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Spectroscopic Study of the Forbidden Lines [OIII] and [SII] of Crab Nebula Supernova Remnant

Lana T. Ali*
Department of Astronomy and Space, College of science, Baghdad University, Baghdad, Iraq

Abstract

As a star explode as a supernova its ejecta will directly interact with relatively low density interstellar medium with high shock wave velocity, and due to this interaction many of forbidden emission lines will give a raise from both the excitation and ionization of the atom in the region. So, the study of these emission lines can reveal many physical properties of the region, in this case the remnant of the supernova, such as temperature, density, composition, and many other important physical processes. In this paper the optical spectrum of the young galactic supernova remnant which is the Crab Nebula has used, in order to calculate it's electron temperature (T_e) and electron density (n_e) by using the [OIII] and [SII] forbidden lines. From the obtained results it's found that, the remnant has T_e reach to $17{,}000 \mp 500$°K that raises from high shock velocity according to the intensity ratio of $HeI\,\lambda5870/\,(H_\beta)$ which is found to be ≈ 0.8, although the remnant has such high T_e and high shock velocity it's found that, only about 64% of pre-shock helium is fully pre-ionized in the remnant. In addition to that when the intensity ratio of both [OII] and [SII] lines has taken it's found that, the remnant is an intermediate density remnant which has n_e equal to 1300 ± 10 cm^{-3}.

Keywords: supernova, forbidden lines, electron temperature, electron density.

دراسة طيفية للخطوط الممنوعة الاوكسجين و الكبريت لبقايا المستعرة العظمى سديم العقرب

لانه طالب علي*
قسم الفلك والفضاء، كلية العلوم، جامعة بغداد، بغداد، العراق

الخلاصة

عند انفجار النجم كمستعرة عظمى فان مقذوفاته سوف تصطدم مباشرة مع مادة ما بين النجوم ذات الكثافة الواطئة نسبياً بسرعة عالية ونتيجة لهذا التصادم يحدث تهيج للمادة الموجودة في تلك المنطقة وبالتالي فان عدد كبير من خطوط الانبعاث الممنوعة سوف تبدء بالظهور. لذلك فان دراسة هذه الخطوط ممكن ان تزودنا بمعلومات وافرة عن الخصائص الفيزياوية لتلك المنطقة، بقايا المستعرة العظمى، كدرجة الحرارة، الكثافة، المكونات الكيميائية، و عدد كبير من العمليات الفيزيائية التي تحدث في تلك المنطقة. في هذا البحث تم اعتماد الطيف البصري لاحدى بقايا المستعرات العظمى الفتية في مجرتنا والتي هي بقايا سديم العقرب لغرض حساب درجة حرارتها الالكترونية وكثافتها الالكترونية باستخدام خطوط الاوكسجين والكبريت الممنوعة [OIII] و [SII]. النتائج اوضحت بان درجة الحرارة الالكترونية للبقايا تصل الى $17{,}000 \mp 500$ كلفن والناتجة من سرعة الصدمة العالية محسوبة من نسبة الشدة لخطوط $HeI\,\lambda5870/\,(H_\beta)$ والتي وجد بانها $\approx 0{,}8$. بالرغم من ان هذه البقايا لها درجة حرارة عالية وسرعة موجة صدمة عالية فقد كانت فقط 64% من الهيليوم متاين كلياً. بالاضافة الى ذلك عند استخدام نسب الشدة لخطوط كل من [OII] و [SII] تبين ان هذه البقايا متوسطة الكثافة اي ذات كثافة الاكترونية مساوية الى 1300 ∓ 10 سم$^{-3}$.

*Email: lana_talib@yahoo.com

Introduction:

All massive stars end their life as core collapse supernova after they reach the iron stage from their thermonuclear reaction stages, since the radiation pressure at this point is no longer able to support the core against the tremendous gravity and the iron core collapse ending their life as stars and begging their new life as supernova, with remarkable explosion that out shine the entire galaxy with a total energy of 10^{53} erg. Approximately 99% of this energy is radiated away in the form of energetic neutrinos as a result of the deleptonization of the stellar core as it collapses into either a neutron star or a black hole (depending on the star core mass) while the remaining (kinetic) energy of about 10^{51} erg is contained in a strong shock propagating through the stellar layer, and ultimately drives the expansion of the Supernova Remnant (SNR) [1].

