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Spectroscopic studies of a plasma focus afterglow

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Abstract Carbon spectrum produced in the afterglow of a 2kJ Plasma focus operated with an admixture of 20% acetylene in hydrogen at a pressure of 5 mb was studied in the 4000 – 6000Å region using a 1m Czerny – Turner Spectrograph The spectrum consisted mainly of lines due to CI, CII, CIII and CIV and hydrogen Balmer series From the observed line width of H_β and H_γ lines the electron density of the plasma was evaluated and found to be of the order of 6×10^{16}/cc From the intensity of the carbon ion lines the temperature of the afterglow plasma was evaluated Band spectrum of C_2 molecule also was observed Vibrational temperature calculated indicated the existence of a cooler zone Details of the experimental findings are presented in this paper

Keywords Plasma spectra, afterglow, electron density temperature

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1. Introduction

Plasma diagnostics by emission spectroscopic method is a well developed branch of plasma spectroscopy [1]. From the emitted wavelengths, intensities and shapes of the spectral lines, it is possible to gain valuable information about a plasma and understand the different processes of plasma formation. While in conventional spectroscopy one deals with atoms and molecules in isolated environment, the radiating atoms and molecules in a plasma are influenced by electric, and magnetic fields and also multiple collisions. These effects are reflected on the shape of the spectral lines. Two of the basic plasma parameters, the electron density and temperature can be evaluated from the Stark broadening and intensity of the emitted lines respectively.

An interesting application of emission spectroscopy for plasma diagnostics is the analysis of the afterglow plasma in a low energy plasma focus device. Neutron Physics Division of B. A. R. C. has a 2kJ plasma focus source being used as a fusion neutron source [2]. A hot deuterium plasma lasting for about 100ns is produced in this device. After the hot phase,

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having a temperature of several million degree Kelvin, the plasma expands and cools and also interacts with the electrodes, leading to erosion of electrodes. Most of the visible light emission in the device comes from this afterglow plasma. This afterglow plasma causes deposition of eroded electrode material on glass insulator which in turn has a deleterious effect on the plasma produced in the subsequent discharge. This contamination of the plasma during the initial phase of the discharge is responsible for the failure of the neutron yield.

In this paper, a preliminary study of the time integrated carbon spectra obtained using acetylene mixed with hydrogen as working gas and the results obtained are presented. Using the Stark broadened line width of the H_β line, the density of the plasma at the time of maximum emission of the line is determined. By the line intensity ratio method, the excitation temperatures of various species of carbon at the time of their maximum emission are determined. From this temperature and Saha's equation, the density is evaluated. This is found to agree with the density from the H_β Stark broadening. An interesting result is the observation of the C_2 molecular band spectra, which indicate a vibrational temperature of 4900°K.

2. Experimental setup

The source used to generate the carbon plasma is a pulsed Z-pinch plasma focus device. Figure 1 shows the schematic of the device. It has multiple cathodes arranged around a central

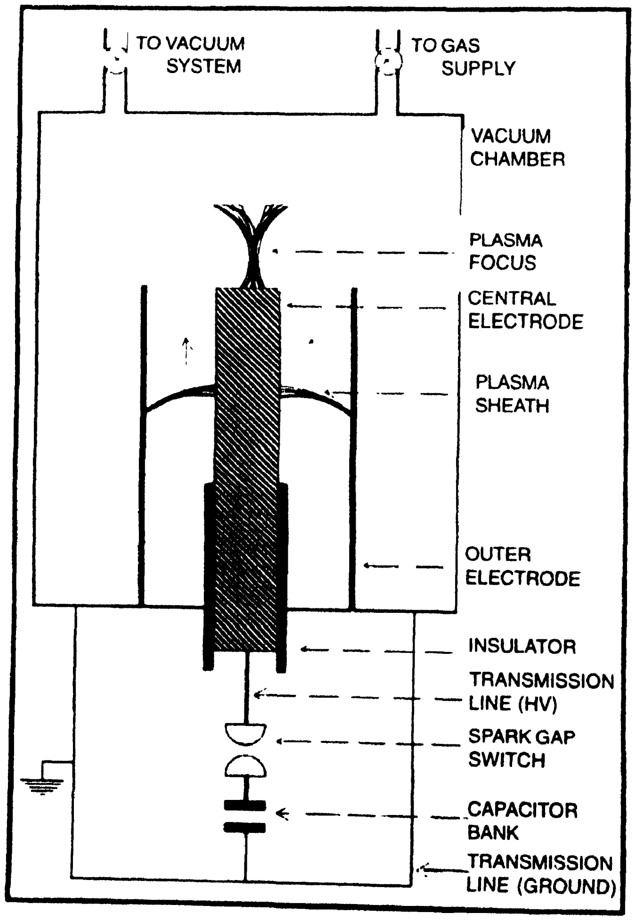

Figure 1 Schematic of a plasma focus source.

