Low and high resolution spectroscopy of the comet C/2009 R1 (McNaught) ⋆

Galin Borisov, Tanyu Bonev, Ilian Iliev, Ivanka Stateva
Institute of Astronomy and NAO, Bulgarian Academy of Sciences, BG-1784 Sofia
gborisov@astro.bas.bg

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Abstract. The comet C/2009 R1 (McNaught) was observed in the period 17–21 June 2010 with 2m Ritchey-Chretien-Coude (RCC) telescope and a 2-channel focal reducer (FoReRo2) and Coude spectrograph at Bulgarian National Astronomical Observatory (BNAO) Rozhen. The FoReRo2 was used to obtain a low resolution spectrum of the comet in the range 3500–7000 Å, with an inverse linear dispersion 108 Å/mm in the blue channel and 216 Å/mm in the red channel. For the first time at Rozhen NAO a high spectral resolution (R=28 000) CCD spectrum of a comet was obtained using the Coude spectrograph. The molecule band of CN(0,0) at the transition $B^2\Sigma^+$–$X^2\Sigma^+$ was observed. From the low resolution spectra the spatial distribution of the gas and dust along the slit was investigated. The dust and gas production rates, Afρ values, parent and daughter scalelengths of investigated molecules (namely CN, C_3, C_2, NH_2), and the reddening of the dust coma were determined. The results are as follows: Dust production rates – $Q^d_{4835} = 1890.7$ kg/s, $Q^d_{5225} = 1905.3$ kg/s, $Q^d_{6850} = 2095.8$ kg/s corresponding to Afρ values $Af\rho_{4835} = 64.5$ cm, $Af\rho_{5225} = 65.0$ cm, $Af\rho_{6850} = 71.5$ cm. Gas production rates – $Q^{CN}_{3870} = 1\times10^{23}$, $Q^{C_3}_{4060} = 3\times10^{21}$, $Q^{C_2}_{5125} = 5\times10^{25}$, $Q^{NH_2}_{5720} = 5\times10^{25}$, and corresponding parent and daughter scale lengths in 10^3 km – $l^{CN}_p = 15$ and $l^{CN}_d = 75$, $l^{C_3}_p$=15 and $l^{C_3}_d = 150$, $l^{C_2}_p = 4$ and $l^{C_2}_d = 18$, $l^{NH_2}_p = 1$ and $l^{NH_2}_d = 25$. The obtained reddening of the dust continuum is 5.45% over 1000 Å. From the high resolution spectrum the rotational temperature of 652±46 °K for the CN molecule in the comet's coma was calculated.

Key words: comets, spectroscopy, C/2009 R1 (McNaught)

Introduction

Understanding the physics and chemistry of comets can lead to a significant improvement of our knowledge of the Solar System formation. Such studies allow to put constraints on the physical conditions in the protoplanetary nebula, on the dynamical evolution of the disk and of planetesimals, and on the chemical evolution of these bodies.

First spectroscopic observations of comets were made by Giovanni Donati on August 5, 1864 and by Sir William Huggins, who visually compared the spectrum of comet Winnecke (1868 II) with flame spectra in 1868 and found that the bands, seen in the comet and in the flame [Brandt, J. & Chapman, R., 2004], now known as the "carbon" or "Swan bands", were similar.

Schwarzschild and Kron [Schwarzschild & Kron, 1911] studied the intensity distribution in P/Halley's straight tail during the 1910 passage and suggested that the emission could be explained by the effect of absorption of solar light, followed by re-emission, i.e. fluorescence. Polydor Swings (1941) answered the long-standing question "why the violet CN bands (3875 Å) in

⋆ Based on data collected with 2-m RCC telescope at Rozhen National Astronomical Observatory cometary spectra did not resemble CN laboratory spectra and varied in appearance?": because of the crowding of absorption lines in the solar spectrum, the intensity at the exciting wavelengths is critically depended on the Doppler shift caused by the comet's motion relative to the Sun, and thus determines the strength of the fluorescence emission lines in the comet's spectrum. This is now known as the Swings effect.