Behind the supernova remnant type, after the supernova explosion occur the original blast wave, that was produced and rebound during the core collapse of the progenitor star, will send the outer layers of the star outward while extends into the interstellar medium in the forward direction. In the same time, due to the pressure difference between the expanding ejecta and swept- up interstellar matter a reverse shock will be created, and begins to propagate towards the center of the supernova remnant heating the ejecta that lie in its direction [2].

However, as the shock wave propagates it will accelerate, compress and heat the ambient medium causes its pressure to exceed the thermal pressure of the ejecta, so it forms an expanding shell that output copious amount of synchrotron radiation due to the acceleration of electron in the presence of a magnetic field [3]. This expanding shell surrounds an area of relatively low density, so the interaction of this shell with this low density medium makes the gas flow following the shock front to reach a maximum temperature, after which the gas cool in rough pressure equilibrium producing a stratified temperature and density structure [4]. Therefore measurements of the usual nebular emission line ratios should show a broad range of gas temperature and densities behind the shock front.

However, these nebular emission lines are differ from other spectra (continuous, emission or absorption) since they form under some unusual physical conditions such as a low-density, optically thin media or in very hot plasmas that heated by a hot radiation source. So they created a number of characteristic spectral lines that violated the selection rules of quantum mechanics, these lines are known as forbidden lines which noted by square brackets around the atomic or molecular species in question, e.g. [OII],[OIII],and [SII] [5]. Since it discover in 1922 by Datta in gaseous nebula [6] till now the study of the forbidden lines received its greatest motivation, since its intensity consider a function of the temperature of the exciting source and of the density and temperature of the plasma itself . In this paper, some of these forbidden lines will be used to determine the electron temperature and density of the most famous observed plerion remnant which is the Crab Nebula, that characterized by its pulsar that continue to inject energy and synchrotron radiation to the remnant which in turn increase the intensity line ratio of the remnant and as a result increasing its temperature

Theory of calculations:

However, in space environments, densities may be only a few atoms per cubic centimeter, which is below the critical density, which is the electron density where the rate of spontaneous radiative decay equals the rate of collisional de-excitation for an excited state, making atomic collisions implausible [7]. Under such conditions, the collision rate is so small thus an electron (or atom or molecule) that has been excited from the 1s state to the 2s state, for example, for any reason cannot decay back to the 1s state, because the difference in the angular momentum (Δl) between the two state = 0 . Such a transition is forbidden according to the selection rules. Instead it can be excited even further by collision with another electron and then de-excite all the way to the 1s state again (which takes minutes or even hours) by emitting a forbidden-line photon [8].

As a result, the intensity of these emission lines that arise from these different atomic processes within the gas cloud are all dependent on the electron temperature T_e, density n_e, and chemical composition of the nebula, and hence the observations of these emission lines of importance in astrophysics because of the information which they can yield about the state of the ionized gas and on the conditions in their source.

Moreover, in order to determine the electron temperature the ratio of lines intensities emitted from a single ion from two levels with different excitation energies must be used. The most widely used nebular `thermometers' is the [OIII] ion, of which the [OIII] λ4363 line originates from a different energy level compared to the [OIII] λ4959, 5007 lines, and these different levels have different excitation energies (as shown in Fig.1) that depend very strongly on Te. So the line strength ratio λ 4363 / (λ 4959+ λ 5007) (or even λ 4363/ λ 5007) immediately tell us how hot the electron plasma in a nebula is via using the following equation [9]:

$$[OIII]\left(\frac{\lambda 4363 A^{o}}{\lambda 4959 A^{o}+\lambda 5007 A^{o}}\right)=0.14\ e^{-3.3\times10^{4}\ T_e^{-1}} \quad (1)$$

In some cases if one of these emission lines is unavailable the full half width maximum ($\delta_{1/2_\lambda}$) equation can be used for determination the electron temperature by using the following eq. [10]:

$$\delta_{1/2_\lambda}=\frac{1.67\,\lambda_o}{c}\sqrt{\frac{2kT_e}{m}} \quad (2)$$

Where:

λ_o is the wavelength of the selected line, c is the speed of light, k Boltzmann constant, and m is the mass of the selected ion.

