Detection of interstellar H_3^+ in a region in Cygnus

Exercise for *The physics of the interstellar medium MN1*

November 25, 2005

1 Introduction

The H_3^+-molecule is of key significance for the chemistry of the interstellar medium. It reacts easily with most molecules and neutral atoms, and may thus initiate the build-up of various heavy molecules. It is also responsible for the formation of OH, CO and H_2O which play important roles in star formation. Interstellar H_3^+ was discovered in 1996 by T. R. Gelballe and T. Oka in dense molecular clouds towards young stellar objects. More recently, absorption lines from the molecule have been discovered towards two stars (no. 5 and 12) in the Cyg OB2 association.

2 The detected H_3^+ lines

The three lines, denoted R(1,1)$^+$, R(1,0) and R(1,1)$^-$, are part of the R branch of the vibrational fundamental band ("$\nu_2 \leftarrow 0$"). The values in parenthesis give the rotational quantum numbers (J,K) of the lower level. The two R(1,1) lines rise from the lowest energy level of para-H_3^+ (total nuclear spin $I = \frac{1}{2}$) and the R(1,0) line from the lowest energy level of ortho-H_3^+ ($I = \frac{3}{2}$). The energy difference between the para and the ortho levels is 32.87, measured in K. The populations of these states are set by collisions even in diffuse clouds, so that the population ratio of the two states may be calculated from Boltzmann statistics for an electron temperature T_e:

$$\frac{N_\mathrm{ortho}}{N_\mathrm{para}} = \frac{g_\mathrm{ortho}}{g_\mathrm{para}} e^{-(E_\mathrm{ortho}-E_\mathrm{para})/kT_\mathrm{e}} = 2\mathrm{e}^{-32.87/T_\mathrm{e}}. \quad (1)$$

The population of other states but the lowest states may be neglected. Data for the transitions are given in Table 1. Here, the squares of the transition dipole moments (μ) are given in the third column. For an optically thin line one may write

$$W_\lambda = \frac{8\pi^3\lambda}{3hc} N_\mathrm{level} \frac{|\mu|^2}{4\pi\varepsilon_0} \quad (2)$$

where N_level is the column density of molecules in the level under consideration and the remaining symbols have their usual meaning. Data for the two stars observed (denoted on the Palomar Sky Chart) are given in Table 2. Spectra, observed with the UKIRT (UK Infrared Telescope on Hawaii) and the 4m Mayall telescope at Kitt Peak, are enclosed.

Measure the equivalent widths and estimate the column densities of molecules in the two lower states. Deduce from that the total column density of H_3^+ molecules in the lines of sight towards both stars.

3 The chemistry in molecular clouds

Next, proceed to derive number densities of H_2 by noting that the formation of H_3^+ in dense clouds begins with the formation of H_2^+ by cosmic rays ionizing H_2. The rate of formation per H_2 molecule is assumed to be $R(\mathrm{CR}) \approx 3 \cdot 10^{-17}\ s^{-1}$. This is followed by a reaction

$$\mathrm{H}_2^+ \ + \ \mathrm{H}_2 \ \longrightarrow \ \mathrm{H}_3^+ \ + \ \mathrm{H}. \tag{3}$$

The rate per H_2^+ is here $2 \cdot 10^{-15}\mathrm{m}^3\ \mathrm{s}^{-1}$.

The destruction of H_3^+ in diffuse clouds occurs due to recombinations with electrons. These electrons are thought to be mainly produced by photoionization of the most abundant chemical element with an ionization energy less than 13.6 eV (i.e. that of hydrogen – *why is that?*). The recombination rate, β, may be written

$$\beta = 4.6 \cdot 10^{-12} T_\mathrm{e}^{-0.65}\ \mathrm{m}^3\mathrm{s}^{-1}. \tag{4}$$

Assume steady state and estimate the column length of gas L towards the two Cyg OB2 association stars, as well as the number density of hydrogen molecules n(H_2). Include error estimates based on the uncertainties of your equivalent width measurements in the estimates of all quantities. Compare L with the distance to the association. Discuss the result.

One may assume that most of the carbon is in singly ionized form, and that most of the hydrogen is in molecular form. The carbon abundance is [C/H]$= -0.5$ and a value for the solar carbon abundance can be found e.g. in the textbook (Dyson & Williams). The standard gas-to-dust ratio can be expressed as $N(\Sigma\mathrm{H})/\mathrm{E(B-V)} \simeq 5.8 \cdot 10^{25}$ (Bohlin et al. 1978, ApJ 224, 132), where $N(\Sigma\mathrm{H}) = N(\mathrm{H}) + 2N(\mathrm{H}_2)$ is measured in m^{-2} and E(B−V) magnitudes (Table 2).

