in a 0.0625 GHz width spectral window centered near 308.449 GHz (velocity resolution of 0.045 km s^{-1}), and the ND₃ line lay in another 0.0625 GHz width spectral window centered near 309.94 GHz. The 970 μm dust continuum flux was extracted by averaging channels within two bands of 1.992 GHz width centered near 308.053 and 309.873 GHz. The CH₃OH and H₃O⁺ lines in the bands were flagged before averaging to avoid possible contamination. In the continuum image, the peak flux is 76 mJy/beam and the integrated flux is 840 mJy. The rms in the image is 1.1 mJy/

beam (an excellent S/N of 70) and the synthesized beam size is $5''.04 \times 3''.16$ at a position angle of 80° .

At 340 GHz, a 10 point mosaic covering the same $\sim 65'' \times 80''$ region was observed on 6 occasions in 2014 April with the Morita Array component of ALMA with 15 minutes of on-source integration time per mosaic pointing. Eleven 7 m antennas were used for the observations with a maximum baseline of 50 m. The 850 μm dust continuum flux was extracted by averaging channels free of molecular line emission. The rms is 3.3 mJy, which is a factor of 3 higher than that in the 970 μm continuum image, and the synthesized beam size is $4''.4 \times 2''.9$ at a position angle of 94° . The peak flux density of the 850 μm dust continuum is 72 mJy/beam and the integrated flux is 730 mJy. The 970 μm continuum image thus has a much higher signal-to-noise ratio (S/N) and better preserves the low-level extended emission. Therefore, we use the 970 μm data in the subsequent analysis.

The ALMA/NAASC staff performed bandpass calibration with the quasar J1733-1304 or J1427-4206, and the flux was calibrated with Titan. The phase calibrator was J1626-2951. The uncertainty in the absolute flux is 10%. The calibrated visibilities were deconvolved and CLEANed with the CASA software package (version 4.2).

Single-dish observations of the 1 mm molecular transitions were carried out in 2013 May–June using the 10.4 m Leighton Telescope of the CSO on Mauna Kea, Hawaii. We used the wideband 230 GHz facility SIS receiver and the FFTS backend that covers the full 4 GHz IF range with a 270 kHz channel spacing (0.37 km s^{-1} at 220 GHz). Pointing of the telescope was checked by performing five-point continuum scans of planets and strong dust continuum sources. The CSO main-beam efficiency at 230 GHz at the time of the observations was determined from total-power observations of planets to be $\sim 65\%$. The absolute calibration uncertainty of the individual measurements is $\sim 15\%$. The FWHM CSO beam size is $\sim 35''$ at 220 GHz, which is comparable to the Band 1 HIFI beam size.

3. RESULTS

3.1. *Herschel* Space Observatory

The overall morphology of the region, as observed with *Herschel*, is shown in Figure 1. The color image shows the integrated intensity of the 557 GHz water emission between -15 and 25 km s^{-1} . The location of IRAS 16293 is marked by the black contours of the integrated intensity of high-energy SO line emission, observed simultaneously, while the prestellar core is outlined by the white NH₂D contours. There is an anti-correlation between the NH₂D and water emission which surrounds and avoids the prestellar core. This can be seen even more clearly in the velocity channels maps (Figure 2) at blueshifted velocities. The strongest peak of the H₂O emission is seen toward IRAS 16293. However, two secondary peaks are present to the northwest and southwest of the prestellar core. The blueshifted emission toward the northern peak extends to $\sim -8 \text{ km s}^{-1}$, while the emission toward the south-western peak stops at $\sim -2 \text{ km s}^{-1}$. Water is generally considered to be an excellent tracer of molecular outflows because water molecules are mostly frozen on dust grains in the cold gas and the spectra are less confused by foreground envelope absorption or emission compared to other tracers. We note that water vapor was detected in the isolated prestellar core L1544 in a very long HIFI integration (Caselli et al. 2012). A low gas-phase water

¹³ <http://iram.fr/IRAMFR/GILDAS>

Figure 1. Color image of the integrated line intensity of the fundamental rotational transition of o-H₂O between -15 and 25 km s^{-1} , with overlaid white contours of the integrated intensity of the fundamental rotational transition of NH₂D between 1.7 and 5.5 km s^{-1} (including the 3 hyperfine components). The NH₂D emission shows the location of the prestellar core, while the location of the solar-type protostar IRAS 16293 driving the molecular outflow is shown by the black contours of the excited SO emission (average of the three transitions listed in Table 1). Contour levels for NH₂D are from 20% to 95% of the peak (0.65 K km s^{-1}) with a step of 15%. For SO, the contour levels are 50%, 70%, and 90% of the peak (2.25 K km s^{-1}). Black triangles mark the locations of IRAS 16293 A and B (lower and upper, respectively). The red and blue arrows mark the directions of the compact CO outflows observed with the SMA (Girart et al. 2014), which have opposite polarity to the large-scale outflows seen in earlier single-dish studies (e.g., Stark et al. 2004). E1 and E2 mark the locations of the two SiO clumps of Hirano et al. (2001).

abundance in this source is maintained by UV photons locally produced by the interaction of H₂ molecules with galactic cosmic rays.