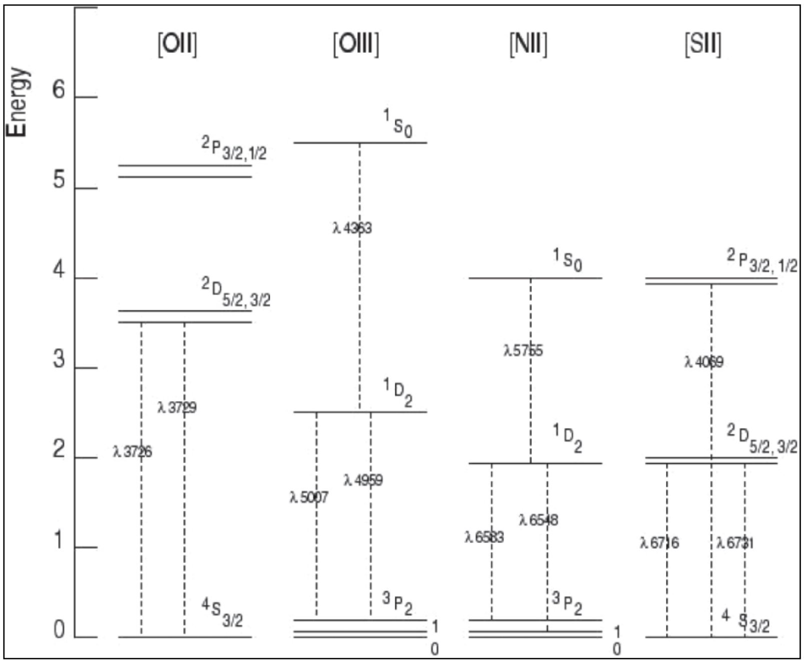

Figure 1- OII, OIII, NII, SII Energy levels (eV). [9]

In a similar manner to electron temperature measurements, the electron density can be determined from the ratio of intensities of lines emitted from a single ion from two levels with similar energies but varying radiative transition probabilities. The [OII] λ 3726, 3729 or [SII] λ 6717, 6731 lines can be used for measuring the electron density, since their atomic structure and hence the density dependence is essentially the same and there are quite strong in the spectra of most nebulae due to the relatively large abundance of oxygen and sulphur as well as the two levels involved in each line for each ion have different radiative transition probabilities that mean the relative populations of the levels depend strongly on the density [11]. Besides, [SII] has an electronic structure similar to that of [OII] (Fig.1) except that the sulphur ion has one more closed shell, and according to Seaton (1954a) calculation prediction the intensity ratio of the red [SII] line λ 6717 and λ 6731 changes with an intensity ratio of [OII] lines λ 3726& 3729 [12]. In our case the [SII] line λ 6717, λ 6731 has been used in order to calculate the electron density by using the following equation [13]:

$$[SII]\left(\frac{\lambda 6717 A^{o}}{\lambda 6731 A^{o}}\right)=\frac{1.01+5.61e^{\frac{-1.4}{t}}+X\left(1.97+2.84e^{\frac{-1.4}{t}}\right)}{1.2+3.74e^{\frac{-1.4}{t}}+X\left(7.9+7.42e^{\frac{-1.4}{t}}\right)} \quad (3)$$

Where

$X=10^{-2}n_e/T_e^{1/2}$

$t=10^{-4}T_e$

Calculations, Results, and Discussions:

Almost all information temperature, density, composition, and many other important physical processes of an astronomical object came from the spectroscopic study. In this paper the integrated spectrum of the Crab Nebula that shown in Figure-2 has been used to determine the intensity ratio of some selected forbidden lines which in turn will be used in order to determine the electron temperature and density and some other physical parameters of this selected remnant.