Check your discussion with that of McCall et al. (2002, ApJ 567, 391).

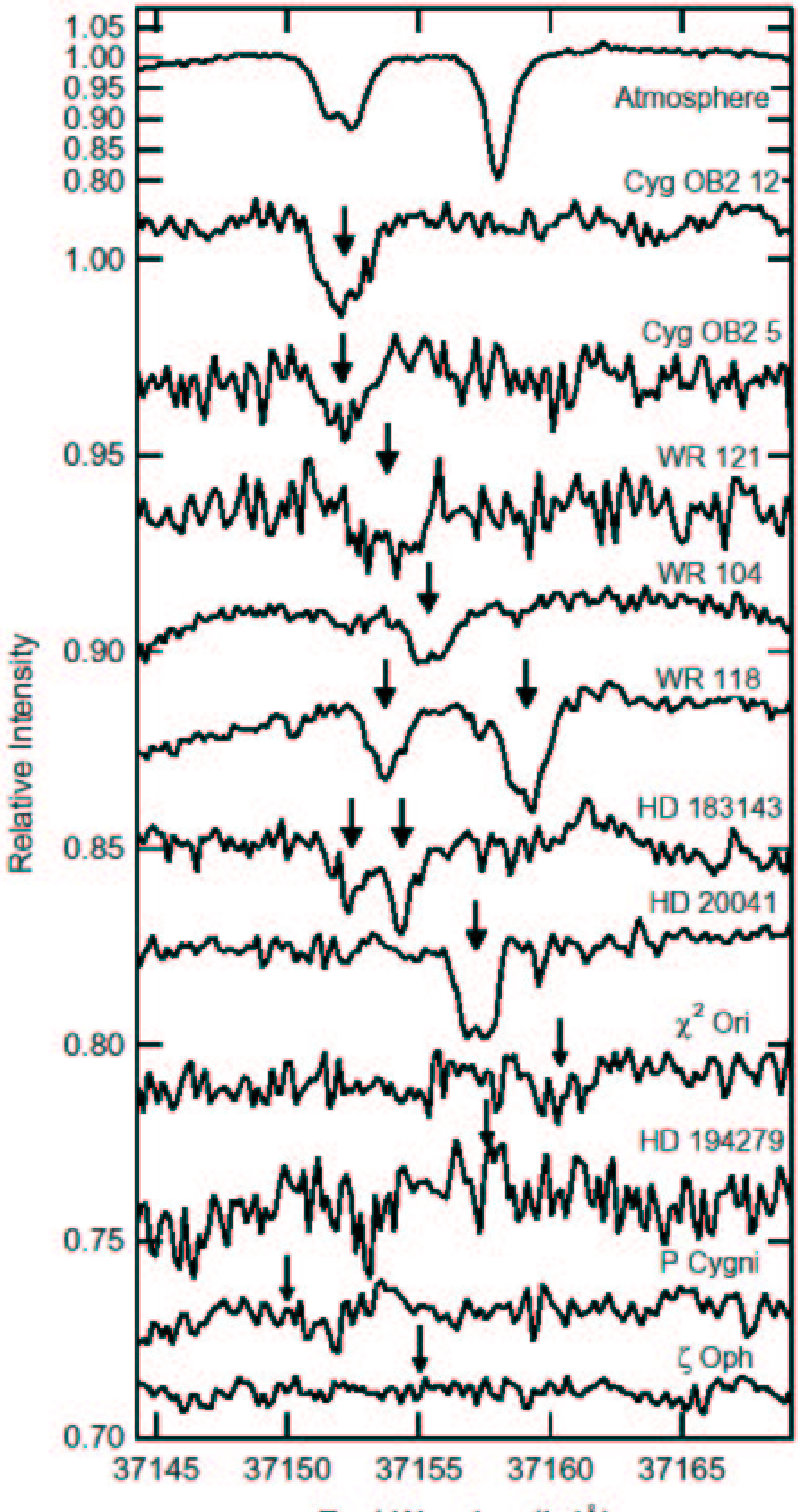
Table 1. Data for transitions of H_3^+.

