

# Gas kinetic temperature in molecular clouds of supernova S140

**Dr. Ziad Abdulahad Toma**

Al\_Mustansiriyah University,  
College of Education, Physics Department

## Abstract

In order to obtain an estimation of the kinetic temperature of the molecular gas for the supernova S140, the spectra of the symmetric-top molecule methyl acetylene ( $\text{CH}_3\text{C}_2\text{H}$ ) lines and spectra of the molecules carbon monoxide (CO) and its isotopic variant  $^{13}\text{CO}$  were analyzed to compare the results on temperature with those got from methyl acetylene.

This study had done depending data from radio telescope (20-meter sub-mm) in Onsala Space Observatory on the web site: <http://www.oso.chalmers.se/>, the data are in two different observation modes, frequency- and beam switching, respectively. The results obtained rather similar which is equal to 32.2 K and 36 K.

*Keywords: Radio astronomy, supernova, Molecular clouds.*

## 1. Introduction

Methyl acetylene was first detected in the Galactic Center by Snyder and Buhl (1973) and is a very useful probe of molecular cloud kinetic temperatures because it is possible to separate the effects of temperature and density in its excitation. The rotational energy levels of a symmetric top molecule are given by  $E = hBJ(J+1) + h(A-B)K^2$  (A and B are the rotational constants) [1]. Methyl acetylene is an effective thermometer because the separate K-ladders connected only through collisions, and therefore the relative populations of the K-ladders depends primarily on the kinetic temperature of the colliding particles, molecular hydrogen,  $\text{H}_2$ . Furthermore, for  $\text{CH}_3\text{C}_2\text{H}$  the line frequencies are nearly the same for transitions having the same value of J but in different K-ladders. Therefore, lines, which arise from widely different energy levels, can be observed simultaneously reducing uncertainties due to telescope pointing and calibration. Other symmetric top molecules useful for measuring kinetic temperatures are  $\text{NH}_3$  (ammonia) and  $\text{CH}_3\text{CN}$  (methyl cyanide). [2]

## 2. Theory

### 2.1 The observation modes

There are two observation modes can be used beam switching and frequency switching. In beam switching mode, one switches the location of the beam between source and an "empty" place in space. Through this method, one can remove the power effects of the receiver, atmosphere and the ground/Earth

(coming in through the side lobes). The advantages of this method is that one will receive a very at baseline and it works well for weak lines. On the other hand, it is time-consuming since half the observation time will be spending off the source.

The other method is frequency switching, in which one slightly changes the frequency, giving a spectra with the peak at slightly different frequencies. Using the two spectra power effects that can be taken away. The advantage of frequency switching is that it is more time-efficient, since all the observation time is spend on the source. However, one cannot use this method if there are many close or very weak lines. [3]

### 2.2 The Rotational Diagram

The integrated intensities of the CH<sub>3</sub>CCH K-multiplet, could combined in a population diagram, in order to get the excitation temperature and column density of the molecule.

For an optically thin transition, the column density  $N_u$  of the upper state given by: [4]

$$N_u = \frac{8\pi k\nu^2}{hc^3 A_{ul} \eta_{mb}} \int T_A d\nu \quad (1)$$

Where  $A_{ul}$  is the Einstein coefficient for spontaneous emission,  $\eta_{mb}$  is the main

beam efficiency of the telescope ( $\sim 0.5$  at 102 GHz), and  $\int T_A d\nu$  is the

integrated antenna temperature  $T_A$ ,  $k$  is the Boltzmann constant,  $h$  is the Planck constant,  $c$  is the speed of light. The  $A_{ul}$  coefficient for the observed transitions of CH<sub>3</sub>CCH depends on the angular momentum of the upper state  $J_u$ , the frequency of the transition  $\nu$  and the dipole moment  $\mu$ : [5]

$$A_{ul} \sim 1.165 \times 10^{-11} \nu^3 \times \mu^2 \frac{J_u^2 - K^2}{J_u(2J_u + 1)} \quad (2)$$

With  $\nu$  in GHz and  $\mu = 0.75$  Debye.

