Tracing the evolutionary stage of Bok globules: CCS and NH₃[★]

C. Marka¹, K. Schreyer¹, R. Launhardt², D. A. Semenov², and Th. Henning²

¹ Astrophysikalisches Institut und Universitätssternwarte (AIU), Schillergäßchen 2-3, 07745 Jena, Germany
 e-mail: p3macl@astro.uni-jena.de

² Max-Planck-Institut für Astronomie (MPIA), Königstuhl 17, 69117 Heidelberg, Germany

Received 8 March 2010 / Accepted 12 October 2011

ABSTRACT

Aims. We investigate a previously proposed correlation between the chemical properties and the physical evolutionary stage of isolated low-mass star-forming regions. The $N_{\text{NH}_3}/N_{\text{CCS}}$ abundance ratio has been proposed to be a potentially useful indicator of the evolutionary stage of cloud cores, and we study its applicability for isolated Bok globules.

Methods. We searched for CCS(2_1-1_0) emission in 42 Bok globules both with and without signs of current star formation. A set of NH₃ measurements was compiled from measurements available in the literature and from our own observations. The abundance ratio of both molecules is discussed with respect to the evolutionary stage of the objects and in the context of chemical models.

Results. We determine the $N_{\text{NH}_3}/N_{\text{CCS}}$ ratio for 18 Bok globules and find that it is moderately high and roughly similar across all evolutionary stages from starless and prestellar cores towards internally heated cores harboring protostars of Class 0, Class I, or later. We do not find any Bok globules with extremely high CCS abundances analogous to carbon-chain producing regions in dark cloud cores. The observed range of $N_{\text{NH}_3}/N_{\text{CCS}}$ implies that all of the observed Bok globules are in a relatively evolved chemical state.

Key words. ISM: clouds – stars: formation – ISM: molecules – radio lines: ISM

1. Introduction

Bok globules, named in honor of the astronomer Bart Bok who drew attention to those objects and their possible role in the star formation process (Bok & Reilly 1947), appear as small and isolated dark clouds. Although the majority of stars in the Galaxy are formed in giant molecular cloud complexes, the small globules have been recognized as particularly interesting targets for a study of low-mass star formation, since they represent a less complex environment and are therefore more easily described by theoretical models. The conditions inside Bok globules and the properties of the young stellar objects (YSOs) embedded therein have been studied at various wavelengths in several surveys in the past. Thermal radio emission arising from dust is observed at centimeter (Moreira et al. 1997, 1999) and millimeter wavelengths (Launhardt & Henning 1997, hereafter LH97; Henning & Launhardt 1998); submillimeter emission provides evidence of deeply embedded protostars (Huard et al. 1999). With near-infrared observations, YSO candidates have been identified and examined (Yun & Clemens 1995; Alves & Yun 1994; Racca et al. 2009). Molecular line observations provide information about the physical conditions, e.g. temperature, density, and magnetic fields, and trace the velocity structure of the clouds. They can be used to identify collapsing clouds (Wang et al. 1995) and reveal powerful molecular outflows (Yun & Clemens 1992, 1994b). A comprehensive overview of star formation in different stages is achieved by multi-wavelength studies (Launhardt et al. 2010, hereafter L2010).

In globules and cloud cores, a large variety of molecules have been identified. The complex chemical processes leading to their formation and destruction are ruled by the local conditions, including surface reactions on ice-covered grains in the coldest and densest parts of the cloud, and are influenced by the heating of a forming star within the core or the ionizing interstellar radiation close to the cloud surface (review by, e.g., van Dishoeck & Blake 1998). While ammonia was the first polyatomic molecule to be discovered in the interstellar medium (review e.g. by Ho & Townes 1983), the CCS radical was first identified far more recently (Saito et al. 1987) and the main pathways leading to its formation remain a subject of discussion (Suzuki et al. 1992; Petrie 1996; Sakai et al. 2007), although it is frequently observed along with other carbon-chain molecules (e.g., Hirota et al. 2009).

From a study of CCS and NH₃ among other molecules, Suzuki et al. (1992) found that carbon-chain molecules are abundant in the early evolutionary phases of dark cloud cores, while ammonia tends to be more abundant in more evolved, actively star-forming regions. This result was also supported by their chemical model calculations, where CCS is formed but also destroyed rapidly, while in turn a replenishment of the molecule is impeded by the increasing lock-up of carbon atoms in CO. In contrast, NH₃ forms in a sequence of very slow reactions and reaches its highest abundance in the late evolutionary phases. Therefore, they proposed the $N_{\text{NH}_3}/N_{\text{CCS}}$ abundance ratio to be a possibly useful indicator of the evolutionary stage of star-forming clouds. In the following years, the abundances of both molecules in a number of Bok globules and around Herbig Ae/Be stars (Scappini & Codella 1996), as well as in a larger sample of intermediate-mass and low-mass star-forming regions with H₂O maser emission (de Gregorio-Monsalvo et al. 2006, hereafter dGM06), were examined. However, both studies have been limited by the small number of CCS detections, which has

[★] Based on observations obtained with the 100-m telescope of the MPIfR (Max-Planck-Institut für Radioastronomie) at Effelsberg and the 64-m Parkes radio telescope. The Parkes radio telescope is part of the Australia Telescope National Facility which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

in turn prevented a definitive judgment about the above hypothesis. Analyzing the statistics of a large number of dense cores within the Perseus molecular cloud, [Foster et al. \(2009\)](#) provided evidence of a lower fractional abundance of CCS in protostellar cores relative to starless cores.

In this paper, we focus on small Bok globules, which typically form only single or few low-mass stars, because they represent the most secluded star-forming environments available for investigation. Any interference by other nearby, possibly high-mass, forming stars can be excluded. Moreover, for these isolated globules any mixing with ambient material that could modify the chemical composition and exacerbate a comparison with theoretical models, which may happen for a dense core inside a larger cloud complex, can be assumed to be implausible. An overview of the sample examined in this work is given in Sect. 2, followed by a description of the observational results and analysis in Sect. 4. The discussion of the derived physical parameters is presented in Sect. 5, and our concluding remarks are given in Sect. 6.

2. Description of the sample

Our sample consists of 42 Bok globules from the catalogs of [Clemens & Barvainis \(1988\)](#) for the northern hemisphere and [Bourke et al. \(1995a\)](#) for the southern globules. A search for $\text{NH}_3(1,1)$ and $(2,2)$ emission in the northern sources was conducted with the Effelsberg 100-m telescope in the survey of [Lemme et al. \(1996, hereafter L96\)](#), while the southern globules are included in the NH_3 survey of [Bourke et al. \(1995b, hereafter BHR95b\)](#), so that a uniform set of ammonia measurements is available for comparison with our data. Table 1 lists the positions of the CCS measurement, the IRAS point sources associated with the globules (sources in brackets were located outside the telescope beam), and their distance. Following the classification scheme of [L2010](#), we sorted the objects into three groups according to the presence and evolutionary class (cf. [Lada 1987; André et al. 1993](#)) of any embedded YSOs:

- Group –I: starless or prestellar globules, or only very young and very low-luminosity embedded source.
- Group 0: globules harboring a Class 0 protostar.
- Group I: globules containing YSOs of Class I or later.

The classifications of the individual clouds are presented in Table 2. Where scarce observations of the specific globule prevented a reliable identification of the evolutionary group, a presumptive classification is given in brackets. We note that both prestellar cores and Class 0 protostars in particular most probably remain unidentified when there is a lack of detailed maps of molecular emission and/or millimeter continuum emission. A detailed discussion of most globules in the sample can be found in [L2010](#) and the references therein, while a number of southern globules has been classified in [Racca et al. \(2009\)](#). In the following, we therefore comment only briefly on the globules that are not described there.

CB 3. A compact submillimeter source without infrared counterpart is located at the center of a bipolar molecular outflow ([Yun & Clemens 1994b](#)) and was suggested to consist of an aggregate of Class 0 sources ([Huard et al. 2000](#)). The source IRAS 00259+5625, whose near-infrared counterpart was classified as a Class II object ([Yun & Clemens 1994a, 1995](#)), is located $15''$ away. The globule also harbors a H_2O -maser ([Scappini et al. 1991, dGM06](#)), and is believed to be rather an evolved intermediate to high-mass star-forming region ([Launhardt et al. 1998b; Codella & Bachiller 1999](#)).

Table 1. Overview of the observed globules.

