IRSTI 41.25.29 https://doi.org/10.26577/RCPh.2023.v86.i3.01

A.B. Manapbayeva[1], A.Zh. Omar[1], N.Sh. Alimgazinova[1], T. Komesh[1,2],
M.T. Kyzgarina[1*], J. Esimbek[3], Zh. Assembay[1]
[1]Al-Farabi Kazakh National University, Kazakhstan, Almaty
[2]Nazarbayev University, Kazakhstan, Astana
[3]Xinjiang Astronomical Observatory, Chinese Academy of Sciences, China, Urumqi
*email: meir83physics@gmail.com

DETERMINATION OF PHYSICAL PARAMETERS OF THE W40 HII REGION USING OBSERVATIONS OF H110α RADIO RECOMBINATION LINE

HII regions are ionized regions of interstellar gas, which ionized by intensive ultraviolet radiation from nearby hot stars. Radio recombination line is one of the main tools for investigating the HII region, in particular, the distribution of HII is obtained and the main physical conditions of the interstellar matter are determined from hydrogen lines. This study was carried out based on the analysis of the H110α recombination emission line toward the W40 HII region, which is one of the most active star-forming regions in the Aquila Molecular Cloud. We used archival observational data of the H110α radio recombination line in the Aquila Molecular Cloud, obtained during February in 2015 using the 26m NanShan radiotelescope in the Xinjiang Astronomical Observatory of the Chinese Academy of Sciences.

During the period of the study, an integrated intensity map of H110α toward the W40 HII region and the corresponding spectra were constructed. The electron density and temperature of the HII region, the emission measure, the optical thickness, the Lyman continuum flux, the excitation parameter, the radius of the Strömgren sphere, and the mass of ionized hydrogen inside the sphere were calculated. The values of the emission measure and optical thickness indicate that the H110α recombination radio line is optically thin and traces a very dense region (<6462 AU) with a high electron temperature. The numbers of photons of the Lyman continuum indicates the presence of a massive O9.5 star, that equivalent to a zero-age main-sequence star located within the HII region. The obtained values of the physical parameters indicate that the region of ionized hydrogen under study is an ultracompact region. The results of this article lay the foundation for further research aimed at studying the evolution of HII regions, as well as their role in the processes of starformation.

Key words: radiorecombination lines, HII regions, starformation, W40 region.

А.Б. Манапбаева[1], А.Ж. Омар[1], Н.Ш. Алимгазинова[1], Т. Көмеш[1,2],
М.Т. Қызғарина[1,*], Ж. Есімбек[3], Ж. Әсембай[1]
[1]Әл-Фараби атындағы Қазақ ұлттық университеті, Қазақстан, Алматы қ.
[2]Назарбаев университеті, Қазақстан, Астана қ.
[3]Шыңжаң Астрономиялық Обсерваториясы, Қытай Ғылым Академиясы, ҚХР, Үрімжі қ.
*email: meir83physics@gmail.com

W40 HII аймақтың физикалық параметрлерін H110α рекомбинациялық радиосызығын бақылау арқылы анықтау

HII аймақтары – жақын маңдағы ыстық жұлдыздардың қарқынды ультракүлгін сәулеленуімен иондалған жұлдызаралық газдың иондалған аймақтары. HII аймағын зерттеу үшін радиорекомбинациялық сызықтар негізгі құралдардың бірі болып табылады, атап айтқанда, HII таралу сутегі сызықтарынан алынады және жұлдыз аралық ортаның негізгі физикалық жағдайлары анықталады. Бұл зерттеу Aquila молекулалық бұлтындағы ең белсенді жұлдыз түзетін аймақтардың бірі болып табылатын W40 HII аймағы бағытында H110α рекомбинациялық эмиссия сызығын талдау негізінде жүргізілді. Бұл зерттеуді жүргізу үшін біз 2015 жылдың ақпан айында Қытайдың Шыңжаң Астрономиялық Ғылым академиясының 26 м Нань-Шань радиотелескопында алынған Aquila молекулалық бұлтындағы H110α радиорекомбинация сызығының мұрағаттық бақылау деректерін қолдандық.