Transition	Rest wavelength λ [μm]	$\frac{\lvert\mu\rvert^2}{4\pi\varepsilon_0}$ [SI units]
R(1,1)$^+$	3.6680	$0.0158 \cdot 10^{-49}$
R(1,0)	3.6685	$0.0259 \cdot 10^{-49}$
R(1,1)$^-$	3.7155	$0.0140 \cdot 10^{-49}$

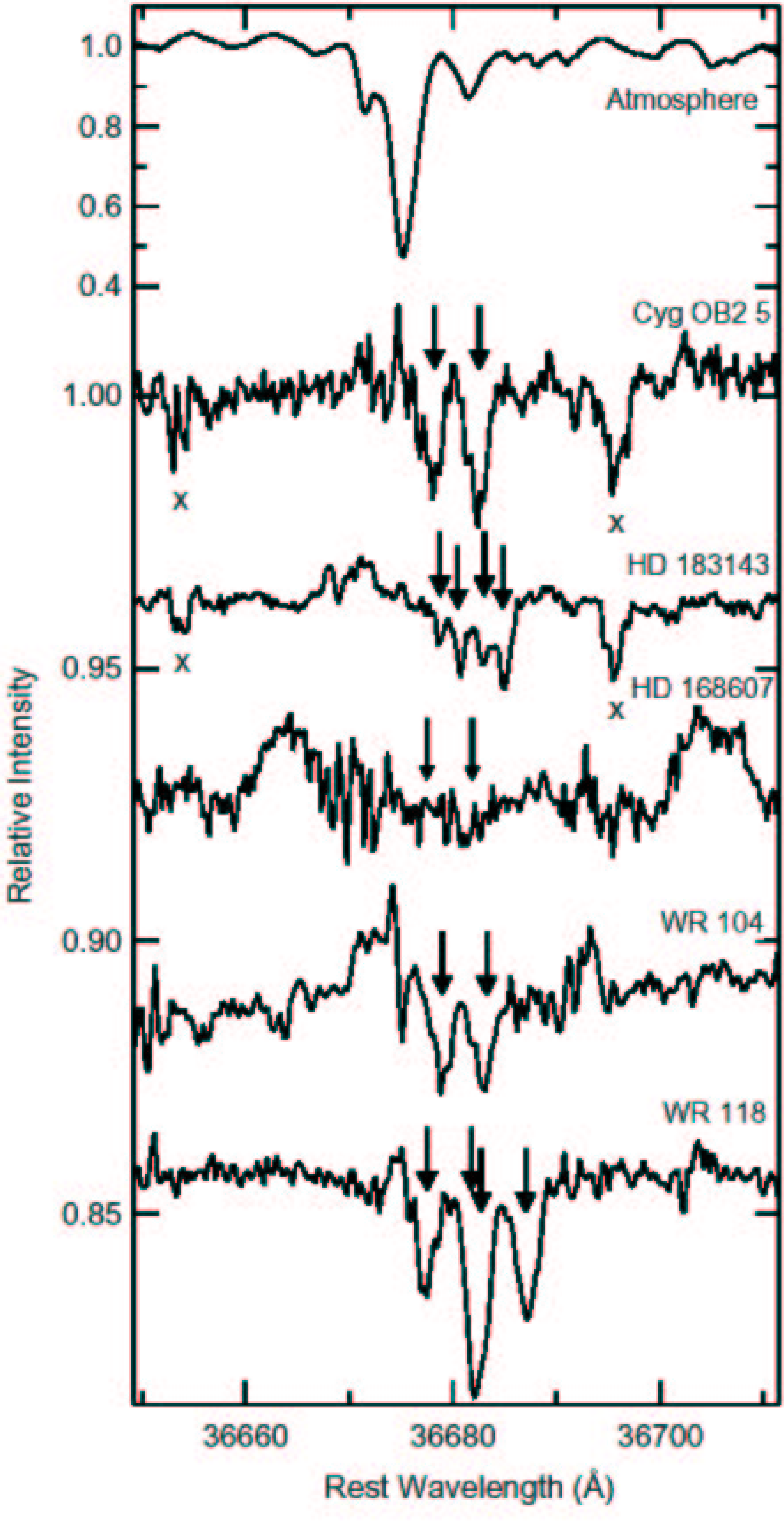
Table 2. Data for the two OB stars in Cygnus.