Object	RA (B1950) (h m s)	Dec (B1950) (° ' ")	Associated IRAS Source	Distance (Ref.) [pc]
CB 3	00 25 59.0	+56 25 32	00259+5625	2500 (2)
CB 6	00 46 34.4	+50 28 25	00465+5028	600 (3)
CB 12	01 35 24.3	+64 47 59	01354+6447	800 (2)
CB 17	04 00 32.9	+56 47 52	(04005+5647)	250 (3)
CB 22	04 37 23.5	+29 49 17	...	140 (2)
CB 23	04 40 20.5	+29 33 26	...	140 (2)
CB 26	04 55 56.1	+52 00 17	04559+5200	140 (3)
CB 28	05 03 51.3	−04 00 18	05038-0400	450 (3)
CB 34	05 44 05.7	+20 59 30	05440+2059	1500 (3)
CB 44	06 04 43.0	+19 28 19	(06047+1923)	700 (3)
CB 68	16 54 27.2	−16 04 48	16544-1604	160 (3)
CB 125	18 12 39.0	−18 12 14	(18121-1813)	200 (2)
CB 179	19 01 57.0	−05 25 35	(19018-0525)	200 (2)
CB 188	19 17 54.0	+11 30 10	19179+1129	300 (3)
CB 222	20 32 49.9	+63 52 00	20328+6351	400 (3)
CB 224	20 35 30.9	+63 42 48	20355+6343	400 (3)
CB 230	21 16 50.8	+68 04 52	21169+6804	400 (3)
CB 232	21 35 14.4	+43 07 17	21352+4307	600 (3)
CB 243	23 22 51.9	+63 20 11	23228+6320	700 (3)
CB 244	23 23 48.9	+74 01 10	23238+7401	200 (3)
CB 246	23 54 12.0	+58 17 27	...	140 (3)
BHR 12	08 07 39.0	−35 55 54	08076-3556	400 (1)
BHR 13	08 26 44.1	−33 36 31	08267-3336	400 (1)
BHR 15	07 14 27.5	−43 52 26	07144-4352	400 (1)
BHR 23-1	08 33 42.6	−40 28 02	08337-4028	500 (1)
BHR 28	07 26 20.0	−50 58 18	...	400 (1)
BHR 34	08 25 03.4	−50 30 34	08250-5030	200 (3)
BHR 36	08 24 15.9	−50 50 44	08242-5050	400 (1)
BHR 41	08 26 11.5	−51 00 39	08261-5100	400 (1)
BHR 55	09 44 57.0	−50 52 06	09449-5052	300 (1)
BHR 59	11 05 03.0	−61 49 36	...	200 (4)
BHR 71	11 59 03.1	−64 52 11	11590-6452	200 (3)
BHR 74	12 19 21.0	−66 10 30	...	175 (4)
BHR 86	13 03 41.4	−76 44 03	13036-7644	180 (3)
BHR 111	15 38 34.0	−52 38 21	...	250 (4)
BHR 121-1	16 54 59.6	−50 30 58	16549-5030	125 (4)
BHR 121-2	16 55 27.8	−50 31 01	16554-5031	125 (4)
BHR 137	17 18 08.6	−44 06 17	(17181-4405)	700 (3)
BHR 138	17 15 54.0	−43 24 04	17159-4324	225 (4)
BHR 139-1	17 17 15.9	−43 16 54	17172-4316	225 (4)
BHR 140-1	17 19 18.8	−43 19 24	17193-4319	225 (4)
BHR 148	17 01 09.2	−36 13 59	17011-3613	175 (4)

References. (1) [Bourke et al. \(1995b\)](#); (2) [Launhardt & Henning \(1997\)](#); (3) [Launhardt et al. \(2010, and priv. comm.\)](#); (4) [Racca et al. \(2009\)](#).

CB 12. An associated IRAS point source is detected at 60 and $100\mu\text{m}$, but neither a molecular outflow ([Yun & Clemens 1992](#)) nor dust continuum emission at 1.3 mm ([LH97](#)) point towards the presence of an embedded protostar.

CB 22 and CB 23. Both globules are not detected in the far-infrared (no IRAS sources) or in the 1.3 mm dust continuum ([LH97](#)). According to the shape of the spectral lines, CB 22 seems to be quiescent, while CB 23 shows signatures of possible infall motion ([Lee et al. 1999, 2004](#)).

CB 28. Only emission longward of $60\mu\text{m}$ was detected by IRAS towards this globule; searches for outflows ([Yun & Clemens 1994b](#)) and YSO candidates in the near-infrared ([Yun & Clemens 1994a](#)) resulted in no detections.

CB 34. Numerous studies suggest that multiple star formation takes place in this globule. Five submillimeter sources were

Table 2. Derived CCS(2₁–1₀) line parameters and column densities for CCS and ammonia, and the corresponding abundance ratio $N_{\text{NH}_3}/N_{\text{CCS}}$.

Source	Group	ν_{LSR} [km s ⁻¹]	T_{mb} [mK]	$\Delta\nu_{\text{obs}}$ [km s ⁻¹]	$\int T_{\text{mb}} d\nu$ [mK km s ⁻¹]	$\Delta\nu_{\text{nth}}$ [km s ⁻¹]	N_{CCS} [10 ¹² cm ⁻²]	N_{NH_3} (Ref.) [10 ¹⁴ cm ⁻²]	$N_{\text{NH}_3}/N_{\text{CCS}}$
CB 3	0	...	<96	...	...	...	<1.42	1.54 ± 0.26* (1)	>104
CB 6	I	...	<90	...	...	...	<1.32	0.29 ± 0.07*	>22
CB 12	–I	...	<117	...	...	...	<1.70	1.45 ± 0.24* (1)	>86
CB 17	–I ^a	–4.65 ± 0.02	233 ± 37	0.45 ± 0.06	112 ± 12	0.44 ± 0.06	4.89 ± 0.53	13.84 ± 3.74	201 ± 47
CB 22	–I	–1.03 ± 0.01	233 ± 37	0.15 ± 0.05	36 ± 7	0.08 ± 0.08	1.42 ± 0.29	3.64 ± 0.87 (1)	257 ± 80
CB 23	–I	4.86 ± 0.01	375 ± 39	0.17 ± 0.02	66 ± 8	0.11 ± 0.03	2.39 ± 0.28	10.1 ± 1.1 (1)	422 ± 67
CB 26	I	...	<114	...	...	...	<1.67	0.48 ± 0.18* (1)	>28
CB 28	–I	9.01 ± 0.02	223 ± 40	0.29 ± 0.04	69 ± 9	0.26 ± 0.05	3.48 ± 0.45	1.95 ± 1.18 (1)	56 ± 34
CB 34	0	0.17 ± 0.05	119 ± 37	0.60 ± 0.14	57 ± 10	0.59 ± 0.15	2.64 ± 0.53	0.92 ± 0.44* (1)	34 ± 17
CB 44	(–I)	...	<132	...	...	...	<1.95	0.65 ± 0.15* (1)	>34
CB 68	0	...	<120	...	...	...	<1.48	12.7 ± 0.9 (1)	>860
CB 125	(I)	...	<132	...	...	...	<1.88	6.01 ± 1.63 (1)	>320
CB 179	–I	...	<102	...	...	...	<1.49	0.59 ± 0.15* (1)	>40
CB 188	I	6.14 ± 0.04	111 ± 35	0.44 ± 0.08	52 ± 10	0.42 ± 0.09	2.21 ± 0.41	1.10 ± 0.33* (1)	50 ± 17
CB 222	–I	–2.70 ± 0.05	102 ± 25	0.34 ± 0.12	36 ± 12	0.31 ± 0.14	1.54 ± 0.53	0.65 ± 0.08*	42 ± 15
CB 224	0 ^b	...	<144	...	...	...	<2.61	6.23 ± 1.17 (1)	>239
CB 230	I ^c	2.41 ± 0.03	190 ± 49	0.33 ± 0.12	66 ± 16	0.30 ± 0.13	2.79 ± 0.66	0.71 ± 0.24* (1)	26 ± 9
CB 232	–I ^d	12.50 ± 0.03	138 ± 41	0.23 ± 0.07	34 ± 9	0.19 ± 0.09	1.42 ± 0.38	0.54 ± 0.21* (1)	38 ± 15
CB 243	–I ^e	...	<114	...	...	...	<1.67	2.77 ± 1.04 (1)	>166
CB 244	0	4.18 ± 0.03	162 ± 41	0.31 ± 0.07	54 ± 10	0.29 ± 0.07	1.96 ± 0.37	8.08 ± 2.37** (1)	412 ± 143
CB 246	–I	–0.65 ± 0.01	462 ± 39	0.24 ± 0.03	120 ± 11	0.21 ± 0.03	5.67 ± 0.49	7.70 ± 1.01 (1)	136 ± 18
BHR 12	I+0 ^f	6.36 ± 0.07	190 ± 68	0.35 ± 0.15	71 ± 23	0.33 ± 0.16	2.75 ± 0.88	5.4 (2)	196 ± 62
BHR 13	(I)	...	<294	...	...	...	<7.14	0.68 ± 0.22*	>10
BHR 15	(–I)	...	<221	...	...	...	<5.40	0.7 (2)	>13
BHR 23	(I)	...	<206	...	...	...	<5.01	4.07 ± 0.67* (2)	>81
BHR 28	(–I)	...	<209	...	...	...	<5.08	3.2 (2)	>63
BHR 34	0	...	<244	...	...	...	<5.95	0.91 ± 0.50*	>15
BHR 36	I	5.23 ± 0.11	125 ± 61	0.94 ± 0.17	124 ± 26	0.93 ± 0.17	4.13 ± 0.86	7.22 ± 2.01	175 ± 60
BHR 41	I ^g	...	<198	...	...	...	<5.07	1.02 ± 0.54*	>20
BHR 55	0 ^h	–5.36 ± 0.05	173 ± 93	0.27 ± 0.10	100 ± 62	0.25 ± 0.11	3.38 ± 2.11	5.30 ± 1.45	157 ± 107
BHR 59	(0)	...	<221	...	...	...	<5.37	2.19 ± 0.32* (2)	>41
BHR 71	0 ⁱ	–4.52 ± 0.08	209 ± 78	0.87 ± 0.14	193 ± 33	0.86 ± 0.14	6.63 ± 1.15	12.25 ± 2.75	185 ± 51
BHR 74	(–I)	–5.89 ± 0.09	111 ± 45	0.52 ± 0.22	61 ± 18	0.50 ± 0.22	2.19 ± 0.66	1.3 (2)	59 ± 18
BHR 86	0	...	<264	...	...	...	<7.23	5.0 (2)	>69
BHR 111	(0)	–0.07 ± 0.03	186 ± 44	0.30 ± 0.06	59 ± 12	0.28 ± 0.07	2.42 ± 0.48	3.6 (2)	149 ± 29
BHR 121-1	I	...	<212	...	...	...	<5.14	0.42 ± 0.23*	>8
BHR 121-2	I	...	<201	...	...	...	<4.90	0.48 ± 0.35*	>10
BHR 137	(0)	...	<245	...	...	...	<5.95	4.3 (2)	>72
BHR 138	0	...	<223	...	...	...	<5.41	<0.46*	...
BHR 139-1	I	...	<211	...	...	...	<5.12	<0.45*	...
BHR 140-1	0	–0.63 ± 0.07	221 ± 55	1.21 ± 0.16	285 ± 31	1.21 ± 0.16	11.1 ± 1.20	20.4 (2)	184 ± 20
BHR 148	0	...	<282	...	...	...	<3.52	<0.80*	...