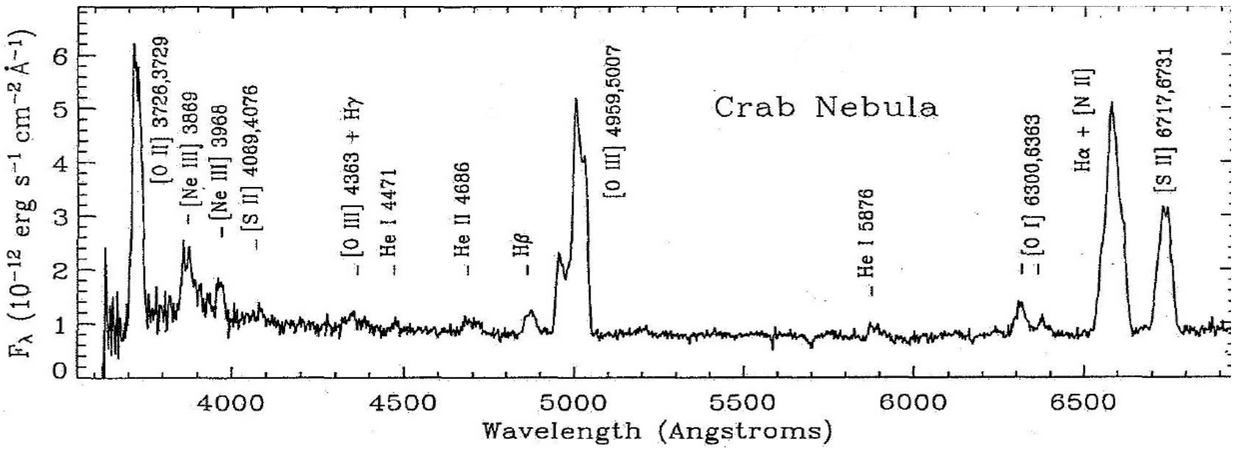

Figure 2- Integrated spectrum of SNR Crab Nebula [14]

Each line in the spectrum of the nebula considers as an indicator of the physics of the nebula itself, for example, in our case the dominant line in the remnant of the Crab Nebula is the oxygen with all its ionization stat, but each of these ionization state considers a reference of the region that it emitted from. Such as the existence of [OI] consider as an indicator for a thick, very dense region in the filaments where the atoms are shielded from the ionization by the synchrotron radiation via the outer layer of gas that absorbs the photon and become ionized leaving the neutral oxygen in the center. While [OIII] emission comes from a shell of gas that surround the synchrotron nebula which has cool immediately behind the shock. Which means that, this line is form by both photoionization from the discontinuity and the radiative cooling from behind the shock at the edge of the nebula where the synchrotron nebula has expand due to a constant energy input from the pulsar, that increase the speed of the shock which in turn affects on the cooling time of the shocked gas. When each of eqs. (1) & (2) applies using the [OIII] emission line it has been notice that, the Crab Nebula has T_e equal to 17,000∓500 k^o, 15,700℃K according to both equations respectively which is consider very good result compare with the observations result which ranging from 11,000 to 18,000 ℃K [7].

In addition to that it's found, the strength of HeI λ5870 in the spectrum of the Crab Nebula is much greater than $0.13 \times I(H_\beta)$, (≈ 0.8) which according to Raymond (1979) would indicate that the remnant is travel with very high shock velocity.

Even though the Crab Nebula has such high T_e and high shock velocity it's found that, not all pre-shock helium is fully pre-ionized in the remnant but only about 64% from it has be pre-ionized when the following eq. has been apply [4]:

$$f(He^{+}) = \frac{10}{v_s/100\ km.s^{-1}} \times \frac{I(He\ \lambda 4686)}{I(H_\beta)} \quad (4)$$

The reason behind that, it may be some of the helium of the remnant lay in dense region of the filament (as [OI]) so it will be obscured from the ionization or it may lie in region where the dust grains are available which absorb must of the synchrotron radiation.