Зерттеу барысында W40 HII аймағы бағытында H110α интегралды сәулелену қарқындылығының картасы және сәйкес спектрлер құрастырылды. Зерттеу нәтижесінде HII аймағының электрон тығыздығы мен температурасы, эмиссия өлшемі, оптикалық қалыңдық, Лайман континуум ағыны, қозу параметрі, Стремгрен сферасының радиусы және сфера ішіндегі иондалған сутегінің массасы анықталды. Эмиссиялық өлшемнің және оптикалық қалыңдықтың мәндері H110α рекомбинациялық радио сызығы оптикалық тұрғыдан жұқа және электрон температурасы жоғары өте тығыз аймақты (<6462 AU) қадағалайтынын көрсетеді. Лиман континуумындағы фотондар саны HII аймағында орналасқан нөлдік жастағы негізгі тізбекті жұлдызға тең массивті O9,5 жұлдызының бар екенін көрсетеді. Физикалық параметрлердің алынған мәндері зерттелетін иондалған сутегі аймағы ультра жинақы аймақ екенін көрсетеді. Бұл зерттеудің нәтижелері HII аймақтарының табиғаты мен эволюциясын, сондай-ақ олардың жұлдыздардың пайда болу процестеріндегі кеңірек контексттегі рөлін зерттеуге бағытталған одан әрі зерттеулердің негізін қалады.

Түйін сөздер: рекомбинациялық радиосызығы, HII аймағы, жұлдызқалыптасу, W40 аймағы.

А.Б. Манапбаева[1], А.Ж. Омар[1], Н.Ш. Алимгазинова[1], Т. Комеш[1,2], М.Т. Кызгарина[1,*], Ж. Есимбек[3], Ж. Асембай[1]

[1]Казахский национальный университет имени аль-Фараби, Казахстан, г.Алматы

[2]Назарбаев университет, Казахстан, г.Астана

[3]Синьцзянская астрономическая обсерватория Академии наук Китая, г. Урумчи, Китай

*email: meir83physics@gmail.com

Определение физических параметров области W40 HII по наблюдениям рекомбинационной радиолинии H110α

Области HII - это ионизированные области межзвездного газа, которые были ионизированы интенсивным ультрафиолетовым излучением близлежащих горячих звезд. Для изучения области HII одним из основных инструментов являются радиорекомбинационные линии, в частности по линиям водорода получают распределение HII и определяют основные физические условия межзвездной среды. Данное исследование проведено на основе анализа рекомбинационной линии излучения H110α в направлении региона W40 HII, который является одним из самых активных областей звездообразования в молекулярном облаке Aquila. Для проведения данного исследования нами были использованы архивные данные наблюдений радиорекомбинационной линии H110α в молекулярном облаке Aquila, полученные в течение февраля 2015 года на 26-м радиотелескопе Нань-Шань Синьцзянской астрономической обсерватории Китайской академии наук.

В ходе исследования построена карта интегральной интенсивности излучения H110α в направлении области W40 HII и соответствующие спектры. В исследовании были определены электронная плотность и температура региона HII, мера эмиссии, оптическая толщина, поток лаймановского континуума, параметр возбуждения, радиус сферы Стремгрена и масса ионизированного водорода внутри сферы. Значения меры эмиссии и оптической толщины указывают на то, что рекомбинационная радиолиния H110α оптически тонкая и прослеживает очень плотную область (<6462 а.е.) с высокой электронной температурой. Число фотонов континуума Лаймана показывает наличие массивной звезды типа O9.5, эквивалентной звезде главной последовательности нулевого возраста, расположенной внутри области HII. Полученные значения физических параметров указывают на то, что исследуемая область ионизированного водорода является ультракомпактной областью. Результаты проведенного исследования закладывают основу для дальнейших исследований, направленных на изучение природы и эволюции областей HII, а также их роли в более широком контексте в процессах звездообразования.

Ключевые слова: рекомбинационная радиолиния, область HII, звезообразование, область W40.

