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THE PHYSICAL CONDITIONS OF THE CENTRAL PART OF ORION A HII REGION BY THE RADIO RECOMBINATION LINES AT 8 AND 13 MM

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ABSTRACT. Observations of recombination radio lines (RRL) of hydrogen, helium (H, He) and carbon (C) were carried out in several positions of the HII region Orion A with RT22 radio telescope (Pushchino, Russia) at the wavelengths of 8 and 13 mm. The information about the ionization structure of the HII region was received. It is obtained that the measured helium abundance increases in the directions to "North" and "West" with a maximum at angular distances of 100-150″ after which it declines. The maximum measured relative helium abundance, $y^+ = n(He^+)/n(H^+)$, is in the range of 9.4 – 11.0 %, therefore the actual He abundance n(He)/n(H)) is ≥ 9.4(±0.5) %. With these estimates, the lower limit of the primordial helium abundance Yp ≥ 25.19 (±1.15) % should be expected. This limit is still not strong enough to assert the excess over Yp predicted by the standard cosmological model (≈ 24.8%), but it admits the existence of unknown light particles. The y^+ behavior and model calculations indicate that T_{eff} (effective temperature) of θ^1 Ori C star is 35000 – 37500 K, corresponding to the star spectral type of ≈ O6.5 V, which is important for the calibration of hot OB-stars. Measured electron temperatures (T_e) of the HII region, taking into account the deviations from the LTE, are in the range of 6600 – 8400 K and are strictly decreasing in direction to the “East”. Alas information on the turbulent velocities of the ionized gas and its electron density was obtained.

Keywords: ISM: abundances – HII regions – Radio Lines: Orion Nebula

1. Introduction

Recombination radio lines (RRL), being one of the powerful tools for interstellar medium studies (Sorochenko & Gordon, 2003), *also allow* to check the standard cosmological model (SCM), in parts of primordial nucleosynthesis in the Universe that has taken place the first 2–3 minutes after the Bing Bang. Due to the Universe’s expansion, only several light elements were produced during primordial nucleosynthesis which are helium-4 (hereafter, He), deuterium, helium-3, tritium and lithium. While almost all these elements are indicators of baryonic density of the Universe, the primordial helium-4 abundance also can be an indicator of the presence or absence of unknown light particles (Tsivilev et al., 2004, 2013; Tsivilev, 2009). The presence of unknown light particles may imply deviations from the SCM.

One of the most reliable methods of measurements of primordial helium abundance, *Y*p = (He/H), is based on the optical and radio observations of H (hydrogen) and He (helium) recombination lines from HII regions. Optical observations can cover large number of sources including extragalactic ones. Comparing with optical observations, RRL observations are significantly less affected by systematic effects because, in radio range, helium can be treated as a hydrogen-like system with high accuracy meaning that coefficients of populations of identical hydrogen and helium levels are equal and canceled out in the (He/H) ratio, thus, allowing to directly estimate the $n(He^+)/n(H^+)$ value (see, e.g., Tsivilev, 2009; Tsivilev et al., 2013).

Our experience shows that moreover it is desirable to study the HII regions, especially their ionization structure, when estimating the He abundance in these HII regions. One of such HII regions is Orion A nebulae. We have been investigating this region for a long time (Tsivilev et al., 1986; Poppi et al., 2007; Tsivilev et al., 2014; Tsivilev, 2014) by observations of RRL which are mainly at the wavelengths of 8 and 13 mm. As a result of these investigations, we constructed the model of the HII region and obtained that the distribution of measured $y^+ = n(He^+)/n(H^+)$ values has a maximum of $y^+ = 10.0$ (±0.8) %, that probably is close to the actual abundance of helium (n(He)/n(H)) in this region (Poppi et al., 2007). In present study, we decided to repeat RRL observations in Orion A with RT22 radio telescope (Puschino) at the 8 mm wavelength using an upgraded hardware in order to improve estimates of the position and value of the maximum of $n(He^+)/n(H^+)$ distribution as well as to obtain physical parameters of the HII region and to obtain the new estimate of Yp.

The positions in Orion A at which the new observations of H, He and C RRLs at 8 and 13 mm were carried out are shown in Figure 1. Part of the observations at 8 mm was published (Tsivilev, 2014), these positions are marked in Figure 1 as large circles with a size equal to the RT22 beam size at 8 mm.