anode enclosed in a metallic vacuum chamber maintained at a pressure of 10^{-4} mbar. A 2 kJ capacitor bank having an internal inductance of 100 nH is used to drive the plasma focus source. For producing carbon plasma a graphite cap was fitted on to the central anode made of copper. The plasma gas used was hydrogen with ~ 20% acetylene. The pressure inside the chamber was 5 mbar. Cathodes were of copper. It was observed that the addition of acetylene, enhanced the intensity of carbon lines considerably and spectral lines from copper were suppressed. A one meter Czerny-Turner spectrograph was used for photographing the spectrum. A fibre optic wave guide was used to collect the emitted light and focus it on to the entrance slit of the spectrograph. The carbon spectrum was recorded in the region 4000-6800 Å, using ORWO NP7 photographic film. The lower limit was imposed by the fibre optic cable and the higher limit by the photographic emulsion. The resolution obtained was of the order of 1 Å. The intensity profiles were recorded using a recording micro densitometer. More details about the experimental setup, recording of the spectrum and calibration procedures are dealt with in ref. [3, 3a]

3. Results and discussions

A detailed analysis of the spectrum emitted from the 2 kJ plasma focus device was carried out. The emitted lines were mainly due to CII, CIII and CIV. Very few lines of neutral carbon were observed as most of the intense lines are in the UV-VUV region. Since the plasma gas was hydrogen, H_α, H_β and H_γ were also observed with good intensity. In addition to these, a few bands were observed They were assigned to C_2 Swan System [4]. Table 1 contains wavelengths of the observed lines

Table 1. Observed lines from a carbon plasma source

Species	λ(Å)	Intensity (mm)	Transition	J - J
CI	4771.75	33	$3s\,^3P^0-4p\,^3P$	2-2
	5380.34	40	$3s\,^1P^0-4p\,^1P$	1-1
CII	4267.00	192	$3d\,^2D-4f\,^2F^0$	3/2-5/2
	4267.26*		$3d\,^2D-4f\,^2F^0$	5/2–7/2
	4372.35	10	$3d\,^4P^0-4f\,^4D$	3/2–3/2, 5/2
	4372.49*		$3d\,^4P^0-4f\,^4D$	1/2–1/2
	4374.27	12	$3d\,^4P^0-4f\,^4D$	5/2-7/2
	4411.16	32	$3d\,^2D^0-4f\,^2F$	3/2–5/2
	4411.51*		$3d\,^2D^0-4f\,^2F$	5/2–7/2
	4618.40	34	$3d\,^2F^0-4f\,^2G$	5/2–7/2
	4619.23	36	$3d\,^2F^0-4f\,^2G$	7/2–9/2
	5132.94	59	$3s\,^4P^0-3p\,^4P$	1/2–3/2
	5133.28*		$3s\,^4P^0-3p\,^4P$	3/2–5/2
	5143.49	85	$3s\,^4P^0-3p\,^4P$	3/2–1/2
	5145.16	123	$3s\,^4P^0-3p\,^4P$	5/2–5/2
	5151.09	63	$3s\,^4P^0-3p\,^4P$	5/2–3/2