Notes. (*) Optical thin approximation was used to derive N_{NH_3} , (**) N_{NH_3} derived from available map and map-averaged T_{rot} and T_{ex} , since NH₃ peak lies outside the CCS beam. ^(a) Main core is prestellar (SMM1+2), but there is a low-luminosity Class I source 20'' away, slightly outside the beam. ^(b) Main core is Class 0 (SMM1), but there is a Class I source 30'' away (not inside the telescope beam). ^(c) Contains two Class I IR sources 10'' apart. ^(d) Main core is most likely prestellar (SMM), but there is a Class I source 12'' away. ^(e) Main core is most likely prestellar (SMM1), but there is a Class I source 10'' away. ^(f) A Class 0 and Class I YSO with cores of similar mass separated by 20'' inside the beam. ^(g) Two close (4'' separation) infrared sources of Class I (Santos et al. 1998). ^(h) Two close lines with comparable width ≈ 0.27 km s⁻¹ in CCS. ⁽ⁱ⁾ Double protostellar core with two IR sources 17'' apart.

References. (1) Lemme et al. (1996); (2) Bourke et al. (1995b).

detected and classified as probable Class 0 objects by Huard et al. (2000). The aggregate of protostars is associated with a system of multiple outflows (Codella & Scappini 2003) and jets (Moreira & Yun 1995). Evidence of more evolved Class I and Class II objects is provided by the detection of several very red objects in the near-infrared (Alves & Yun 1995).

CB 44. The associated IRAS source cited by Clemens & Barvainis (1988) resides at the very edge of the globule. Two 3.6 cm continuum sources without infrared counterparts, which are candidate Class 0 objects, were detected by

Moreira et al. (1999) but no detection was possible at shorter wavelengths (e.g. at 1.3 mm by LH97).

CB 125. Several IRAS point sources are located in the vicinity of this source, but none within the area of highest extinction visible on optical images of the globule. Both IRAS 18127-1803 and IRAS 18122-1818 have reliable fluxes only at 12 and 25 μm , and are considered as candidate pre-main sequence star (LH97) and YSO (Lee & Myers 1999), respectively. The 100 μm detection towards IRAS 18130-1824 was considered as cirrus emission owing to the lack of submillimeter continuum

emission (Huard et al. 1999). Line observations in CS towards IRAS 18126-1820 at the southern edge of CB 125 show unsuspicious Gaussian line profiles (Launhardt et al. 1998a). Owing to the presence of candidate YSOs close to the cloud, we assume that the source is at an evolved stage.

CB 179. The association with a cold infrared source detected only at 60 and 100 μm , the absence of 1.3 mm continuum emission (LH97), and narrow, weak CO lines (Clemens et al. 1991) suggest that this source is in an early evolutionary stage.

CB 222. Towards this globule, there is neither an associated IRAS source detected at wavelengths shortward of 60 μm , nor 1.3 mm dust emission found (LH97). Owing to this and simple Gaussian line profiles measured in CS (Launhardt et al. 1998a), we assume an early evolutionary stage for CB 222.

BHR 13. The narrow CO line profiles observed towards this cometary globule are supposed to arise from cold, quiescent gas (Otrupcek et al. 2000), while the associated IRAS source was identified as a T Tauri star (Sahu & Sahu 1992).

BHR 15. The IRAS source associated with this cometary globule is detected only at 60 and 100 μm , and CO line profiles typical of cold, quiescent gas have been observed (Otrupcek et al. 2000). Therefore, we assume an early evolutionary stage.

BHR 23. Santos et al. (1998) conclude from near-infrared observations that an aggregate of several YSOs might be harbored by this globule. High-velocity wings in CO lines detected by Urquhart et al. (2009) and Otrupcek et al. (2000) might indicate the presence of a molecular outflow. Methanol maser emission, which is believed to be associated with high-mass star formation, was also observed towards this source by Walsh et al. (1997).

BHR 28, BHR 59, BHR 74, and BHR 111. These globules do not harbor any IRAS sources. Profiles of CO lines observed towards BHR 74 and the cometary globule BHR 28 suggest the presence of cold and quiescent gas (Otrupcek et al. 2000). In BHR 59 and BHR 111, the detection of line wings might indicate that there are either several blended velocity components or outflow motions (Otrupcek et al. 2000). However, no more detailed observations are available for those globules.

BHR 41. Santos et al. (1998) classified the two near-infrared sources separated by 4'' seen at the position of the IRAS source as likely Class I objects. However, no 1.3 mm dust emission has been detected towards this source (L2010).

BHR 137. Santos et al. (1998) detected three infrared sources at the IRAS position, two of which are likely Class II objects. However, the IRAS source is located at the rim of the globule and it is unclear whether it is related. Emission in the 1.3 mm dust continuum was detected by Henning & Launhardt (1998), as well as a blue wing in the CO emission. L2010 suggest a rather early evolutionary stage.

Some of the globules are known to contain multiple sources in different evolutionary stages, namely CB 3 (Yun & Clemens 1994a; Huard et al. 2000), CB 34, CB 224, CB 232, CB 243, CB 244, and BHR 12 (L2010). In these cases, where there are sources of different evolutionary stage within the beam of the NH_3 and CCS observations, we assigned the globule to the evolutionary group that agrees with the source from which most of the millimeter dust emission arises, i.e., which has the largest reservoir of cold gas and therefore dominates the detected line emission. However, it cannot be excluded that one of the other sources also contributes to the detected line emission. In addition, the maturity of individual globules might be underestimated, because an evolved YSO close to a pre/protostellar core might affect its chemistry, especially since in most cases the projected separation between the differently evolved sources is only a few thousand AU. We have noted these cases in Table 2.

3. Observations

We carried out observations in $\text{CCS}(2_1-1_0)$ of all objects from the Clemens & Barvainis (1988) catalog listed in Table 1, as well as $\text{NH}_3(1,1)$ and $(2,2)$ observations of three globules, with the Effelsberg 100-m telescope of the Max-Planck-Institut für Radioastronomie (MPIfR) on March 14 and 15, 1999. A maser receiver at the primary focus was used with a 1024 channel autocorrelator. The system temperature was between 80 K and 110 K. For the $\text{CCS}(2_1-1_0)$ line at 22.344 GHz, the total 6.25 MHz bandwidth of the spectrometer was used, providing a velocity resolution of 0.08 km s^{-1} . The autocorrelator was split into 2×512 channels for the observations of the $\text{NH}_3(1,1)$ and $(2,2)$ lines at 23.694 GHz and 23.722 GHz, respectively, corresponding to a velocity resolution of 0.15 km s^{-1} . At the frequencies used, the beam diameter (FWHP) was 40''. Frequency switching was adopted with a total integration time per source of 30–60 min for the CCS line and 5–30 min for the NH_3 lines. The pointing was checked every two hours by cross-scans of nearby quasars. The pointing accuracy was typically higher than 5'' at similar elevations. The focus was checked on strong continuum sources at the beginning of the observing run and after sunset and sunrise. The data were calibrated using cross scans of continuum sources with known flux densities (Ott et al. 1994). We used NGC 7027 as a primary calibrator. The antenna temperatures were converted to a main beam brightness temperature T_{mb} by correcting with the elevation-dependent gain, and the beam and aperture efficiencies. The calibration is estimated to be accurate within $\sim 15\%$.

The 21 sources from the catalog of Bourke et al. (1995a) were observed with the Parkes 64 m telescope during March 2010 in the $\text{CCS}(2_1-1_0)$ transition, and ten of them additionally in $\text{NH}_3(1,1)$ – namely those sources, where the core or YSO of interest was not included in the beam of BHR95b. The 13MM receiver and a digital filterbank with a bandwidth of 8 MHz and 2048 channels were employed, resulting in a velocity resolution of 0.05 km s^{-1} . The beam diameter was 1' and the pointing was estimated to be accurate to within 20''. Except for BHR 15, BHR 23, and BHR 28, which were observed in the position switching mode, frequency switching with a throw of 1 MHz for the CCS and 0.3 MHz for the NH_3 line, respectively, was used with integration times of 20–60 min. Typical system temperatures ranged from 70 K to 130 K. After correction for the elevation-dependent gain, we applied a relative calibration by means of repeated observations of BHR 71 and comparing them to the measurements of BHR95b. Hereby, it is ensured that the scale of our measurements and those of BHR95b, which were used in the calculation of the $N_{\text{NH}_3}/N_{\text{CCS}}$ ratio, agree. Although with this approach the absolute accuracy of our calibration is not expected to be optimal, a comparison of the CCS observations for CB 28 carried out in Parkes and calibrated with the aforementioned method shows consistency with observations of the same source carried out in Effelsberg. The spectra for all globules displaying (possible) detections of the CCS line are shown in Fig. 1.

4. Results

The results of the observations are summarized in Tables 2 and 3. Among the 42 globules observed, thirteen were detected in the $\text{CCS}(2_1-1_0)$ line with a signal-to-noise ratio of at least three. An additional five globules display emission at a slightly lower significance level, but we conclude that these are real detections because their LSR velocities agree with those of ammonia lines

Fig. 1. Spectra for the globules with detected CCS(2_1-1_0) emission. For each source, a velocity window of about 20 km s⁻¹ around the line is displayed. The derived line parameters are given in Table 2.

observed by BHR95b. In contrast, NH₃(1,1) remained undetected only towards three globules of our sample.

We excluded CB 3, CB 34, and BHR 23 from the further discussion, because they likely contain clusters or high-mass star-forming regions, as well as BHR 13, BHR 59, and BHR 111 owing to their very uncertain evolutionary stage, and BHR 12 owing to two equally massive sources in different evolutionary groups (the source is however included in Figs. 2 and 6). Considering only the globules with fairly reliably determined evolutionary group (i.e. group given without brackets in Table 2), we find CCS emission in 70% (seven of ten objects) of the globules belonging to the starless or prestellar globules of group -I, in 40% of the objects of group 0 (clouds containing Class 0 protostars; four detections), and in 33% of the group I objects (YSOs of Class I or later embedded; three of nine detected). The overall detection rate (43%) of CCS(2_1-1_0) in our sample is therefore higher than found in some earlier studies of low-mass star-forming regions, globules and dark clouds (about 18–33% in the studies of Scappini & Codella 1996, dGM06, and Suzuki et al. 1992), and closer to the 50% detection rate of a survey of dense cores in the Perseus molecular cloud (Rosolowsky et al. 2008; Foster et al. 2009). For ammonia, strong emission in the sense that

the hyperfine structure of the NH₃(1,1) transition is detected, is present in 80% of the objects from group -I, and in 70% and 22% of the objects of group 0 and I, respectively.