A high-resolution spectrum of the NH₂D line toward the prestellar core is shown in Figure 3 (upper panel). The hyperfine structure (HFS) is well resolved spectrally, given the narrow line width of 0.38 km s^{-1} . The HFS fit parameters (the line center velocity and width, the excitation temperature, and the line center optical depth) are given in Table 2. The weakest hyperfine component is optically thin ($\tau \sim 0.5$). The spectrum of NH₃ (lower panel) looks very peculiar, as only the weakest HFS component is clearly seen, with an intensity lower than that of the weakest NH₂D hyperfine component. The NH₃ emission is clearly sub-thermally excited, and the resulting spectrum is affected by the strong temperature and density gradients along the line of sight. A likely explanation of the peculiar line shape is that the two strongest NH₃ hyperfine components are almost completely absorbed by the foreground gas. The NH₃ spectrum toward IRAS 16293 shows absorption at $\sim 3.85 \text{ km s}^{-1}$ (red vertical lines in Figure 3, lower panel). Since the molecular emission toward the prestellar core is blueshifted with respect to the envelope velocity, the weakest blueshifted NH₃ hyperfine component is much less affected by foreground absorption. An alternative explanation that the strongest NH₃ emission feature corresponds to the main HFS component at a velocity of $\sim 2.5 \text{ km s}^{-1}$, and that the weakest

HFS component is simply not detected, can be discarded as there are no other molecular tracers emitting at 2.5 km s^{-1} in this source. Due to the contamination by the foreground absorption, the optical depth of the NH₃ line cannot be directly determined from the HFS fit, and thus the line is not useful for quantitative determination of the molecular column density and the isotopic D/H ratio.

Figure 4 shows the integrated line intensity of the weakest NH₃ HFS component with overlaid contours of the NH₂D and SO emission. In the vicinity of the prestellar core, NH₃ peaks $\sim 10''$ to the east of NH₂D. The offset may be indicative of an abundance gradient between the two ammonia isotopologues. However, given the high opacity of the NH₃ line, it may simply be due to radiative transfer effects.

An interaction with the outflow should have an effect on the velocity field of the prestellar core. Figure 5 shows the NH₂D line center velocity and width as a function of position (top left and right panels, respectively). There is a clear trend of the line velocity and width increasing from the northeast to the west/southwest. The NH₂D spectra at three selected positions, shown in the bottom row, display this transition from a quiescent gas with a narrow line width in the northeast to a much more perturbed gas in the western/south-western part of the core.

3.2. ALMA Compact Array

To further investigate the morphology of the prestellar core, we have imaged the $970 \mu\text{m}$ dust continuum emission together with a number of molecular tracers, including deuterated species, using the ACA. The N₂D⁺ emission (Figure 6, color image and white contours) extends south/southwest from the peak of the NH₂D emission, as observed with HIFI (blue star), and peaks $\sim 5''$ to the north with respect to the dust continuum (black contours, left panel). While the northern tip of the N₂D⁺ emission coincides with the NH₂D peak, the very large $44''$ HIFI beam prevents a detailed comparison of the morphology on the angular scales probed by the ACA. We note, however, that the dust emission terminates rather abruptly in this part of the core, with the molecular emission extending further to the north. The ND₃ emission (black contours, right panel) more closely resembles N₂D⁺ than the dust continuum emission, although the ND₃ emission peak is displaced by $\sim 2''.5$ east with respect to N₂D⁺ (possibly due to optical depth effects, as the N₂D⁺ line has a significant opacity; see Table 2).

Figure 7 shows N₂D⁺ and ND₃ spectra toward the respective emission peaks with single velocity component HFS fits overlaid in red. Vertical green lines mark the velocities and relative intensities of the HFS components. The HFS fit parameters are given in Table 2. The N₂D⁺ emission is quite optically thick and does not directly trace the molecular column density. The derived excitation temperature, which can be taken as a lower limit of the gas kinetic temperature (the emission does not have to be thermalized), is significantly lower than the isothermal dust temperature of 16 K derived from a spectral energy distribution fit by Stark et al. (2004). However, these authors point out that a cold, high-density region with $T_d \ll 16 \text{ K}$ can easily be hidden at the center of the core. In fact, in a recent study, Bacmann et al. (2016) derive a temperature profile increasing from 11 K at the core center to 16 K in the outer envelope. Even lower dust temperatures, in the range of $8\text{--}16 \text{ K}$, are derived by Pagani et al. (2016).

Figure 2. Channel maps of the blueshifted 557 GHz water emission, between -5.2 and 3.8 km s^{-1} with overlaid white contours of the NH_2D integrated line intensity between 1.7 and 5.5 km s^{-1} showing the location of the prestellar core and black contours of the excited SO emission showing the location of the protostar IRAS 16293. Contour levels are the same as in Figure 1.