If it assumed that all observed transitions have the same excitation temperature (rotational temperature), the population of the levels is giving by the Boltzmann equation:

$$N_u = \frac{Z}{N} g_u e^{\frac{-E_u}{KT}} \quad (3)$$

Here  $N$  is the total column density of the molecule,  $Z$  is the partition function,  $g_u$  is the statistical weight of the upper level and  $E_u$  its energy above ground. The

partition function can be approximated by  $Z \sim 0.523 \times T^{3/2}$ .

The statistical weight of each level is given by the energy degeneracy of  $J, K, I$  quantum numbers, ( $I$ ) being the nuclear spin. The total statistical weight is given by  $g_u = g_K g_I (2J_u + 1)$ , with

$$\begin{cases} g_K = 1, K = 0 \\ g_K = 2, K \neq 0 \end{cases} \text{ and } \begin{cases} g_I = \frac{1}{2}, K = 0, 3, 6, 9, \dots \\ g_I = \frac{1}{4}, K \neq 0, 3, 6, 9, \dots \end{cases} \quad (4)$$

Taking the natural logarithm of both sides of Eq. 3, we write

$$\ln \frac{N_u}{g_u} = \ln \frac{N}{Z} - \frac{E_u}{kT} \quad (5)$$

The column density of the upper state of the observed transitions  $N_u$  is known from Eq. 1. The unknowns of our problem are now  $N$  and  $T$ , and can be estimated by a linear fit of Eq. 5. To do this, the value of  $N_u/g_u$  against  $E_u$  was plotted for all the observed transitions and fit for the equation  $y = Ax + B$  and in this case  $A = -1/kT$  and  $B = \ln(N/Z)$ .

The rotational temperature has been estimated from  $A$ , and this value can be used to calculate  $Z$ . By substituting  $Z$  into  $B$ , the total column density  $N$  of the  $CH_3CCH$  molecule were found. [6]

### 3. Data Reduction and Analyses

#### 3.1 The CO method

First step in the analyzing is to set the coordinates of the source, the frequency of the line(s) that will be study, and the observation mode. The gas cloud S140 were aimed with coordinates  $RA = 22^h 17^m 24^s.0$  and  $Dec = 63^\circ 03' 45''$  (B1950) observing the  $J = 0$  to  $J = 1$  transitions of CO and  $^{13}CO$ , frequencies 115 GHz and 110 GHz respectively, using frequency switching method. The bandwidths used for both CO and  $^{13}CO$  were 80 MHz and the frequency which we shifted, i.e. the frequency switching width, was 40 MHz. Took 10 spectra, each 30-second long and then integrated them all to get the final spectrum for each isotope.

The reasons to use frequency switching method for these observations are:

- It is difficult to find special off-positions for CO in the sky, since this is the second most abundant molecule in the universe.
- CO line is a very bright and isolated in the spectrum.

- To minimize the observation time.

The system temperature ( $T_{\text{sys}}$ ) which is a quantity to describe the noises due to both atmosphere and the telescope, was measured as 1225 and 450 for CO and  $^{13}\text{CO}$  respectively which shows that the noise sources are more destructive in CO frequency region.

### 3.2 The $\text{CH}_3\text{C}_2\text{H}$ method

The molecule  $\text{CH}_3\text{C}_2\text{H}$  have been used as a probe of kinetic temperature in molecular clouds because it is possible to separate the effects of density and temperature in their excitation. [7]

In this method,  $K = 0, 1, 2, 3$  multiples of the  $J=6$  to  $J=5$  transition in  $\text{CH}_3\text{C}_2\text{H}$  was studied, and this time observation mode used was beam switching. The frequency was tuned to 102 GHz which is related to  $K=2$  transition, a line in the middle of the spectra. Here the bandwidth used is 160 MHz so that all multiples in the same spectrum can be seen. During the observations, 100 spectra were taken which is ten times more than that taken in the  $\text{CO}/^{13}\text{CO}$  method. This difference is made due to that  $\text{CH}_3\text{C}_2\text{H}$  is much less abundant compared to CO, thus produces much fainter lines.

