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DETERMINATION OF THE ZANSTRA TEMPERATURES OF THE CENTRAL STARS OF NGC 246 AND NGC 7293 PLANETARY NEBULAE

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ABSTRACT. In this work from processed the spectra of the NGC 246 and NGC 7293 planetary nebulae we have determined the fluxes in the H_β and HeII emission lines. Spectra of these planetary nebulae were taken from the archive of the European Southern Observatory. From the determined fluxes we calculated Zanstra temperatures according to the HI and HeII lines of the central stars of planetary nebulae. Respectively, the temperatures of 53723.14 K and 100871.43K were found for the central stars of NGC 246, the temperatures of 51072K and 89073.4K were found for the central stars of NGC 7293. The results obtained were also compared with results of other authors.

Keywords: central star, temperature, flux in the H_β emission line, flux in the HeII emission line.

АНОТАЦІЯ. Планетарні туманності є ідеальною лабораторією для дослідження взаємодії між випромінюванням і речовиною. Вся енергія, яку отримує планетарна туманність, надходить від центральної зорі. Частина випромінювання поглинається туманністю. Центральна зоря планетарної туманності є продуктом еволюції зір малої і помірної маси. Такі зорі проходять через стадію зорі асимптотичної гілки гігантів. Температура центральної зорі є важливим параметром від якого залежать характеристики самої планетарної туманності. Він зумовлює ступінь збудження та іонізації атомів речовини туманності. У цій роботі зі спектрів планетарних туманностей NGC 246 і NGC 7293, які попередньо були нами оброблені, ми визначили потоки в лініях випромінювання H_β і HeII. Спектри цих планетарних туманностей були взяті з архіву Європейської Південної Обсерваторії. З визначених потоків в лініях ми розрахували температури за методом Занстра відповідно по вищевказаних ліній центральних зір планетарних туманностей. Відповідно для центральної зорі туманності NGC 246 були знайденні значення температур 53723.14 K і 53723,14 K, а для центральної зорі туманності NGC 7293 − 51072 K і 89073,4 K. Отримані результати порівнюються з результатами інших авторів.

Ключові слова: центральні зорі, температура, потоки в емісійних лініях Гідрогену і Гелію.

1. Introduction

Planetary nebulae (PNe) are an ideal laboratory for the study of the interaction between radiation and matter. All the energy of a nebula is derived from a single source, the central star. Radiation emitted by the star is absorbed and processed by the nebula. Central stars of planetary nebulae (CSPN) are the final products of the evolution of low- and intermediate-mass stars, the stars that most likely go through the asymptotic giant branch (AGB) phase. By the time, a star departs the AGB, it loses most of its outer envelope, and if the remnant core evolves to high temperature before the ejected envelope disperses it will be visible as a PN for the rather short ≈ 10000 yrs time.

As known, the temperature of the CSPN is essential parameter for studying the evolution of these stars. The nebula characteristics are related to the stellar temperature, especially the level of excitation and ionization of the nebula, and intensity of some nebular lines. Studying the CSPN is difficult, and the standard methods for the temperature determination cannot be applied.

We report here on the determination of the fluxes in the H_β and HeII emission lines and the temperature determination for NGC 246 and NGC 7293 by using the Zanstra method based on HI and on a single ionized HeII lines. We discuss our results and compare these values to temperatures (Pottash, 1992; Phillips, 2003; Montez et al., 2015; Frew et al., 2016) reported by various authors.

2. Determination of the Zanstra hydrogen T_Z(H) and helium T_Z(HeII) temperatures

Zanstra (1927) developed the method to derive the central star temperature by comparing the nebular recombination flux with the stellar continuum magnitude. This method is based on the assumption that the number of Lyman continuum photons absorbed in the nebula is equal to the total number of recombinations to all levels excluding the ground state.