The ND_3 emission is optically thin. A HFS fit gives a slightly larger line width compared to N_2D^+ (Table 2), which however is consistent with that of the NH_2D emission in the ten times larger HIFI beam. We thus see no evidence in our deuterated ammonia data for the turbulent velocity to vary with radius, as seen in some sources. The complex HFS of N_2D^+ and a limited S/N of the ND_3 spectrum prevent us from drawing any conclusions about the presence of possible infall motions in the core. The ~ 0.4 km s^{-1} FWHM line width roughly corresponds to the H_2 thermal line width at 7 K and is 3–4 times larger than the expected thermal line width of ND_3 , NH_2D , or N_2D^+ . This shows that the line broadening is mainly non-thermal and that sonic or somewhat sub-sonic turbulent motions are dominant even in the northern, quiescent part of the core. This is different from the typical prestellar cores in Taurus where line widths are essentially thermal and is perhaps related to the interaction with the outflow.

Figure 8 shows the distribution of the CH_3OH and SO emission in the vicinity of the prestellar core (blue contours, left and right panels, respectively). The background image is the blueshifted H_2O emission observed with HIFI, while the black contours show the 970 μm dust continuum emission. A significant fraction of the CH_3OH and SO emission ($\sim 80\%$ – 85%) is resolved out in the ACA images. However, we see strong methanol emission associated with the two blueshifted water peaks to the northwest and southwest of the prestellar core, while the SO emission is only associated with the weaker south-western blueshifted water peak. Pagni et al. (2016) report the presence of a new outflow which could be responsible for the emission peak southwest of the prestellar core. No SO or methanol emission is detected toward the prestellar core.

3.3. Caltech Submillimeter Observatory

To study further the large-scale morphology and kinematics of the molecular gas in the vicinity of the prestellar core, we have mapped the 1 mm lines of DCO^+ , DCN , DNC , and N_2D^+ , as well as their hydrogenated counterparts HCO^+ , HCN , HNC , and N_2H^+ , using the CSO (Table 1).¹⁴ The resulting maps of deuterated species are shown as color images in Figure 9. Although all deuterated species peak in the general vicinity of the prestellar core, significant differences among their morphologies can be seen. The prestellar core, as traced by the NH_2D emission, is best seen in the DNC and N_2D^+ images. The DCO^+ emission, being the brightest and thus most suitable for mapping of extended areas, is not confined to the immediate vicinity of the prestellar core and shows a clear extension toward the E1 shocked region, while DCN peaks in between the prestellar core and E1. This is not surprising, as this molecule has been suggested to be produced by “warm chemistry” driven by CH_2D^+ in the gas with temperatures of the order of 50 K, where the H_2D^+ driven deuteration reactions are already suppressed (Roueff et al. 2007; Parise et al. 2009). We note that, similar to NH_2D , the single-dish N_2D^+ and DNC emission also peaks to the north of the ACA N_2D^+ and ND_3 sources. Among the hydrogenated molecular tracers, only N_2H^+ emission reveals the prestellar core, peaking close to the location of the ACA N_2D^+ and ND_3 sources. All of the other tracers largely follow the distribution of the blueshifted water emission, peaking toward the E1 source with a secondary peak to the southwest (labeled HE2 by Castets et al. 2001).

¹⁴ The N_2H^+ data have previously been used in the models of Daniel et al. (2016a) to derive the nitrogen isotopic ratio in L1689N.

Figure 3. Spectra of the NH_2D and NH_3 lines toward the prestellar core ($\alpha_{J2000} = 16^{\text{h}}32^{\text{m}}29^{\text{s}}.40$, $\delta_{J2000} = -24^{\circ}28'53''$) taken with the HRS spectrometer. The green line in the upper panel is the HFS fit, which gives the line center optical depth of 2.7 ± 0.07 and the excitation temperature of 6.5 ± 0.8 K. The H_2O spectrum observed with the WBS is shown in blue in the lower panel. Red vertical lines marked the velocities of the NH_2D and NH_3 HFS components, with the relative line intensities corresponding to optically thin LTE emission (5:3:1). The NH_3 HFS components are plotted with respect to the velocity of the foreground cloud envelope at 3.85 km s^{-1} , as determined from the NH_3 absorption spectrum toward IRAS 16293.

Table 2
Results of the HFS Fits

Line	v_0 (km s^{-1})	Δv (km s^{-1})	T_{ex} (K)	τ_0
NH_2D	3.34	0.38	6.5	2.7
ND_3	3.45	0.40	6.5	0.43
N_2D^+	3.68	0.34	7.9	3.3

Note. Formal 1σ fit uncertainties provided by CLASS are $\sim 0.002 \text{ km s}^{-1}$ for the line velocity and width, and $\sim 2.5\%$ for the line center optical depth.