The reasons of choosing beam switching for these observations are:

- $\text{CH}_3\text{C}_2\text{H}$  is much less abundant in the universe, thus we can easily find off-positions in the sky.
- The four lines in the spectrum are close to each other and all faint, which makes them impossible to be detected in frequency switching mode.

### 3.3 Data Reduction

The data has to be reducing with the XS software:

<http://www.chalmers.se/rss/oso-en/observations/data-reduction-software>.

The reduction procedure goes as follows:

- Opening all fits files in the software, which includes all the spectra for each specific molecule. (Both data from 2010 and 2011 observations are used).
- Fitting a baseline, as a polynomial of order three for the first observation (CO and  $^{13}\text{CO}$ ), since the spectra using frequency switching give a non-linear baseline. For  $\text{CH}_3\text{C}_2\text{H}$  a first order polynomial can be used since beam switching gives a rather straight baseline.
- Obtaining a flat baseline, using the baseline tool in XS software by selecting parts of the spectra.
- Creating one image taking an average of all the spectra, in order to increase the S/N ratio.
- (Just for the data from frequency method) Inverting the negative spectra and folding the two spectrum by applying the frequency switching width and had a set for the observations.
- (Just on the  $\text{CH}_3\text{C}_2\text{H}$  spectrum, in which more than one emission line) Identifying all the lines to its specific K transition.

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- Fitting one or more Gaussian curves on each emission line on the spectrum in order to estimate the tail of the lines more exact.
  - Just for the CO and  $^{13}\text{CO}$ ) Reading the amplitude of fitted Gaussian curve.
  - (Just for the  $\text{CH}_3\text{C}_2\text{H}$ ) Integrating the area under the Gaussian curve for each line to obtain the integrated intensity.

#### 4. Conclusions and Results

##### 4.1 The CO & <sup>13</sup>CO method

The spectrum obtained from CO and <sup>13</sup>CO, with their fitted Gaussian, are shows in figures 1 and 2 respectively.

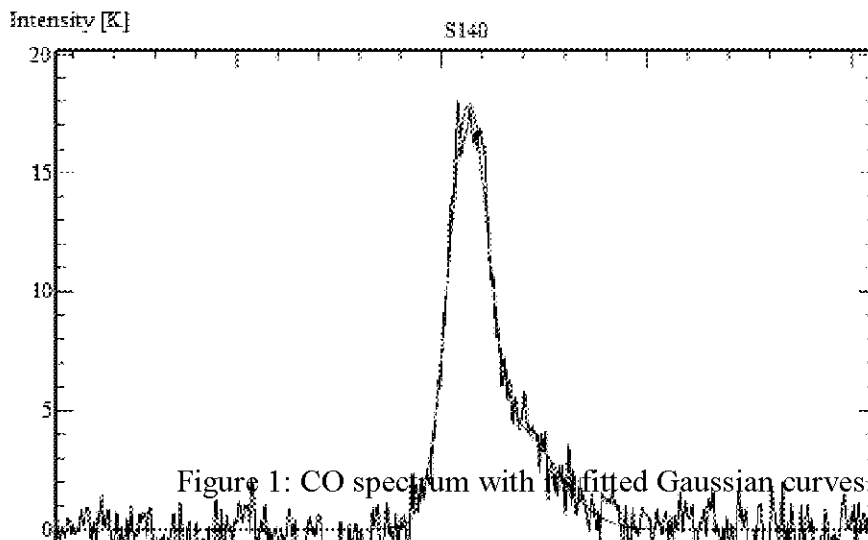


Figure 1: CO spectrum with fitted Gaussian curves.

