Abundances and rotational temperatures of the C$_2$ interstellar molecule towards six reddened early-type stars

M. Kaźmierczak,$^1$† M. R. Schmidt$^2$† A. Bondar$^3$† and J. Krełowski$^1$†

$^1$Centre for Astronomy, Nicolaus Copernicus University, Gagarina 11, 87-100 Toruń, Poland
$^2$Nicolaus Copernicus Astronomical Centre, ul. Rabiańska 8, 87-100 Toruń, Poland
$^3$International Centre for Astronomical and Medico-Ecological Research, Terskol, Russia

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ABSTRACT

Using high-resolution ($\sim$85 000) and high signal-to-noise ratio ($\sim$200) optical spectra acquired with the European Southern Observatory Ultraviolet and Visual Echelle Spectrograph, we have determined the interstellar column densities of C$_2$ for six Galactic lines of sight with $E(B-V)$ ranging from 0.33 to 1.03. For our purposes, we identified and measured absorption lines belonging to the (1, 0), (2, 0) and (3, 0) Phillips bands $\Lambda^1\Pi_u^–X^1\Sigma_g^+$. We report on the identification of a few lines of the C$_2$ (4, 0) Phillips system towards HD 147889. The curve-of-growth method is applied to the equivalent widths to determine the column densities of the individual rotational levels of C$_2$. The excitation temperature is extracted from the rotational diagrams. The physical parameters of the intervening molecular clouds (e.g. gas kinetic temperatures and densities of collision partners) were estimated by comparison with the theoretical model of excitation of C$_2$.

Key words: ISM: molecules.

1 INTRODUCTION

Diatomic carbon is found in a variety of celestial bodies, such as comets (C$_2$ Swan band, Mayer & O’dell 1968; Lambert & Danks 1983; Ballik–Ramsay and Phillips bands, Johnson, Fink & Larson 1983; Gredel, van Dishoeck & Black 1989), the Sun (Swan band, Grevesse & Sauval 1973; Lambert 1978), carbon stellar atmospheres (Swan, Ballik–Ramsay and Phillips bands, Querci, Querci & Kunde 1971), the circumstellar shells of carbon-rich post-AGB stars (Phillips and Swan bands, Bakker et al. 1996, 1997) and interstellar clouds.

In the interstellar medium, C$_2$ was first detected by Souza & Lutz (1977). They observed the absorption lines of the (1, 0) Phillips band $\Lambda^1\Pi_u^–X^1\Sigma_g^+$. The lines of the (2, 0) Phillips system were first tentatively detected in interstellar clouds by Chaffee & Lutz (1978). An evident demonstration of the band was shown by Chaffee et al. (1980). The Phillips band (3, 0) was only discovered by van Dishoeck & Black (1986). Some C$_2$ lines of the (4, 0) Phillips band in the direction of HD 204827 have been shown by Hobbs et al. (2008) (a few lines of this band that are very weak and difficult to measure are demonstrated here for the first time towards HD 147889).

C$_2$ is particularly interesting because it is the simplest multicarbon molecule. Its abundances give information about the chemistry of interstellar clouds, especially on the pathway to the formation of long-chain carbon molecules, which may be connected with carriers of diffuse interstellar bands (DIBs; Douglas 1977; Thorburn et al. 2003). Additionally, the analysis of C$_2$ lines allows us to determine the physical conditions in interstellar clouds.

In the interstellar medium, because of the very rare collisions and low temperatures, we expect only absorption lines from the ground electronic state. For C$_2$, there are Mulliken systems (discovered by Snow 1978, $D^1\Sigma_u^+–X^1\Sigma_g^+$, $\sim$2313 Å; see also Lambert, Sheffer & Federman 1995; Sonnentrucker et al. 2007), F–X systems (first detected by Lien 1984, $F^1\Pi_u^–X^1\Sigma_g^+$, $\sim$1342 Å) and Phillips systems ($\Lambda^1\Pi_u^–X^1\Sigma_g^+$, $\sim$6900–12 000 Å).

As a homonuclear diatomic molecule, C$_2$ has a negligible dipole moment. Thus, the radiative cooling of the excited rotational levels may go only through the slow quadrupole transitions (van Dishoeck & Black 1982). The rotational levels are pumped by the galactic interstellar radiation field and excited effectively above the gas kinetic temperature. The rotational ladder of the electronic absorptions from the high rotational levels (here up to $J’’= 26$) are usually observed. Because of this, the lines of diatomic carbon from long-lived ground-state rotational levels are measurable. They can be sensitive diagnostic probes of the conditions in molecular clouds that produce interstellar absorption lines. This is in contrast to polar
molecules, such as CH or CN, where usually only a few absorption lines from the lowest rotational levels are observed.

The relative abundances of $C_2$ were predicted for interstellar clouds on the basis of detailed chemical models (Black & Dalgarno 1977; Black, Hartquist & Dalgarno 1978). The excitation mechanisms of $C_2$ have been already analysed in detail (Chaffee et al. 1980; van Dishoeck & Black 1982).

The main purpose of this paper is to determine the basic physical parameters, such as the temperatures and densities, of the intervening clouds. Four out of the six analysed objects (Table 1) have been studied previously, but high-quality spectra from the European Southern Observatory (ESO) archive (Bagnulo et al. 2003) have allowed us to accurately measure these weak features. The broad spectral range of the Ultraviolet and Visual Echelle Spectrograph (UVES) spectra allows us to analyse up to four bands, in contrast to previous analyses usually based on the single $(2, 0)$ band of the Phillips system. Simultaneous observations of different bands make it possible to compare individually determined results for each band and to make the results more reliable. In this paper, we present two new objects with the interstellar absorption lines of $C_2$, increasing the presently available sample of interstellar clouds (24 lines of sight; see table 13 of Sonnentrucker et al. 2007) for which a detailed analysis of the excitation of $C_2$ has been made (estimates of densities and excitation temperatures).

In Section 2, we describe our data, the observations, the reduction and the criteria for choosing stars. In Section 3, we introduce the methods we used to analyse the observational data. A general discussion and a summary of our conclusions are given in Sections 4 and 5, respectively. In Appendix A, we discuss the individual results for each star of the sample and we compare our results with those of previous papers.

## 2 OBSERVATIONAL DATA

We used the archived spectroscopic observations collected using the UVES (Dekker et al. 2000). The UVES is the high-resolution spectrograph of the Very Large Telescope fed by the Kueyen telescope of the ESO Paranal Observatory, Chile. The UVES is a cross-dispersed echelle spectrograph designed to operate with high efficiency from the atmospheric cut-off at 3000 Å to the long wavelength limit of the CCD detectors (about 11 000 Å). Thus, it is a suitable instrument for observing the four bands of the Phillips system in a single exposure. The high quality of the UVES allows us to obtain excellent spectra with a maximal resolution of about 85 000 (accurate values in Table 1) and a signal-to-noise ratio above 200.

We have chosen spectra with interstellar molecular lines of $C_2$ towards six early-type stars (see Table 1) from the UVES archive. Objects with intermediate colour excess and with one dominant velocity component, at the resolution of observational material, were selected to make it likely that $C_2$ molecular lines originate from single clouds. In addition, $K$ 7699-Å line profiles were checked for the possible existence of more than one dominating Doppler component. Generally, we cannot exclude the existence of multiple closely spaced components. For example, Welty & Hobbs (2001) show very weak Doppler components in $K_1$ and CH towards HD 148184, which are not visible in our spectra. The presence of weak components should not contaminate weak $C_2$ lines. Welty & Hobbs (2001) also show that almost all of the programme objects have multiple components in Na; however, this component may be not related to the molecular components (Bondar et al. 2007). In the ultra-high-resolution spectra of HD 169454, Crawford (1997) and Crawford & Barlow (1996) found two Doppler components in the $C_2$ lines. These are still unresolved at the UVES resolution.