Table 1. *Cont'd*

Species	λ(Å)	Intensity (mm)	Transition	J − J
CII	5640 55	31	$3s^4P^0$–$3p^4S$	1/2–3/2
	5648 07	48	$3s^4P^0$–$3p^4S$	3/2–3/2
	5662 47	62	$3s^4P^0$–$3p^4S$	5/2–3/2
	5889 27	83	$3d^2D$–$4p^2P^0$	3/2–3/2
	5889 77*		$3d^2D$–$4p^2P^0$	5/2–3/2
	5891 59	60	$3d^2D$–$4p^2P^0$	3/2–1/2
CIII	4121 84	18	$4p^1P^0$–$5d^1D$	1–2
	4186 90	71	$4f^1F^0$–$5g^1G$	3–4
	4325 56	14	$3s^1P^0$–$3p^1D$	1–2
	4647 42	65	$3s^3S$–$3p^3P^0$	1–2
	4650 25	34	$3s^3S$ $3p^3P^0$	1–1
	4651 47	30	$3s^3S$ $3p^3P^0$	1–0
	4659 06	20	$3s^3P^0$–$3p^3p$	1–1
	4663 64	32	$3s^3P^0$–$3p^3P$	1–0
	4665 86	39	$3s^3P^0$–$3p^3P$	2–2
	5695 92	51	$3p^1P^0$–$3d^1D$	1–2
CIV	5801.33	43	$3s^2S$–$3p^2P^0$	1/2–3/2
	5811 98	57	$3s^2S$ $3p^2P^0$	1/2–1/2
	4658 30	31	$5f^2F^0$–$6g^2G$	–
H_α	6562 79		$2p^2P^0$–$3d^2D$	
H_β	4861 33		$2p^2P^0$–$4d^2D$	
H_γ	4340 47		$2p^2P^0$ $5d^2D$	

* Blended lines

3.1. Temperature evaluation :

Atomic emission lines are used to evaluate the temperature of the plasma, using the intensity ratio of line pairs. The expression [9] ;

$$T = \frac{5040\,(V_a - V_b)}{\log \frac{(gA)_a}{(gA)_b} - \log \frac{\lambda_a}{\lambda_b} - \log \frac{I_a}{I_b}} \tag{1}$$

where V is the excitation potential (eV), g statistical weight, A is transition probability, λ is the wavelength in Å, I is the intensity the subscript a and b correspond to the two lines used. The intensity of the line is taken as proportional to the peak height (in mm) of the spectral profile. The temperature was evaluated using different line pairs, for CII, CIII and CIV species, and the temperatures so obtained are listed in Table 2. It can be seen that for higher order ionised states the temperature is high which indicates an expanding plasma.

Table 2. Calculation of excitation temperature

Species	line pair (Å)	I_1/I_2	Temperature (°K)
C II	5151 08 / 5648 08	63/48	6193
	5151 08 / 5662 47	63/62	9824
	5151.08 / 5640 55	63/31	3687
CIII	4647 40 / 5695.92	65/51	59807
	4647 40 / 4121 84	65/18	66816
CIV	5801 5 / 4658 30	43/31	525930

3.2. *Electron density evaluation :*

It is a well known fact that in plasma the spectral lines are broadened by Stark effect (pressure effect), Doppler effect, and instrumental effect. Details of the line broadening mechanism are dealt with in great details by Griem [5, 6] and Sobelman [7]. The broadening of the hydrogen lines is mainly from linear Stark effect and is made use of in determining the electron density using the expression [8] ;

$$\Delta\lambda_{1/2} = 2.5\times 10^{-9}\ \alpha_{1/2}\ n_e^{2/3}, \tag{2}$$

where $\Delta\lambda_{1/2}$ is FWHM (full width at half maximum) in Å, n_e is the electron density in cm^{-3}, $\alpha_{1/2}$ is the shape factor. $\alpha_{1/2}$ is weakly dependent on temperature, but remains constant over a wide temperature range. The H_β and H_γ profiles were recorded, and the half widths were evaluated [3] and the n_e was calculated using the above expression. $\alpha_{1/2}$ was taken to be 0.086 for H_β and 0.099 for H_γ. The criteria for selecting this value are discussed by Griem [6]. Figure 2 shows the profile of H_β line. In Table 3 the average values of $\Delta\lambda_{1/2}$ from different