4. DISCUSSION

4.1. Properties of the Dust Continuum Source

The $970 \mu\text{m}$ continuum source detected with ACA is elongated approximately in the north–south direction. A two-dimensional Gaussian fit gives a FWHM source size of $13''.2 \times 8''.6$ at a position angle of 2° . After deconvolving the beam, the intrinsic source size is $12''.9 \times 7''.0$, or $1540 \times 840 \text{ au}$, assuming a distance of 120 pc (Loinard et al. 2008). The column density profile of the core is well described by a two-dimensional Gaussian. However, the spatial

Figure 4. Color image of the integrated line intensity of the weakest NH_3 HFS component between -0.8 and 1.9 km s^{-1} with overlaid contours of NH_2D and SO (white and black, respectively). Contour levels and symbols are the same as in Figure 1.

dynamical range in the current image is rather low: only ~ 3.5 . Higher angular resolution observations with the main ALMA array will thus be required to study this important aspect.

The peak $970 \mu\text{m}$ continuum flux is 76.0 mJy/beam and the integrated flux is 0.84 Jy . To estimate the H_2 column density and the mass of the compact dust source, we scale the grain opacity coefficient $\kappa_{1.3 \text{ mm}} = 0.005 \text{ cm}^2 \text{ g}^{-1}$ (Motte et al. 1998), which is appropriate for dense prestellar clumps, with a ν^2 frequency dependence. This leads to $\kappa_{970 \mu\text{m}} = 0.009 \text{ cm}^2 \text{ g}^{-1}$.¹⁵ For a 16 K dust temperature (Stark et al. 2004), we derive an H_2 column density of $1.8 \times 10^{23} \text{ cm}^{-2}$. However, if the dust temperature is 11 K , as suggested by Bacmann et al. (2016), then the corresponding column density increases to $3.3 \times 10^{23} \text{ cm}^{-2}$. Even in the latter case, the dust emission is optically thin (a $970 \mu\text{m}$ optical depth of ~ 0.01). Assuming a ν^2 frequency dependence, the dust opacity at 557 GHz is also low. Therefore, the observed anticorrelation between water and NH_2D emission, as seen by HIFI, cannot be explained by foreground dust absorption.

Assuming a line-of-sight source size of $9''.5$ or 1140 au , equal to the geometric mean of the FWHM sizes in the plane of the sky, we derive an H_2 volume density of $(1.1\text{--}1.9) \times 10^7 \text{ cm}^{-3}$, depending on the dust temperature. This is an order of magnitude higher than the values derived in earlier single-dish studies (Stark et al. 2004; Vastel et al. 2012), but is consistent with the best-model value of $1.4 \times 10^7 \text{ cm}^{-3}$ in the recent study of Bacmann et al. (2016). The high central density in the model of Bacmann et al. (2016) is in fact directly related to the presence of a temperature gradient. The best-fit power-law density exponent in these latest models is 1.7 , as compared to the low value of ~ 1 in the isothermal model of Stark et al.

¹⁵ Stark et al. (2004) used a grain opacity coefficient of $\kappa_{1.2 \text{ THz}} = 0.1 \text{ cm}^2 \text{ g}^{-1}$. When extrapolated with a ν^2 frequency dependence, this gives $\kappa_{970 \mu\text{m}} = 0.008 \text{ cm}^2 \text{ g}^{-1}$, which is about 25% lower than the value used here.

Figure 5. (Top) Maps of the NH_2D line velocity and width across the prestellar core (left and right, respectively). Black contours show the NH_2D integrated line intensity and white contours blueshifted H_2O emission between -0.2 and 3.8 km s^{-1} . Contour levels are from 20% to 95% of the peak (0.65 and 1.11 K km s^{-1} for NH_2D and H_2O , respectively), with a step of 15%. The $(0, 0)$ position corresponds to $\alpha_{J2000} = 16^{\text{h}}32^{\text{m}}28^{\text{s}}.84$, $\delta_{J2000} = -24^{\circ}28'57''$. (Bottom) NH_2D spectra at three positions across the prestellar core, marked by white squares in the top row, demonstrating the change in the line velocity and width from the northeast to the southwest. The spectra have been convolved with a $25''$ Gaussian to improve the S/N.

(2004). The prestellar core can also be identified with source 84 (SMM 19) of Pattle et al. (2015), who derive a temperature of 11.8 K and a density of $3.3 \times 10^7 \text{ cm}^{-3}$. The new single-dish and interferometric data presented here provide additional constraints for detailed radiative transfer modeling, which will be the subject of a separate study.

The total mass of the compact continuum source seen in the ACA image is $0.22 M_{\odot}$, assuming a dust temperature of 16 K ($0.42 M_{\odot}$ for a dust temperature of 11 K), a small fraction of the total mass of the prestellar core $2.45 M_{\odot}$ (Stark et al. 2004; assuming a 16 K dust temperature and scaling to the distance of 120 pc used here). Pattle et al. (2015) derive a mass of $0.30 M_{\odot}$ (after scaling to the distance of 120 pc). This source thus has a mass characteristic of the Very Low Luminosity Objects (VeLLOs) detected by *Spitzer* (see, e.g., Dunham et al. 2014 and references therein), which have bolometric luminosities below $0.1 L_{\odot}$ (Di Francesco et al. 2007). Stark et al. (2004) derive a total bolometric luminosity of $1.3 L_{\odot}$ toward the prestellar core in L1689N, after scaling to the distance of 120 pc . However, it is not clear what fraction of this luminosity is associated with the compact continuum source detected in the ACA data, as *Spitzer* IRAC images do not reveal any $4.5 \mu\text{m}$ continuum sources at this location (Pagani et al. 2016).