The comet C/2009 R1 (McNaught) was discovered by R. H. McNaught [McNaught *et al.*, 2009] on five images obtained on September 9, 2009 by the Siding Spring Survey with the 0.5-m Uppsala Schmidt telescope.

1 Observations

The observations of the comet C/2009 R1 (McNaught) were obtained with the 2-metre RCC Telescope at Rozhen NAO. The low resolution spectroscopy was performed on June 17, 2010 using the spectroscopic mode of FoReRo2 [Jockers *et al.*, 2000] and the high resolution spectroscopy – on June 21, 2010 with the Coude spectrograph. The geometric conditions during the observations and taken exposures' information are presented in table 1.

Table 1. Observing geometric conditions and taken exposure information

Date	r^a, AU	Δ^b, AU	STO^c, deg	Exposures, sec
2010 06 17	0.575	1.136	63.17	3x120
2010 06 21	0.508	1.155	61.55	4x900

[a] heliocentric distance
[b] geocentric distance
[c] phase angle (Sun-Target-Observer)

The low resolution spectroscopy covered the range 3500–7000 ÅÅ with an inverse linear dispersion 108 Å/mm (2.6 Å/px) in the blue channel and 216 Å/mm (5.2 Å/px) in the red channel of FoReRo2 (see fig.1). The high resolution spectroscopy was obtained with Coude spectrograph using B&L 22° grating which gives spectral resolution R=28 000 and an inverse linear dispersion of 2.8 Å/mm or 0.0678 Å/px (see fig.4).

2 Results

2.1 Low resolution spectroscopy

As the low resolution spectroscopy was obtained using a long slit, the spatial distribution can be derived from profiles along the slit at a desired wavelength range corresponding to a continuum window or molecular bands. The selected spectral ranges can be seen in table 2 for both – continuum and selected molecules, namely CN, C_3, C_2, NH_2.

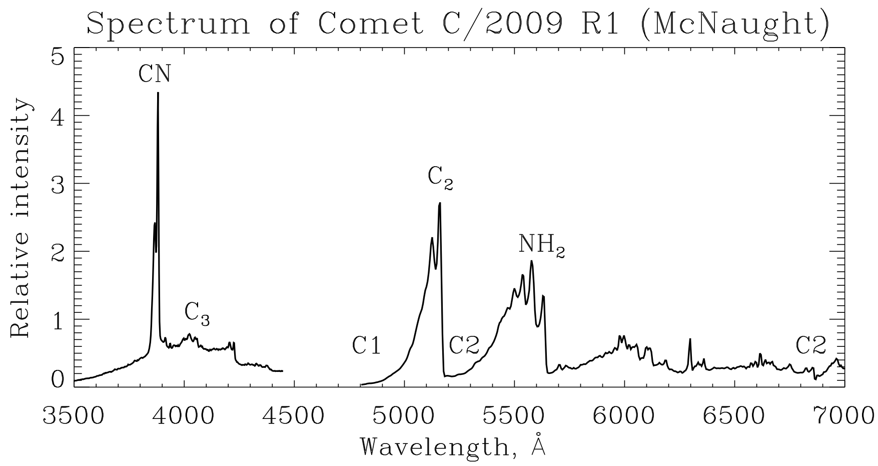

Fig. 1. The low resolution spectrum of the comet C/2009 R1 (McNaught). The observed molecules CN, C_3, C_2 and NH_2 and continuums C1, C2 and C3 are marked.