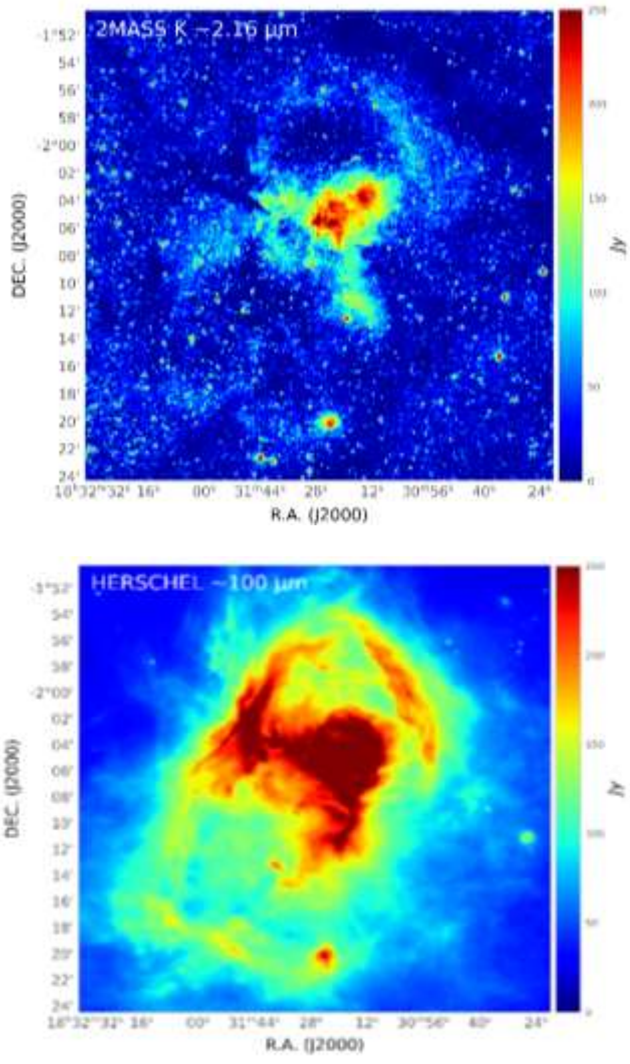
Introduction

HII regions are ionized regions of interstellar gas that mainly consists of hydrogen (H) atoms which ionized by intensive ultraviolet radiation from nearby hot stars. HII regions can be either extended to several hundred light years or be very compact. Thus HII regions have a wide range of densities, from a few atoms/cm^3 to millions of atoms/cm^3 for the most compact regions, and temperature in HII regions is around 10000 Kelvin [1]. In our Galaxy, HII regions are distributed in a pattern similar to that of the molecular clouds from which stars form, and are similarly concentrated in the spiral arms of other galaxies. They are also found in association with newly formed stars in all irregular galaxies, making them highly visible traces of active star formation. Therefore, they are often associated with young massive stars and serve as indicators of ongoing star formation [2].

HII regions emit at certain frequencies, including radio frequencies, which can be observed as recombination lines. Recombination radio lines (RRLs) provide valuable information about the physical conditions in the HII region. By studying the intensity and characteristics of recombination lines, one can gain insight into the properties of HII regions, including their temperature, density, size, mass, ionization state and kinematics [3-5]. This information helps us to understand the formation and evolution of stars, as well as the dynamics of interstellar gas in galaxies.

Materials and Methods

In this article we study the HII region in the Aquila Molecular Cloud, which coincides with the star formation region W40 (Figure 1). The central dense W40 HII region with coordinates RA(J2000)=18^{h}31^{m}29^s, DEC(J2000)= -02^{0}05′24″ has a diameter of ≈ 3.5 pc, and the width of the HII region is ≈ 1 pc [6]. Infrared radiation sources of large masses are used here (IRS 1A South, IRS 2B, IRS 3A и IRS 5), which illuminate the HII region [7, 8].



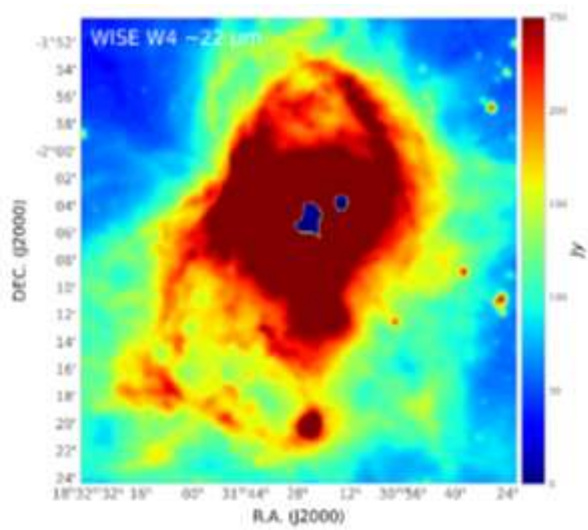


Figure 1 – W40 HII starformation region in Aquila Molecular Cloud at different wavelengths according to the data of 2MASS (2.16 μm), WISE (22 μm) and HERSCHEL (100 μm) [15]. Intensity is given in Jy.