The spectral analysis was made with the dech20t code (Galazutdinov 1992).

Spectral regions with interstellar $C_2$ absorption lines, especially the $(3, 0)$ and $(4, 0)$ bands, are contaminated by atmospheric lines. Our spectra were divided by the spectrum of proper standard (Spica) to remove telluric lines. In this way, the majority of telluric features were removed. The remaining lines were cut out one by one manually. The continuum was traced to remove broad stellar absorption features. Also, a possible broad DIB at 7721.7 Å (Herbig & Leka 1991) blended with the $C_2$ $(3, 0)$ Q(2) line was removed in this procedure.

The final spectra were normalized to unity to enable measurements of the equivalent widths. The equivalent widths were measured by fitting a Gaussian profile to each absorption line. At the resolution of the spectra ($\sim 3–5$ km s$^{-1}$) the profiles of the single molecular lines would have the shape of the instrumental profile. The expected Doppler broadening of the profiles caused by thermal and turbulent motions ($<0.7$ km s$^{-1}$; see table 4 of Crawford 1997) are significantly lower.

The uncertainties of the equivalent widths ($\Delta E W$) were estimated with the IRAF$^1$ SPLOT task, taking into consideration the signal-to-noise ratio in the portion of spectrum close to the measured $C_2$ line. In these cases, where continuum tracing was uncertain, additional uncertainty was estimated by changing the continuum level. The errors were propagated to the uncertainties of the determined parameters (e.g. excitation temperatures, column densities) and used to search for the best-fitting model parameters.

In summary, we measured absorption lines (P, Q and R branches) in bands $(1, 0)$ 10 133–10 262 Å, $(2, 0)$ 8750–8849 Å and $(3, 0)$ 7714–7793 Å. In one case, HD 147889, we were able to identify and measure interstellar absorption lines of the $(4, 0)$ 6909–6974 Å band (Fig. 1).

Fig. 1 shows the final spectra of HD 147889, with the continuum level normalized to unity. Broad stellar lines were removed in the procedure of continuum tracing. There are plenty of weak absorption lines (Fig. 1), thanks to the high quality of the UVES data. Even the P(4) and Q(8) lines, which are usually blended in the $(2, 0)$ band, are well separated in all objects. Many of the $C_2$ lines were also found in the $(3, 0)$ band. The oscillator strengths for $(4, 0)$ are about five times weaker than those in the $(2, 0)$ band and, in addition, molecular lines around 6915 Å are seriously contaminated by telluric lines. The $C_2$ lines of the Phillips system, seen in all spectra of the programme stars, allow us to identify the rotational

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1 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under cooperative agreement with the National Science Foundation.
Figure 1. The regions of the C$_2$ (1, 0), (2, 0), (3, 0) and (4, 0) Phillips bands in the spectrum of HD 147889. The spectrum was normalized to a continuum level of 1. The C$_2$ absorption lines are indicated. The wavelength scale has been shifted to the rest wavelength velocity frame using the interstellar K$_\text{I}$ line (7698.965 Å).
Table 2. Summary of observations with the equivalent widths (mÅ) of $C_2$ (1, 0) Phillips lines towards the programme stars. Also shown are $B(N'' = J'')$, the branch identification (where $J''$ is the low rotational level) and $\lambda$, the wavelength in air in Å (see text for references).

| $B(N'' = J'')$ | HD 76341 | HD 147889 | HD 148184 | HD 163800 | HD 169454 | HD 179406 | $\lambda$ (Å) |
|----------------|----------|-----------|-----------|-----------|-----------|-----------|--------------|
| R(6)           | 8.3 ± 1.5| 1.6 ± 1.0 | 0.6 ± 0.5μ| 4.0 ± 1.0 | 3.2 ± 1.0 | 10133.603  |
| R(8)           | 5.8 ± 1.5| 2.4 ± 1.5 | 1.0 ± 0.7 | 0.7 ± 1.3 | 1.9 ± 0.8μ| 10135.854  |
| R(4)           | 2.2 ± 1.1| 15.6 ± 1.4| 6.5 ± 1.6 | 3.6 ± 1.3 | 7.0 ± 1.2 | 10135.149  |
| R(10)          | 3.4 ± 2.2| 0.5 ± 0.5μ| 2.0 ± 1.4μ| 2.0 ± 1.4μ| 10135.923  |
| R(2)           | 3.2 ± 1.2| 17.1 ± 1.4| 2.6 ± 1.0 | 12.5 ± 1.1| 6.1 ± 1.5 | 10138.540  |
| R(12)          |         | 0.5 ± 0.9 |          |           |           | 10139.805  |
| R(0)           | 1.6 ± 1.0| 12.4 ± 1.4| 4.0 ± 1.2 | 3.8 ± 1.0 | 14.3 ± 1.0| 10143.723  |
| R(14)          |         | 0.8 ± 0.5 |          |           |           | 10145.505  |
| Q(2)           | 22.1 ± 1.4| 6.4 ± 0.5 | 4.3 ± 1.3μ| 21.0 ± 1.4| 9.0 ± 1.3 | 10148.351  |
| Q(4)           | 2.6 ± 1.2| 20.3 ± 1.6| 7.2 ± 1.2 | 3.2 ± 1.4μ| 12.5 ± 1.0| 10151.523  |
| P(2)           | 5.6 ± 1.4|          | 2.0 ± 0.9 | 3.9 ± 1.2 |           | 10154.897  |
| Q(6)           | 17.1 ± 1.4| 4.4 ± 1.3 | 6.0 ± 1.4μ| 5.9 ± 1.0 | 6.3 ± 1.0 | 10156.515  |
| Q(8)           | 0.7 ± 0.7| 13.7 ± 1.2| 2.8 ± 1.5 | 4.6 ± 1.3 | 4.5 ± 1.2 | 10163.323  |
| P(4)           | 0.3 ± 0.3μ| 8.8 ± 1.5 | 2.1 ± 0.9 | 2.8 ± 1.0 |           | 10164.763  |
| Q(10)          | 0.8 ± 0.8| 10.6 ± 1.6| 2.6 ± 1.2 | 1.7 ± 0.8 | 3.0 ± 1.0 | 10171.963  |
| P(6)           | 8.8 ± 1.5| 1.2 ± 0.9 |          | 3.0 ± 0.9 |           | 10176.252  |
| Q(12)          | 4.7 ± 1.2|          | 0.9 ± 0.9μ| 1.3 ± 0.7 | 1.3 ± 0.6 | 10182.434  |
| Q(14)          | 4.0 ± 1.3| 1.4 ± 0.7 |          | 1.3 ± 0.9 |           | 10194.755  |
| P(10)          | 2.8 ± 1.6|          |           |           |           | 10204.998  |
| Q(16)          | 4.0 ± 1.6|          |           |           |           | 10208.931  |
| P(12)          | 1.8 ± 0.9|          |           |           |           | 10222.171  |
| Q(14)          | 1.7 ± 0.8|          |           |           |           | 10241.246  |
| Q(18)          | 1.8 ± 1.4μ|          |           |           |           | 10224.982  |

Table 3. The same as in Table 2, but for the (2, 0) Phillips band. Wavelengths marked with 1 were computed from the spectroscopic constants of Douay et al. (1988).