Table 2. Ranges of continuum and neutral species in the spectrum and corresponding red and blue continuum regions

Species	Spectral range, Å	Blue continuum, Å	Red continuum, Å
Continuum 1	4820 – 4850	–	–
Continuum 2	5200 – 5250	–	–
Continuum 3	6800 – 6900	–	–
CN	3830 – 3905	3700 – 3815	3910 – 3970
C_3	3975 – 4150	3910 – 3970	4155 – 4190
C_2	4860 – 5185	4780 – 4850	5195 – 5295
NH_2	5673 – 5766	5653 – 5670	5769 – 5790

From the continuum ranges the corresponding $Af\rho$-values were calculated using the relation proposed by A'Hearn, [A'Hearn *et al.*, 1984] (Eq. 1).

$$Af\rho = \frac{\left(2\Delta r_h^2\right)^2}{\rho}\frac{F_C}{F_S} \qquad (1)$$

where A is Bond albedo, f – filling factor, Δ – geocentric distance, r_h – heliocentric distance, ρ – cometocentric distance, F_C – flux of the comet and F_S is the Solar flux at distance 1 AU.

This quantity is proportional to $1/\rho$ and it can be calculated not only from aperture photometry, but also from interpolated radial continuum profiles calibrated in unit of Af over the cometocentric distance ρ. The results are presented in Figure 2.

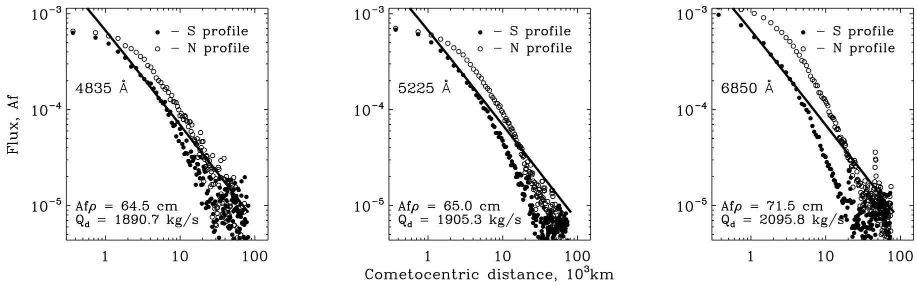

Fig. 2. The S–N continuum profiles in the tree selected continuum ranges

From computed $Af\rho$-values we can calculate the dust production rate using the relation proposed by Weaver [Weaver *et al.*, 1999]:

$$Q_d = \frac{0.67 \cdot Af\rho \cdot v \cdot r \cdot \rho_d}{p} \qquad (2)$$

where r is the average particle radius in μm, v – the outflow velocity from the nucleus in km s^{-1}, ρ_d – density in g cm^{-3} and p is the geometric albedo. The values used for our calculations are: $r = 1\,\mu$m, $v = 0.13 r_h^{-0.5} = 0.175\, km\, s^{-1}$, $\rho_d = 1\, g\, cm^{-3}$ and $p = 0.04$

The results for $Af\rho$ and dust production rate are presented in table 3 and also are marked near each profile in Figure 2.

The dust color, or so called "reddening" representing the changing of the dust reflectivity with wavelength is calculated using the relation given by Jewit, [Jewitt & Meech, 1986]:

$$C_{(\lambda_1,\lambda_2)} = \frac{\partial F/\partial \lambda}{F_{mean}} \qquad (3)$$

The obtained reddening is 5.45% over 1000Å. This quantity is connected with the dust grains size distribution. Greater reddening suggest that large dust particles are dominating the brightness of the dust coma.

From the spectral ranges containing light emitted from molecules by resonance fluorescence, we can calculate not only the production rates, but also the so-called daughter and parent scale lengths. They are connected with lifetimes of the molecules, with the physical conditions at the comet's position, and with the solar activity at the time the observations have been obtained.

Table 3. Result for dust production rate

Quantity	4835 Å	5225 Å	6850 Å
$Af\rho$, cm	64.5	65.0	71.5
Q_d, kg/s	1890.7	1905.3	2095.8

For derivation of the above mentioned parameters the molecular radial profiles were compared to the Haser model [Haser, 1957] presented in Eq. 4:

$$n(\rho) = \frac{Q}{4\pi v \rho^2} \frac{l_d}{l_p - l_d} \left(e^{\left(-\frac{\rho}{l_p}\right)} - e^{\left(-\frac{\rho}{l_d}\right)} \right) \quad (4)$$

where Q is the production rate, l_p and l_d are parent and daughter scalelengths and ρ is the distance from the nucleus.