4.2. Interaction with the Outflow

The environment of L1689N shows a complex morphology. Optically thick molecular lines show a pronounced self-reversal at the systemic velocity of $\sim 3.8 \text{ km s}^{-1}$. The parent molecular cloud has a mean density of $(2-3) \times 10^4 \text{ cm}^{-3}$ and a kinetic temperature of 12 K based on ammonia observations (Menten et al. 1987). Multiple large-scale molecular outflows are present, driven by IRAS 16293 (Mizuno et al. 1990; Lis et al. 2002a; Stark et al. 2004). The SMA observations of Yeh et al. (2008) imply a primarily east–west outflow with blueshifted emission to the west. These authors suggest that this small-scale outflow may be the inner part of the large-scale east–west outflow. More recent SMA data (Girart et al. 2014) suggest that the CO emission at moderately high velocities arises from two bipolar outflows, which appear perpendicular to each other and both originate from IRAS 16293A. The more compact outflow is impacting the circumstellar gas around component B, and is possibly being redirected. The directions of the two compact outflows, as indicated by the SMA observations of Girart et al. (2014), are marked in Figure 1.

The outflow originates in the two sources at the center of IRAS 16293A: A-E and A-W. In fact, VLA observations reveal that the continuum source A-E orbits A-W, which had a recent continuum ejection event (Loinard et al. 2007). That event defined the flow originating in A-W with the redshifted

Figure 6. Integrated line intensity of the N_2D^+ emission (color image and white contours) with overlaid black contours of the $970\ \mu\text{m}$ continuum emission (left panel) and integrated line intensity of the ND_3 emission (right panel). N_2D^+ emission has been integrated over velocities $3.04\text{--}4.17$ and $5.24\text{--}5.77\ \text{km s}^{-1}$, including two groups of the strongest hyperfine components, while the ND_3 emission has been integrated over velocities $3.08\text{--}3.79$ and $4.32\text{--}4.97\ \text{km s}^{-1}$, including the two strongest hyperfine components (including the weaker hyperfine components does not improve the S/N in the resulting images). Contour levels for N_2D^+ and the continuum emission are $-5, 5, 10, 20, 35,$ and 50 times the rms ($3.84 \times 10^{-2}\ \text{Jy/beam km s}^{-1}$ and $1.11 \times 10^{-3}\ \text{Jy/beam}$, respectively). For ND_3 , contour levels are $-3, 3, 5, 7, 10,$ and 14 times the rms ($3.67 \times 10^{-2}\ \text{Jy/beam km s}^{-1}$). The synthesized beams are $4''.71 \times 2''.69$ at 78° for N_2D^+ (shown in the lower left corner of the left panel), $4''.70 \times 3''.00$ at 73° for ND_3 (lower right corner of the right panel), and $5''.04 \times 3''.16$ at 80° for $970\ \mu\text{m}$ continuum (lower right corner of the left panel). Symbols mark the location of the emission peaks: N_2D^+ (circle; $16^{\text{h}}32^{\text{m}}28^{\text{s}}.88, -24^\circ29'05''.0$), ND_3 (triangle; $16^{\text{h}}32^{\text{m}}29^{\text{s}}.07, -24^\circ29'04''.9$), continuum (square; $16^{\text{h}}32^{\text{m}}29^{\text{s}}.01, -24^\circ29'09''.9$), and NH_2D (star; $16^{\text{h}}32^{\text{m}}29^{\text{s}}.2, -24^\circ28'59''.4$).

Figure 7. N_2D^+ and ND_3 spectra (left and right panels, respectively) toward the respective emission peaks. HFS fits are shown in red, with the best-fit parameters shown in the upper left corners. For N_2D^+ the LSR velocity scale is plotted with respect to the CDMS frequency of $308.422.27\ \text{GHz}$.