4.1. Analysis of CCS lines

In Table 2, Col. 1 lists the object number from the Clemens & Barvainis (1988) and Bourke et al. (1995a) catalogs, 2 the assigned evolutionary group (cf. Sect. 2), 3 the LSR-velocity, 4 the main beam brightness temperature, 5 the observed line width (FWHM) including instrumental broadening (of 0.08 km s⁻¹ and 0.05 km s⁻¹ for the CB and BHR sources, respectively), and 6 the integrated intensity of the line. Column 7 contains the non-thermal linewidths, 8 the calculated total column densities for CCS, 9 the ammonia column densities from own observations or collected from the literature, and 10 the abundance ratio $N_{\text{NH}_3}/N_{\text{CCS}}$. The source velocity v_{LSR} , linewidth Δv_{obs} , peak intensity T_{mb} , and integrated intensity $\int T_{\text{mb}} dv$ were derived from Gaussian fits to the lines using CLASS¹. The error in T_{mb} listed

¹ Part of the program package GILDAS (Grenoble Image and Line Data Analysis Software), see <http://www.iram.fr/IRAMFR/GILDAS/>

Table 3. Results of the NH₃(1, 1) and NH₃(2, 2) observations.

Source	$\nu_{\text{LSR}(1,1)}$ [km s ⁻¹]	$T_{\text{mb}(1,1)}$ [K]	$\Delta\nu_{\text{obs}(1,1)}$ [km s ⁻¹]	$\nu_{\text{LSR}(2,2)}$ [km s ⁻¹]	$T_{\text{mb}(2,2)}$ [K]	$\Delta\nu_{\text{obs}(2,2)}$ [km s ⁻¹]	$\tau_{\text{m}(1,1)}$ [K]	T_{ex} [K]
CB 6	-12.45 ± 0.09	0.15 ± 0.05	0.62 ± 0.18	...	<0.14	...	...	6*
CB 17	-4.65 ± 0.01	1.71 ± 0.10	0.34 ± 0.02	-4.70 ± 0.06	0.17 ± 0.04	0.79 ± 0.18	2.8 ± 0.6	5.4 ± 0.4
CB 222	-2.71 ± 0.04	0.29 ± 0.05	0.72 ± 0.10	...	<0.11	...	...	6*
BHR 13	6.44 ± 0.06	0.30 ± 0.07	1.25 ± 0.18	...	...	...	...	6*
BHR 34	4.78 ± 0.04	0.50 ± 0.10	0.69 ± 0.11	...	...	...	...	6*
BHR 36	5.27 ± 0.02	1.21 ± 0.07	0.52 ± 0.04	...	...	...	1.9 ± 0.5	4.3 ± 0.2
BHR 41	5.46 ± 0.05	0.36 ± 0.08	0.92 ± 0.16	...	...	...	...	6*
BHR 55	-5.50 ± 0.01	1.45 ± 0.11	0.51 ± 0.04	...	...	...	1.2 ± 0.3	5.1 ± 0.4
BHR 71	-4.39 ± 0.02	3.56 ± 0.11	0.71 ± 0.03	...	...	...	1.5 ± 0.3	8.0 ± 0.6
BHR 121-1	-12.61 ± 0.04	0.26 ± 0.06	0.61 ± 0.08	...	...	...	...	6*
BHR 121-2	-12.52 ± 0.05	0.27 ± 0.07	0.68 ± 0.15	...	...	...	...	6*
BHR 138	...	<0.21	...	...	...	...	...	6*
BHR 139-1	...	<0.20	...	...	...	...	...	6*
BHR 148	...	<0.36	...	...	...	...	...	6*

Notes. (*) T_{ex} is adopted as average value from Lemme et al. (1996) and Bourke et al. (1995b).

in Table 2 corresponds to the root mean square (rms) noise of the spectrum, and for the other quantities to the standard deviations in the Gaussian fits to the lines. The average rms noise level of the obtained spectra is 38 mK for the CB sources and 72 mK for the BHR sources. As upper limits for the non-detections, a peak intensity of 3 rms is given. In the case of CB 34 and BHR 55, the observed CCS line was not approximated well by a Gaussian profile, hence the value in Table 2 represents the intensity integrated under the actual line rather than under the fitted profile.

We calculated the total column densities N_{CCS} under the assumption of local thermodynamic equilibrium (LTE)

$$N = \frac{8\pi\nu_{ij}^2 g_0}{c^2} \frac{Q(T_{\text{ex}})}{g_j} \frac{e^{E_j/kT_{\text{ex}}}}{A_{ji} (e^{h\nu_{ij}/kT_{\text{ex}}} - 1)} \int \tau_{\nu} d\nu, \quad (1)$$

where ν_{ij} denotes the frequency of the transition, g_0 and g_j are the statistical weights of the ground state and of the upper rotational level, respectively, E_j is the energy of the upper level, $Q(T_{\text{ex}})$ denotes the partition function for an excitation temperature T_{ex} , A_{ji} is the Einstein coefficient for spontaneous emission, and τ_{ν} is the optical depth. We assumed the emission to be optically thin, thus the relation between optical depth and main beam brightness temperature T_{mb} from the radiative transfer equation is given by

$$\int \tau_{\nu} d\nu = \frac{k}{hc} \left(\frac{1}{e^{h\nu_{ij}/kT_{\text{ex}}} - 1} - \frac{1}{e^{h\nu_{ij}/kT_{\text{bg}}} - 1} \right) \int T_{\text{mb}} d\nu, \quad (2)$$

where $T_{\text{bg}} = 2.73$ K is the cosmic background temperature. Since only one rotational transition of CCS was observed, the excitation temperature could not be determined. We adopted $T_{\text{ex}} \approx 5$ K, which is equal to the average value derived for a number of dark cloud cores by Suzuki et al. (1992). Applying this to the measured CCS(2₁-1₀) transition with $A_{2_1-1_0} = 4.33 \times 10^{-7} \text{ s}^{-1}$ and $E_{2_1}/k = 1.61$ K (Wolkovitch et al. 1997), and $Q_{\text{ex}}(5 \text{ K}) = 23.80$ (Lai & Crutcher 2000), the column density is given by

$$N_{\text{CCS}} [\text{cm}^{-2}] = 2.92 \times 10^{13} \int T_{\text{mb}} d\nu [\text{K km s}^{-1}]. \quad (3)$$

A 4 K higher excitation temperature would result in a moderate increase of about 40% in the column density. For the non-detected lines, the upper limit to $\int T_{\text{mb}} d\nu$ was estimated as $1.06 T_{\text{mb}} \overline{\Delta\nu}$, where $\overline{\Delta\nu}$ was taken to be the average of the detected line widths, i.e., 0.32 km s⁻¹ for the CB sources and 0.64 km s⁻¹ for the BHR sources.

4.2. Ammonia lines

For most of the sources in our sample, ammonia column densities have been derived in the papers of L96 and BHR95b. For our own ammonia observations, we derived column densities as outlined in the following. If the hyperfine structure for the NH₃(1, 1) transition was sufficiently strong, a fit with the available procedure within the CLASS package was performed to determine the optical depth of the main line $\tau_{\text{m}(1,1)}$ and the intrinsic linewidth $\Delta\nu_{\text{int}}$. Otherwise a Gaussian profile was fitted to the main line. The derived line parameters are summarized in Table 3, where $\Delta\nu_{\text{obs}(1,1)}$ refers to the intrinsic linewidth in the case of CB 17, BHR 36, BHR 55, and BHR 71, and to the width of a single Gaussian fitted to the main line for the other sources. For the further analysis we followed the standard procedures and assumptions described in, e.g., Ungerechts et al. (1980) and Stutzki (1984). The excitation temperature T_{ex} was calculated from

$$T_{\text{ex}} \approx \frac{T_{\text{mb}(1,1)}}{f_b (1 - e^{-\tau_{\text{m}(1,1)}})} + T_{\text{bg}}, \quad (4)$$

where f_b is the beam filling factor and $T_{\text{mb}(1,1)}$ is the brightness temperature of the main line. The column density in the (1, 1) levels then follows as

$$N_{(1,1)} = \frac{4\pi^{3/2}}{\sqrt{\ln 2}} \frac{\nu_{11}^3}{c^3} \frac{\Delta\nu_{\text{int}}}{A_{11}} \frac{\tau_{\text{m}(1,1)}}{s_m} \frac{1 + e^{-h\nu_{11}/kT_{\text{ex}}}}{1 - e^{-h\nu_{11}/kT_{\text{ex}}}}, \quad (5)$$

where $A_{11} = 1.67 \times 10^{-7} \text{ s}^{-1}$ is the rate coefficient, ν_{11} is the frequency of the NH₃(1, 1) transition, and s_m denotes the line strength at the main line, the value of which depends on the intrinsic linewidth of the hyperfine components blended in the main line. The total column density follows from

$$N_{\text{NH}_3} = N_{(1,1)} \left(1 + \frac{1}{3} e^{\frac{22.7 \text{ K}}{T_{\text{rot}}}} + \frac{5}{3} e^{\frac{41.2 \text{ K}}{T_{\text{rot}}}} + \frac{14}{3} e^{\frac{100.3 \text{ K}}{T_{\text{rot}}}} \right). \quad (6)$$

Since we did not observe the NH₃(2, 2) transition in most cases, we could derive the rotational temperature (for calculation see e.g. Ungerechts et al. 1980) only for CB 17 ($T_{\text{rot}} = 8.1 \pm 0.5$ K). For the other sources, we adopted a rotational temperature of 10 K for normal and 13 K for cometary globules (BHR 12, BHR 13, BHR 15, BHR 28), which are the average values from the papers of L96 and BHR95b, for the calculation.