Both of Zanstra methods can only be applied to nebulae that are optically thick in L_c. In optically thick nebulae all L_c quanta are radiated by the star that absorbed by the nebula (Gleizes et al., 1989). At this time, it is assumed that the star radiates as a black body. It is assumed that the HI and He++ ions in the nebula absorb all radiation in the λ<912 Å and λ<228 Å regions from the star. Each L_c quantum emitted by the core in the Lyman series limit of hydrogen being swallowed up in the nebula produces one L_α quantum and one Balmer series quantum. When each L_c quantum is absorbed in the limit of Layman series, during the L_c quantum recombination of HeII, it can produce the L_α quanta and Balmer continuum quantum of ionized helium.

The number of Balmer quanta emitted by the nebula defines the number of quanta emitted by the star in the ultraviolet region of the spectrum. The temperature of the star can be determined by comparing these quanta with quanta emitted in the visible region of the spectrum. In a practice, the HeII λ4686 Å line is used for determination Tz(HeII).

If we assume that a star with radius R_s and temperature T radiates as a black body, the luminosity in the $d\nu$ interval will be $L_\nu d\nu$

$$L_\nu = 4\pi^2 R_s^2 B_\nu(T) \quad (1)$$

Here, B_ν is the Planck function. $\nu \geq \nu_i$ the number of stellar quanta will be:

$$Q_i = \int_{\nu_i}^{\infty} (L_\nu / h\nu)\, d\nu = \frac{8\pi^2 R_s^2}{c^2} \left(\frac{kT}{h}\right)^3 G_i(T) \quad (2)$$

ν_1 – is a limit of Lyman series, the energy of this quantum is sufficient to ionize hydrogen. ν_4 – is a limit of the main series of HeII, the energy of this quantum is sufficient for ionizing singly ionized helium.
Here,

$$G_i(T) = \int_{h\nu_i/kT}^{\infty} x^2 (e^x - 1)^{-1}\, dx. \quad (3)$$

For determination of the temperature we first replaced the integral $G_i(T)$ by the sum (Alili et al. 2023):

$$\int_{x_0}^{\infty} \frac{x^2 dx}{e^{x_i} - 1} = \sum_{n=0}^{\infty} \int_{x_0}^{\infty} e^{-(n+1)x} x^2 dx\,. \quad (4)$$

ν_0 – is the boundary of the mainserieses of HI and HeII. It is enough to add up to the value n=3, even the temperatures obtained from n=3 with n=2, they differ from each other only by 0.01. The observed $F(H_\beta)$ and $F(4686)$ radiation fluxes of the nebula will be as follows:

$$4\pi d^2 F(H_\beta) = h\nu(H_\beta) \int n_e\, n(H^+) \alpha(H_\beta) dv \quad (5)$$

and

$$4\pi d^2 F(4686) = h\nu(4686) \int n_e\, n(He^{++}) \alpha(4686) dv \quad (6)$$

Here, the frequency of the $\nu(H_\beta)$ – H_β line is the effective recombination coefficient related to the generation of $\alpha(H_\beta)$ – H_β quanta. $\alpha(4686)$ – He^{++} is the effective recombination coefficient related to the generation of quanta. Considering ($L_\nu = 4\pi d^2 F_\nu$), (5) and (6) in L/L_0 expression (L_0 is the luminosity of the Sun) of luminosity in terms of the stars' radiation fluxes F_ν we get the following expressions:

$$\frac{F(H_\beta)}{F_\lambda} = 3.95 \cdot 10^{-11} T^3 G_1(T) \left[e^{26650/T} - 1\right] \quad (7)$$

and

$$\frac{F(4686)}{F_{\lambda(vis)}} = 8.49 \cdot 10^{-11} T^3 G_4(T) \left[e^{26650/T} - 1\right]. \quad (8)$$