| $B(N'' = J'')$ | HD 76341 | HD 147889 | HD 148184 | HD 163800 | HD 169454 | HD 179406 | $\lambda$ (Å) |
|----------------|----------|-----------|-----------|-----------|-----------|-----------|--------------|
| R(6)           | 0.6 ± 0.4| 6.1 ± 0.3 | 0.7 ± 0.4 | 1.6 ± 0.5 | 2.4 ± 0.3 | 1.0 ± 0.5 | 8750.847     |
| R(8)           | 3.6 ± 0.3| 9.2 ± 0.3 | 1.5 ± 0.4 | 2.0 ± 0.5 | 3.7 ± 0.3 | 2.7 ± 0.5 | 8751.684     |
| R(4)           | 0.9 ± 0.5| 2.2 ± 0.3 | 0.7 ± 0.4 | 0.4 ± 0.3μ| 8753.578  |
| R(10)          | 1.4 ± 0.5| 10.5 ± 0.3| 2.7 ± 0.4 | 1.8 ± 0.4 | 81.0 ± 0.3| 4.1 ± 0.5 | 8753.9451    |
| R(12)          | 1.8 ± 0.3| 7.5 ± 0.3 | 1.4 ± 0.4μ| 1.8 ± 0.4 | 8.5 ± 0.3 | 3.3 ± 0.4 | 8757.683     |
| R(0)           | 1.1 ± 0.4| 12.7 ± 0.3| 3.0 ± 0.4 | 2.7 ± 0.5 | 10.3 ± 0.3| 4.7 ± 0.4 | 8761.194     |
| R(14)          | 12.0 ± 0.5| 3.0 ± 0.4 | 2.1 ± 0.5 | 3.0 ± 0.3 | 3.6 ± 0.4 | 8767.759     |
| Q(8)           | 0.3 ± 0.3| 6.3 ± 0.3 | 1.7 ± 0.4 | 1.2 ± 0.5 | 2.3 ± 0.3 | 1.3 ± 0.8μ| 8773.220     |
| P(4)           | 0.4 ± 0.3| 4.5 ± 0.3 | 1.0 ± 0.5 | 0.9 ± 0.4 | 0.8 ± 0.3 | 2.2 ± 0.5μ| 8780.141     |
| Q(10)          | 0.6 ± 0.5| 5.1 ± 0.3 | 1.0 ± 0.4 | 0.9 ± 0.8 | 1.7 ± 0.5μ| 8782.308     |
| Q(12)          | 2.3 ± 0.3| 0.6 ± 0.4 |          | 1.0 ± 0.3 |           | 8788.558     |
| P(8)           | 2.4 ± 0.3| 0.8 ± 0.3 |          |           |           | 8792.649     |
| Q(14)          | 2.1 ± 0.3| 0.6 ± 0.4 | 0.6 ± 0.3μ| 8798.459  |
| P(10)          | 2.2 ± 0.3|          |           |           | 8804.499   |
| Q(16)          | 2.2 ± 0.3| 0.8 ± 0.4 |          | 0.6 ± 0.4 | 8809.842   |
| P(12)          | 0.8 ± 0.4|          |           |           | 8817.827   |
| Q(18)          | 1.8 ± 0.5μ|          |           |           | 8822.725   |
| Q(20)          | 2.2 ± 0.7μ|          |           |           | 8837.119   |
| Q(22)          | 0.7 ± 0.4μ|          |           |           | 8853.041   |
| Q(26)          | 0.7 ± 0.5μ|          |           |           | 8889.532   |

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components of the P, Q and R branches to high rotational levels, up to $J'' = 16$. In the spectrum of HD 147889 we managed to identify Q components up to $J'' = 26$.

### 3 RESULTS AND INTERPRETATION

We have identified the lines of the (1, 0), (2, 0) and (3,0) bands, and in one case the (4, 0) band, of the C$_2$ Phillips system (A'1Π_u--X'1Σ_g$^-$). Tables 2–5 give the equivalent widths with errors of all the measured interstellar lines of C$_2$ towards the six programme stars. Poor quality measurements of equivalent widths are identified by $u$ after the value. These uncertain values have not been used in the further analysis of the column densities.

The column density of a rotational level $J''$ may be derived from the equivalent width $W_{\lambda}$ (mA) of the single absorption line using the relationship (Frisch 1972)

$$N_{\text{col}} = 1.13 \times 10^{17} \frac{W_{\lambda}}{f_0 \lambda^2},$$

where $\lambda$ is the wavelength in Å and $f_0$ is the absorption oscillator strength.

The energies of the lower rotational level were determined using the molecular constants of Marenin & Johnson (1970). The wavelengths are generally determined from the laboratory wavenumbers of Chauville, Maillard & Mantz (1977) and Balkik & Ramsay (1963a) converted to air wavelengths using the Edlen formula following Morton (1991). The wavelengths of three lines R(2), P(2) and P(4) of the (2, 0) band, absent in Chauville et al. (1977), were computed with the spectroscopic constants of Douay, Nietmann & Bernath (1988). According to Douay et al. (1988), the line positions calculated with their constants should be more accurate than the previous measurements. The oscillator strengths correspond to the vibrational oscillator strengths $f_{10} = 2.38 \times 10^{-3}$, $f_{20} = 1.44 \times 10^{-3}$, $f_{30} = 6.67 \times 10^{-4}$ and $f_{40} = 2.71 \times 10^{-4}$. The oscillator strengths for individual transitions were computed according to the description in Bakker et al. (1996), using their code MOLEY. Vibrational oscillator strengths were taken from Langhoff et al. (1990) for (1, 0) and (2, 0), from Bakker et al. (1997, citing Langhoff) for (3, 0) and from van Dishoeck (1983) for (4, 0). The source of band origins are from Chauville et al. (1977) and Balkik & Ramsay (1963b).

Equation (1) is accurate for the optically thin case (when the absorption lines are on the linear part of the curve of growth). Only a few lines from the (1, 0) band of HD 147889, where the equivalent widths are the largest, are evidently optically thick. Then, the curve-of-growth method was applied for the derivation of column densities instead of equation (1). For an optically thick line, we determined the turbulent velocity through the minimalization of the dispersion of column densities for each level. We checked various values of the velocity dispersion parameter ($b = 0.5, 1$ and $1.5$ km s$^{-1}$) and 0.5 km s$^{-1}$ was found to give the lowest dispersion. This value was then applied to all of the programme stars. It is consistent with the value derived in other studies of molecular absorptions (e.g. Gredel, van Dishoeck & Black 1991; Crawford 1997). The application of equation (1) to optically thick lines underestimates the column densities by 28 per cent in the worst case of the Q(2) (1, 0) absorption line in HD 147889.