The resulting approximation and the obtained parameters for CN, C_3, C_2 and NH_2 molecules are presented in figures 3, respectively and in table 4.

Table 4. Obtained Haser model parameters – daughter and parent scalelengths and production rates

Quantity	CN	C_3	C_2	NH_2
l_p, 10^3km	15	15	4	1
l_d, 10^3km	75	150	18	25
Q, s^{-1}	1×10^{23}	3×10^{21}	5×10^{25}	5×10^{25}

2.2 High resolution spectroscopy

With the Coude spectrograph of the 2m RCC telescope we can examine the comets' molecules with a spectral resolution in order of several tens of thousands. With such observations we can investigate the rotational structure of the comets' molecular species. The easiest species to be observed and interpreted are diatomic molecules like the most abundant in the comets' coma CN an C_2.

Diatomic molecules are molecules composed by only two atoms, of either the same or different chemical elements. They cannot have any other geometry but linear, as any two points always lie in a line. This is the simplest spatial arrangement of atoms after the sphericity of single atoms. The expression for its rotational energy is:

$$E_{rot} = \frac{h^2}{8\pi^2 I} J(J+1) = hcBJ(J+1) \quad (5)$$

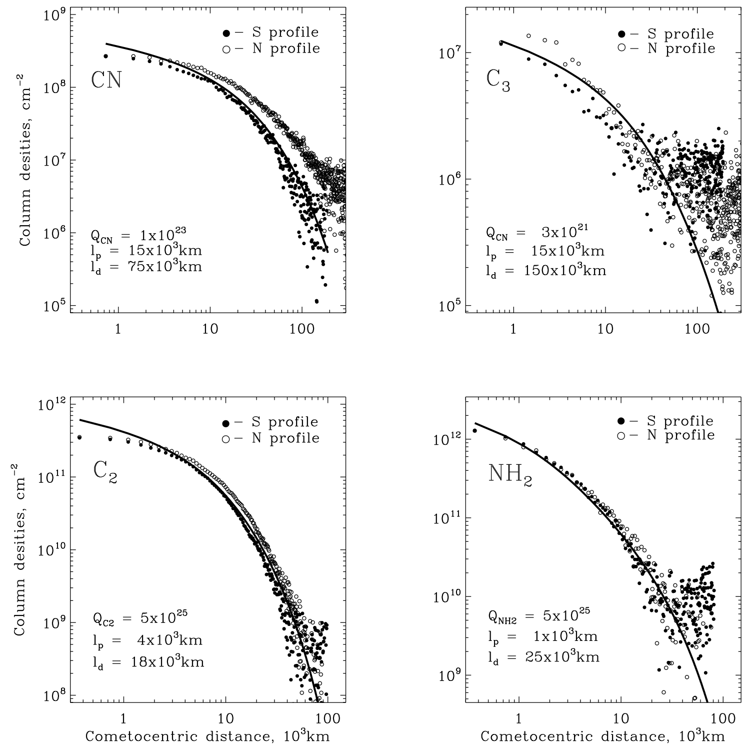

Fig. 3. CN, C_3, C_2 and NH_2 North and South radial profiles with the best fit of the Haser model and the obtained parameters' values

where $B = [h/(8\pi^2 cI)]$ is the rotational constant of the molecule, J is the rotational quantum number and can take values $0, 1, 2, ...$ and $I = \mu r_0^2$ is the moment of the inertia of the molecule (μ is the reduced mass of the molecule and r_0 is the average distance between the two atoms in the molecule).

The temperature determined from the application of the Boltzmann law to the rotational lines is generally called *rotational temperature*. For the rotational levels, the exponential factor $e^{-E/kT}$ is given by $e^{-BJ(J+1)hc/kT}$.