Name	V	E(B−V)	Spectral type	Distance [pc]
Cyg OB2 5	9.2	1.99	O7e	1700
Cyg OB2 12	11.4	3.35	B5Iab	1700

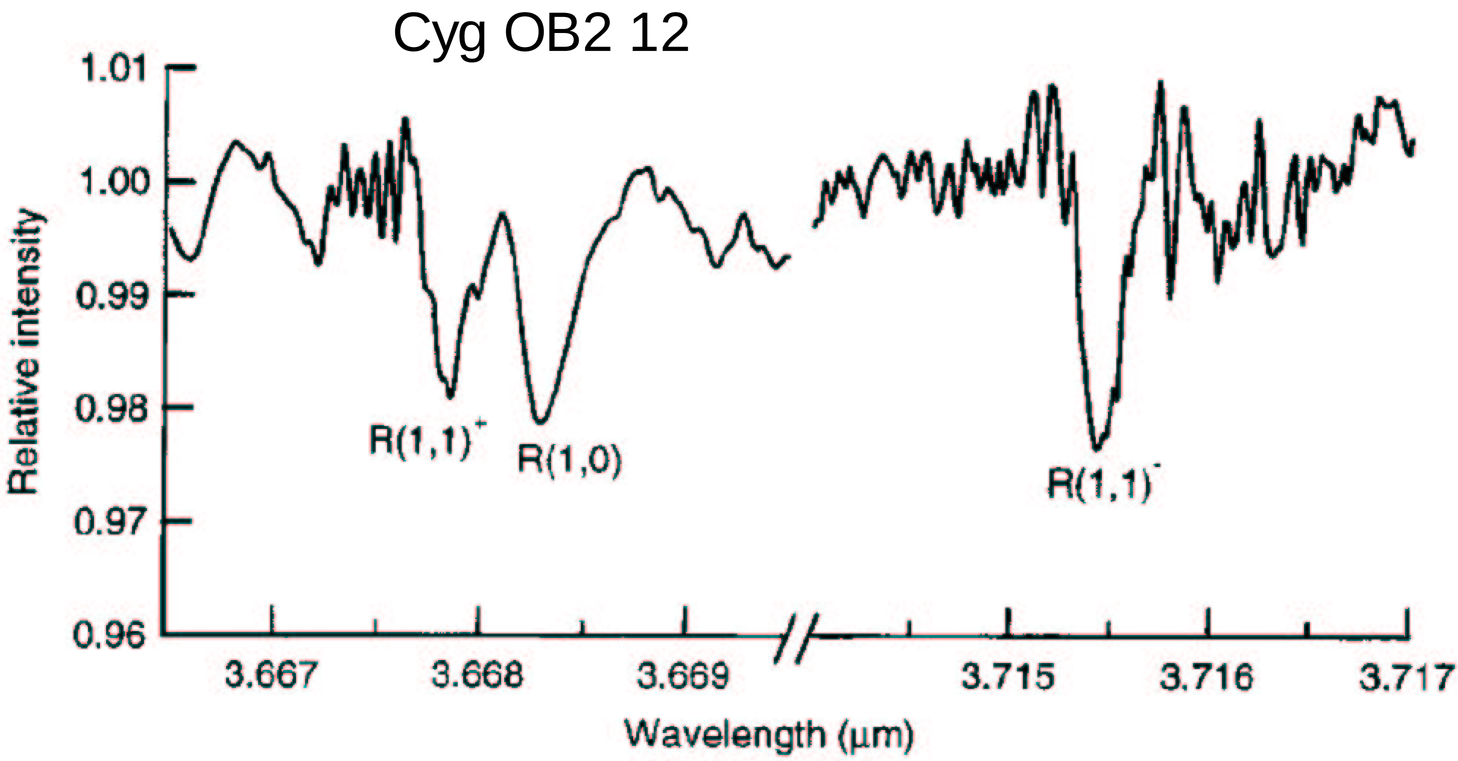
Second edition 2003 12 01 (Torgny Karlsson).
Third edition 2005 11 25 (Ulrike Heiter).



1.05
1.00
0.95
0.90
0.85
0.80
Atmosphere
Cyg OB2 12
1.00
Cyg OB2 5
0.95
WR 121
WR 104
0.90
WR 118
HD 183143
0.85
HD 20041
χ² Ori
0.80
HD 194279
0.75
P Cygni
ζ Oph
0.70
37145
37150
37155
37160
37165
Rest Wavelength (Å)
Relative Intensity



1.0
0.8
0.6
0.4
Atmosphere
Cyg OB2 5
1.00
x
x
HD 183143
x
0.95
HD 168607
x
Relative Intensity
0.90
WR 104
WR 118
0.85
36660
36680
36700
Rest Wavelength (Å)


Cyg OB2 12
1.01
1.00
0.99
0.98
0.97
0.96
Relative intensity
R(1,1)+
R(1,0)
R(1,1)-
3.667
3.668
3.669
3.715
3.716
3.717
Wavelength (μm)