Where the hyperfine structure was weak or only the main line of the NH₃(1, 1) transition was detectable, such that the optical

depth could not be derived, we estimated the column densities in the optically thin approximation with

$$N_{(1,1)} = \frac{16\pi\nu_{11}^3}{c^3} \frac{k}{h\nu_{11}} \frac{1}{f_b A_{11}} \frac{1 + e^{h\nu_{11}/kT_{\text{ex}}}}{1 - \frac{e^{h\nu_{11}/kT_{\text{ex}}}}{e^{h\nu_{11}/kT_{\text{bg}}}} - 1} \int T_{\text{mb}(1,1)} d\nu, \quad (7)$$

where $\int T_{\text{mb}(1,1)} d\nu$ is the intensity integrated over the main component of the NH₃(1, 1) transition. For the excitation temperature in Eq. (7), we assumed the average value $T_{\text{ex}} = 6$ K found by L96 and BHR95b. The total column density was then calculated from Eq. (6), adopting $T_{\text{rot}} = 10$ or 13 K as mentioned above. We estimated upper limits with the same approach described for the CCS lines, using an average linewidth of the NH₃(1, 1) main line of 0.85 km s⁻¹. This optically thin approximation was also applied to sources that were detected, but for which no column density has been derived in the papers of L96 and BHR95b. We note that for CB 230 and CB 232 the NH₃ measurement positions of L96 are offset by about one beam from the submillimeter cores detected by L2010 (which are identical to the CCS measurement positions), hence N_{NH_3} can be expected to underestimate the column density towards these cores.

When calculating the column densities given in Table 2, we adopted the beam filling factors f_b in the following way: for sources included in L96 and BHR95b, the source sizes derived there were used to calculate the beam filling factor applied to our Parkes CCS measurements, assuming that CCS and ammonia emission have comparable spatial extents (which is an approximation, see e.g. Codella & Scappini 1998a). For the other sources, we used the average source sizes from the papers of L96 and BHR95b to calculate an average beam filling factor of $f_b = 0.81$ for the BHR, and 0.69 for the CB objects.

5. Discussion

5.1. Column densities and fractional abundances

The column densities of CCS and NH₃, shown in Table 2, do not strongly depend on the evolutionary group of the corresponding source, although the highest values of N_{CCS} are found for group 0 objects. The column densities of NH₃ versus those of CCS are displayed in Fig. 2 (without the omitted sources mentioned in Sect. 4). The lower right part of the plot is occupied exclusively by sources undetected in CCS (i.e. only upper limits for N_{CCS}); all sources with $N_{\text{NH}_3} < 1.5 \times 10^{14}$ cm⁻² have ammonia column densities obtained with the optical thin approximation. Sources with reliable detections of both molecules are found preferentially in the upper left side of the plot, as if the highest CCS column densities are present (or excited) only in globules with high ammonia column densities, while lower values of N_{CCS} can be found in objects with a wider range of N_{NH_3} . However, no clear distinction is visible between the distribution of the presumably younger objects of group -I and the actively star-forming globules (groups 0 and I).

The large scatter in the column densities likely results from differences in the hydrogen densities of the individual clouds, hence a comparison of fractional abundances is required for a reasonable discussion of possible evolutionary trends. For several globules, hydrogen column densities or masses have been derived from dust emission in the paper by L2010, from C¹⁸O measurements by L96, Wang et al. (1995), and Vilas-Boas et al. (1994), and from extinction by Racca et al. (2009). Some globules of our sample are included simultaneously in three of these studies; for these the column densities N_{H} of L2010 (derived by dividing the hydrogen masses from their work by both the

Fig. 2. Column densities of NH₃ versus CCS. Arrows indicate upper limits; filled and open circles represent objects with evidence of ongoing star formation (group 0 and I) and no signs of current star formation (group -I), respectively. Grey symbols denote sources with an uncertain evolutionary group (given in brackets in Table 2).

proton mass and the physical area enclosed by the 1.3 mm dust emission in the maps) and L96 are found to be systematically larger than those of Wang et al. (1995) by a factor of 7.6 and 2 (within 20%), respectively. Thus, we assumed the same conversion factors for the remaining globules in the respective studies to bring them onto the scale of Wang et al. (1995), but we did not use this approach for the data from both Racca et al. (2009) and Vilas-Boas et al. (1994) since there is an overlap of only one source with the other studies. For 15 globules with reliably determined evolutionary stages, this yields fractional abundances $N_{\text{CCS}}/N_{\text{H}}$ from 7×10^{-11} to 6×10^{-10} and values of $N_{\text{NH}_3}/N_{\text{H}}$ between 2×10^{-9} and 1×10^{-7} . For CCS, the fractional abundance averaged over globules of the same evolutionary group is very similar for groups -I, 0, and I (about 3×10^{-10}). For NH₃, it is highest for group 0 (6×10^{-8}) and lowest for group I (1×10^{-8}), but this variation should not be considered significant owing to the large scatter in the values for individual globules and their small number. These estimated fractional abundances are comparable to those of several chemical models from the literature and our own model, which is described in Sect. 5.2, at evolutionary times close to 10^5 yrs. Comparing with the fractional abundances observed for dense cores in cloud complexes by Foster et al. (2009), the ratio $N_{\text{NH}_3}/N_{\text{H}}$ for the globules is similar, but $N_{\text{CCS}}/N_{\text{H}}$ is about one order of magnitude smaller than in the dense cores. However, as pointed out earlier in this section, the hydrogen column densities of the globules vary by up to one order of magnitude between different studies, hence the fractional abundances of CCS and NH₃ estimated here have to be considered as uncertain to the same degree.

5.2. NH₃/CCS ratio in comparison with chemical models

In contrast, the relative abundance $N_{\text{NH}_3}/N_{\text{CCS}}$ can be discussed independent of the hydrogen densities, under the assumption that both molecules trace similar cloud regions, which is likely because of the comparable excitation conditions and similar telescope beams of both sets of observations. Figure 3 shows $N_{\text{NH}_3}/N_{\text{CCS}}$ versus evolutionary group. Altogether, we derive abundance ratios from about 20 to 860, while the observable range is limited to about $N_{\text{NH}_3}/N_{\text{CCS}} \leq 2000$ by our CCS detection limit.

Fig. 3. Abundance ratio $N_{\text{NH}_3}/N_{\text{CCS}}$ versus evolutionary group; arrows indicate lower limits and gray symbols sources with an uncertain evolutionary group (slight horizontal offsets around the group positions were made solely to improve the visibility of individual data points).

Compared to the samples presented in earlier papers, the $N_{\text{NH}_3}/N_{\text{CCS}}$ ratios derived for isolated Bok globules are on average similar to those of dense cores in the Perseus molecular cloud (Rosolowsky et al. 2008), but a factor of two higher than those in the dark clouds studied by Suzuki et al. (1992). This is because, despite the comparable range of ammonia column densities for the Suzuki et al. (1992) sample and our globules, we do not find extremely high CCS column densities typical of carbon-chain producing regions (e.g. Hirota et al. 2009, where carbon-chain producing regions are defined as those for which $N_{\text{NH}_3}/N_{\text{CCS}} \leq 10$).

The number of sources is too small to permit a rigorous statistical analysis, but taking into account only sources with reliable evolutionary stages, the following picture arises: within each evolutionary stage, a relatively large range of abundance ratios $N_{\text{NH}_3}/N_{\text{CCS}}$ spanning about one order of magnitude is observed, but there is comparatively little variation in the values between the different groups. Figure 3 appears to display a slightly decreasing trend of $N_{\text{NH}_3}/N_{\text{CCS}}$ going from group 0 to group I globules, but this trend is only marginal. Thus, we conclude that the ratio $N_{\text{NH}_3}/N_{\text{CCS}}$ is rather similar for all the Bok globules observed in this study, although their YSOs are at different evolutionary stages.

We note that the $N_{\text{NH}_3}/N_{\text{CCS}}$ ratio, in particular, does not increase going from the presumably youngest objects of group -I to the most evolved presumed of group I. This finding does not appear to comply with the general predictions of most chemical models, according to which CCS as an early-phase molecule is expected to have an abundance that decreases rapidly around 10^6 yr, while the slowly forming ammonia reaches its maximum abundance at a later stage of the chemical evolution – leading to the anticipation of steadily increasing $N_{\text{NH}_3}/N_{\text{CCS}}$ ratio along with the evolutionary stage of the globules.

In Fig. 4, we show the $N_{\text{NH}_3}/N_{\text{CCS}}$ ratio versus the chemical age of a cloud, where the abundance ratio was calculated from the evolution of CCS and NH_3 abundances for four chemical models in the literature. The models of Suzuki et al. (1992, dash-dotted line) and Scappini et al. (1998, dashed line) use pseudo-time-dependent chemical models in which the gas density is constant with time. In contrast, Bergin (2000, solid line) and Aikawa et al. (2001, dotted line) take into account the dynamics of a collapsing core, as well as the depletion of species from

Fig. 4. NH_3/CCS ratio from the chemical model calculations (see Sect. 5.2) of Suzuki et al. (1992, dash-dotted line), Scappini et al. (1998, dashed line), Bergin (2000, solid line), and Aikawa et al. (2001, dotted line), and this work (10 K warm group -I model marked with open circles, 15 K group 0 model with filled circles and 25 K group I model with asterisks). The observed range of $N_{\text{NH}_3}/N_{\text{CCS}}$ is designated by the shaded area.

the gas phase onto, and desorption from, dust grains. However, both models do not include reactions on grain surfaces except of H_2 formation and ion-electron recombination in Aikawa et al. (2001). As initial condition, all models assume that hydrogen is in molecular form and both carbon and sulfur are ions, their initial abundances being assumed to be typical of diffuse clouds or depleted by a certain factor from solar abundances; Bergin (2000) allow the cloud to evolve for 1.5×10^5 yr at constant density and assume the chemical compositions after this time as initial values for the dynamically evolving core. All models consider the chemical evolution in a region that is both at a constant temperature of 10 K and shielded from external UV radiation. Aikawa et al. (2001) follow the chemical evolution of an infalling fluid element in a collapse described by the Larson-Penston solution (we show here their result for a collapse decelerated by a factor of ten). From Bergin (2000), we show the model for a collapse with ambipolar diffusion and dust grains covered with a CO mantle. Both papers consider several variations of their models (e.g. grain properties, collapse timescales), which result in somewhat different time evolutions of the molecular abundances, which do not however deviate significantly from the examples shown in Fig. 4.