A dense dark cloud about 20′ in diameter surrounds the H II region [9–10]. The space between the hot, ionized HII region and the cold molecular cloud is marked by a thin HII region and an accompanying neutral interface [11]. The average radio continuum flux density in the HII region is 34 Jy [12]. W40 is located at a distance of 37 pc above the plane of the Galaxy [13]. The distance to the W40 region is 436 ± 9 pc (1420 ± 30 light years) [14], we suppose it to be one of the closest places for the formation of massive O and B type stars.

The W40 HII star formation region has been studied in detail by many authors. Most studies, however, have focused on studies in the infrared, X-ray, and radio ranges [16, 17]. However, studies of this region at the frequencies of hydrogen recombination lines have not been found; therefore, it is of interest to study and determine the physical parameters of the W40 HII region. Figure 1 shows distribution maps of interstellar matter toward the W40 HII region at various infrared wavelengths. We see that the intensity of the emission of interstellar matter in W40 HII lies in a wide range of values and the apparent sizes of the region differ at different wavelengths.

Results and Discussion

This section disclosures main concept of the work and contains an analysis and discussion of research results as well as conclusions on the results obtained during the research. Results and Discussion is one of the most important sections of article. Analysis of the present work's results and discussion on them in comparison with previous works, analyzes and conclusions, must be done.

To study the HII region, radio recombination lines are one of the main tools, in particular, the distribution of HII is obtained from hydrogen lines and the main physical conditions of the interstellar medium are determined.

To conduct this study, we used archival observational data of the H110α radio recombination line (ν_0 = 4874.1570) in the Aquila molecular cloud, obtained during February in 2015 at the 26 m NanShan radiotelescope in the Xinjiang Astronomical Observatory of the Chinese Academy of Sciences [18].

Figure 2 illustrates a integrated intensity map H110α toward the W40 HII region. Since the most direct way to track the ionized gas is likely to be dust emission, which dominates at these frequencies in the continuum, the presented integrated map of the H110α emission shows the contours of the dust continuum, according to [19]. The position of the peak in the velocity-integrated linear radiation, equal to 86 Jy/beam km/s, coincides with the position of the dust continuum. The spectrum of the H110α line is shown in Figure 3. The range of integration velocities is from -20 to 10 km/s. For the HII region, from the size of the deconvolutional beam of the observations used, we obtain the internal size Θ_S =632″,456.

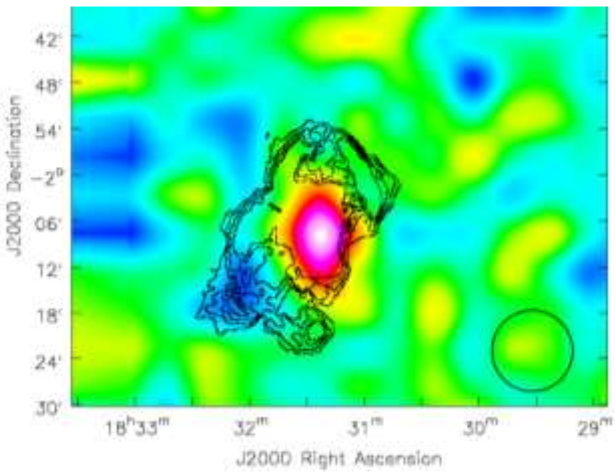


Figure 2 – Integrated intensity map of H110α toward W40 HII region in the Aquila Molecular Cloud. The contours of the continuum radiation are superimposed in black. The black ellipse shown in the lower right corner indicates the beam size at half power, which is equal to 10′

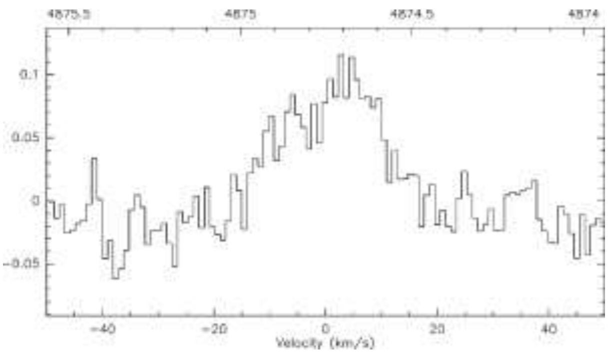


Figure 3 – A spectra of H110α line

An analysis of the intensity maps of the 13CO (1-0) line and the maps of the H2CO formaldehyde absorption line in our previous studies [20] formaldehyde absorption line in our previous studies H110α line in W40 HII has no analogue in this profile at lower velocities, but there will be a weak spectral component in the absorption spectrum for the H2CO line at -8.5 км/s. At the maximum continuum temperature of 3.33 К the ratio T_L/T_c has a peak value of 0,038 with an average optical depth of 0.15. The profile of the H110α resembles a spherical (blueshifted) outflow with an approximate shape $(1-(V/V_0)^2)^n$, where the outflow velocity of matter V_0 is around of 25 km/s. The local thermodynamic equilibrium electron temperature T_e^* is determined by the formula [21]:

$$T_e^* = \left[3.624 \times 10^4 \cdot \left(\frac{T_c}{T_L} \cdot \Delta\nu\right)\right] 0.87, \qquad (1)$$

where T_e^* has the value of 7300 K assuming maximum optical depth and linewidth at half power of 24 km/s. This value makes sense when all H110α radiant fluxes occur on the outskirts of a typical HII region.

In order to characterize the emissivity of the HII region under certain conditions in spectral lines the emission measure (EM) is used, which is determined under the assumption $T_e = T_e^*$ from the equation [22, 23]:

$$EM = 7.1 pc\ cm^{-6} \left(\frac{S_L}{Jy}\right)\left(\frac{\lambda}{mm}\right)\left(\frac{T_e}{K}\right)^{1.5}\left(\frac{\Delta V}{km\ s^{-1}}\right)\left(\frac{\theta_S}{arcsec}\right), \qquad (2)$$

where θ_s = 632''.456 is internal size. For H110α line the maximum line intensity is S_L= 452.64 Jy. For HII region we obtain $EM = 7.4 \times 10^6 pc\ cm^{-6}$ at the observed wavelength which is equal to λ = 6 cm. Electron density $n_e = 1.54 \times 10^4\ cm^{-3}$ is estimated by $EM = n_e^2 \left(\frac{L}{AU}\right) f_\nu$, where $L = 10.2 \times tg(\theta_s)$ is the path in kpc and $f_\nu = 1$ is the volume filling factor. The length of the region under consideration was 6462 AU. Continuous optical depth τ_c in central part of HII region is determined from [24]:

$$\tau_c = 0.08235 \alpha(\nu, T_e)\left(\frac{\nu}{GHz}\right)^{-2.1}\left(\frac{T_e}{K}\right)^{135}\left(\frac{EM}{pc\ cm^{-6}}\right) \qquad (3)$$

we obtain $\tau_c \approx 0.13$ at $\alpha(\nu, T_e) \approx 1$.

The above parameters indicate that the H110α line is optically thin and traces a very dense region (<6462 AU) with a high temperature (T_e^* = 7300 K). It also indicates that the HII region under consideration may be ultra-compact, which directly surrounds newly formed stars of spectral types O and early B.

To determine the appropriate type of star in the HII region under consideration, we use the Lyman continuum flux N_L, which determines the number of photons emitted by the star per second, and the excitation parameter characterizing the state of gas ionization in the vicinity of the star. The number of photons (N_L) and the excitation parameter (U) are determined from the equations:

$$N_L = 4.761 \times 10^{48} s^{-1} \alpha(\nu, T_e)^{-1}\left(\frac{\nu}{GHz}\right)^{0.1}\left(\frac{D}{kpc}\right)^2 \times \left(\frac{S_\nu^{gas}}{Jy}\right)\left(\frac{T_e}{K}\right)^{-0.45}, \qquad (4)$$

$$U = 2.706 \times 10^{-16} pccm^{-2}\left(\frac{T_e}{K}\right)^{\frac{4}{15}}\left(\frac{N_L}{s^{-1}}\right)^{\frac{1}{3}}, \qquad (5)$$

where $D = 0.436 kpc$ is the distance of HII regions from Sun at $\alpha(\nu, T_e) \approx 1$. Based on our obtained physical parameters, assuming optical fineness and conditions of local thermodynamic equilibrium, we have obtained two upper limits: $N_L = 9 \times 10^{47} s^{-1}$ and $U = 28.0\ pc\ cm^{-2}$. This means that the estimated number of Lyman continuum photons requires a massive star equivalent to a zero-age main-sequence star located inside the HII region.