2. Ionization Structure and Helium Abundance

In HII regions, the measured ($y^+ = n(He^+)/n(H^+)$) and actual helium abundance ($y = n(He)/n(H)$) are related through the structure factor R:

$$y^{+} = R * y,$$

where R is determined by the ionization structure, i.e. by the ratio of sizes and emission measures of He^{+} и H^{+} zones (see, e.g., Tsivilev et al., 2013).

In our previous works (Tsivilev et al., 1986; Poppi et al., 2007), it was shown that the Orion A HII region has a "blister-type" structure with the core–halo density distribution. The current study, as well as previous ones, shows that ionized helium zone is smaller than ionized hydrogen zone, i.e. the factor R is lower than 1 and *has a different value in the core and halo*. The factor R is lower for the core (where we see the HII region is ionization bounded only) than for the halo, where we see the HII region is partly ionization bounded and partly density bounded, and the contribution of these parts into the observed emission varies with a position. In the positions, where the peak values of y^{+} are observed, the factor R probably is close to 1 (see Figure 9 in Poppi et al., 2007) , i.e. one can directly measure the actual helium abundance in these positions.

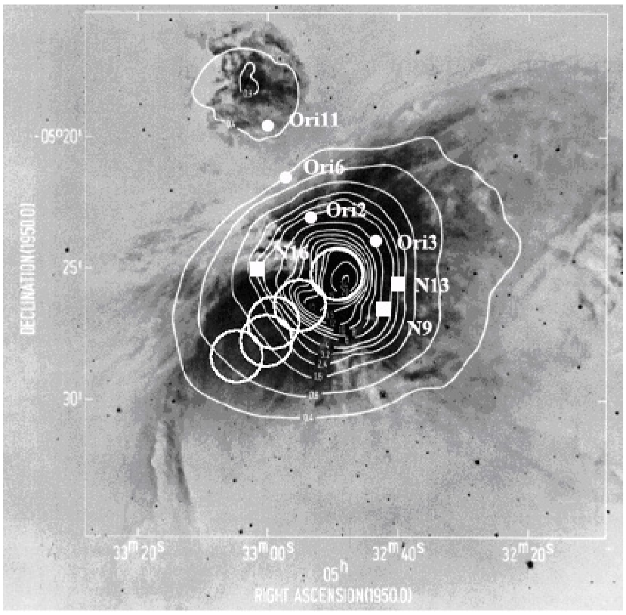

Figure 1: Optical image of Ori A region in Hα and NII lines from Hua & Louise (1982). Contours (faint white lines) designate 23 GHz continuum (Wilson & Pauls, 1984). Circles (large and small) and squares show positions at which our observations, respectively at 8 mm and 13 mm, were carried out.

Figure 2 shows the obtained distribution of $n(He^{+})/n(H^{+})$ towards different directions in Orion A. In the previous study (Poppi et al., 2007), we found that the y^{+} maximum is located in positions Ori2 and Ori3 (see Figure 1). In this study, we obtained that the y^{+} maximum is located close to the position marked as N13 (see Figure 1) where measured y^{+} values are in the range of 9.4 – 11.0 %. For the established ionization structure, this means that the actual helium abundance in Orion A, $n(He)/n(H)$, should not be lower than 9.4(±0.5) %. Further, in this position, we also can estimate the lower limit of primordial helium abundance (Yp). The helium abundance measured in the interstellar medium consists of ~ 90 %, the one produced during the era of primordial nucleosynthesis in the Universe, and of ~10 % one produced by stars during their evolution (Hoyle & Teyler, 1964). To account the contribution of stars one can use the dependence of the helium abundance (Y, on a mass) on the abundance of heavy elements (Z) (Tsivilev, 2009). Taking the slope of this dependence, dY/dZ = 1,62 (± 0.29), from the literature (Izotov & Thuan, 2010) and the abundance of heavy elements in Orion A, Z = 0.0112 (±0.0022) (Baldwin et al., 1991), we obtain:

$$Yp \geq 25.19\ (\pm 1.15)\ \%.$$

This limit is still not strong enough to claim the overabundance comparing with Yp predicted by the SCM (≈ 24.8%), however this limit admits the existence of unknown light particles in agreement with previous works (Tsivilev et al., 2004; 2013; Tsivilev, 2009).

