ISSN 1024-588X. Вісник Львівського університету. Серія фізична. 2023. Випуск 60. С. 137-142
Visnyk of the Lviv University. Series Physics. 2023. Issue 60. P. 137-142

УДК 524.37, 524.5, 524.7
PACS 98.38.Am, 98.38.Ly
https://doi.org/10.30970/vph.60.2023.137

MODELING THE RADIAL DISTRIBUTION OF CHEMICAL COMPOSITIONS IN CRAB NEBULA FILAMENTS

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The chemical compositions within the filaments of the Crab Nebula were determined using a 3-stage optimized photoionization modeling method of the nebular gas, employing diagnostic ratios between emission line intensities. The radial distribution of chemical compositions within the Crab Nebula filaments was analyzed using observed data obtained from seven distinct aperture positions on the Crab Nebula filaments. Our results do not confirm an increase of the relative abundance of chemical elements in the outward direction obtained previously by diagnostic method.

Key words: Crab Nebula, nebular diagnostics, photoionization modelling.

1. Intoduction

The filaments observed within the Crab Nebula represent the remnants of a supernova explosion observed from Earth in 1054 AD, as documented by Japanese and Chinese astronomers of the time.

The spectra of these filaments resemble those of planetary nebulae, consisting of rarefied nebular plasmas primarily heated through photoionization by the ionizing radiation emitted from their central stars. In the case of the Crab Nebula, the emission from the filaments stems from the ionization of its amorphous mass by ionizing quanta emitted by relativistic (synchrotron) electrons accelerated by the strong magnetic field of the central pulsar.

Several scientists have investigated the chemical compositions within the filaments of the Crab Nebula [1–4]. The data obtained by these researchers reveal significant spatial variations in the chemical compositions. These variations do not stem from observational errors; rather, they appear to be intrinsic. Holovatyy and Pronik [4] demonstrated an increase in chemical abundances in the outward direction within the Crab Nebula, a result that challenges the theory of stellar nucleosynthesis. In this study, we aim to verify this claim using an optimized photoionization modeling approach.

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2. Input data for modeling

In our study, we present novel approach into the chemical compositions of the filaments within the Crab Nebula. Before our research, we analyzed observed spectra [3]. To improve the precision of our chemical composition determinations, we employed an innovative 3-stage method based on optimized photoionization modeling (OPhM) of the nebular gas [5].

Using the FREE_DIAGN code, we derived electron temperatures T_e, electron densities n_e, ionic abundances, and chemical compositions for individual filaments of the Crab Nebula. This code incorporates the ionization-correction factors (ICFs) for planetary nebulae to account for density inhomogeneities within the nebular gas [6].

The distances from the center of the Crab Nebula to the individual filaments have been recalculated, assuming a distance to Earth of 1800 pc. To determine the distances to the observed parts of the Crab Nebula, we used averaged radial and electron density-weighted ionic abundances, specifically $\mathrm{O^+/H^+}$ and $\mathrm{O^{++}/H^+}$.

In [7], a relationship was established between the distances from the center of the Crab Nebula to the observed filaments and the oxygen ionic abundances there:

$$R = 689,70 \times \left(\frac{O^{++} + O^{+}}{H^{+}} - 7,02 \times 10^{-4} \right) \text{ pc.} \tag{1}$$

As a result, in [7], the radial distribution of chemical compositions in the Crab Nebula filaments were determined using diagnostic results. It was obtained that there is an increase in abundances as one moves outward from the central region for He/H, O/H, and Ne/H, while no such increase was observed for S/H and N/H:

$\mathrm{He/H} = -0.225(\pm 0.011) + 0.461(\pm 0.015) * \mathrm{R}$,
$\log(\mathrm{O/H}) = -4.39(\pm 0.43) + 0.80(\pm 0.48) * \mathrm{R}$,
$\log(\mathrm{Ne/H}) = -5.30(\pm 0.51) + 0.99(\pm 0.28) * \mathrm{R}$,
$\log(\mathrm{N/H}) = -4.51(\pm 0.63) + 0.09(\pm 0.73) * \mathrm{R}$,
$\log(\mathrm{S/H}) = -4.56(\pm 0.77) - 0.49(\pm 0.90) * \mathrm{R}$.