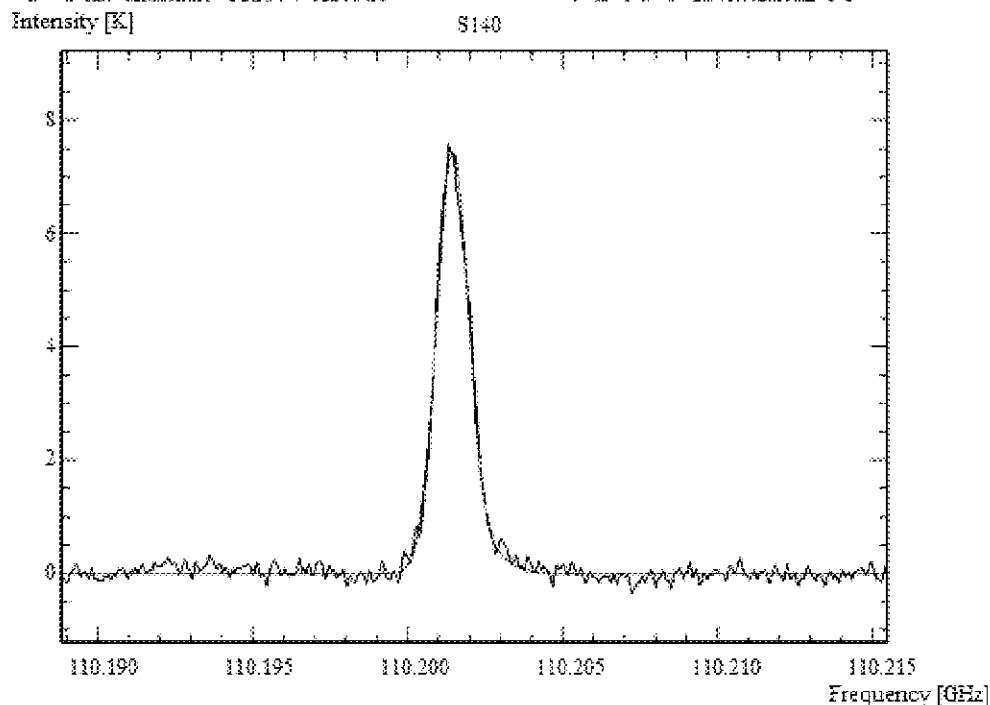


Figure 2: <sup>13</sup>CO spectrum with the fitted Gaussian curve.

The amplitudes of the peak could be reading with the software using the cursor. The values of amplitudes are 15.60 K for CO and 7.52 K for <sup>13</sup>CO. In order to obtain brightness temperature ( $T_b$ ) we used the following equation:

$$T_b = \frac{I_A}{\eta_{MB}} \quad (6)$$

Where  $\eta_{MB}$  is the efficiency of the main beam lobe which has been determined to 0.5 for the antenna used. This gives a brightness temperature for each molecule as below:

$$T_b^{CO} = 32.2 \quad (7)$$

$$T_b^{13CO} = 14.8 \quad (8)$$

Therefore the ratio is:

$$\frac{T_b^{CO}}{T_b^{13CO}} \approx 2 \quad (9)$$

As it was discussed in the Theory section, if the optical depth for CO is much larger than 1 (i.e it is optically thick), this gives:

$$T_b^{CO} = T_{ex} = T_{kin} \quad (10)$$

Where  $T_{ex}$  is the excitation temperature for the transition of the molecular cloud and  $T_{kin}$  is the internal gas kinetic temperature of the molecular cloud. This gives the final estimated temperature of the molecular cloud to 32.2 K.

#### 4.2 The CH<sub>3</sub>C<sub>2</sub>H method

The spectrum obtained for the observation of CH<sub>3</sub>C<sub>2</sub>H, including all four K multiples and their labels are shown in figure 3.