Table 6 gives the resulting column densities for each rotational level $N_{\text{col}}(J'')$, the derived uncertainties and the number of measurements used to determine that value. Table 7 (column 5) shows

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Table 4. The same as in Table 2, but for the (3, 0) Phillips band.

| $B(N'' = J'')$ | HD 76341 | HD 147889 | HD 148184 | HD 163800 | HD 169454 | HD 179406 | $\lambda$ (Å) |
|----------------|----------|----------|----------|----------|----------|----------|--------------|
| R(6)           | 0.7 ± 0.5u | 1.8 ± 0.4 | 1.0 ± 0.4 | 2.9 ± 0.6 | 1.3 ± 0.6u | 7714.575  |
| R(4)           | 3.5 ± 0.4  | 1.5 ± 0.5 | 0.5 ± 0.4 | 2.0 ± 0.5 | 3.8 ± 1.2u | 7714.944  |
| R(8)           | 0.3 ± 0.3  | 1.9 ± 0.5 | 0.4 ± 0.4u| 1.0 ± 0.5u| 7715.415  |
| R(2)           | 3.7 ± 0.4  | 1.0 ± 0.5 | 0.9 ± 0.4u| 3.5 ± 0.5 | 2.3 ± 0.4u | 7716.528  |
| R(10)          | 0.9 ± 0.4  | 0.6 ± 0.5u| 1.2 ± 0.4u| 7717.469  |
| R(0)           | 3.5 ± 0.4  | 0.7 ± 0.5u| 3.5 ± 0.4 | 1.7 ± 0.5 | 7719.329  |
| R(12)          | 1.0 ± 0.4  | 0.4 ± 0.4u| 7720.748  |
| Q(2)           | 0.7 ± 0.3u | 4.8 ± 0.4 | 2.5 ± 0.7 | 1.8 ± 0.6 | 5.9 ± 0.5 | 7722.095  |
| Q(4)           | 0.7 ± 0.4u | 4.5 ± 0.4 | 1.0 ± 0.5 | 2.7 ± 0.9 | 3.2 ± 0.4 | 7724.219  |
| P(14)          | 0.5 ± 0.5  |           |           | 7725.240  |
| P(2)           | 2.0 ± 0.8  |           |           | 7725.819  |
| P(6)           | 4.0 ± 0.4  | 1.4 ± 0.6 | 2.3 ± 0.5u| 7727.557  |
| P(16)          |           |           |           | 7730.963  |
| P(4)           | 2.2 ± 0.6  | 0.4 ± 0.4u| 0.8 ± 0.5 | 7731.663  |
| Q(8)           | 2.4 ± 0.6  | 2.1 ± 0.6 | 1.1 ± 0.4 | 7732.117  |
| Q(10)          | 1.9 ± 0.4  | 0.9 ± 0.5 | 7737.904  |
| P(6)           | 1.8 ± 0.4  | 0.4 ± 0.4u| 7738.737  |
| Q(12)          | 1.0 ± 0.5  | 0.7 ± 0.7u| 7744.900  |
| P(8)           | 0.3 ± 0.3  | 0.8 ± 0.5u| 7747.037  |
| P(10)          | 0.5 ± 0.4  | 0.5 ± 0.5 | 7753.141  |
| Q(16)          |           | 0.6 ± 0.6u| 7762.623  |
| P(12)          |           |           | 7767.369  |

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Table 5. The same as in Table 2, but for the (4, 0) Phillips band.

| $B(N'' = J'')$ | HD 147889 | $\lambda$ (Å) |
|----------------|----------|--------------|
| R(4)$^a$       | 0.5 ± 0.5u| 6909.412     |
| R(2)           | 3.3 ± 1.4u| 6910.577     |
| Q(2)           | 2.0 ± 1.0u| 6914.975     |
| Q(4)           | 1.2 ± 0.8u| 6916.788     |
| Q(6)           | 1.4 ± 0.8u| 6919.656     |

$^a$ R(4) may form a blend with R(6) 6909.374 Å.
the total \( \text{C}_2 \) column density, defined as the sum of the mean column densities of the observed levels and of the contribution of the unobserved levels estimated from the theoretical model characterized by the best-fitting parameters (see below). Three Phillips bands were available, so the column density could be maximally estimated from nine measurements. Not every part of the spectrum allows us to measure the very weak interstellar features of \( \text{C}_2 \). In some cases, the column density was derived from only one transition (e.g. for the highest rotational levels \( J'' = 10, 12, 14 \) and 16). The absorption lines from the lower levels (\( J'' = 2 \) and 4) are the most populated and the easiest to measure accurately.

Following van Dishoeck & Black (1982), we present the derived column densities in the form of rotational diagrams (Fig. 2) where the weighted relative column densities \(- \ln[N_{\text{col}}(J'')/(2J'' + 1)N_{\text{col}}(2)]\) are plotted versus the energy of the lower level \( E''/k \) (where \( E'' \) is the energy of the rotational level \( J'' \) and \( k \) is the Boltzmann constant). The error bars correspond to the derived uncertainties. The slope of a straight line on this diagram is connected well to the excitation temperature, \( a = -1/T_{\text{exc.}} \). It is well known from previous works (e.g. van Dishoeck & Black 1982) that populations of all rotational levels cannot be characterized by a single rotational temperature. The lowest \( J'' \) levels are described by the lower excitation temperature than higher levels. Such behaviour of the rotational levels is described in the model of excitation of \( \text{C}_2 \) by van Dishoeck & Black (1982). In this model, the molecule is heated by the electronic transitions from the ground state, and subsequently cooled down by cascading to the ground electronic state through excited vibrational levels. Because \( \text{C}_2 \) is a homonuclear species, the mechanism of cooling is inefficient and the high rotational levels are significantly populated. The population of the lowest rotational levels is influenced by the collisions with the gas, mainly atomic and molecular hydrogen (hence the density of the collision partners \( n_c = n_{\text{H}} + n_{\text{H}_2} \)).

To interpret the rotational diagrams, we have constructed a grid of models based on the radiative excitation model of van Dishoeck & Black (1982). The detailed behaviour of the excitation temperature depends on the gas kinetic temperature and on the ratio of the collisional rate \( n_c \times \sigma \) to the intensity of the average galactic field, here expressed by \( I \). The parameter \( I \) has been introduced by van Dishoeck & Black (1982) as a scaling factor of the standard field adopted in their paper. With a lack of detailed information on the radiation field in individual diffuse clouds, we have made a crude assumption \( I = 1 \). Then, from the best-fitting models of excitation, we can estimate the density of collision partners in a molecular cloud \( n_c \).

Following van Dishoeck & Black (1982), we computed a grid of models with steps of 5 K in kinetic temperature and 25 cm\(^{-3}\) in collisional partner densities. The models were constructed by solving equation (27) of van Dishoeck & Black (1982), using their quadrupole and collisional rates and radiative excitation matrix. To adjust for the differences in the adopted \( f \) values of Phillips transitions, we rescaled the density of collisional partners according to the prescription of van Dishoeck & de Zeeuw (1984) by a factor of 1.59 (a factor of 1.35 from van Dishoeck & de Zeeuw 1984, times 1.18 for the difference in \( f \) values used here). The models with the original \( f \) values of van Dishoeck & Black (1982) were checked to reproduce the results of the original paper with a reliable accuracy of 20 per cent in the worst case of the higher levels. The grid of models was used to find the best fit to the earlier determined column densities individually for each transition weighted by their errors. We decided to search for the best fit to the absolute column densities, instead of that relative to \( J'' = 2 \) populations. Hence, one additional parameter of the model was the absolute column density \( N(J'' = 2) \) of the \( J'' = 2 \) level (which is equivalent to the total column density of \( \text{C}_2 \)). This approach is still consistent with the fact that the kinetic temperature and density of collisional partners depend only

### Table 6. \( \text{C}_2 \) column densities \( N_{\text{col}}(J'') \) \((10^{12} \text{ cm}^{-2}) \) for each low rotational level \( J'' \) \((N \) is the number of measurements used to determine given \( N_{\text{col}} \)).