To determine the region of fully ionized gas that surrounds a hot O9.5 star, we examine the parameters of the Strömgren sphere: the radius and mass of ionized hydrogen inside the sphere. The radius of the Strömgren sphere is the distance from the central star to the point where the ionizing photons emitted by the star are no longer able to support the ionization of the surrounding gas. When limited by ionization in a medium containing only hydrogen, it is equal to

To determine the region of fully ionized gas that surrounds a hot O9.5 star, we examine the parameters of the Strömgren sphere: the radius and mass of ionized hydrogen inside the sphere [25]. The radius of the Strömgren sphere is the distance from the central star to the point where the ionizing photons emitted by the star are no longer able to support the ionization of the surrounding gas. When limited by ionization in a medium containing only hydrogen, it is equal to

$$R = \left(\frac{3N_L}{4\pi\alpha N_e N_{H^+}}\right)^{1/3} \qquad (6)$$

where N_L is total number of Lyman photons emitted per second by an O9.5 star, and $\alpha = 2.06 \cdot 10^{11} T_e^{\frac{-1}{2}} \cdot \varphi_2$ –is the recombination coefficient of hydrogen of the upper levels. $\varphi_2 = 1.389$ factor depends on temperature weakly. From (6), taking into account $N_e = N_{H^+}$, we obtain an expression for the mass of ionized hydrogen in a sphere depending on the electron density:

$$\frac{M_{HII}}{[M_\odot]} = \frac{8.4 \cdot 10^{-58} N_L}{\alpha N_e}. (7)$$

This equation shows that an O9.5-type star ionizes a larger mass of gas in a rarefied medium than in a dense one. Since the rate of recombination is proportional to N_e^2, then ion lifetime H^+ is more in HII regions with lower density. For this reason, the same photon flux in a rarefied medium ionizes more hydrogen atoms than in a dense medium. For these HII regions mass of ionized hydrogen is $M_{HII} = 0.15 M_\odot$ and the diameter of the Strömgren sphere is 0,09 pc.

Thus a study of the intensity and characteristics of the H110α recombination line in W40 region provides some information about the physical parameters in HII region (table 1), which, in turn, made it possible to attribute the W40 HII region to an ultracompact type.

Table 1 – Physical parameters of the HII region

S_L [Jy]	EM $[pccm^{-6}]$	n_e $[cm^{-3}]$	N_L $[c^{-1}]$	U $[pccm^{-6}]$	M_{HII} $(M_\odot)$	Size [pc]	Spectra.Type of stars	Type of HII regions
452,64	7,4×10^6	1.54×10^4	9×10^{47}	28.0	0.15	0,09	O9.5	Ultra-compact

Conclusion

For the first time we have analyzed the radio astronomical observations of the H110α recombination line in the southern regions of the W40 HII in the Aquila Molecular Cloud, which were obtained using the 26 m Nan Shan radiotelescope in the Xinjiang Astronomical Observatory of the Chinese Academy of Sciences.

During the study, a integrated intensity intensity map of H110α and the spectra of this line were obtained. Based on the analysis of observational data, the electron temperature, emission measure, electron density, and continuous optical depth were calculated. The analysis of these parameters led to several important conclusions. Firstly, the H110α line was determined to be optically thin, indicating that the observed radiation is not significantly affected by absorption or scattering processes. This characteristic allows a more accurate interpretation of the physical properties of the region. Secondly, the obtained physical parameters showed that the region is characterized by a very dense medium (<6462 AU). This suggests a compact and concentrated distribution of ionized gas, consistent with the ultra-compact HII region. Such regions are known to surround newly formed stars, especially those of spectral types O and early B, due to intensive ultraviolet radiation and strong ionization.

In addition, the number of Lyman continuum photons and the excitation parameter were determined and used to determine the appropriate type of star associated with the region. The estimated number of Lyman continuum photons requires a massive star equivalent to an O9.5-type zero-age main-sequence star located within the HII region. For the HII region under study, the Strömgren sphere radius and the mass of ionized hydrogen in it were calculated. For the W40 HII region, the mass of ionized hydrogen $M_{HII} = 0.15 M_\odot$, and the diameter of the Strömgren sphere is 0.09 parsec.

In general, the determination of the physical parameters of the W40 HII region through observations of the H110α recombination radio line provided a significant insight into its properties and evolutionary processes. These results contribute to our broader understanding of star-forming regions, their ionization dynamics, and the role of massive stars in shaping their physical characteristics. Future studies may build on these results to further explore the nature and evolution of HII regions and their relationship to star formation processes.

Acknowledgments

This research was funded by the Science Committee of the Ministry of science and Higher Education of the Republic of Kazakhstan (Grant Nos. AP14870504 and AP13067768). JE acknowledges support from the Regional Collaborative Innovation Project of Xinjiang Uyghur Autonomous Region grant 2022E01050.