Figure 8. Integrated line intensity of the blueshifted H_2O emission between -0.2 and 3.8 km s^{-1} (color image) with overlaid black contours of the $970 \mu\text{m}$ continuum emission and blue contours of the integrated line intensity of the CH_3OH and SO emission (left and right panels, respectively). N_2D^+ emission has been integrated over velocities -2.56 to 5.49 km s^{-1} , while the SO emission has been integrated over velocities 0.90 to 4.21 km s^{-1} . Contour levels for the CH_3OH and the continuum emission are $-5, 5, 10, 20, 35$, and 50 times the rms ($6.8 \times 10^{-2} \text{ Jy/beam km s}^{-1}$ and $1.11 \times 10^{-3} \text{ Jy/beam}$, respectively). For SO , contour levels are $-3, 3, 6, 10, 15$, and 20 times the rms ($6.7 \times 10^{-2} \text{ Jy/beam km s}^{-1}$). The synthesized beam for the CH_3OH and SO images is $4''.88 \times 3''.19$ at 81° for ND_3 (lower right corner of the right panel) and $5''.04 \times 3''.16$ at 80° for $970 \mu\text{m}$ continuum (shown in the lower right corner). Symbols are the same as in Figure 6.

emission to the southwest. VLBI water maser observations agree with this picture, showing a very well-defined bow-shock among the redshifted masers to the southwest (A. Wootten 2016, private communication). Source A-E, in orbit around A-W, also shows maser outflow, approximately parallel to that in A-W and in the same sense, i.e., redshifted emission to the southwest. On larger scales, the overall complexity of the L1689N region makes the interpretation of the outflow difficult. However, one clear conclusion is that there is a lot of moderate-velocity blueshifted gas in the immediate vicinity of the prestellar core, and the change in the observed NH_2D line velocity and width is direct evidence that this gas is interacting with the prestellar core.

Interestingly, the polarity of both compact CO outflows seen in the SMA data (Girart et al. 2014) seems opposite to that of the large-scale outflows seen in the earlier lower-resolution single-dish data (Mizuno et al. 1990; Lis et al. 2002a; Stark et al. 2004; compare, e.g., Figure 1 of Girart et al. 2014 and Figure 17 of Stark et al. 2004). The northern peak of the blueshifted water emission appears to be a part of the main east–west outflow detected in the SMA CO data. VLBA observations of the water maser proper motions (Wootten et al. 1999) also show that the IRAS 16293A outflow proceeds red NE, blue SW, from within a few astronomical units of the sources.

The key observational aspects of the new data presented here that have to be satisfactorily explained by a source model are the following: (a) the change in the NH_2D line center velocity and width across the core (Figure 5); (b) the apparent offset between the peak of the $970 \mu\text{m}$ dust continuum emission and the emission of deuterated molecular tracers in the ACA data (Figure 6).

One possible explanation is that the prestellar core in L1689N is simply a pre-existing density enhancement that had formed independently of IRAS 16293. This region is characterized by some of the highest deuteration levels known in galactic sources. For example, it is one of a handful of sources where triply deuterated ammonia has been detected (Roueff et al. 2005). Such cores are generally rare, but Barnard 1 offers another example of a similar region. Here, a dense prestellar core, B1b (also referred to as SMM1), with very high deuteration levels, which has been suggested to host the first hydrostatic core (Gerin et al. 2015), is also located in close proximity to more evolved protostellar sources, B1a (SMM6) and B1c (SMM2), driving pronounced outflows (Hatchell et al. 2007; Hiramatsu et al. 2010). High deuteration levels require a low temperature, high density, and consequently high CO depletion. Such conditions are found in isolated prestellar cores, e.g., L1544, which are characterized by a centrally peaked density distribution that can be traced well by dust continuum emission. However, our ACA data reveal no bright compact dust continuum sources in the northern part of the core, where the strongest emission of deuterated molecular tracers is seen in single-dish maps.

Lis et al. (2002a) suggested that this region may be a part of the ambient cloud that is pushed and compressed by the outflow. The shock-compressed, dense gas then cools efficiently to low temperatures, and the gas-phase chemistry quickly drives up abundances of deuterated molecular species. This scenario is in fact consistent with the observations presented here. The blue lobe of the IRAS 16293 east–west outflow impacts the prestellar core from the back. The shock could have already propagated through the northeastern part of the core, where we now see narrow, undisturbed line profiles in the cold, compressed post-shock gas, blueshifted

Figure 9. CSO maps of deuterated species in L1689N (color images) with overlaid white contours of their hydrogenated counterparts. N_2D^+ and DNC are the best tracers of the prestellar core with N_2D^+ being more centrally peaked. Both DCO^+ and DCN emission show extensions toward the E1 source in the northwest. Black contours show the distribution of NH_2D as observed with the ACA, while the blue contours show the distribution of CH_3OH . Contour levels are 5–17.5 with a step of 2.5 K km s^{-1} for HCO^+ , 2.5–7 with a step of 1.5 K km s^{-1} for N_2H^+ , 2–8 with a step of 1.5 K km s^{-1} for HCN, and 1–3 with a step of 0.5 K km s^{-1} for HCO^+ . ACA contour levels are 10, 20, and 40 times the rms. The star marks the location of the NH_2D emission peak observed with HIFI.

with respect to the systemic velocity of the ambient cloud. An order of magnitude density enhancement, as compared to the ambient cloud, expected in the post-shock gas produces conditions that are propitious for the high deuteriation levels observed. The west/southwest part of the core is, however, still interacting with the outflow, hence the disturbed appearance of the molecular line profiles with broader line widths. The shock to the north/northwest of the core (traced by, e.g., the SiO or CH_3OH emission) may be associated with a higher-velocity component of the flow, possibly a jet or jet remnant, as the highest blueshifted water and CO emission occurs there. There may also be a pre-existing density enhancement at this location which happens to lie in the path of the higher-velocity component of the flow, which was further compressed and heated up by the shock. This would explain the strong emission of high-density molecular tracers such as HCO^+ , HCN, HNC, and SiO in the single-dish images (Figure 9; Hirano et al. 2001). This region also stands out in the ACA CH_3OH image and thus shows the classic outflow-dense gas interaction signatures.