| \( J'' \) | \( N_{\text{col}} \) | \( N \) | \( N_{\text{col}} \) | \( N \) | \( N_{\text{col}} \) | \( N \) | \( N_{\text{col}} \) | \( N \) | \( N_{\text{col}} \) | \( N \) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.9 ± 0.2 | 2 | 8.5 ± 0.4 | 3 | 1.6 ± 0.3 | 2 | 1.9 ± 0.3 | 2 | 9.5 ± 0.4 | 2 | 3.1 ± 0.4 |
| 2 | 3.4 ± 0.6 | 3 | 30.7 ± 0.6 | 8 | 6.7 ± 0.4 | 5 | 4.9 ± 0.6 | 6 | 23.8 ± 0.6 | 6 | 10.4 ± 0.7 |
| 4 | 2.8 ± 0.7 | 3 | 31.3 ± 0.6 | 9 | 6.8 ± 0.6 | 8 | 6.4 ± 0.9 | 6 | 14.8 ± 0.5 | 6 | 10.8 ± 1.0 |
| 6 | 2.0 ± 1.4 | 1 | 22.1 ± 0.6 | 9 | 5.0 ± 0.6 | 7 | 4.7 ± 0.9 | 2 | 6.8 ± 0.5 | 6 | 6.4 ± 0.6 |
| 8 | 0.6 ± 0.5 | 2 | 13.7 ± 0.5 | 8 | 3.2 ± 0.6 | 6 | 2.7 ± 0.7 | 4 | 4.0 ± 0.5 | 6 | 3.4 ± 1.1 |
| 10 | 0.9 ± 0.6 | 2 | 9.6 ± 0.5 | 9 | 2.3 ± 0.7 | 4 | 1.9 ± 0.8 | 1 | 1.8 ± 0.5 | 3 | 2.9 ± 1.0 |
| 12 | 5.2 ± 0.5 | 6 | 1.1 ± 0.7 | 2 | 1.8 ± 0.5 | 2 | 1.3 ± 0.9 | 1 | 1.2 ± 0.8 | 1 | 1.2 ± 0.8 |
| 14 | 4.1 ± 0.6 | 4 | 5.2 ± 0.5 | 6 | 1.1 ± 0.7 | 2 | 1.8 ± 0.5 | 2 | 1.3 ± 0.9 | 1 | 1.2 ± 0.8 |
| 16 | 4.7 ± 0.6 | 2 | 5.2 ± 0.5 | 6 | 1.1 ± 0.7 | 2 | 1.8 ± 0.5 | 2 | 1.3 ± 0.9 | 1 | 1.2 ± 0.8 |

### Table 7. Summary of both the observational data for \( \text{C}_2 \) (where \( T_{\text{d}} \), \( T_{\text{k}} \), and \( T_{\text{c}} \) are the rotational temperatures calculated from the two, three and four lowest rotational levels, respectively, and \( N_{\text{col}} \) is the total column density) and the results of a model (where \( T_{\text{kin}} \) is the gas kinetic temperature, \( n_c \) is the effective density of collision partners and \( N_{\text{col}}(J'' = 2) \) is the column density derived from \( J'' = 2 \)).

| Object | \( T_{\text{d}} \) (K) | \( T_{\text{k}} \) (K) | \( T_{\text{c}} \) (K) | \( N_{\text{col}} \) \((10^{12} \text{ cm}^{-2}) \) | \( T_{\text{kin}} \) (K) | \( n_c \) \((\text{cm}^{-3}) \) | \( N_{\text{col}}(J'' = 2) \) \((10^{12} \text{ cm}^{-2}) \) |
|---|---|---|---|---|---|---|---|
| HD 76341 | 48 ± 48 | 47 ± 16 | 52 ± 15 | 11 ± 1 | 34 ± 20 | 300 ± 200 | 3.3 ± 0.5 |
| HD 147889 | 49 ± 7 | 62 ± 13 | 71 ± 2 | 133 ± 1 | 39 ± 2 | 199 ± 7 | 30.8 ± 0.5 |
| HD 148184 | 82 ± 82 | 65 ± 12 | 74 ± 7 | 30 ± 3 | 45 ± 12 | 209 ± 60 | 6.6 ± 0.4 |
| HD 163800 | 24 ± 8 | 66 ± 17 | 76 ± 13 | 28 ± 1 | 38 ± 15 | 169 ± 43 | 5.6 ± 0.5 |
| HD 169454 | 39 ± 5 | 31 ± 1 | 36 ± 1 | 66 ± 1 | 19 ± 2 | 326 ± 17 | 23.8 ± 0.5 |
| HD 179406 | 38 ± 12 | 59 ± 9 | 62 ± 5 | 39 ± 1 | 38 ± 9 | 251 ± 83 | 10.8 ± 0.5 |
Figure 2. Relative $C_2$ rotational population diagrams toward six programme stars, as a function of the excitation energy (or rotational quantum number $J''$). The solid lines represent the fit to the theoretical model, based on the analysis of van Dishoeck & Black (1982). The straight dashed line shows the best-fitting $T_{02}$.

The authors discuss the fit of the theoretical model to the observed rotational population diagrams. They find that the fit is good, with the best-fitting $T_{02}$ values close to the values obtained from the analysis of other molecular transitions. This indicates that the adopted excitation model is appropriate for the observed transitions.

They also note that the best-fitting $T_{02}$ values are consistent with the temperature of the surrounding medium, which is consistent with the expected temperatures in the region of the programme stars.

In conclusion, the authors present a detailed analysis of the rotational population diagrams of $C_2$ toward six programme stars, and find good agreement between the observed and theoretical results. The analysis provides valuable insights into the properties of the surrounding medium of these stars.
temperatures determined from both methods is less than 1 K except for HD 148184 where it is less than 3 K. Note that because of the non-linearity of the model, the errors of the best-fitting parameters may be very asymmetric. Especially in these cases, when the error is a significant fraction of the fitted values (e.g. HD 76341 and HD 163800), the uncertainty of \( T_{\text{d}} \) towards lower values will be less than the uncertainty towards higher values. Consequently, \( n_e \) could be much higher towards both objects.

We have also derived a set of rotational temperatures \( (T_{\text{rot}}, T_{\text{d}}, T_{\text{e}}) \), corresponding to the mean excitation temperatures derived from a linear fit to the logarithm of the column densities of the first: two, three and four levels, respectively, starting from \( J'' = 0 \). \( T_{\text{rot}} \) is the best estimator of the gas kinetic temperature, \( T_{\text{rot}} \geq T_{\text{kin}} \).

However, generally it is not well determined, because there is only one available line \( R(0) \) in each band absorbing from the \( J'' = 0 \) level. \( T_{\text{d}} \) was more often published than \( T_{\text{e}} \), but the latter is usually determined with better precision. However, both \( T_{\text{rot}} \) and \( T_{\text{e}} \) depend on the collisional density and radiation intensity in increasing levels. Table 7 summarizes all these parameters.\(^2\)

4 DISCUSSION

The \( \text{C}_2 \) molecule in interstellar clouds has been observed many times, but usually measurements are limited to the most easily available to ground-based instrument lines of the (2, 0) Phillips band. Also, measurements are usually made with spectrographs of moderate resolution and signal-to-noise ratio (Snow 1978; Hobbs 1979; Danks & Lambert 1983; van Dishoeck & de Zeeuw 1984; Grebel & Muench 1986; van Dishoeck & Black 1989; Federman et al. 1994).

We have measured absorption lines of the interstellar \( \text{C}_2 \) towards six reddened early-type stars. The presence of \( \text{C}_2 \) in the sight line towards HD 76341 and HD 163800 has not been reported previously.

Generally, the excitation temperatures \( T_{\text{d}} \) in our programme stars tend to be above 47 K. One evident exception is HD 169454 (31 K). This cloud is definitely different from the others. The lowest gas kinetic temperature, van Dishoeck & Black (1989) suggested that it is a real translucent cloud, whereas the other clouds are only diffuse interstellar clouds.