The intensity of a rotation line in the emission can be written as:

$$I_{em} = C\nu^4 S_J e^{-BJ(J+1)hc/kT} \tag{6}$$

where I_{em} is the intensity of the emission line, C – constant, ν – the frequency of the line, S_J – the rotational line strength factor or the so called the Hönl–London factor, B – the rotational constant of the molecule, J – the rotational level, h – the Planck constant, c – the speed of light, k – the Boltzmann constant and T is the rotational temperature.

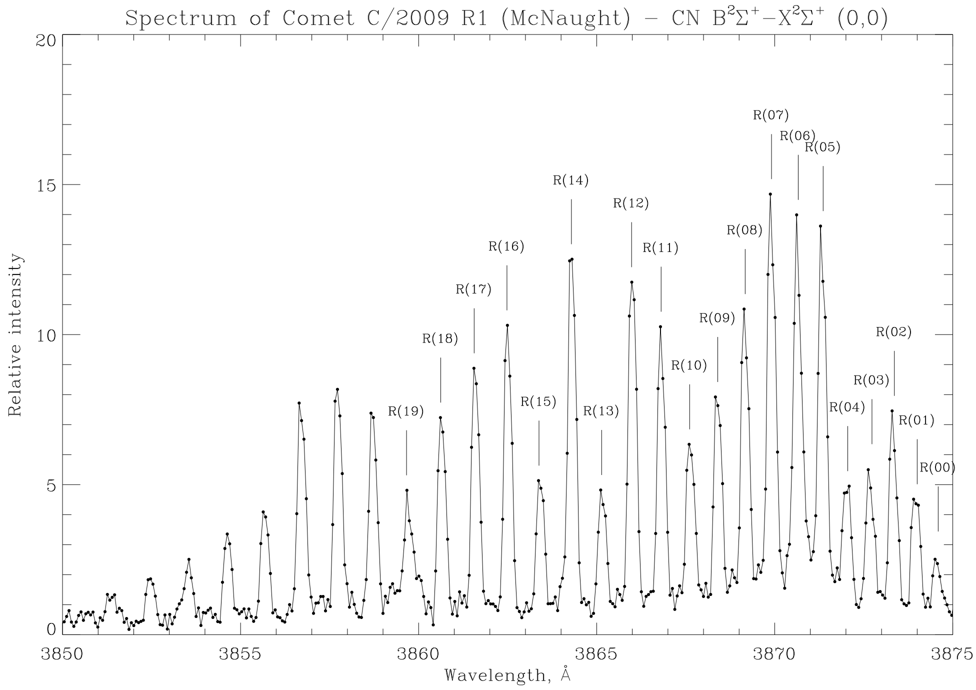

Fig. 4. The obtained R–branch of the CN $B^2\Sigma^+$–$X^2\Sigma^+$ (0,0) spectrum

For diatomic molecules $\Delta\Lambda = \Lambda' - \Lambda$ with Λ as ground state and Λ' as excited state the Hönl–London factor for R–branch is:

$$S_J^R = \frac{(J+1+\Lambda)(J+1-\Lambda)}{(J+1)} \tag{7}$$

For the observed CN $B^2\Sigma^+$–$X^2\Sigma^+$ (0,0) $\Lambda' = \Lambda = 0 \Rightarrow S_J^R = J+1$

If we plot $\log(I_{em}/S_J^R)$ as a function of $J(J+1)$ the result should be a straight line and the rotational temperature can be calculated from the slope.

The obtained R–branch of the CN $B^2\Sigma^+$–$X^2\Sigma^+$ (0,0) spectrum is presented in Fig.4. In Figure 5 the $\log(I_{em}/S_J) - J(J+1)$ approximation is presented. The calculated rotational temperature is 652±46 °K.

Conclusions

– Comet C/2009 R1 (McNaught) was observed in the period 17–21 June 2010 with the 2m RCC telescope and FoReRo2 and Coude spectrograph at BNAO Rozhen.