References

1 Ridpath I.A. Dictionary of Astronomy: H II region (2nd rev. ed.). – Oxford: Oxford University Press. – 2012.

2 Anderson L.D., Bania T.M., Jackson J.M. The molecular properties of galactic HII regions //The Astrophysical Journal Supplement Series. – 2009. – Vol.181, 1. – P.255–271.

3 Tsamis Y.G., Barlow M.J., Liu X-W. Heavy elements in Galactic and Magellanic Cloud H II regions: recombination-line versus forbidden-line abundances //Monthly Notices of the Royal Astronomical Society. – 2003. – Vol.338, 3. – P. 687–710.

4 Zhang C.-P., Wang J.-J., Xu J.-L., Wyrowski F., & Menten K.M. Submillimeter array and very large array observations in the hypercompact HII region G35.58-0.03 //The astrophysical journal. – 2014. – Vol.784. – P.107.

5 Zhang C.-P., Yuan J.-H., Xu J.-L. Searching for initial stage of massive star formation around the H II region G18.2–0.3 //Research in Astronomy and Astrophysics. – 2017. – Vol.17, 6. – P.57.

6 Fich M., Blitz L. Optical HII regions in the outer galaxy //The astrophysical journal. – 1984. – Vol.279. – P.125-135.

7 Smith T.R., Kennicutt R.C. The HII region luminosity function of the milky way //Publications of the astronomical society of the pasific. – 1989. – Vol.101. – P.649-652.

8 Shuping R.Y., Snow T.P., Crutcher R., Lutz B.L. CO and C2 absorption toward W40 IRS 1A //The astrophysical journal. – 1999. – Vol.520. – P.149.

9 Vallee J.P. The warm C II region betwwen the hot ionized region S 64 = W 40 and the cold molecular cloud G 28.74 + 3.52 //Astronomy and astrophysics. – 1987. – Vol.178. – P.237-241.

10 Dobashi K., Uehara H., Kandori R. VizieR Online Data Catalog: Atlas and Catalog of Dark Clouds //Publications of the astronomical society of Japan. – 2005. – Vol.57, 1. – P.S386.

11 Dobashi K. Atlas and Catalog of Dark Clouds Based on the 2 Micron All Sky Survey //Publications of the astronomical society of Japan. – 2011. – Vol.63. – P.S362.

12 Kuhn M.A., Getman K.V. A Chandra Observation of the Obscured Star-forming Complex W40 //Astrophysical Journal. – 2010. – Vol.725, 2. – P.2485–2506.

13 Rodney S.A., Reipurth B. The W40 Cloud Complex. Handbook of Star Forming Regions. – 2008. – Vol.II: The Southern Sky ASP Monograph Publications. 5. – P.43.

14 Ortiz-León G.N. The Gould's belt distances survey //Astrophysical Journal. – 2017. – Vol.837, 2. – P.143.

15 https://vizier.cds.unistra.fr – A complete library of published astronomical catalogues

16 Sun J., Gutermuth R.A., Wang H. Deep near-infrared survey towards the W40 and Serpens South region in the Aquila Rift: A comprehensive catalogue of young stellar objects //Monthly Notices of the Royal Astronomical Society. – 2022. – Vol.516, 4. – P. 5244-5257.

17 Shenoy S.S., Shuping R., Vacca W.D. Multi-Wavelength Study of W40 HII Region //American Astronomical Society Meeting Abstracts. – 2013. – Vol.24. – P.349.

18 Komesh T., Esimbek J. H2CO and H110α Observations toward the Aquila Molecular Cloud //Astrophysical Journal. – 2019. – Vol.874, 2. – P.1-10.

19 Komesh T., Manapbaeva A.B., Esimbek J. Interpretacija radioastronomicheskih nabljudenij H2CO i H110α v oblastjah zvezdoobrazovanija W40 i Serpens South molekuljarnogo oblaka Aquila //Recent Contributions to Physics. – 2020. – No 3 (74). – P.19-28. (in Russ).

20 Manapbaeva A.B., Esimbek J., Alimgazinova N.Sh., Kyzgarina M.T., Atamurat A.B. N22 shan kopirshikteri zhanyndagy zhas zhuldyz obektilerin anyqtau //QR UGA Habarlary. Fizika-matematika serijasy. – 2021. – Vol.3. – P.96–105. (in Kaz).