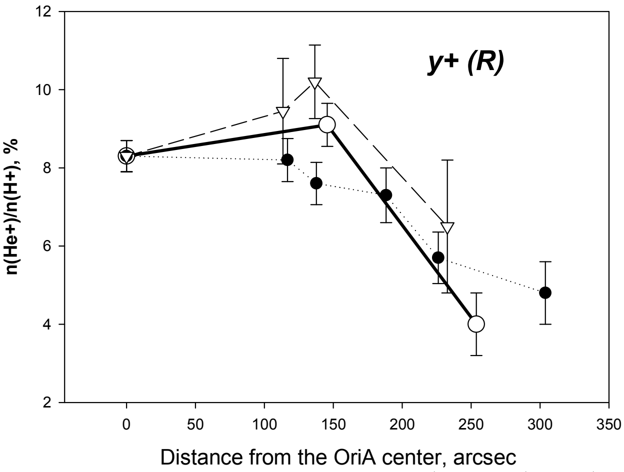

Figure 2: The distribution of measured $y^{+} = n(He^{+})/n(H^{+})$ values with the distance from the OriA center (θ^{1} Ori C star). Black cirlces – in direction to the "East": OriA – OriBar (large circles in Figure 1); white circles – in direction to the "North": OriA – Ori6; open triangles – in direction to the "West": OriA – Ori3 and N13.

3. Effective Temperature of θ^{1} Ori C Star

In figure 2, it is seen that, in directions to the "North" and "West", the measured helium abundance increases with increasing distance from the OriA center (r) and has a maximum at angular distances of 100-150" after which it goes down. In direction to the "East", the measured $y^{+}(r)$ always decreases with increasing r which means that along this direction the HII region is bounded by ionization only. This fact can be used to estimate the ionizing source (star or group of stars) of the HII region (Polyakov & Tsivilev, 2007). In the case of an ionization bounded HII region, the factor R will strongly depend on stellar properties, mainly on stellar effective temperature T_{eff} (Tsivilev et al., 2013). In Orion A, this star is θ^{1} Ori C.

Our model calculations of $y^{+}(r)$ behavior on the "East" direction show that T_{eff} of the ionizing source is in the range of 35000 – 36500 K. If one take into account that the HII region is ionized by not a single star but by a group of stars (Copeti & Bica, 1983) then the actual T_{eff} of θ^{1} Ori C star should be higher (by ~ 1000 K) and will be in the range of 36000 – 37500 K. This is in good agreement with our earlier estimates (Polyakov & Tsivilev, 2007).

Optical studies of Stahl et al. (2008) shown that the θ^1 Ori C spectral type is ~ O7 V. However, on our opinion, their data indicate that more likely the spectral type was ~ O6.5 V (see Figure 6 from Stahl et al., (2008)). It is known that one of the problems is a calibration of OB-stars, i.e. the correspondence of a given spectral type to T_{eff}. For example, for a star of O6.0 V spectral class Vacca et al. (1996) assign $T_{eff}\approx 43\ 600$ while Pottasch et al. (1979) assign much smaller value $T_{eff}\approx 36\ 500$ K.

Our data (see Figure 3) indicate in a favor of Pottasch et al. (1979) and Massey et al. (2005) calibrations, which is an important result.

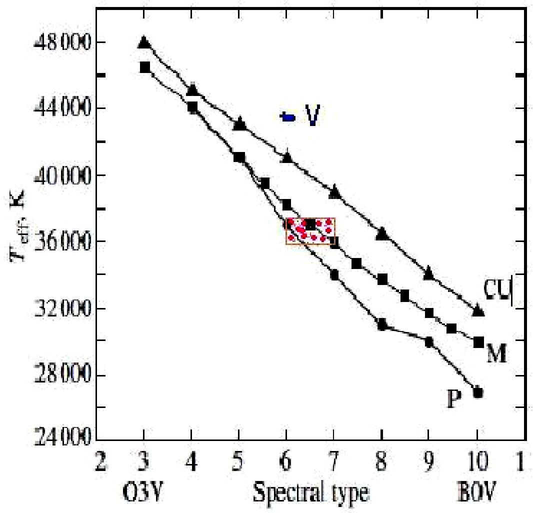

Figure 3: Spectral type-T_{eff} calibration for OB-stars from P – Pottasch et al. (1979), M – Massey et al. (2005), CU – Conti & Underhill (1988), V – Vacca et al. (1996). Our estimates for θ^1 Ori C star are shown as a rectangle in the figure center.