$F_{\lambda(vis)}$ – m_v is the radiation flux in the visible region of the spectrum is determined by the size of the visible star:

$$F_\lambda = 3.68 \cdot 10^{-9} \cdot 10^{-m_v/2,5} \left[erg/(cm^2 \cdot s \cdot Å)\right] \quad (9)$$

m_v – is the visual magnitude. In each of the fluxes on the left side of (7) and (8) equalitity absorption in the interstellar medium was taken into account as follows:

$$lg \frac{F_{\lambda(theor.)}}{F_{\lambda(obs.)}} = \frac{A_{5450}\ E_{B-V}}{2,5} \quad (10)$$

$$lg \frac{F(H\beta)_{(theor.)}}{F(H\beta)_{(obs.)}} = \frac{A_{4861}\ E_{B-V}}{2,5} \quad (11)$$

$$lg \frac{F_{4686(theor.)}}{F_{4686(obs.)}} = \frac{A_{4686}\ E_{B-V}}{2,5} \quad (12)$$

Here, A is the absorption coefficient in the interstellar medium, and E_{B-V} is the extinction. $F(H_\beta)_{(obs.)}$ and $F_{4686(obs.)}$ were determined from the processing of the spectra of the 2 planetary nebulae that we have studied. We have determined the temperatures of the central stars by the method of successive approximation from equations (7) and (8), and the results are given in Table 3.

3. Determination of the fluxes F(H_β) and F(4686)

The fluxes F(H_β) and F(4686) in the expression (7) and (8) are determined from processing the spectra for each planetary nebula. For this purpose, we studied the spectra of nebulae. We took them from the Southern Observatory (ESO) website. These spectra were observed in 2016, ESO-VLT-U2 (8-meter) and ESO-3P6 (3.6-meter) telescopes. The spectra were processed using the DECH 30 software package (Galazutdinov, priv. comm.). According to the magnitudes of the studied nebulae in different filters (UBVR) energy distribution curves were constructed in absolute flux units $\left[erg \cdot cm^{-2} s^{-1} Å^{-1}\right]$. Using the energy distribution curve and spectrum it is possible to estimate the flux in any spectral line. So, the value of the flux in the continuum near the spectral line given by multiplying the value of the equivalent width of the line, a flux is definitely found in any spectral line in the sphere. The flux in the spectral line is given in $[erg \cdot cm^{-2} s^{-1}]$. In the figures you can see the HI and HeII lines profiles of each nebula.

Table 1:

PN	V	W (Å)	F(H_c) $\times 10^{-13}$	$lgF_{\lambda(obs.)}$	$lgF_{obs}(H_\beta)$	E(B–V)	Referens
NGC 246	11.76	980.5	0.35	–13.138	–9.6	0.02	(Frew, 2016), SIMBAD
NGC 7293	13.52	7.18	57.85	–13.844	–10.38	0.02	(Frew, 2016), SIMBAD

H_β in $erg \cdot cm^{-2}s^{-1}$.

Table 2:

PN	W (Å)	F($HeII_c$) $\times 10^{-13}$	$lgF_{obs}(4686)$	A(5450)	A(4861)	A(4686)	Referens
NGC 246	259.6	12.3	–10.47	3.14	3.63	3.8	(Pottash, 1992)
NGC 7293	569	0.289	–10.78	3.14	3.63	3,8	(Pottash, 1992)

Table 3:

PN	T_z(HI)	T_z(HeII)	T(HI)	T(HeII)	T(HeII)	Ref.
NGC 246	53723	100871	42000	88600	140000	(Pottash, 1992), (Phillips, 2003), (Montez, 2015)
NGC 7293	51072	89073		107000	110000	(Phillips, 2003), (Frew, 2016)

The obtained results are given in the table 1 and in the table 2. In the 2nd column of the table 1, we give the visual stellar magnitudes of the nebulae, in the 3rd column, H_β line equivalent widths in each nebulae, in the 4th column, H fluxes in the continuum (H_c), in the 5th column, the stars' radiation fluxes, in the 6th column, the observed fluxes of the H_β and in the 7th column, the extinctions. In the 2nd column of the table 2, we give HeII line equivalent widths in each nebulae in the 3rd column, He fluxes in the continuum ($HeII_c$), in the 4th, 5th and 6th columns, the coefficients.

In the 2nd and 3rd column of the table 3, we show the Zanstra temperature calculated with lines HI and HeII by us, in the 4th, 5th and 6th column of the table 3, the Zanstra temperature calculated witrh line HeII by other authors are given.