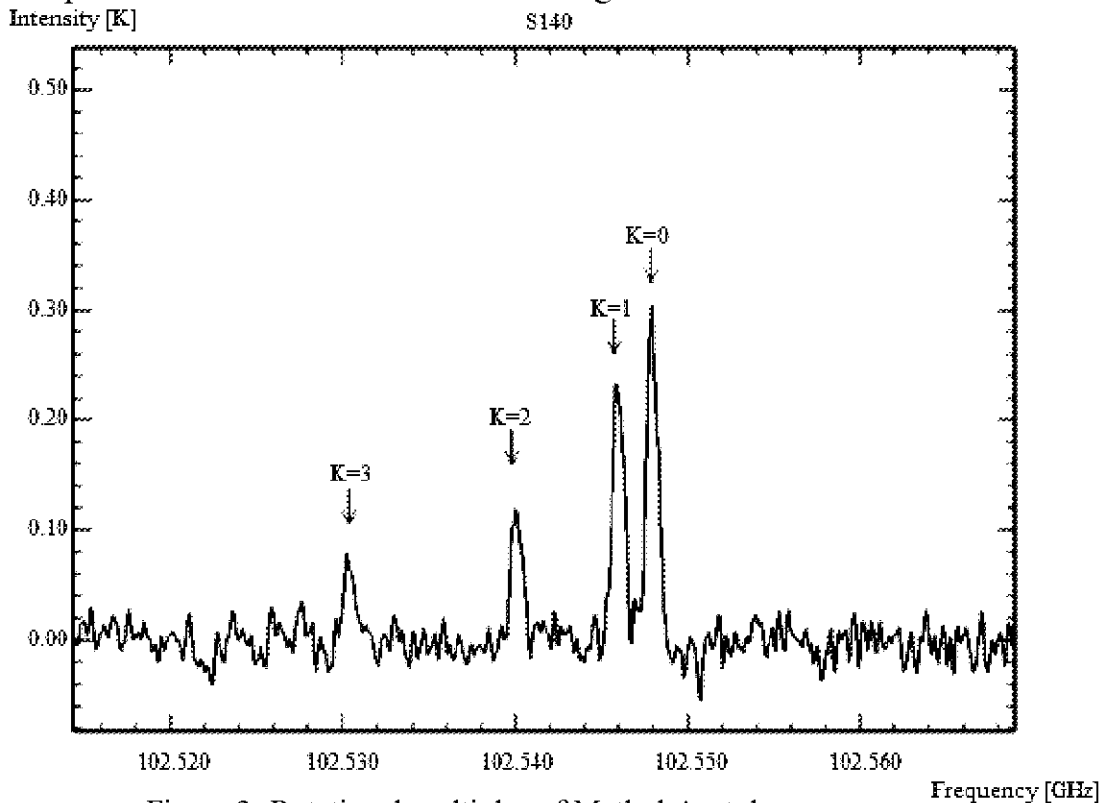


Figure 3: Rotational multiples of Methyl Acetylene.

The integrated intensity for each line could be obtained using the XS software, the values are as follows:

$$K_0 = 0.739 \pm 0.019 K \frac{K_m}{s} \quad (11)$$

$$K_1 = 0.569 \pm 0.019 K \frac{K_m}{s} \quad (12)$$

$$K_2 = 0.262 \pm 0.019 K \frac{K_m}{s} \quad (13)$$

$$K_3 = 0.187 \pm 0.019 K \frac{K_m}{s} \quad (14)$$

As mentioned before, the  $N_u/g_u$  versus  $E_u/k$  was plotted. Then a line to the four points was fitted by using the equation below.

$$\ln \frac{N_u}{g_u} = \ln \frac{N}{Z} - \frac{E_u}{KT}$$

The temperature of the molecular cloud then be estimated as the inverse of the slope of the fitted line, so the temperature to approximately 36 K was obtained, which is in the error bar - of 32.2 K which was the value obtained from the method using CO and  $^{13}\text{CO}$ .