4. Electron Temperature of the Ionized Gas

The RRLs, using the line/continuum contrast, allow estimate electron temperature (T_e) of the ionized gas (Sorochenko & Gordon, 2003). We made such estimates assuming LTE (local thermodynamic equilibrium) as well as non-LTE using tabulated departure coefficients from LTE of Salem & Brocklehurst (1979) and electron density values estimated by Mesa-Delgado et al. (2008) from optical observations. The results are shown in Figure 4 where it is clearly seen that, towards the "East" direction, T_e strictly decreases as the distance from the OriA center increases. The T_e decrease in direction to the "North" is doubtful. Optical data also show that T_e decreases with distance from the center (Mesa-Delgado et al., 2008). Such a decrease towards the region periphery can be related to either decreasing density (Wilson & Jaeger, 1987) or to an increase towards the region periphery of the abundance of heavy elements, especially oxygen and sulfur, which are cooling agents (Spitzer, 1981).

5. Turbulent velocities of the Ionized Gas

According to RRL theory, line profile at the considered wavelengths has a Gaussian shape with the width that is a convolution of thermal and turbulent broadening (Sorochenko & Gordon, 2003). As we have measured T_e, we can calculate thermal broadening and then extract turbulent one from the observed RRL width. In this way, we obtain turbulent velocities of the ionized gas (V_t). Figure 5 shows the V_t distribution obtained using hydrogen as well as helium lines. It is seen that there is no clear dependence of V_t on the distance, however there is a weakly apparent peak at distances of 100-150" from the OriA center. This peak can represent the presence of boundary of the core of the HII region at these distances. The V_t values obtained are in good agreement with the previous measurements of, for example, Sorochenko & Berulis (1969).

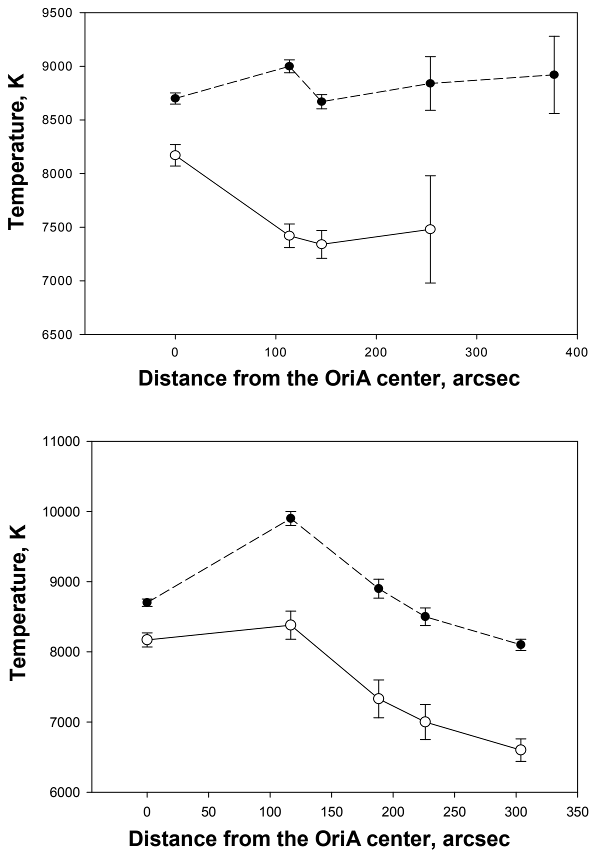

Figure 4: The dependence of electron temperature on the distance from the OriA center. Top panel shows the results obtained in direction to the "North"; bottom panel shows the results obtained in direction to the "East". Open circles show the results obtained taking into account non-LTE effects; filled circles show the results obtained assuming LTE

6. Electron density of the Ionized Gas

RRL theory (Sorochenko & Gordon, 2003) also predicts that for the quantum levels of atoms excited to principal quantum numbers of 100 and higher, Stark broadening due to collisions with electrons becomes apparent. Stark broadening is characterized by a Lorentz profile and an observed RRL has a Voight profile. In the same spectrum at 13 mm (i.e. with the same frequency setup and angular resolution), we see simultaneously H65α and H93γ RRLs (see Figure 6). The observed line width of H93γ is higher than the one of H65α in all observed positions. We suggested that H65α is broadened only thermally while H93γ line is additionally broadened by Stark effect.

