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ON THE QUESTION OF THE HELIUM ABUNDANCE IN ORION A MEASURED BY RADIO RECOMBINATION LINES. AND THE PRIMORDIAL HELIUM ABUNDANCE.

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ABSTRACT. Recombination radio lines (RRLs) of hydrogen (H), helium (He-4), and carbon (C) are a powerful tool for studying the interstellar medium (ISM) in space. The RRLs observations allow to obtain the physical parameters of regions of ionized hydrogen (HII regions) as well as of the photo-dissociation regions; and to estimate the effective temperature of stars that ionize the HII region. There is also an important cosmological task for RRL – measuring Primordial helium abundance produced at the stage of Primordial nucleosynthesis of the Universe. It turned out that the Orion A nebula is an interesting object for the latter task. At the time, the recombination radio lines observations of hydrogen, helium (H, He), and carbon (C) at a number of positions in the Orion A HII region were carry out with the RT22 radio telescope (Pushchino) at wavelengths of 8 and 13 mm. The relative helium abundance, $y^+ = n(He^+)/n(H^+)$, in these positions was obtained. The behavior of this value over the nebula showed that the helium ionization zone is smaller than the hydrogen one with different ratios for the core and halo. The location where the maximum y^+ value is expected was also determined. For the established ionization structure, it means that the actual helium abundance in Orion A, $n(He)/n(H)$, will not be less than the maximum y^+value. This allows to estimate the limitations on the Primordial helium abundance. In this work, new H and He RRL observations were made at 13 mm in the direction of the expected maximum of y^+. RRLs were observed in two transitions - 65α and 66α. It was found that the maximum y^+ value is in the range of $10 - 12\%$. Hence, we can expect that the Primordial helium abundance (Yp, the ratio He/H by mass) lies in the range of $\approx 26.4 - 29\%$, and the number of light neutrino-type particles during Primordial nucleosynthesis may exceed the standard value. To refine the result the work will be continue.

Keywords: Cosmology; Radio astronomy, HII regions, radio recombination lines.

АНОТАЦІЯ. Рекомбінаційні радіолінії (РРЛ) водню (H), гелію (He-4) і вуглецю (C) є потужним засобом дослідження міжзоряного середовища (МЗС) у космосі. Вони дозволяють отримувати фізичні параметри областей іонізованого водню (HII областей) і областей фотодисоціації; оцінювати ефективну температуру зірок, які іонізують HII області. Є і важливе космологічне завдання для РРЛ - вимірювання первинного змісту гелію, виробленого на стадії первинного нуклеосинтезу Всесвіту. Виявилося, що для останнього завдання цікавим об'єктом є туманність Оріона А. Свого часу на радіотелескопі РТ22 (Пущино) на хвилі 8 і 13 мм були проведено спостереження рекомбінаційних радіоліній водню, гелію (H, He) і вуглецю (C) в ряді напрямків області HII Оріон А. Було отримано відносний вміст гелію, $y^+ = n(He^+)/n(H^+)$, у цих напрямках. Поведінка цієї величини вздовж туманності показало, що зона іонізації гелію менша зони іонізації водню, з різним співвідношенням для ядра і гало. Було визначено також розташування місця, де очікується максимальне значення величини y^+. Для встановленої іонізаційної структури знайдено, що дійсний вміст гелію в Оріоні А, $n(He)/n(H)$, буде не менше, ніж максимальне значення y^+. Це дозволяє оцінити обмеження і на первинний вміст гелію. У даній роботі були проведені нові спостереження РРЛ H і He на 13 мм у напрямку на очікуваний максимум величини y^+. РРЛ спостерігалися у двох переходах – 65α і 66α. Було отримано, що максимальне значення y^+ знаходиться в інтервалі $10 - 12\%$. Звідси можна очікувати, що первинний вміст гелію (Yp, відношення He/H по масі) лежить в інтервалі $\approx 26.4 - 29\%$, а число легких частинок типу нейтрино під час первинного нуклеосинтезу може перевищити стандартне значення. Робота по уточненню цього результату буде продовжена.

Ключові слова: Космологія; Радіоастрономія, HII області, радіорекомбінаційні лінії.