We decided to recalculate the chemical compositions using a method based on optimized photoionization modeling to improve the accuracy of the diagnostic method. We started to solve this task in paper [7] and performed OPhM only for three aperture positions. Here we represent OPhM for rest aperture positions.

3. Optimized photoionization modeling

The chemical compositions in the filaments of the Crab Nebula were determined using a novel 3-stage method [5] based on OPhM of the nebular gas. This method relies on the utilization of specific diagnostic ratios (DRs) between emission line intensities, which are sensitive to electron temperature and/or electron density, as well as on the interrelationships between emission line intensities of chemical elements in adjacent ionization stages, which are sensitive to the shape of ionizing radiation spectra, and were employed to reproduce the observed data [5]: λ6731[SII] / λ6716[SII], λ7323[OII] / λ7332[OII], λ3727[OII] / λ6300[OI], λ4686(HeII) / λ4471(HeI), λ4686(HeII)/ λ5876(HeI), λ4471(HeI) / λ5412(HeII), λ5876(HeI) / λ5412(HeII), λ4959[OIII] / λ4363[OIII], λ5007[OIII] / λ4363[OIII], λ5007[OIII] / λ3727[OII], λ6731[SII] / λ6312[SIII].

At the first stage, we determined the ionization structure of the nebula primarily by reproducing the observed diagnostic ratios between line intensities. In the second stage, we adjusted the abundances of chemical elements based on the previously obtained ionization structure. In the final third stage, we optimized all free parameters to mitigate any consequences stemming from the assumptions, allowing us to divide the optimization process into the initial two stages.

We analyzed the impact of variations in each of the free parameters on the results of OPhM. Our analysis led to the conclusion that He/H, O/H, and, for high abundances, S/H should be included as free parameters in the first calculation stage. Additionally, the N/H abundance should be included if it attains high values.

The following free parameters were employed for the OPhM of the Crab Nebula: hydrogen density, covering factor, energy distribution in ionizing spectra, and chemical abundances (He/H, O/H, and sometimes S/H for Stage I; all available chemical elements for Stage II and Stage III). To initialize the chemical composition of elements, we used corresponding data previously obtained through diagnostic methods.

For the comparison of modeling results with observed data, we used the relative intensities of emission lines, the flux in the H_β line, the nebular outer radius, and the diagnostic ratios. Additionally, we replicated the observed relationship between the H_α and H_β lines.

The ionizing Lyman continuum (Lyc) spectrum was also adjusted during the optimization process. This allowed us to reproduce the optimal energy distribution in the ionizing radiation spectrum within corresponding modeling region. As a result, a detailed investigation of the ionizing radiation transfer from the pulsar to the modeled (observed) part of the nebula was not required.

We have used Peter van Hoof's optimization algorithm Phymir (*http://dissertations.ub.rug.nl/faculties/science/1997/p.a.m.van.hoof*) to minimize the χ^2-function. For the OPhM of the nebular gas in the filaments, we employed Gary Ferland's Cloudy 08.00 code (*http://www.nublado.org*), which was enhanced to include the shape of the ionizing spectrum as a free parameter and to compare the model diagnostic ratios with the observed ones. We analyzed the sensitivity of relative line intensities and diagnostic ratios to variations in chemical abundances and accounted for these factors.

The radial distribution of chemical elements in the filaments of the Crab Nebula was examined using OPhM results for all seven available parts of the Crab Nebula filaments. However, as it can be seen in Fig. 1 the OPhM results did not confirm an increasing of chemical elements abundance from the central region of the nebula in outward direction.

Conclusions

The radial distribution of chemical compositions in the filaments of the Crab Nebula was examined using OPhM results for all seven available segments of this nebula filaments. The OPhM results did not confirm an increase in the abundance of chemical elements from the central region of the nebula. Thus, the stellar evolutionary nucleosynthesis theory is no longer in conflict with the results of the determination of chemical abundances in the Crab Nebula. In our view, the diagnostic errors in determini-