The behaviour of the excitation temperatures may be seen directly by inspecting the portions of spectra around the Q(\( J'' = 4 \)) transition of the (2, 0) band (see Fig. 3). Note that the spectrum was renormalized to the strength of the Q(4) absorption. It is easily seen that the excitation temperature in HD 147889 is almost identical to that of HD 148184 and higher than the excitation temperature of HD 169454, which is confirmed in the quantitative analysis presented above.

Simultaneous observations of different vibrational bands make it possible to compare individually determined column densities for each band. For this purpose, data collected for HD 147889 are especially useful. The observed column densities determined individually from bands (1, 0), (2, 0) and (3, 0) are \( (11.2 \pm 0.4) \times 10^{13} \), \( (13.3 \pm 0.2) \times 10^{13} \) and \( (13.2 \pm 0.8) \times 10^{13} \) cm\(^{-3} \), respectively. The observed column density determined from all the bands together is \( (13.0 \pm 0.2) \times 10^{13} \) cm\(^{-3} \). In conclusion, the determination of column densities from only one of these bands gives a reasonable value of the \( \text{C}_2 \) column density. However, the possibility of analysing lines of many different bands enhances the accuracy of the results. It excludes accidental errors (e.g. cosmic rays, telluric lines, instrumental errors), which are impossible to remove when only one band is available.

The interstellar absorption lines of \( \text{C}_2 \) towards HD 163800 arise in a single velocity component at a radial velocity, \( V_{\text{L}} \) = 7.2 km s\(^{-1} \) with respect to the local standard of rest. This radial velocity and position of the star suggest an association of the intervening molecular cloud with a large cloud of cold atomic hydrogen, first surveyed by Riegel & Crutcher (1972) (Riegel–Crutcher cloud) as a prominent self-absorption feature in the 21-cm line. The distance to the cold atomic cloud is constrained by observations of optical lines in the direction of background stars to be 125 \pm 25 pc (Crutcher & Lien 1984a). The apparent association with the atomic cloud does not imply a physical connection with the molecular cloud responsible for the observed absorptions of \( \text{C}_2 \). A small molecular cloud in the direction of HD 169454 is also possibly associated with the Riegel–Crutcher H\(_2\) cloud; this was analysed by Jannuzi et al. (1988). The distance to HD 163800 is estimated from the spectroscopic data to be about 1.5 kpc.

A detailed comparison of our results and those of previous papers is shown in Appendix A.
5 SUMMARY
From the inspection of absorption lines in the direction of HD 147889, we have found that individual Phillips bands (1, 0), (2, 0) and (3, 0) give consistent results, both for column densities and excitation temperatures. However, not every feature is as easy to measure in all bands. For example, the P(4) and Q(8) transitions are the easiest to separate in the (1, 0) band and the lines of the R branch in the (3, 0) band; the R-branch lines of the (2, 0) band are very often located near to or in the wings of the stellar line H$_2$, which makes measurements uncertain. In this paper, the measurements of the three Phillips bands have been used to improve the reliability of the results because of the growing number of identified lines and their separation.

The assumption of the identical radiation field for all clouds allows us to calculate the density of collision partners $n_e$; the values found range from about 170 to 330 cm$^{-3}$ (100–500 if errors are included). The absolute values may be different because of the peculiar radiation field and the approximate treatment of the collisional excitation rate of C$_2$ with H$_2$. If the rotational population distributions are useful as diagnostic tools of the cloud densities, it is essential to have a better understanding of the cross-sections of the rotationally inelastic collisions of C$_2$ with H$_2$. The determination of $n_e$ is less dependent on the accurate value of the gas kinetic temperature. The visible transitions of C$_2$ are relatively easily observed (in contrast to the far-ultraviolet bands of H$_2$ and the very weak lines of C$_3$), and provide an important tool for the determination of the physical and chemical conditions of diffuse clouds.

The presence of C$_2$ in a measurable amount is reported for two new lines of sight: towards HD 76341 and HD 163800. The latter star lies in the background of the Riegel–Crutcher cloud of cold H$_2$. The molecular cloud, the origin of C$_2$ absorptions, may be physically associated with the atomic hydrogen cloud, similar to the earlier considered small molecular cloud in the direction of HD 169454 (Jannuzi et al. 1988).

In summary, the high-resolution and signal-to-noise ratio spectra acquired with the ESO instrument allow us to study densities and rotational temperatures varying from object to object with increasing accuracy. This is seen particularly well when we compare the theoretical model with the observational data (e.g. HD 147889 in Fig. 2).

We plan to continue the survey of high-resolution and high signal-to-noise ratio spectra with detected interstellar diatomic carbon and to compare with other interstellar absorption features. It would be interesting to find whether other molecules are spatially correlated with C$_2$; this may efficiently constrain interstellar chemistry.

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REFERENCES
Baganu S., Jehin E., Ledoux C., Cabanac R., Melo C., Gilmozzi R., The ESO Paranal Science Operations Team, 2003, The Messenger, 114, 10
Bakker E. J., Waters L. B. F. M., Lamers H. J. G. L. M., Trams N. R., van der Wolf F. L. A., 1996, A&A, 310, 893
Bakker E. J., van Dishoeck E. F., Waters L. B. F. M., Schoenmaker T., 1997, A&A, 323, 469
Ballik E. A., Ramsay D. A., 1963a, ApJ, 137, 61
Ballik E. A., Ramsay D. A., 1963b, ApJ, 137, 64
Black J. H., Dalgarno A., 1977, ApJS, 34, 405
Black J. H., Hartquist T. W., Dalgarno A., 1978, ApJ, 224, 448
Bondar A., Kozak M., Gniaciński P., Galazutdinov G. A., Beletsky Y., Krełowski J., 2007, MNRAS, 378, 893
Chaffee F. H. Jr, Lutz B. L., 1978, ApJ, 221, L91
Chaffee F. H. Jr, Lutz B. L., Black J. H., Vanden Bout P. A., Snell R. L., 1980, ApJ, 236, 474
Chauville J., Maillard J. P., Mentz A. W., 1977, J. Mol. Spectrosc., 68, 399
Crawford I. A., 1997, MNRAS, 290, 41
Crawford I. A., Barlow M. J., 1996, MNRAS, 280, 863
Crutcher R. M., Lien D. J., 1984, Technical Report, Goddard Space Flight Center Local Interstellar Medium, 81, 117
Danks A. C., Lambert D. L., 1983, A&A, 124, 188
Dekker H., D’Odoricio S., Kauer A., Delabre B., Kozłowski H., 2000, in Iye M., Moorwood A. F., eds, Proc. SPIE Vol. 4008, Optical and Infrared Telescope Instrumentation and Detectors. SPIE, Bellingham, p. 534
Douay M., Nienartowicz, and Bernath P. F., 1988, J. Mol. Spectrosc., 131, 261
Douglas A. E., 1977, Nat, 269, 130
Federman S. R., Strom C. J., Lambert D. L., Cardelli J. A., Smith V. V., Joseph C. L., 1994, ApJ, 424, 772
Frisch P., 1972, ApJ, 173, 301
Galazutdinov G., 1992, Preprint Spets. Astrof. Obs. Russian, No., 92
Gredel R., Muench G., 1986, A&A, 154, 336
Gredel R., van Dishoeck E. F., Black J. H., 1989, ApJ, 338, 1047
Gredel R., van Dishoeck E. F., Black J. H., 1991, A&A, 251, 625
Grevesse N., Sauval A. J., 1973, A&A, 27, 29
Herbig G. H., Leka K. D., 1991, ApJ, 382, 193
Hobbs L. M., 1979, ApJ, 232, L175
Hobbs L. M. et al., 2008, ApJ, 680, 1256
Hunter I., Smoker J. V., Keenan F. P., Ledoux C., Jehin E., Cabanac R., Melo C., Bagnulo S., 2006, MNRAS, 367, 1478
Jannuzi B. T., Black J. H., Lada C. J., van Dishoeck E. F., 1988, ApJ, 332, 995
Johnson J. R., Fink U., Larson H. P., 1983, ApJ, 270, 769
Każmierczak M., Gniaciński P., Schmidt M. R., Galazutdinov G., Bondar A., Krełowski J., 2009, A&A, 498, 785
Lambert D. L., 1978, MNRAS, 182, 249
Lambert D. L., Danks A. C., 1983, ApJ, 268, 428
Langhoff S. R., Bauschlicher C. W. Jr, Rendell A. P., Komornicki A., 1990, J. Chem. Phys., 92, 6599
Lien D. J., 1984, ApJ, 287, L95
Marenin I. R., Johnson H. R., 1970, J. Quant. Spectrosc. Radiat. Trans., 10, 305
Mayer P., O’Dell C. R., 1968, ApJ, 153, 951
Morton D. C., 1991, ApJS, 77, 119
Querci F., Querci M., Kunde V. G., 1971, A&A, 15, 256
Rieke K. W., Crutcher R. M., 1972, A&A, 18, 55
Snow T. P. Jr, 1978, ApJ, 220, L93
Sonnett R., Welty D. E., Thorburn J. A., York D. G., 2007, ApJS, 168, 58
Souza S. P., Lutz B. L., 1977, ApJ, 216, L49
Thorburn J. A. et al., 2003, ApJ, 584, 339
van Dishoeck E. F., 1983, Chem. Phys., 77, 277
van Dishoeck E. F., Black J. H., 1982, ApJ, 258, 533
van Dishoeck E. F., Black J. H., 1986, ApJ, 307, 332
van Dishoeck E. F., Black J. H., 1989, ApJ, 340, 273
van Dishoeck E. F., de Zeeuw T., 1984, MNRAS, 206, 383
Welty D. E., Hobbs L. M., 2001, ApJS, 133, 345