1. Introduction

Recombination radio lines (RRLs) of hydrogen (H), helium (Ne-4), and carbon (C) are a powerful tool for studying the interstellar matter (ISM)(see Gordon and Sorochenko,2003). The RRLs observations allow to obtain the physical parameters of the ionized hydrogen regions (HII regions) formed around young and hot stars as well as of the photo dissociation regions, which are intermediate layer between the HII zone and the parent molecular cloud (e.g., Sorochenko and Tsivilev, 2010); the effective temperatures of the stars ionized of HII regions could also be estimated (e.g., Polaykov and Tsivilev,2007). There is also an important cosmological task for RRL - measurement of the Primordial helium abundance. As Hoyle and Taylor (1964) have showed at their time, about 90% of the observed amount of helium was formed at the pregalactic phase of the Universe's evolution, and most likely at the stage of Primordial nucleosynthesis. During Primordial nucleosynthesis (the first 2-3 minutes after the Big Bang), in addition to He-4, several other light elements were formed: deuterium (D), helium-3 (He-3), tritium (T), and lithium (Li-7). But if the yield of these elements depended only on the baryon density of the Universe, then the yield of helium (He-4) dependent to a greater extent on the conditions of the neutron-proton ratio (n/p) was frozen out (Klapdor-Kleingrothaus, Zuber, 2000). One of these conditions was the number of light relativistic particles at the time of this freezing out ($\sim 10 - 20$ s after the Big Bang).

Thus, if the above elements are indicators of the baryon density of the Universe, then the Primordial helium abundance is also an indicator of the presence or absence of unknown light particles. The contribution of known light particles in the framework of Standard Cosmological Model (SCM) is calculated with good accuracy (Klapdor-Kleingrothaus, Zuber, 2000). The available observations of fluctuations in the microwave background give the values of the Primordial helium abundance (Yp) within the Standard cosmological model (SCM) with high accuracy. (For example, the He/H ratio by mass is, $Yp = 24.84(B \pm 0.02)\%$ – Coc, Vangioni (2017)). And it would seem what the experiment can give in this situation, because it is difficult to achieve such accuracy in observations? At the moment, the SCM assumes the presence of three neutrino species. However, for example, Yang et al. (1984) showed that the presence of an additional fourth neutrino would lead to a $Yp \geq 25.3\%$. The difference in Yp values would be already quite noticeable and measurable. Thus, the presence of additional unknown light particles like neutrinos may indicate a deviation from the Standard Cosmological Model, which will manifest itself in the measured excess of the Primordial helium abundance from the SCM predictions. Within the framework of this formulation of the problem (search for deviations from the SCM), the source – Orion A HII region - turned out to be interesting object. For a number of years, we have intensively investigated the well-known Orion A nebula by RRLs of H, He and C at wavelengths of 13 mm and 8 mm. It was found that the He^+ ionization zone is less than the H^+ zone. Under these conditions, the maximum of the obtained value $n(He^+)/n(H^+)$ makes it possible to refine the lower limit of the Yp value.

2. Results and Discussion

At the indicated radio frequencies (the optically thin case and the absence of Stark broadening of lines) the relative helium abundance, $y = n(He)/n(H)$, was calculated as the ratio of integrals of the He and H RRLs, corresponding to the same transition numbers, using the following formula:

$$y = \frac{T_l(He)^{-}\Delta V(He)}{T_l(H)^{-}\Delta V(H)} \quad (1)$$

where T_l – line amplitude, ΔV –line width at half intensity level in km/s.

In reality, we measure the RRL of an ionized gas, i.e. the ratio of the ionized components of He^+ and H^+. In the HII regions, the measured ($y^+ = n(He^+)/n(H^+)$) and the actual ($y = n(He)/n(H)$) helium abundance are related by a structural factor R:

$$y^+ = R \times y \quad (2)$$

where R is determined by the ionization structure, i.e. the ratio of the sizes and emission measures of the He^+ and H^+ zones. The relative helium abundance by mass (Y) is expressed by the following formula:

$$Y = 4y \times (1 - Z)/(1 + 4y) \quad (3)$$

where Z is the relative mass abundance of other elements heavier than helium, often called metallicity. Then it need to take into account the stars contribution to the production of helium. In the case of Orion A (Tsivilev, 2009) the Primordial helium abundance can be determined by the following formula, using the dependence of Y on Z due to the contribution of stellar evolution:

$$Yp = Y - dY/dZ \times Z \quad (4)$$

In our previous works, it was shown that the ionization structure in Orion A has a core-halo structure, where the He^+ zone is smaller than the H^+ one, i.e. R < 1 as a whole for the nebula with a different value for the core and halo. Under these conditions, the maximum measured value y^+ will mean the lower limit on the actual helium content, $y = n(He)/n(H) \geq y^+_{max}$. This opens the way for estimating the lower

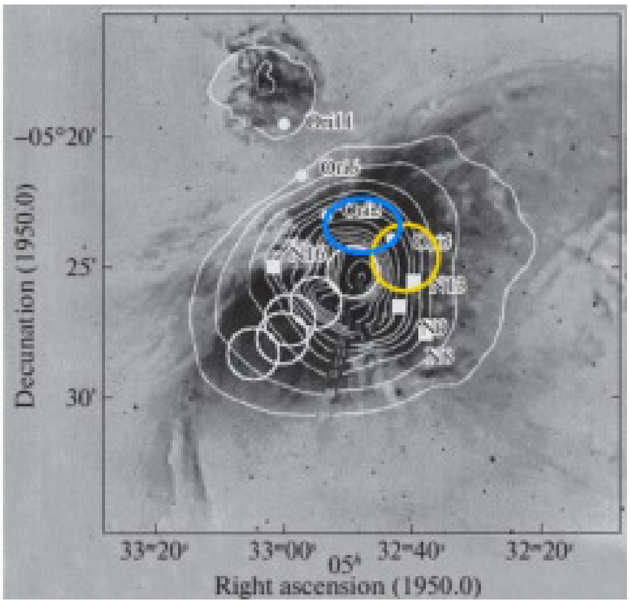

Figure 1: Positions in Orion A (see f.e. Tsivilev et al., 2019) where RRL observations with RT22 (Pushchino) were made at wavelengths of 8 mm (large and small circles) and 13 mm (squares). The yellow circle is the position where the maximum relative helium abundance was observed at 13 mm. (The size of the yellow circle corresponds to the size of the RT22 beam at 13 mm, the size of the white circle corresponds to at 8 mm one).

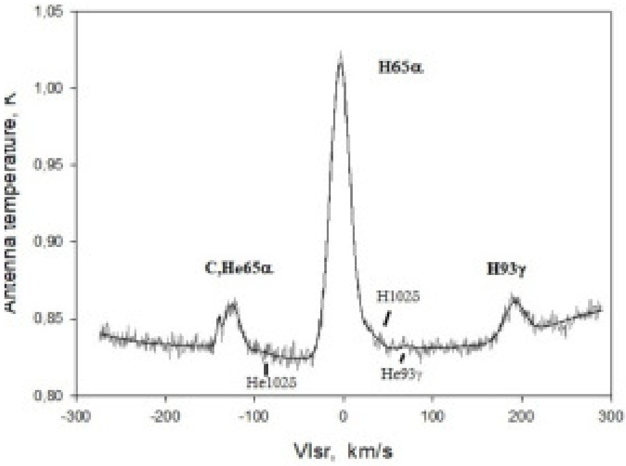

Figure 2: Obtained spectrum (transition 65α) in the direction of the y^+ maximum in Orion A at 13 mm. The vertical axis – antenna temperatures in Kelvins, on the horizontal – radial velocities in km/s. Zero corresponds to the zero velocity for RRL H. The gray line is the resulting spectrum, and the black smooth line is the fitted spectrum.

bound on the Primordial helium abundance (Yp). So, the task was to find y^+_{max} in Orion A.