On the other hand when eq. (3) applied using [SII] line it's found that the remnant has n_e equal to 1300 ± 10 cm^{-3}, which is consider very acceptable result compare with the other researcher result which found it equal 1300 cm^{-3} [7], where most of this density are concentrated in the filaments of the remnant. Besides that, another density indicator has been used which is the [OII] $\left(\frac{\lambda 3729A^o}{\lambda 3726A^o}\right)$ ratio that usually has a value ranging from (0.47-0.5) where the lowest value is for the highest density lowest brightness region. When this ratio has taken for Crab Nebula it's found that, it has a value of 0.9 and this value consider very acceptable result since the Crab Nebula believe to be an intermediate density remnant with an electron density of about 1300 cm^{-3}.

Conclusions:

From the obtained results its found that, the remnant has electron temperature ranging between (15,700 to 17,000) ∓ 500℃K which consider very reasonable value compare with its high shock velocity where the later has been obtained from the intensity ratio of $HeI\,\lambda 5870/\,(H_\beta)$ that found to be 0.8 which indicate to high shock velocity. However the Crab Nebula has such high T_e and high shock velocity but it's found that, not all pre-shock helium is fully pre-ionized in the remnant but only about 64% from it has be pre-ionized due to the obscuration of some of the helium from the ionization process in the densest region in the remnant. On the other hand when the intensity ratios of both [SII] $\left(\frac{\lambda 6717A^o}{\lambda 6731A^o}\right)$ and [OII] $\left(\frac{\lambda 3729A^o}{\lambda 3726A^o}\right)$ its found that, the remnant has an electron density of about 1300 ± 10 cm^{-3}.

References:

1. Durrer, R., **2008**. *The cosmic microwave background.* New York: Cambridge University Press, p. 252.
2. Vink, J. **2012**. Supernova remnants: the X-ray perspective. *Astronomy and Astrophysics Reviews*, 20, pp: 1-78.
3. Wang, C-Y. **2011**. Rayleigh-Taylor instabilities in type Ia supernova remnants undergoing cosmic-ray particle acceleration-low adiabatic index solution. *Monthly Notice of Royal Astronomical Society*, 415, pp: 83 -94.
4. Fesen, R. and Kirshner, R. **1980**. Spectrophotometry of the supernova remnant IC 443. *Astrophysical Journal*, 242, pp: 1023-1040.
5. Bridgman, W. **2007**. The Cosmos in Your Pocket: How Cosmological Science Became Earth Technology. I. *Astrophysics*, 1, p.p: 1-26
6. Bates, D. 2012. *Atomic and Molecular Processes*. United Kingdom: Academic press, INC. London. LTD, p. 412.
7. Loll, A. **2010**. Northwest-Southeast Asymmetry in the Crab Supernova Remnant. Ph.D.Thesis, Arizona State University. Arizona, USA. p. 23
8. Luridiana, V., Morisset, C. and Shaw, R. **2014**. PyNeb: a new tool for analyzing emission lines I. Code description and validation of results. *Astronomy & Astrophysics*, 573, A42.
9. Acker, A. **2011**. Spectrometry of nebulae. *EAS Publications Series,* 47, pp: 189–214.
10. Qiuping, Z., Cheng, C. and Yuedong, M. **2009**. Electron Density and Temperature Measurement by Stark Broadening in a Cold Argon Arc-Plasma Jet at Atmospheric Pressure. *Plasma Science and Technology*, 11(5), pp: 559-563.
11. Hughes, T. **2010**. A Phenomenological Study of Star Formation and Chemical Evolution in Nearby Galaxies. Ph.D. Thesis, Cardiff University, Wales, UK. p. 135.
12. Osterbrock, D. **1955**. Electron Densities in the Orion Nebule. *Astrophysical Journal*, 122, p.235.
13. Saleh, Z., Ayyash, A. **2013**. Spectroscopic Study of Electron Density and Electron Temperature for Supernova 2010j. *International Journal of Science and Technology,* 3, pp: 53-59.
14. Smith, N. **2003**. The integrated optical spectrum of the Crab nebula and evidence for its fading synchrotron continuum. *Monthly Notice of Royal Astronomical Society*, 346, pp: 885–889.