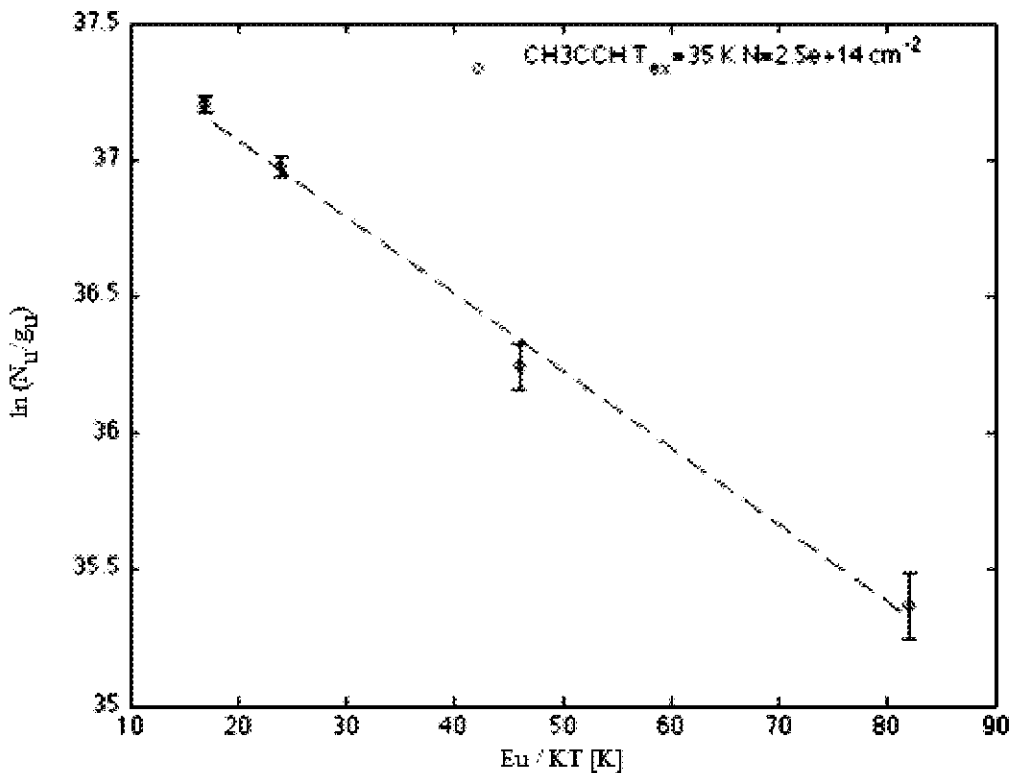


Figure 4: Points corresponding to four transitions and inverse of the slope of the fitted line determines the temperature of the molecular gas cloud.



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**درجة حرارة الغاز الحركية في السحب الجزيئية للمستعرات العظمى S140**

د. زياد عبد الأحد توما

الجامعة المستنصرية، كلية التربية، قسم الفيزياء/بغداد/العراق

**الخلاصة**

لغرض ايجاد تخمين لدرجة الحرارة الحركية في السحب الغازية الجزيئية للمستعرات العظمى S140، تم تحليل خطوط طيف جزيء الميثيل أستيلين (CH<sub>3</sub>C<sub>2</sub>H) وطيف جزيئات اول اوكسيد الكربون والنظير المماثل له <sup>13</sup>CO لمقارنة نتائج درجات الحرارة مع تلك التي تم الحصول عليها من ميثيل الاستيلين.

وهذه الدراسة تمت باستخدام بيانات المرصد الراديوي الدولي (20-meter sub-mm) لجامعة كالمر في اونسالا والموجودة على الموقع التالي: <http://www.oso.chalmers.se>. ان هذه البيانات مسجلة باستخدام طريقتين مختلفتين للرصد والمراقبة، وهي طريقة محول التردد (frequency swtiching) وطريقة محول الحزمة (Beam swtiching) وحسب الترتيب. تم الحصول على نتائج لدرجات الحرارة متشابهة الى حد ما حيث كانت مساوية الى 32.2 كلفن و 36 كلفن.