Despite the different approaches, all models agree that there is a rapid increase in the $N_{\text{NH}_3}/N_{\text{CCS}}$ ratio by three orders of magnitude at an evolutionary time of several 10^5 yr, which is caused by a rapid decrease in the CCS abundance caused by depletion onto grains, destruction by reactions, and missing replenishment. The first broad peak seen in the results of Scappini et al. (1998) and Aikawa et al. (2001) is due to a very slow formation of, and increase in, the NH_3 abundance, while CCS continues to form efficiently.

In general, the absolute values observed should be compared with those from modeling with caution. The initial conditions assumed and the exact starting point for reactions defined in chemical models might not necessarily be in good agreement with real globules, and a certain scatter has to be expected owing to the natural fluctuations in the initial conditions for the variety of globules. Nevertheless, when comparing the measured values of the $N_{\text{NH}_3}/N_{\text{CCS}}$ abundance ratio with the models, the observed

objects all appear to be in an evolved state matching the region after 10^5 yr despite their different evolutionary stages.

In addition, we employed our own chemical model to calculate the abundances of NH₃ and CCS for sources of the three groups –I, 0, and I. We used the recent chemical network including a variety of grain surface reactions described in [Semenov et al. \(2010\)](#) along with a simplified physical model. The representative physical parameters of each group were taken from the globule study of [L2010](#), i.e. the density is described by a power law function of radius (with exponent between –1 and –2) in the outer region and flattening towards the core center. We used a temperature of 10 K for group –I, 15 K for group 0, and 25 K for group I sources, respectively, based on observations and models of the mass-averaged dust temperature ([L2010](#) and references therein). Starting from “low metal” atomic abundances ([Lee et al. 1998](#)) as initial values, the evolution of both the NH₃ and CCS abundances relative to H was calculated separately for the typical physical conditions of each group. We refrained from constructing a piecewise model with sharp transitions from one group to the next at defined timesteps, since in reality a smooth transition of physical conditions can be expected, and the lifetimes of the different groups are not tightly constrained. We now discuss instead the qualitative differences between the three models.

The resulting evolution of ammonia and CCS fractional abundances is displayed in Fig. 5. In our chemical model, CCS forms rapidly in a neutral-neutral reaction of CCH and S, and reaches its maximum concentration early. Ammonia is partly formed on dust grains by means of surface hydrogenation of nitrogen, and partly in the gas phase mainly via a sequence of ion-molecule reactions. The desorption from grain surfaces occurs mainly through cosmic-ray heating and cosmic-ray-induced far-UV photons in the cold and shielded environments considered here. After a few 10^5 yrs, CCS is efficiently removed from the gas phase by freeze out onto dust grains or destruction by reactions with oxygen, and its abundance rapidly declines. For the 15 and 25 K warm group 0 and group I models, prior to this late-time depletion of CCS a number of competitive surface reactions become active, which enhance the CCS (re)production and lower the NH₃ abundance, resulting in a temporary drop in the NH₃ abundance at about 10^5 yrs and a slightly increased CCS peak abundance relative to the 10 K model of group –I sources. For other carbon-chain molecules, a similar enhancement in moderately warm environments (“warm carbon-chain chemistry”) has been found (e.g. [Sakai et al. 2008](#); [Aikawa et al. 2008](#); [Hassel et al. 2008](#)). These differences in the chemical evolution properties of our models originate primarily from the different temperatures, while the difference in density profiles has a smaller influence. For simplicity, we refer to the models of the three groups (–I, 0, and I) by their temperature (10, 15, and 25 K) in the following.

As a result, in the early phase the ratio $N_{\text{NH}_3}/N_{\text{CCS}}$ evolves very slowly from values close to unity to a few dozen for all three models. For the 10 K model, the abundance ratio starts to increase more rapidly with time at 10^5 yrs and crosses the range observed in the Bok globules of our sample within 2.5×10^5 yrs. For the somewhat warmer 15 K model, $N_{\text{NH}_3}/N_{\text{CCS}}$ increases earlier and more rapidly, while for the 25 K model the abundance ratio remains low (<10) until $>1 \times 10^5$ yrs, before increasing rapidly to $>10^3$ as in the other two models. In Fig. 4, the evolution of $N_{\text{NH}_3}/N_{\text{CCS}}$ for the three parameter sets of our chemical model is designated by open and filled circles (10 K and 15 K, respectively) and asterisks (25 K).

Fig. 5. Upper part: evolution of the NH₃ fractional abundance resulting from our model described in Sect. 5.2 for group –I model (10 K, solid line), group 0 model (15 K, dashed line) and group I model (25 K, dotted line). Lower part: the same for CCS.

When comparing the models with the observational data shown in Fig. 3, we can see that the observed range of $N_{\text{NH}_3}/N_{\text{CCS}}$ ratios could be compatible with the rapidly increasing parts of our three model curves at evolutionary times of a few 10^4 – 10^5 yrs. However, the 10 K and 15 K models are close to the lower $N_{\text{NH}_3}/N_{\text{CCS}}$ limit derived from our observations for most of their evolutionary time, while the 25 K model remains at significantly smaller values up to 10^5 yrs. Thus, if one assumes that the intrinsic chemical ages of the Bok globules may have a perceivable scatter, one could expect to find globules with very small $N_{\text{NH}_3}/N_{\text{CCS}}$ ratios (≤ 5) if the group I model is applicable – but such small ratios are not measured for our sample. The range of fractional abundances estimated from the observations in Sect. 5.1 agrees for NH₃ with both the 10 K and 15 K models for times $>10^4$ yrs, while the NH₃ abundance in the 25 K model remains slightly below the observed range for the whole time span covered by the model. For CCS, the peak abundances of the 10 K and 15 K model around 10^4 – 10^5 yrs fall in the observed range, while the 25 K model exceeds it. Although we have to consider the uncertainties in the estimated fractional abundances, this may be another indication that the 25 K model does not agree with the observations, while both the 10 K and 15 K warm models fit them equally well.

The choice of 10–25 K for the models of the different groups was originally motivated by both models (e.g., [Shirley et al. 2002](#); [Galli et al. 2002](#); [Bergin et al. 2006](#)) and observations (e.g. for CB 244 in [Stutz et al. 2010](#)) of the dust temperature.

In general, dust temperatures are expected to be moderately high (~ 15 K) close to the cloud surface heated by the interstellar radiation field, and lower (~ 10 K) in the moderately dense envelope where CO line radiation cools the gas efficiently. In the center of prestellar cores, they may be as low as 5 K (depending on the external radiation field), or accordingly warmer in the case of an internal heating source (20–30 K in Shirley et al. 2002). In the dense ($n_{\text{H}} \geq 10^5 \text{ cm}^{-3}$) inner regions, gas and dust are expected to be tightly coupled by means of collisions, hence similar in temperature.

In contrast, the beam- (BHR95b) or map-averaged (L96) NH_3 rotational temperatures (which represent a good estimate of the kinetic temperature at the low temperatures prevalent in globules, see e.g. Stutzki 1984) are 9–16 K for globules of all evolutionary stages (L96; BHR95b). This is most likely because the warm cores of Class 0 and more evolved objects have typical sizes of a few thousand AU (L2010), hence comprise only a small fraction of the NH_3 beam area for the average globule distance of our sample. In addition, the innermost warmest and densest parts of the core may not be traced well by NH_3 because of the high optical depth. Thus, with the large beam of the NH_3 observations considered here, cool (~ 10 – 15 K) gas from the moderately dense envelope can be expected to dominate the signal (see also Crapsi et al. 2007, where the central gas temperature drop in a prestellar core was detectable with interferometric, but not single-dish observations).

Moreover, a scatter in the temperatures across the range 10–15 K for the bulk of gas may also result from differences in the size, density, and local UV background radiation for the individual globules, and not only from their evolutionary stage. In Foster et al. (2009), the kinetic temperatures inferred from the NH_3 data of the protostellar and starless cores cover a similar range as those for our globules, and the slight differences between the star-forming and starless group detected by them may be discernable only for sample sizes significantly larger than ours.

If indeed, as suggested by our chemical model, small temperature differences of ~ 5 K could already perceptibly affect the progression of the $N_{\text{NH}_3}/N_{\text{CCS}}$ ratio around 10^5 yrs, then the superposition of $N_{\text{NH}_3}/N_{\text{CCS}}$ evolution curves for several initial temperatures could lead to a relatively large scatter in the $N_{\text{NH}_3}/N_{\text{CCS}}$ ratios within one evolutionary group, while simultaneously smearing out differences between the evolutionary groups (differences in other initial physical parameters such as density may also contribute, but we do not address them here in detail because the observational data are too limited in size to permit an accurate comparison). This would agree with the observation that the (beam-averaged) $N_{\text{NH}_3}/N_{\text{CCS}}$ ratio is rather similar across globules of all evolutionary stages and exhibits a relatively large scatter within each group. Additional contributions to the scatter in the $N_{\text{NH}_3}/N_{\text{CCS}}$ abundance ratio among globules of a single group may arise from the significant fraction of globules containing adjacent objects at different evolutionary stages (Sect. 2), which would be indicative of sequential star formation, and a range of ages even among the objects compiled in one evolutionary group.