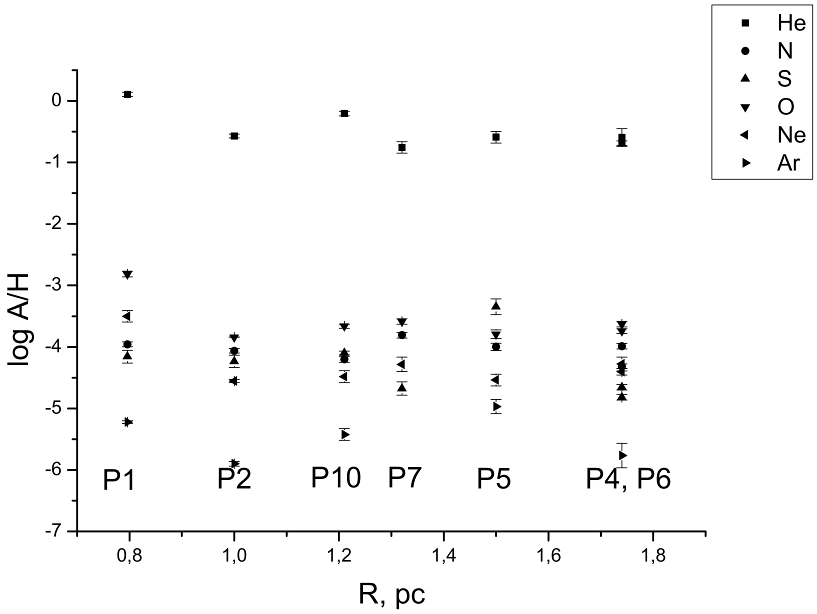

Fig. 1. The radial distribution of the chemical compositions in Crab Nebula filaments based on OPhM results.

ng the chemical abundances through diagnostic methods are due to the use of ICFs of planetary nebulae. It appears necessary to derive ICFs separately for supernova remnants. This necessity arises at least from photoionization models, as they should be calculated based on synchrotron spectra of ionizing radiation, rather than on the spectrum from models of stellar atmospheres (as in the case of planetary nebulae photoionization models). Only such photoionization models can be used to derive the new ICFs for supernova remnants.

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Статтю отримано: 16.10.2023
Прийнято до друку: 06.11.2023

Модельний радіальний розподіл хімічного вмісту у волокнах Крабоподібної туманності

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Хімічний вміст волокон Крабоподібної туманності було визначено за допомогою 3-стадійного методу пошуку оптимізаційних фотоіонізаційних моделей світіння (ОФМС) небулярного газу. Цей метод використовує діагностичні співвідношення між інтенсивностями емісійних ліній. На першій стадіїї розрахунку ОФМС визначається іонізаційна структура туманності шляхом відтворення спостережуваних діагностичних співвідношень між інтенсивностями емісійних ліній та відношень між інтенсивностями ліній йонів у сусідніх стадіях іонізації. На другій стадіїї корегується хімічний вміст при знайденій попередньо іонізаційній структурі. На третій стадії розрахунку ОФМС всі вільні параметри залучаються до оптимізаційного процесу одночасно, щоб уникнути потенційних неточностей, які можуть бути результатом припущень, зроблених під час поділу процесу оптимізації на перші два етапи. При оптимізаційному моделюванні було використано наступні вільні параметри: густина водню, фактор заповнення туманності газом, енергетичний розподіл іонізуючого спектру та хімічний склад. Для порівняння результатів моделювання зі спостережуваними даними були використані наступні параметри: модельні емісійні спектральні лінії, потік в лінії H_β, зовнішній радіус туманності та відповідні діагностичні співвідношення. Іонізуючий Lyc-спектр також змінювався при оптимізаційному моделюванні. Для мінімізації χ^2-функції було використано оптимізаційний алгоритм *Phymir* Пітера ван Гофа (*http://dissertations.ub.rug.nl/faculties/science/1997/p.a.m.van.hoof*). Для розрахунку ОФМС небулярного газу у волокнах Крабовидної туманності було використано програму Гарі Ферланда *Cloudy* 08.00 (*http://www.nublado.org*), яка була попередньо модифікована нами з метою включення параметрів, що задають форму спектру іонізуючого випромінювання, до вільних параметрів оптимізаційних моделей, а також з метою порівняння модельних та спостережуваних співвідношень між інтенсивностями емісійних ліній. Було проаналізовано радіальний розподіл хімічних вмістів у волокнах Крабоподібної туманності на основі розрахунків 7 оптимізаційних моделей. Результати не підтвердили зростання вмісту хімічних елементів з відстанню від центру туманності.

Ключові слова: Крабоподібна туманність, небулярна діагностика, фотоіонізаційне моделювання.