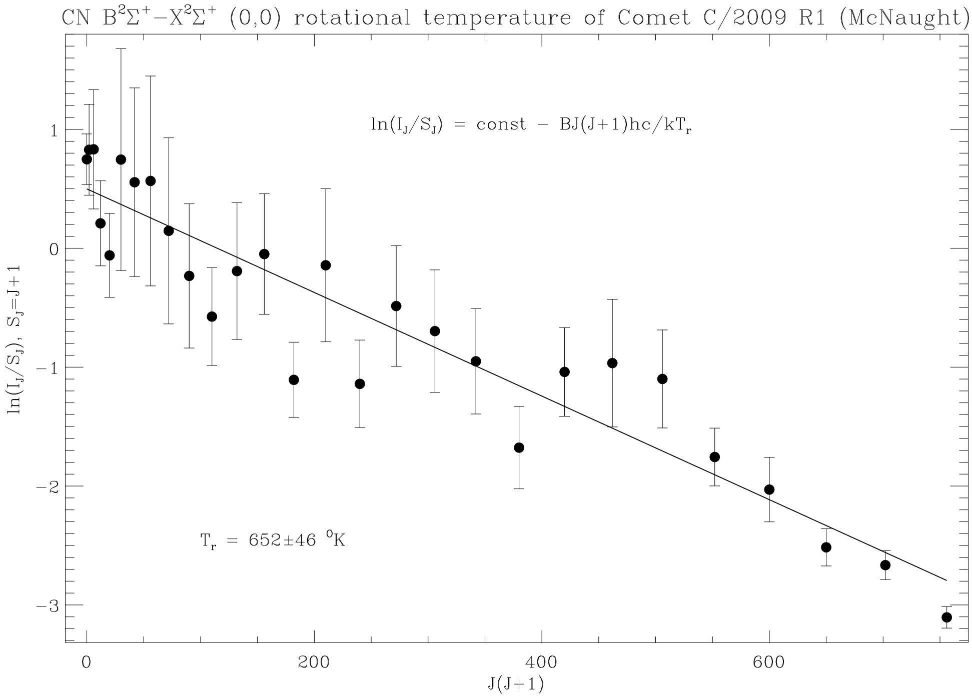

Fig. 5. Rotational temperature calculated from $\log(I_{em}/S_J) - J(J+1)$ approximation

- From the low resolution spectroscopy with FoReRo2 of the 2m RCC telescope the radial intensity distribution along the slit of CN, C_3, C_2, NH_2 and two continuum windows in the comet spectrum were investigated.
- The molecular profiles were fitted with Haser model and a production rates Q_{3870}^{CN}=1×10^{23}, $Q_{4060}^{C_3}$=3×10^{21}, $Q_{5125}^{C_2}$=5×10^{25}, $Q_{5720}^{NH_2}$=5×10^{25}, and corresponding parent and daughter scalelengths in 10^3 km l_p^{CN}=15 and l_d^{CN}=75, $l_p^{C_3}$=15 and $l_d^{C_3}$=150, $l_p^{C_2}$=4 and $l_d^{C_2}$=18, $l_p^{NH_2}$=1 and $l_d^{NH_2}$=25 were derived.
- From the dust continuum in the comet spectrum the $Af\rho$ values for different wavelengths Afρ_{4835}=64.5 cm, Afρ_{5225}=65.0 cm, Afρ_{6850}=71.5 cm and the corresponding dust production rates Q_{4835}^d=1890.7 kg/s, Q_{5225}^d=1905.3 kg/s, Q_{6850}^d=2095.8 kg/s were calculated and a dust coma reddening of 5.45% over 1000Åwas obtained.
- For the first time at Rozhen NAO a high resolution CCD spectrum of the comet at the molecular band of CN(0,0) at the transition B$^2\Sigma^+$–X$^2\Sigma^+$ was obtained using the Coude spectrograph of the 2m RCC telescope.
- The rotational temperature of the CN was calculated from $\log(I_{em}/S_J) - J(J+1)$ relation to be 652±46 °K.

Acknowledgments

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