To test this hypothesis in detail, it would be necessary to distinguish the influences of gas temperature and age (i.e. evolutionary group), for which our dataset is significantly too small. It could also be of interest to evaluate a possible increase in the gas temperature and change in the chemistry on small scales close to forming protostars, for which observations of much higher resolution are needed.

Fig. 6. Abundance ratio $N_{\text{NH}_3}/N_{\text{CCS}}$ versus bolometric temperature of embedded sources. Arrows indicate lower limits to the abundance ratio, gray symbols mark T_{bol} of combined spectral energy distributions (cf. Sect. 5.3).

5.3. Abundance ratio and bolometric temperature

It has been pointed out that the evolution of YSOs can be traced by the bolometric temperature T_{bol} , defined as the temperature of a blackbody with the same mean frequency as the spectrum of the observed source (Ladd et al. 1991; Myers & Ladd 1993). Chen et al. (1995) have demonstrated a tight correlation between T_{bol} and the age of protostars and pre-main-sequence stars in particular for embedded sources. For a number of YSOs in globules of our sample, the bolometric temperature has been evaluated by L2010 and Racca et al. (2009). However, T_{bol} is useful mainly for tracing the evolution of Class 0 and more evolved sources, since for most of the coldest, presumably youngest sources (e.g. CB 246, BHR 137) T_{bol} is difficult to derive because the spectral energy distribution is not constrained at shorter wavelengths.

We show our measured $N_{\text{NH}_3}/N_{\text{CCS}}$ abundance ratio versus T_{bol} adopted from the studies of L2010 and Racca et al. (2009), in Fig. 6. In the case of CB 232 and CB 243 (as well as BHR 12 denoted in gray color), where both a prestellar core and a Class I source are included in the beam, T_{bol} represents the value for the combined spectral energy distribution of the adjacent sources, which in both cases is dominated by the Class I source, while the molecular emission is expected to originate mainly from the prestellar cores. However, in both globules the separation of the prestellar core and Class I source equals the typical size of a prestellar core (8000 AU in L2010); in this case, the presence of an evolved YSO might influence the chemistry of the prestellar core and accordingly both may not be completely unrelated. For a definite judgment of this question, a mapping of the line emission at small scales would be required.

From most chemical models in the literature as shown in Fig. 4, an increase in the $N_{\text{NH}_3}/N_{\text{CCS}}$ ratio towards warmer bolometric temperatures, which in turn are thought to represent increasingly older and more evolved sources, would be expected. Despite the limited size of our dataset, there are no indications of such an increase. The $N_{\text{NH}_3}/N_{\text{CCS}}$ abundance ratio instead shows a tentative decrease towards increasing bolometric temperature. However, owing to the small number of globules with both known bolometric temperature and detected CCS emission, an interpretation is even more difficult than in Sect. 5.2.

5.4. Non-thermal linewidths

The observed linewidths Δv_{obs} include an instrumental broadening of $\Delta v_{\text{instr}} = 0.08 \text{ km s}^{-1}$ (Effelsberg) and 0.05 km s^{-1} (Parkes), which can be subtracted under the assumption of a Gaussian profile for the line as well as for the spectrometer

$$\Delta v^2 = \Delta v_{\text{obs}}^2 - \Delta v_{\text{instr}}^2. \quad (8)$$

In the same way, the thermal contribution to the linewidth

$$\Delta v_{\text{therm}} = \sqrt{\frac{8 \ln 2 k T_{\text{kin}}}{m}}, \quad (9)$$

where m denotes the molecular mass of the molecule, was subtracted to obtain the non-thermal linewidths Δv_{nth} in Table 2. We used the rotational temperatures T_{rot} derived by L96 and BHR95b from their ammonia observations as an estimate of the kinetic temperature T_{kin} . Where these values for the individual globules were unavailable, an average temperature of $T_{\text{kin}} = 10 \text{ K}$ was assumed. The typical thermal contribution to the CCS and NH₃ linewidths is 0.09 and 0.16 km s^{-1} , respectively. We note that, because the main line of the NH₃(1, 1) line consists of several hyperfine components distributed over 0.7 km s^{-1} that are usually blended, the linewidths derived from a single Gaussian fit to the main line are dominated by the separation of the blended hyperfine components rather than the intrinsic linewidth for lines with small linewidths. An intrinsic linewidth can in principle be estimated from such fits, but suffers from the large uncertainties in the typically small linewidths observed in Bok globules. We therefore discuss the non-thermal linewidths of only those globules with sufficiently well-detected main and satellite lines of NH₃(1, 1), for which intrinsic linewidths could be derived directly from fits of the hyperfine structure.

For both NH₃ and CCS, the majority of non-thermal linewidths is found in the range $0.2\text{--}0.5 \text{ km s}^{-1}$ for all evolutionary groups. In addition, large non-thermal linewidths $0.6\text{--}1.2 \text{ km s}^{-1}$ are observed in globules of group 0 and I, while very small linewidths $\leq 0.1 \text{ km s}^{-1}$ are present exclusively in globules of group –I. The non-thermal linewidth can be understood as a measure of turbulence in the medium and the existence of unresolved velocity components within the area covered by the telescope beam. A relatively large linewidth Δv_{nth} might be expected for actively star-forming regions because of the turbulence and outflow motions induced by the presence of a protostar. However, for globules at larger distances a physical region of proportionally larger size is enclosed by the beam, hence larger linewidths may be measured. We are fairly confident that our results are not biased by this effect, since no clear relationship between linewidth and distance is discernable for our sample.

Among the starless or prestellar sources of group –I, the globules with extremely small non-thermal linewidths (CB 22 and CB 23) are distinguished from the rest by an absence of IRAS and millimeter sources, i.e. there is no evidence of any embedded sources. In contrast, three of the group –I globules with intermediate Δv_{nth} harbor more evolved Class I sources in the vicinity of the prestellar core, while the remaining globules are poorly studied. The group 0 and I sources with large non-thermal linewidths have lines deviating from Gaussian-shaped profiles (BHR 140-1, BHR 36) or show evidence of at least two velocity components (BHR 71 and BHR 55). However, they do not differ distinctly from the remaining group 0 and I globules in terms of properties such as presence of outflows, multiplicity, etc.

In the majority of globules, the non-thermal CCS linewidths are smaller than those of NH₃, but the opposite case or similar linewidths are observed as well. A possible explanation could be that both molecules do not trace exactly similar cloud regions, as in the cases found by Codella & Scappini (1998b) and Lai & Crutcher (2000) where the most dense parts of cores are preferentially detected in NH₃, while CCS emission originates from a more extended surrounding region. These central depletion holes in evolved sources are also observed for other carbon-bearing species, such as the CCH radical (e.g., Beuther et al. 2008; Padovani et al. 2009), which resembles in many properties, and is thought to be a precursor of, CCS. Since both NH₃ and CCS have roughly comparable critical densities ($\sim 10^3\text{--}10^4 \text{ cm}^{-3}$), a difference in the emitting region is most likely a result of different spatial distributions. This might in turn mean that both molecules trace regions with somewhat different physical conditions, and also result in an incorrect estimate of the thermal component for the linewidths when assuming the same kinetic temperature for both CCS and NH₃.

Altogether, it is difficult to draw firm conclusions about the origin of the spread of non-thermal linewidths because of the sparse dataset and the availability of only single-point measurements.

6. Summary

Observations of 42 Bok globules in CCS and partially in NH₃, supplemented with NH₃ measurements from the literature (L96, BHR95b) have enabled us to measure the abundance ratios of both molecules for 18 objects (and derive lower limits for additional 21 globules) at different evolutionary stages ranging from starless and prestellar globules (designated as group –I), to clouds containing Class 0 YSOs (group 0), and then to globules harboring YSOs of Class I and later (group I). In the following, we summarize our main results:

1. The CCS($2_1\text{--}1_0$) line has been detected in 18 of 42 Bok globules. The detection rate is highest in the objects of group –I (70%) and decreases towards the globules of group 0 and I (40 and 33%, respectively). Ammonia was detected (including literature data) in 39 globules.
2. We have derived $N_{\text{NH}_3}/N_{\text{CCS}}$ ratios in the range 26–422, plus one lower limit of 860, for isolated Bok globules. In particular, within the limits of our survey, we find neither extremely low abundance ratios (≤ 10) similar to those typical of carbon-chain producing regions in dark clouds (Suzuki et al. 1992; Hirota et al. 2009), nor extremely high abundance ratios (several 10^3) as expected for evolved sources according to the chemical models of cloud cores developed by different authors (Fig. 4).
3. We have not found any increase in the $N_{\text{NH}_3}/N_{\text{CCS}}$ abundance ratio going from the starless and prestellar globules towards evolved globules containing Class I or later sources, nor from lower towards higher bolometric temperatures of the embedded YSOs, as would be expected from various chemical models in the literature and this work (Sect. 5.2). Instead, the ratio exhibits a considerable scatter but is roughly constant across all evolutionary groups (Fig. 3), with a tentatively – although statistically insignificant – decreasing trend from globules containing Class 0 protostars (group 0) towards globules with Class I or later YSOs (group I).
4. Our own chemical model (Sect. 5.2) indicates that a slight temperature increase (i.e., 15 K instead of 10 K) could affect

the $N_{\text{NH}_3}/N_{\text{CCS}}$ ratio perceptibly at evolutionary times around 10^5 yrs. Since NH_3 rotational temperatures vary across the same range, this suggests that the observed (beam-averaged) $N_{\text{NH}_3}/N_{\text{CCS}}$ ratios, which are roughly constant across the evolutionary groups but have a scattered distribution of values within each group, could result from a superposition of evolutionary tracks for different initial globule temperatures. In contrast, a 25 K warm model seems less likely, because neither such high gas temperatures, NH_3 and CCS fractional abundances in agreement with the model, nor very low $N_{\text{NH}_3}/N_{\text{CCS}}$ ratios (≤ 5) expected from the model even at late evolutionary times, are observed.