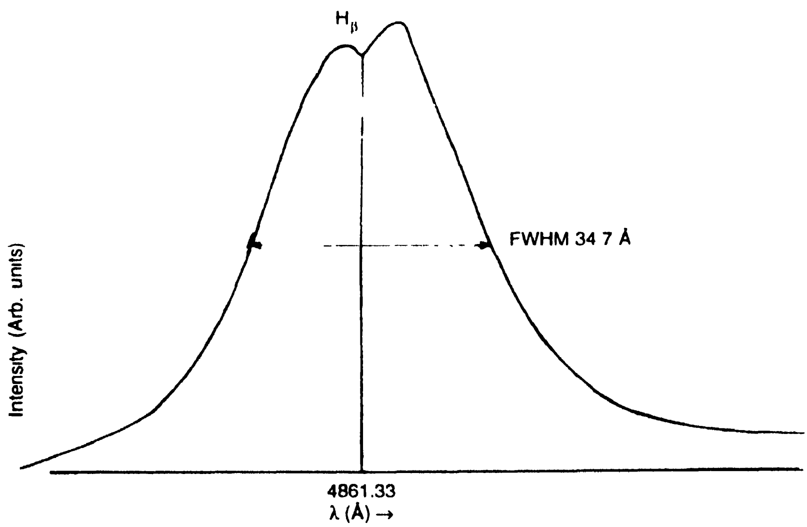

Figure 2 Profile of H_β line

spectra and n_e calculated using H_β and H_γ lines are listed. H_α line was too intense in our spectra and H_δ was too weak, hence they were not used in the present experiments for electron density evaluation. Electron density of the plasma focus device evaluated is 5.9×10^{16}/cc.

Table 3. Evaluation of electron density

Line	$\Delta\lambda_{1/2}$ (Å)	$\alpha_{1/2}$	n_e (x10^{16} / cm^3)
H_β (4861 33Å)	34	0 086	5 21
H_γ (4340 47Å)	36	0 099	5 56

Electron density and temperature of a plasma are interdependent. It is possible to evaluate, temperature of the excitation source if the electron density is known and *vice versa*. We have evaluated the value of n_e using the Saha's expression [9] ;

$$\log n_e = -\log \frac{I^+}{I} + \log \frac{g_q^+ A_{qp}^+ v_{qp}^+}{g_q A_{qp} v_{qp}} - \frac{5040}{T}(V_n + V_q^+ - V_q)$$

$$+3/2 \log T + 15.684, \quad (3)$$

where n_e is the electron density per cc , I is the intensity of neutral line g_q is the statistical weight, A_{qp} is the transition probability, v_{qp} is the wave number in cm^{-1} of the spectral line, V_n is the ionisation potential, V_q the excitation potential in eV and T the temperature in degree Kelvin. The superscript (+) corresponds to values belonging to ionic line. In the present case, taking the temperature evaluated from the line intensity ratio methods from different line pairs, the electron density was evaluated and the value of the $n_e = \sim 6 \times 10^{16}$ cm^{-3}, which agrees well with the electron density evaluated from H_β line width.

3.3 Vibrational temperature evaluation .

In the spectrum of Carbon plasma, we have observed some bands identified as the C_2 Swan System. We have evaluated the vibrational temperature using the expression [1]

$$I_{em}(v', v'') = K V^4 v' v'' [\text{FCF}(v', v'') R_e^2] e^{-G(v')hc/kT} \quad (4)$$

where $I_{v'v''}$ is the band intensity, K is a constant, $V_{v'v''}$ is the band head wave number in cm^{-1}, FCF is the Frank-Condon factor, R_e is the electronic transition moment, $G(v')$ is vibrational energy and T is the temperature. FCFs were calculated for this band system using the constants reported in literature [10]. Assuming electronic transition moment R_e as constant and simplifying above equation reduces to

$$ln\ I_{v'v''} / v^4 v'v'' \text{ FCF} = -G(v'') / 0.6925\ \text{T} + \text{constant} \quad (5)$$

A plot of the LHS against $G(v')$ is a straight line whose slope gives the temperature. The Table 4 gives the details of calculation. The temperature obtained was 4900°K.

4. Conclusion

The observations of CI- CIV lines and C_2 band spectrum at different excitation temperatures indicates that as the afterglow plasma cools during its expansion, various charge states as well as molecular species are formed during recombinations.

Table 4. Evaluation of vibrational temperature from band head intensities

$v'v''$	$\lambda_{v'v''}$	$V_{v'v''}$	I	FCF	$G(v')$	$\ln \frac{I_{v'v''}}{V_{v'v''}}$ FCF
0 – 0	5165.2	19378.44	27	0.735	817.76	–35.88
1 – 0	4737.1	21132.13	45	0.2396	2435.77	34.60
2 – 0	4715.1	21230.38	93	0.3714	4030.44	34.32
3 – 2	4697.6	21311.48	89	0.4189	5601.77	–34.50
4 – 6	5958.7	16777.54	38	0.173	7149.76	–33.52
0 – 1	5635.5	17760.43	18	0.213	817.76	–34.70
1 – 2	5585.5	17919.45	29	0.2872	2435.77	–34.55
2 3	5540.7	18064.38	53	0.2677	4030.44	33.91

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