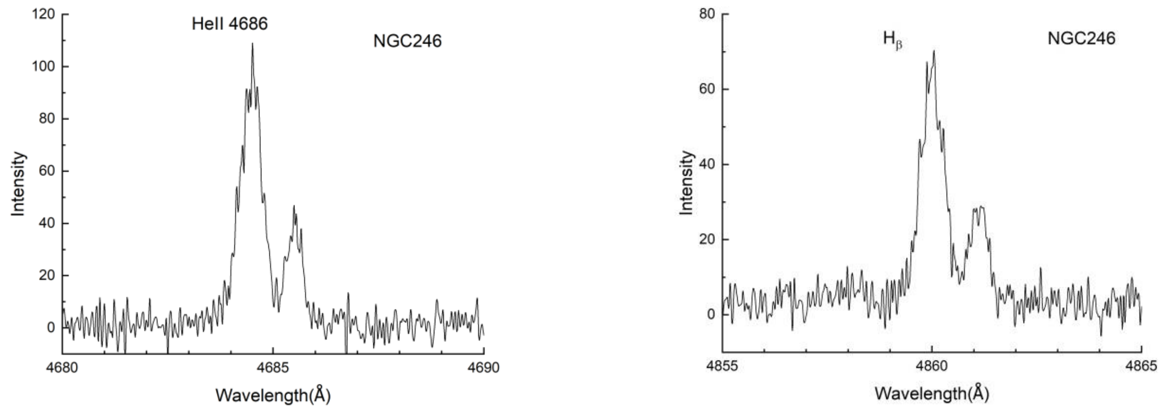

Figure 1: Profiles of the line HeII and H_β in planetary nebula NGC 246

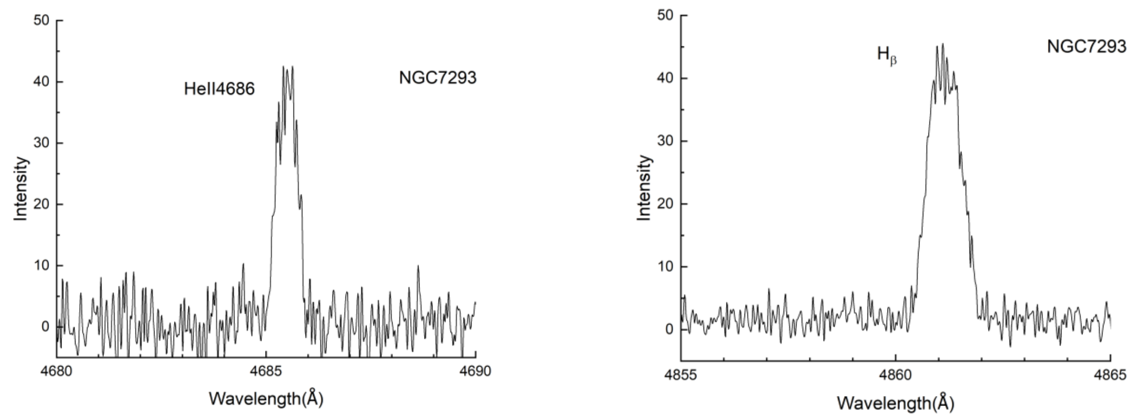

Figure 2: Profiles of the line HeII and H_β in planetary nebula NGC 7293

4. Conclusion

So, as it can be seen from the table 3, the temperatures we determined by the Zanstra method are differs a little bit from the temperatures determined by other authors before us by this method. The reason for this is that the processed spectra are obtained on telescopes with different resolution in different years. The temperatures we determined according to the HI and HeII lines of the central stars also differ from each other. Since the Zanstra method could be applied if the nebula is optically thick in hydrogen (respectively, helium) in the Lyman continuum, PN change from optically thin in H and He at different times (Kwok, 2000). The fact that stellar atmosphere are not well approximated by blackbodies can also contribute to the errors in the Zanstra temperatures.

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