The apparent offset between the dust continuum peak, as observed with the ACA, and the emission of deuterated molecular tracers is another intriguing aspect. Such offsets have been observed in other prestellar cores (e.g., L183; Tiné et al. 2000), or in outflows (e.g., L1157; Fontani et al. 2014). The dust continuum emission is typically taken as a measure of the H_2 column density, indicating the location of the densest central parts of prestellar cores. However, possible variations in the dust temperature may strongly affect this interpretation. In fact, multi-wavelength *Spitzer* and *Herschel* continuum data (Pagani et al. 2016) indicate a NW–SE temperature gradient across the prestellar core, with colder dust located in the north. While the average dust temperature in a single-dish beam is $\sim 16 \text{ K}$ (Stark et al. 2004), this may be dominated by the outer surface layers and the dust temperature in the central, most shielded regions may be significantly lower (see Bacmann et al. 2016). The ACA 850/970 μm flux ratio map shows no evidence for a temperature gradient across the compact source. However, the S/N in our 850 μm continuum image is too low to draw definitive conclusions.

Figure 10. Color images of the single-dish 450 μm dust continuum emission toward the prestellar core, observed with SCUBA (Stark et al. 2004; left panel) and SCUBA-2 (Pattle et al. 2015; right panel), with overlaid contours of the 970 μm continuum, N_2D^+ , and CH_3OH emission observed with the ACA (white, black, and blue contours, respectively). Contour levels are the same as in Figures 6 and 8. The solid magenta contour shows the location of the NH_2D emission, as observed by HIFI, while the dashed magenta contour outlines the location of the H_2D^+ emission (Pagani et al. 2016; 60% contour levels).

Another important aspect is that some of the extended continuum emission may simply be filtered out in the ACA data. Figure 10 shows 450 μm SCUBA and SCUBA-2 dust continuum emission images toward the prestellar core (Stark et al. 2004; Pattle et al. 2015, left and right panels, respectively) with overlaid contours of the 970 μm continuum and N_2D^+ emission observed with the ACA (green and black contours, respectively). The single-dish dust continuum emission in the SCUBA image correlates well with the N_2D^+ emission and is clearly shifted to the north with respect to the 970 μm ACA continuum peak. The lower angular resolution 870 μm SCUBA image shows a similar offset. However, the 450 μm SCUBA-2 image peaks closer to the ACA continuum peak. The small differences between the two images may be caused by limited S/N or pointing offsets. The integrated 345 GHz ACA flux is only 0.72 Jy, as compared to the peak 870 μm broadband flux of 1.4 Jy in the 14'' JCMT beam (Stark et al. 2004). The minimum baseline of the ACA is 8.7 m for a transiting source. The effective baseline depends on the hour angle, but for a transiting source the ALMA Technical Handbook provides a value of 13''8 for the largest angular scale recovered by the interferometer. This strongly suggests that the ACA continuum image may not represent the true H_2 column density distribution in the prestellar core. It appears instead that the northern, quiescent part of the core is characterized by spatially extended continuum emission, which is mostly resolved out by the interferometer, while the southern part is more compact and centrally peaked. This is consistent with the interpretation outlined above in which the northern part of the core is compressed, high-density, cold post-shock gas, which is relatively uniformly distributed and not yet fragmenting to form new stars. This shows that good care should be taken when interpreting ALMA observations of

extended sources, even with the ACA, when the total-power data are not included.

Interestingly, the H_2D^+ emission shows a very distinct morphology compared to any of the tracers studied here, peaking largely to the east/northeast (see Figure 1 of Pagani et al. 2016 and the dashed magenta contour in Figure 10). Pagani et al. (2016) argue that this is in fact the location of the coldest, highest column density gas in the region. We note that a weak 970 μm continuum peak, with a flux density of 6.9 mJy/beam (a 6σ detection) is present within the H_2D^+ emission region, which can be identified with source 86 (SMA 22) of Pattle et al. (2015). An extension in this direction is also seen in the 870 μm SCUBA image. More sensitive observations with the main ALMA array are required to determine the exact nature of this source.