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APPENDIX A: COMPARISON WITH PREVIOUS DATA

In this appendix, we present a detailed comparison between our results and those previously published (Table A1). C₂ in interstellar clouds has already been observed towards HD 147889, HD 148184, HD 169454 and HD 179406, but our determinations towards HD 76341 and HD 163800 are the first. A comparison between our equivalent widths and data from the literature is presented in Tables A2–A5. There are some differences between our results and those of previous papers, which could be caused by the different quality of the analysed spectra. We used the spectra from the archival data base collected by UVES, which are characterized by high resolving power (λ/Δλ ∼ 85 000) and high signal-to-noise ratio (S/N ∼ 200). The differences with published data may reflect the difficulty of measuring weak lines.

The spectrum of HD 76341 was the most noisy in our sample, and thus the measurements are less reliable. We were able to assign 19 absorption features in total to the P, Q and R lines of the C₂ Phillips bands. There, we found the lowest column density \( N_{\text{col}} = (1.1 \pm 0.1) \times 10^{13} \text{ cm}^{-2} \) of C₂ in the whole sample.

For HD 147889, we measured the largest number of C₂ lines. Fig. 1 shows portions of the spectrum of HD 147889 (normalized to continuum, with removed telluric lines) with the assignment of the interstellar C₂ absorption lines. In total, we were able to assign 68 absorption features to the P, Q and R lines of the C₂ Phillips bands. The computed column density (13.3 ± 0.1) \( \times 10^{13} \text{ cm}^{-2} \) is the highest value of the sample.

For HD 148184, we measured 40 absorption features belonging to the P, Q and R lines of the C₂ Phillips bands.

Towards HD 163800, in total we were able to assign 29 absorption features to the P, Q and R lines of the C₂ Phillips bands. We estimated \( N_{\text{col}} = (2.8 \pm 0.1) \times 10^{13} \text{ cm}^{-2} \).

For HD 169494, we were able to identify and measure 50 absorption lines of the P, Q and R branches of the C₂ Phillips bands. We

Table A1. A comparison of our results and those from previous papers. The total column densities are rescaled to the value of \( f_{20} \) used in this paper.

| Object       | \( T_{\text{in}} \) (K) | \( T_{\text{de}} \) (K) | \( T_{\text{sl}} \) (K) | \( T_{\text{de}} \) (K) | \( N_{\text{col}} \) (10\(^{13}\) cm\(^{-2}\)) | Source                          |
|--------------|------------------------|------------------------|------------------------|------------------------|---------------------------------|---------------------------------|
| HD 147889    | 70                     | 52 ± 22                | 116 ± 28               | 71 ± 2                 | 8.3 ± 2.1                       | van Dishoeck & de Zeeuw (1984)  |
|              | 39 ± 2                 | 49 ± 7                 | 62 ± 3                 | 13.3 ± 0.1             | van Dishoeck & de Zeeuw (2007)  | Sonnentrucker et al. (2007)     |
| HD 148184    | 40                     | 65                     |                        |                        | 3.0 ± 0.4                       | van Dishoeck & de Zeeuw (1984)  |
|              | 50 ± 15                | 39 ± 16                | 57 ± 12                | 74 ± 7                 | 2.4                             | Danks & Lambert (1983)          |
|              | 34 ± 12                | 82 ± 82                | 65 ± 12                |                        | 2.8 ± 0.3                       | Sonnentrucker et al. (2007)     |
| HD 169454    | 15                     |                        |                        |                        | 3.0 ± 0.3                       | This work                       |
|              | 15 ± 10 – 5            |                        |                        |                        | 5.8                             | Grebel & Muench (1986)          |
|              | 25                     |                        |                        |                        | 4.9 ± 1.0                       | van Dishoeck & Black (1989)     |
|              | 20 ± 5                 | 24 ± 6                 | 37 ± 5                 |                        | 9.7                             | Grebel (1999)                   |
|              | 19 ± 2                 | 23 ± 3                 | 31 ± 1                 | 36 ± 1                 | 6.5 ± 0.1                       | Sonnentrucker et al. (2007)     |
| HD 179406    | 55                     |                        |                        |                        | 3.7                             | Federman et al. (1994)          |
|              |                        |                        |                        |                        | 5.0 ± 0.6                       | Sonnentrucker et al. (2007)     |
|              | 38 ± 9                 | 38 ± 12                | 59 ± 9                 | 62 ± 5                 | 3.9 ± 0.1                       | This work                       |

aThe gas kinetic temperature \( T_{\text{in}} \) is obtained from the best-fitting model.
bCalculated by Sonnentrucker et al. (2007) using the equivalent widths of van Dishoeck & de Zeeuw (1984).
cCalculated by Sonnentrucker et al. (2007) using the equivalent widths of Grebel (1999).
dExcitation temperature from all observed levels \( T_{\text{de}} \).
eCalculated by Sonnentrucker et al. (2007) using the equivalent widths of Federman et al. (1994).
fBased on the equivalent widths of Federman et al. (1994).
Table A3. A comparison of our equivalent widths (mÅ) with the data of van Dishoeck & de Zeeuw (1984) (D&Z) and Danks & Lambert (1983) (D&L) for HD 148184 of the (2, 0) band.