5. We have detected the smallest non-thermal linewidths of CCS ($\sim 0.1 \text{ km s}^{-1}$), indicating a very low level of turbulence, only in two globules of group –I without any associated infrared or millimeter sources. In contrast, broad CCS lines with evidence of multiple velocity components have been found only among star-forming globules (groups 0 and I). Beyond that, no firm conclusions about the non-thermal linewidths can be drawn owing to the small sample size.

We conclude that our observed $N_{\text{NH}_3}/N_{\text{CCS}}$ abundance ratios derived from single-dish observations with relatively large beams, although related to the evolutionary state of the embedded objects, cannot alone be straightforwardly interpreted as an evolutionary tracer for isolated Bok globules. Another major problem hampering this study is the immediate vicinity of objects in different evolutionary stages found in many of the globules (see L2010), which makes it difficult to assess the amount of emission originating from each source or the possible mutual influence on physical and chemical conditions. In addition, the assumption of NH_3 and CCS tracing the same spatial regions is an approximation that may not hold for all globules. In particular, the distribution of CCS – a central depletion hole or enhanced in the warm core region of evolved sources – is of interest but not yet studied for most globules in our sample. Well-resolved mapping of the line emission of both molecules for a large sample of globules, the assessment of the gas temperature, and a position-dependent evaluation of the $N_{\text{NH}_3}/N_{\text{CCS}}$ ratio, will be required to address the aforementioned problems in greater detail.

Acknowledgements. We would like to express our thanks to the staff of the Effelsberg 100-m telescope and the Parkes 64-m telescope for their assistance with the observations. M. Ilgner contributed with helpful discussions. C.M. acknowledges support from the Deutsche Forschungsgemeinschaft (DFG) through grant SCHR665/7-1 during part of this study. We thank an anonymous referee for valuable comments and suggestions which helped to improve this paper.

References

- Aikawa, Y., Ohashi, N., Inutsuka, S., Herbst, E., & Takakuwa, S. 2001, *ApJ*, 552, 639
- Aikawa, Y., Wakelam, V., Garrod, R. T., & Herbst, E. 2008, *ApJ*, 674, 984
- Alves, J., & Yun, J. 1994, in *Clouds, Cores, and Low Mass Stars*, ed. D. P. Clemens, & R. Barvainis, ASP Conf. Ser., 65, 230
- Alves, J. F., & Yun, J. L. 1995, *ApJ*, 438, L107
- André, P., Ward-Thompson, D., & Barsony, M. 1993, *ApJ*, 406, 122
- Bergin, E. A. 2000, in *From Molecular Clouds to Planetary*, ed. Y. C. Minh, & E. F. van Dishoeck, IAU Symp., 197, 51
- Bergin, E. A., Maret, S., van der Tak, F. F. S., et al. 2006, *ApJ*, 645, 369
- Beuther, H., Semenov, D., Henning, T., & Linz, H. 2008, *ApJ*, 675, L33
- Bok, B. J., & Reilly, E. F. 1947, *ApJ*, 105, 255
- Bourke, T. L., Hyland, A. R., & Robinson, G. 1995a, *MNRAS*, 276, 1052
- Bourke, T. L., Hyland, A. R., Robinson, G., James, S. D., & Wright, C. M. 1995b, *MNRAS*, 276, 1067 (BHR95b)
- Chen, H., Myers, P. C., Ladd, E. F., & Wood, D. O. S. 1995, *ApJ*, 445, 377
- Clemens, D. P., & Barvainis, R. 1988, *ApJS*, 68, 257
- Clemens, D. P., Yun, J. L., & Heyer, M. H. 1991, *ApJS*, 75, 877
- Codella, C., & Bachiller, R. 1999, *A&A*, 350, 659
- Codella, C., & Scappini, F. 1998a, *MNRAS*, 298, 1092
- Codella, C., & Scappini, F. 1998b, *MNRAS*, 298, 1092
- Codella, C., & Scappini, F. 2003, *MNRAS*, 344, 1257
- Crapsi, A., Caselli, P., Walmsley, M. C., & Tafalla, M. 2007, *A&A*, 470, 221
- de Gregorio-Monsalvo, I., Gómez, J. F., Suárez, O., et al. 2006, *ApJ*, 642, 319 (dGM06)
- Foster, J. B., Rosolowsky, E. W., Kauffmann, J., et al. 2009, *ApJ*, 696, 298
- Galli, D., Walmsley, M., & Gonçalves, J. 2002, *A&A*, 394, 275
- Hassel, G. E., Herbst, E., & Garrod, R. T. 2008, *ApJ*, 681, 1385
- Henning, T., & Launhardt, R. 1998, *A&A*, 338, 223
- Hirota, T., Ohishi, M., & Yamamoto, S. 2009, *ApJ*, 699, 585
- Ho, P. T. P., & Townes, C. H. 1983, *ARA&A*, 21, 239
- Huard, T. L., Sandell, G., & Weintraub, D. A. 1999, *ApJ*, 526, 833
- Huard, T. L., Weintraub, D. A., & Sandell, G. 2000, *A&A*, 362, 635
- Lada, C. J. 1987, in *Star Forming Regions*, ed. M. Peimbert, & J. Jugaku, IAU Symp., 115, 1
- Ladd, E. F., Adams, F. C., Casey, S., et al. 1991, *ApJ*, 366, 203
- Lai, S.-P., & Crutcher, R. M. 2000, *ApJS*, 128, 271
- Launhardt, R., & Henning, T. 1997, *A&A*, 326, 329, (LH97)
- Launhardt, R., Evans, II, N. J., Wang, Y., et al. 1998a, *ApJS*, 119, 59
- Launhardt, R., Henning, T., & Klein, R. 1998b, in *Star Formation with the Infrared Space Observatory*, ed. J. Yun, & L. Liseau, ASP Conf. Ser., 132, 119
- Launhardt, R., Nutter, D., Ward-Thompson, D., et al. 2010, *ApJS*, 188, 139 (L2010)
- Lee, C. W., & Myers, P. C. 1999, *ApJS*, 123, 233
- Lee, H., Roueff, E., Pineau des Forets, G., et al. 1998, *A&A*, 334, 1047
- Lee, C. W., Myers, P. C., & Tafalla, M. 1999, *ApJ*, 526, 788
- Lee, C. W., Myers, P. C., & Plume, R. 2004, *ApJS*, 153, 523
- Lemme, C., Wilson, T. L., Tiefertunk, A. R., & Henkel, C. 1996, *A&A*, 312, 585, (L96)
- Moreira, M. C., & Yun, J. L. 1995, *ApJ*, 454, 850
- Moreira, M. C., Yun, J. L., Vazquez, R., & Torrelles, J. M. 1997, *AJ*, 113, 1371
- Moreira, M. C., Yun, J. L., Torrelles, J. M., Afonso, J. M., & Santos, C. A. 1999, *AJ*, 118, 1315
- Myers, P. C., & Ladd, E. F. 1993, *ApJ*, 413, L47
- Otrupcek, R. E., Hartley, M., & Wang, J. 2000, *PASA*, 17, 92
- Padovani, M., Walmsley, C. M., Tafalla, M., Galli, D., & Müller, H. S. P. 2009, *A&A*, 505, 1199
- Petrie, S. 1996, *MNRAS*, 281, 666
- Racca, G. A., Vilas-Boas, J. W. S., & de la Reza, R. 2009, *ApJ*, 703, 1444
- Rosolowsky, E. W., Pineda, J. E., Foster, J. B., et al. 2008, *ApJS*, 175, 509
- Sahu, M., & Sahu, K. C. 1992, *A&A*, 259, 265
- Saito, S., Kawaguchi, K., Yamamoto, S., et al. 1987, *ApJ*, 317, L115
- Sakai, N., Ikeda, M., Morita, M., et al. 2007, *ApJ*, 663, 1174
- Sakai, N., Sakai, T., Hirota, T., & Yamamoto, S. 2008, *ApJ*, 672, 371
- Santos, N. C., Yun, J. L., Santos, C. A., & Marreiros, R. G. 1998, *AJ*, 116, 1376
- Scappini, F., & Codella, C. 1996, *MNRAS*, 282, 587
- Scappini, F., Caselli, P., & Palumbo, G. G. C. 1991, *MNRAS*, 249, 763
- Scappini, F., Cecchi-Pestellini, C., Olberg, M., Casolari, A., & Fanti, C. 1998, *ApJ*, 504, 866
- Semenov, D., Hersant, F., Wakelam, V., et al. 2010, *A&A*, 522, A42
- Shirley, Y. L., Evans, II, N. J., & Rawlings, J. M. C. 2002, *ApJ*, 575, 337
- Stutz, A., Launhardt, R., Linz, H., et al. 2010, *A&A*, 518, L87
- Stutzki, J. 1984, Ph.D. Thesis, Universität Köln
- Suzuki, H., Yamamoto, S., Ohishi, M., et al. 1992, *ApJ*, 392, 551
- Ungerechts, H., Walmsley, C. M., & Winnewisser, G. 1980, *A&A*, 88, 259
- Urquhart, J. S., Morgan, L. K., & Thompson, M. A. 2009, *A&A*, 497, 789
- van Dishoeck, E. F., & Blake, G. A. 1998, *ARA&A*, 36, 317
- Vilas-Boas, J. W. S., Myers, P. C., & Fuller, G. A. 1994, *ApJ*, 433, 96
- Walsh, A. J., Hyland, A. R., Robinson, G., & Burton, M. G. 1997, *MNRAS*, 291, 261
- Wang, Y., Evans, II, N. J., Zhou, S., & Clemens, D. P. 1995, *ApJ*, 454, 217
- Wolkovitch, D., Langer, W. D., Goldsmith, P. F., & Heyer, M. 1997, *ApJ*, 477, 241
- Yun, J. L., & Clemens, D. P. 1992, *ApJ*, 385, L21
- Yun, J. L., & Clemens, D. P. 1994a, *AJ*, 108, 612
- Yun, J. L., & Clemens, D. P. 1994b, *ApJS*, 92, 145
- Yun, J. L., & Clemens, D. P. 1995, *AJ*, 109, 742