Another important factor is that broadband, single-dish continuum images may be contaminated by molecular line emission. As shown in Figure 9, only the classical tracers of dense cold gas, namely, deuterated species and N_2H^+ , peak toward the prestellar core. Other molecular tracers largely avoid the core and peak instead toward the E1 shock. However, a weak H^{13}CO^+ 4–3 emission peak associated with the northern part of the core was detected by Gerin et al. (2006). The blueshifted CO emission to the north of the prestellar core may also influence the broadband continuum images, given the relatively broad line widths. Molecular line contamination may thus effectively shift the broadband continuum peak to the north, away from the compact continuum source seen in the ACA image, explaining the observed morphology. However, one clear conclusion is that there are no strong compact continuum sources embedded in the northern, quiescent part of the prestellar core.

We note that ND₃ emission was detected with a high S/N toward the prestellar core in the single-dish CSO data (Roueff et al. 2005) with an integrated line intensity in the 25'' CSO beam of 0.29 K km s⁻¹ (main-beam brightness temperature), or ~9.4 Jy km s⁻¹. The integrated ND₃ flux in the ACA image is 6.8 Jy km s⁻¹, indicating that a significant fraction of the single-dish flux is in fact recovered by the interferometer.

5. SUMMARY

The combined single-dish and interferometric observations of L1689N presented here show clear evidence of an interaction between the prestellar core seen in the dust continuum and line emission of deuterated molecular tracers, notably NH₂D, ND₃, N₂D⁺, and DNC, and the molecular outflow emanating from the nearby solar-type protostar IRAS 16293. *Herschel* observations of water and singly deuterated ammonia show that the outflow wraps around and largely avoids the prestellar core. A shift in the NH₂D line velocity and width is seen across the core, with the narrowest line profiles observed toward the north-eastern part of the core. We suggest that the shock associated with the outflow has already propagated through this part of the core and we see quiescent, cold, shock-compressed, dense gas that is blueshifted with respect to the systemic velocity of the cloud. The western/south-western part of the core is still interacting with the outflow, as evidenced by the broader, more disturbed line profiles.

The N₂D⁺ emission observed with the ACA shows an elongated distribution, extending south/southwest from the single-dish NH₂D peak. ND₃ shows a similar morphology, although the peak of the emission is shifted ~2.''5 east compared to N₂D⁺, possibly due to optical depth effects. The 970 μm dust continuum emission observed with the ACA is offset ~5'' (one ACA synthesized beam) to the south with respect to the N₂D⁺ and ND₃ emission peaks. A possible explanation is that the material in the northern part of the core is largely uniformly distributed and has not yet fragmented into compact sources that can lead to a second generation of star formation in the region. The continuum emission is thus largely resolved out by the interferometer. However, a compact dust source with a size of ~1100 au and an H₂ mass of ~0.2–0.4 M_☉ is present in the southern part of the core. The sensitivity of the current ACA ND₃ data is not sufficient to determine whether this source is collapsing and the high S/N N₂D⁺ spectra are affected by the complex HFS.

The observations presented here provide clear evidence of a physical interaction between the prestellar core in L1689N and the blue lobe of one of the outflows driven by IRAS16293. How frequent such interactions may be in nearby low-mass star-forming regions is difficult to answer quantitatively. Hiramatsu et al. (2010) suggested that a similar interaction may occur in Barnard 1. They concluded that outflows cannot sustain the turbulence in the main Barnard 1 core, but they are energetic enough to compensate the turbulent energy dissipation in the neighboring, more evolved star-forming region NGC1333. Recent observations of Serpens South and NGC1333 (Plunkett 2015) also suggest that outflows are energetically important and provide sufficient energy to sustain turbulence early in the protocluster formation process without disrupting the entire cluster. Observations of low-mass star-forming regions often show bright DCO⁺ emission, which is assumed to trace cold, dense gas, coinciding with lobes of high-

velocity CO emission rather than dust continuum peaks, marking the locations of embedded protostars (e.g., Lis et al. 2004). Most of these DCO⁺ sources have not been studied in enough detail to determine whether they are true interaction regions, or whether they in fact harbor prestellar cores, as is the case in L1689N. Roueff et al. (2005) also pointed out that NH₂D and ND₃ emission often does not peak at the location of embedded protostars, but instead at offset positions where outflow interactions may occur. In their sample of six sources where ND₃ emission has been detected, L1689N is the only region where a physical interaction has been clearly demonstrated, but an outflow interaction has also been suggested in Barnard 1 (Hiramatsu et al. 2010). Another candidate source is located in NGC1333, at the edge of the blue lobe of the powerful molecular outflow associated with the HH 7–11 jet (Lis et al. 2004). However, this source has not yet been studied sufficiently to make a convincing case.

In conclusion, the observations presented here demonstrate the utility of the fundamental rotational transitions of deuterated ammonia as an additional tracer of the deeply embedded, prestellar phase of star formation. Collisional cross-sections of NH₂D, ND₂H, and ND₃ with H₂ are now available (Daniel et al. 2014, 2016b), allowing detailed modeling using state-of-the-art radiative transfer codes. The lines are accessible to current ground-based submillimeter facilities, in particular ALMA, offering new insights into the early phases of the star formation process.

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