We have fitted H93γ RRL profile with Voight function (Smirnov & Tsivilev, 1982) fixing Doppler width which was determined using H65α RRL. In this way, we estimate Lorentz broadening that is proportional to electron density (N_e) of the ionized gas and proportional to the principal quantum number of excited hydrogen level in the power of ≈ 4.5 (Sorochenko & Gordon, 2003).

As a result, we obtain $N_e = (1.2 \pm 0.2)\ 10^5\ cm^{-3}$ for positions N9-N13 and $N_e = (1.4 \pm 0.4)\ 10^5\ cm^{-3}$ for the nebulae center. This is higher by the order of magnitude than the value estimated by Smirnov et al. (1984) with RRL and the maximum value $N_e \sim\ 2.5\ \ 10^4\ cm^{-3}$ obtained by Mesa-Delgado et al. (2008) using optical observations. Further analysis is required to find out reasons for this inconsistency.

To save a space we do not present a table with estimated RRL parameters however we are ready to send this table on an e-mail on a request. To see shapes of the 8 mm spectra it is possible in Tsivilev (2014) paper.

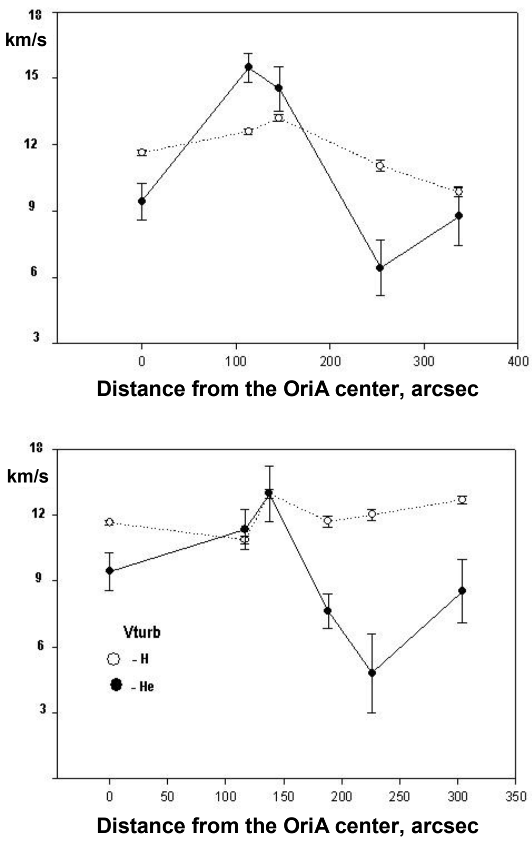

Figure 5: The dependence of turbulent velocities on the distance from the OriA center obtained using H (grey lines) and He (black line) RRLs. Top panel shows the results obtained in direction to the "North"; bottom panel shows the results obtained in direction to the "East"

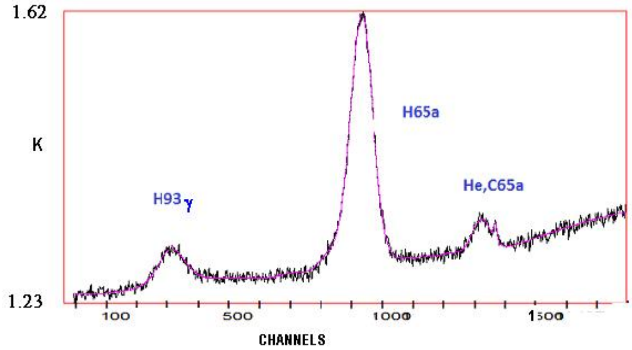

Figure 6: The spectrum at 13 mm averaged between positions N13and N9. Ordinate is antenna temperature; abscissa is a spectral channel number, the frequency increases with increasing channel number. The smooth curve is the fitted spectrum.

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