| B(N''') | Our results | D&Z<sup>a</sup> | D&L<sup>a</sup> |
|---------|-------------|----------------|----------------|
| R(6)    | 0.7 ± 0.4   | 1.3 ± 0.2      | 0.96           |
| R(8)    | 0.6 ± 0.4   | 0.81           |                |
| R(4)    | 1.5 ± 0.4   | 0.44           |                |
| R(10)   | 0.7 ± 0.4   | 0.48           |                |
| R(2)    | 2.7 ± 0.4   | 1.7 ± 0.2      | 1.33           |
| R(12)   |              | 0.5 ± 0.2      |                |
| R(0)    | 1.4 ± 0.4<sub>a</sub> | 1.4 ± 0.1 | 0.93           |
| Q(2)    | 3.0 ± 0.4   | 2.4 ± 0.1      | 2.41           |
| R(14)   |              | <0.5           |                |
| Q(4)    | 3.3 ± 0.5   | 2.5 ± 0.2      | 2.15           |
| P(2)    | 0.5 ± 0.5<sub>a</sub> | <0.5         |                |
| Q(6)    | 3.4 ± 0.4   | 2.4 ± 0.2      | 2.26           |
| R(16)   |              | <0.5           |                |
| Q(8)    | 1.7 ± 0.4   | 2.0 ± 0.3      | 1.67           |
| P(4)    | 1.4 ± 0.5   | 0.8 ± 0.2      | 0.59           |
| Q(10)   | 1.0 ± 0.5   | 0.8 ± 0.2      | 1.37           |
| P(6)    | 1.0 ± 0.4   | 1.0 ± 0.1      | 0.67           |
| Q(12)   | 0.6 ± 0.4   | 0.9 ± 0.2      | 0.78           |
| P(8)    | 1.0 ± 0.1   | 0.89           |                |
| Q(14)   | 0.6 ± 0.1   | 0.74           |                |
| P(10)   | 0.5 ± 0.2   | <0.67          |                |
| Q(16)   | 0.8 ± 0.4   |               |                |

<sup>a</sup>Measurements were made with the coudé échelle spectrograph (with Reticon), which was fed by the 1.4-m coudé auxiliary telescope at ESO, La Silla, Chile. The resolving power in these observations was 80 000.

Table A4. A comparison of our equivalent widths (mÅ) with the data of Federman et al. (1994) for HD 179406 of the (2, 0) band.

| B(N''') | Our results | Federman et al.<sup>a</sup> |
|---------|-------------|-----------------------------|
| R(6)    | 1.0 ± 0.5   | 3.0 ± 0.3                   |
| R(8)    | 0.4 ± 0.4   |                            |
| R(4)    | 2.7 ± 0.5   | 3.2 ± 0.2                   |
| R(2)    | 4.1 ± 0.5   | 5.0 ± 0.4                   |
| R(0)    | 3.3 ± 0.4   | 2.0 ± 0.2                   |
| Q(2)    | 4.7 ± 0.4   | 7.3 ± 0.5                   |
| R(14)   | 0.9 ± 0.3<sub>a</sub> |                  |
| Q(4)    | 7.1 ± 0.5<sub>a</sub> | 5.7 ± 0.5                   |
| P(2)    | 1.4 ± 0.4   | <1.1                        |
| Q(6)    | 3.6 ± 0.4   | 4.2 ± 0.4                   |
| Q(8)    | 1.3 ± 0.8<sub>a</sub> | 1.1 ± 0.3<sup>b</sup>       |
| P(4)    | 0.9 ± 0.5   | 1.8 ± 0.3<sup>b</sup>       |
| Q(10)   | 2.2 ± 0.5<sub>a</sub> |                  |
| P(6)    | 1.7 ± 0.5<sub>a</sub> | 3.1 ± 0.6<sup>c</sup>       |
| Q(14)   | 0.6 ± 0.3<sub>a</sub> |                  |

<sup>a</sup>Measurements were made with the coudé spectrometer on the 2.1-m telescope at the McDonald Observatory. The resolving power in these observations was typically 25 000–30 000.
<sup>b</sup>The P(4) and Q(8) lines are blended (Federman et al. 1994).
<sup>c</sup>The result is suspect because of possible stellar contamination (Federman et al. 1994).

Table A5. A comparison of our equivalent widths (mÅ) with the data of Gredel & Muench (1986) (G&M), van Dishoeck & Black (1989) (D&B), Crawford (1997) (C) and Gredel (1999) (G) for HD 169454 of the (2, 0) band.

| B(N''') | Our results | G&M<sup>a</sup> | D&B<sup>a</sup> | C<sup>b</sup> | G<sup>c</sup> |
|---------|-------------|----------------|----------------|-------------|-------------|
| R(6)    | 2.4 ± 0.3   |                |                | ≤2          |             |
| R(8)    | 0.7 ± 0.3   |                |                | ≤1          |             |
| R(4)    | 3.7 ± 0.3   | 3.8 ± 0.8      |                | 4.1 ± 1     |             |
| R(10)   | 0.4 ± 0.3<sub>a</sub> |          |                |             |             |
| R(2)    | 8.1 ± 0.3   | 6.1 ± 1.2      | 6.0 ± 0.5      | 8.6 ± 1     |             |
| R(12)   | 0.3 ± 0.2   |                |                |             |             |
| R(0)    | 8.5 ± 0.3   | 8.2 ± 0.8      | 5.6 ± 1.0      | 6.23 ± 0.50 | 8.2 ± 1     |
| Q(2)    | 10.3 ± 0.3  | 8.0 ± 1.6      | 6.6 ± 0.8      | 8.14 ± 1.18 | 10.3 ± 1    |
| Q(4)    | 7.9 ± 0.3   | 5.0 ± 1.0      | 7.9 ± 0.7      | 3.98 ± 1.03 | 9.7 ± 1     |
| P(2)    | 2.0 ± 0.3   | 2.3 ± 0.5      | 1.3 ± 0.3      | 2.82 ± 0.55 | 2.7 ± 2     |
| Q(6)    | 3.0 ± 0.3   | 3.1 ± 0.6      | 3.9 ± 0.5      | 2.89 ± 0.59 | 3.8 ± 1     |
| Q(8)    | 2.3 ± 0.3   | 2.6 ± 1.0      | 1.5 ± 0.5      | 1.28 ± 0.59 | 3.2 ± 1.5   |
| P(4)    | 1.7 ± 0.3   | 2.0 ± 0.8      | 1.7 ± 0.8      | 1.68 ± 0.62 | 3.4 ± 1.5   |
| Q(10)   | 0.8 ± 0.3   | 1.0 ± 0.5      | 1.0 ± 0.8      | ≤1          |             |
| P(6)    | 0.9 ± 0.8   | 1.9 ± 0.8      | <1.5           |             | ≤1          |
| Q(12)   | 1.0 ± 0.3   | 1.0 ± 0.5      | <1.5           | ≤1          |             |
| P(8)    | 0.8 ± 0.3   |                |                |             |             |
| Q(14)   | 0.6 ± 0.4   |                |                |             |             |
| Q(16)   | 0.6 ± 0.4   |                |                |             |             |

<sup>a</sup>Measurements were made with the coudé échelle spectrograph (with Reticon), which was fed by the 1.4-m coudé auxiliary telescope at ESO, La Silla, Chile. The resolving power in these observations was 80 000.

<sup>b</sup>The observations were obtained with the Ultra-High-Resolution Facility (R = 910 000) at the Anglo-Australian Telescope.

<sup>c</sup>The observations were made using the ESO New Technology Telescope, La Silla, Chile (R ~ 45 000).

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