21 Lin Y., Wyrowski F., Liu H.B. The evolution of temperature and density structures of OB cluster-forming molecular clumps //Astronomy & Astrophysics. – 2022. – Vol.658, A128. – P.46.

22 Habjan E., Faesi Ch. Direct measurements of electron density, temperature, and chemical abundance of HII regions in NGC 4254 //Bulletin of the American Astronomical Society. – 2023. – Vol.55, 2. – P.9.

23 Sorochenko R.L., Gordon M.A. Radio recombination lines. Physics and astronomy. – Moscow: Fizmatlit. (2003). 392 p. (in Russ).

24 Omar A.Zh., Manapbayeva A.B. Aquila moleculalyq bultynyng aimaktaryn CO tangdamaly diccociacijasy adisimen zertteu //QR UGA Habarlary. Fizika-matematika serijasy. – 2023. – Vol.345. –No1. – P.180-191. (in Kaz).

25 Arenas T.A., Bolivar G.M. Approximate analytic solutions for the ionization structure of a pressure equilibrium Strömgren sphere //Revista Mexicana de Astronomía y Astrofísica. – 2015. – Vol.51. – P.241-246.

References

1 I.A. Ridpath, Dictionary of Astronomy: H II region (2nd rev. ed.), (Oxford: Oxford University Press., 2012).

2 L.D. Anderson, T.M. Bania, J.M. Jackson, Astrophys. J., Suppl. Ser., 181 (1), 255-271 (2009).

3 Y.G. Tsamis, M.J. Barlow, X-W. Liu, MNRAS, 338 (3), 687–710 (2003).

4 C.-P. Zhang, J.-J. Wang, J.-L. Xu, F. Wyrowski, & K.M. Menten, Astrophys. J., 784, 107 (2014).

5 C.-P. Zhang, J.-H. Yuan, J.-L. Xu, Res. Astron. Astrophys., 17 (6), 57 (2017).

6 M. Fich and L.Blitz, Astrophys. J., 279, 125-135 (1984).
7 T.R. Smith, R.C. Kennicutt Publications of the astronomical society of the pacific, 101, 649-652 (1989).
8 R.Y. Shuping, T.P. Snow, R. Crutcher, B.L. Lutz, Astrophys. J., 520, 149 (1999).
9 J.P. Vallee, Astronomy and astrophysics, 178, 237-241 (1987).
10 K. Dobashi, H. Uehara, R. Kandori, Publications of the astronomical society of Japan, 57 (1), S386 (2005).
11 K. Dobashi, Publications of the astronomical society of Japan, 63, S362. (2011).
12 M.A. Kuhn, K.V. Getman, Astrophys. J., 725 (2), 2485–2506 (2010).
13 S.A. Rodney, B. Reipurth, The W40 Cloud Complex, Handbook of Star Forming Regions, Volume II, (The Southern Sky ASP Monograph Publications, 5, 2008), p.43.
14 G.N. Ortiz-León, Astrophys. J., 837 (2), 143 (2017).
15 https://vizier.cds.unistra.fr
16 J. Sun, R.A. Gutermuth, H. Wang, MNRAS, 516 (4), 5244-5257 (2022).
17 S.S. Shenoy, R. Shuping, W.D. Vacca, American Astronomical Society Meeting Abstracts, 24, 349 (2013).
18 T. Komesh, J. Esimbek, Astrophys. J., 874 (2), 1-10. (2019).
19 T. Komesh, A.B. Manapbaeva, J. Esimbek, Rec.Contr.Phys., 374, 19-28 (2020) (in Russ).
20 A.B. Manapbaeva, J. Esimbek, N.Sh. Alimgazinova, M.T. Kyzgarina, A.B. Atamurat, QR UGA Habarlary, Fizika-matematika serijasy, 3, 96–105 (2021). (in Kaz).
21 Y. Lin, F. Wyrowski, H.B. Liu, Astronomy & Astrophysics, 658, A128, 46 (2022).
22 E. Habjan, Ch. Faesi, Bulletin of the American Astronomical Society, 55 (2), 9 (2023).
23 R.L. Sorochenko, M.A. Gordon, Radio recombination lines. Physics and astronomy, (Moscow: Fizmatlit., 2003), 392 p. (in Russ).
24 A.Zh. Omar, A.B. Manapbayeva, QR UGA Habarlary. Fizika-matematika serijasy, 345, (1), 180-191 (2023).
25 T.A. Arenas, G.M. Bolivar, Revista Mexicana de Astronomía y Astrofísica, 51, 241-246 (2015).