In our work Poppi et al. (2007), it has been showed that y^+ increases with distance from the center with a maximum value at an angular distance of $2-3'$, and then falls. The probable area of maximum $y^+ \approx 10\%$ was indicated in the North-West of the region (see Fig. 1, marked as a blue oval) in positions Ori2 and Ori3 (Poppi et al., 2007). In subsequent works (Tsivilev et al., 2016; Tsivilev et al., 2019) a high helium abundance was also found slightly to the south, in the Ori N13 position (Fig. 1). Therefore, the highest y^+ value can be expected between the Ori3 and Ori N13 positions. In this work, we carried out the RRLs observations with RT22 (Pushchino) in this direction by the 65α transition, (large yellow circle in Fig. 1).

Indeed, we obtained a value of $y^+ \approx 12\%$ (see Fig. 2), which is higher than previously measured values. The result is stable to small variations in the spectrometer zero line. Since the result was unusually high, we made additional observations of H and He RRL in this direction for another transition - 66α. Unfortunately, the equipment in these observations worked worse; in particular, the system noise temperature was 1.5 times higher. All observations were carried out from 2017 to 2020, the time of signal accumulation in the transition 65α – $\approx$90 hours, in the transition 66α– $\approx$ 60 hours. Finally, $y^+ = 11.57(\pm 0.59)\%$ was obtained for the 65α transition and $10.0(\pm 1.13)\%$ for the 66α transition. The weighted average value for the two transitions (66α and 65α) is equal to $y^+ = 11.23(\pm 0.52)\%$. The next step was to calculate the Primordial helium abundance using formulas (3) and (4) and taking $Z = 0.0112(B \pm 0.0022)$ (Baldwin et al., 1991) and $dY/dZ = 1.62(B \pm 0.29)$ (Izotov, Thuan, 2010) and assuming that $R = 1$ at the maximum y^+ position:

$$Yp = 29.2(\pm 1.05)\%.$$

Taking minus 3σ (errors), we can estimate a formally "strong lower"constraint:

$$Yp > 26.0\%.$$

Further, conclusions can be drawn about the limitations on the existence of unknown light particles during Primordial nucleosynthesis (Tsivilev, 2009). For example, Pagel (2000) expressed the calculated helium yield during Primordial nucleosynthesis by the analytical formula. Assuming that the free neutron lifetime closes to 887 s, and combining the first and the last (dependence on the baryon density) terms of this formula, and assuming it as the measured SCM value (Yp,o) we obtain a dependence only on the number of light particles of the neutrino type $(N\nu)$:

$$Yp = Yp,o + 0.013(N\nu - 3).$$

Taking the measured SCM value $Yp, o = 24.84\%$ of Coc, Vangioni (2017), as outlined upper in the Introduction, we get:

$$N\nu = (Yp - 24.84)\%/1.3 + 3 \quad (5)$$

Next, we derive $N\nu = 6.35$ for the main Yp value and $N\nu > 3.9$ for the its lower limit, i.e. exceeding over the standard value $N\nu = 3$.

Is there any reason for the existence of such a high Yp value? Some arguments are possible. For example, the presence of a "mirror world"(Okun, 2007). According to Blinnikov and Khlopov (1983), the number of all light particles that affect the expansion rate of the Universe will double. Using formulas available in the literature (for example, the Internet publication http://*www.kaf07.mephi.ru/eduroom/DM/DM_-L9.pdf*), it can be estimated that the value of Yp will increase by a factor ~ 1.2, i.e. $Yp \approx 24.84 \times 1.2 \approx 29.8\%$. It should also be noted that lately there are a lot of talk about the possible presence of fourth type neutrino (for example, Serebrov et al., 2019). It is interesting to note the recent measurements of Yp by absorption lines in intergalactic gas towards distant quasars, which gave the $Yp = 25.0(+3.7; -2.5)\%$ (Cooke and Fumagalli,2018). Since the authors did not take into account the contribution of doubly ionized helium, which is abundant in the intergalactic gas, this value can be considered as some lower limit, which also allows exceeding the accepted SCM Yp value.

3. Conclusions

So, RRL observations in Orion A derived a high helium abundance, $y^+_{max} = 10 - 12\%$, which assumes the possibility of a"high "Primordial helium abundance (by mass), $Yp = 26.4 - 29\%$, and the number of light particles of neutrino type can exceed the standard value. It is clear that the result requires clarification. We will continue to work in this direction and try to carry out additional RRL observations in Orion A.

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