

Photoionisation modelling of the H II regions surrounding star-forming regions within the metallicity range $Z = 0.003\text{--}0.012$

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We present the new approach to the ionisation structure modelling for the high-metallicity H II regions. The method is based on the multicomponent photoionisation modelling (MPhM) of these objects that takes into account their complicate structure due to superwind from the central star-forming region. The complex structure of H II region has been divided into internal and external components. Internal components correspond to the region of free expanding superwind and the cavity of superwind, respectively, while the external ones – to a thick layer of gas compressed by a superwind shock, and hydrodynamically undisturbed outer part of H II region, where the most of observed strong emission lines are formed. The components of the model were calculated within the assumption of spherical symmetry. The gas photoionisation was caused by the ionising quanta of both direct and diffuse ionising radiation. The fluxes of this radiation were calculated during the simulation using the radiative transfer equations which account for all important processes in the H II region causing this transfer. The diffuse ionising radiation was calculated in the Outward Only approach. In the region of free expansion of the superwind the chemical abundances were determined using the evolutionary population synthesis models of a star-forming region. The distributions of the electron temperature and density in the external components were obtained in such modelling as the solutions of the photoionisation energy balance equation. The stop criterion for evolutionary modelling corresponding to the condition of equilibrium of pressure on the boundary between the third and fourth components was adopted. The evolutionary grid of multicomponent high-metallicity models of the H II regions was calculated. It was shown that the internal structure of a H II region under certain conditions can cause the lack of quanta in the spectrum of ionising radiation.

Key words: ISM: H II regions, bubbles, evolution; galaxies: starburst

INTRODUCTION

The chemical abundances in low-metallicity H II regions are important for determination of the primordial helium abundance [8–12]. For more precise determination of its enrichment during the stellar chemical evolution of matter, the abundances of high-metallicity H II regions as well as of other high-metallicity nebular environments (e.g. planetary nebulae) can be also used. In the large spiral galaxies the stellar chemical evolution is much faster than in the dwarf ones. Therefore, the nebular gas in their H II regions is characterised by the higher metallicity (description of the mass-metallicity relation can be found e.g. in [3, 20, 29, 34]). The H II regions are very useful for investigation of the spatial distribution of chemical elements in the spiral galaxies (large surveys such as CALIFA, MaNGA, SAMI are described e.g. in papers [1, 21, 30, 35]), because they produce strong emission lines which can be used

for determination of the chemical composition using the fast diagnostic methods [4, 24, 25].

All mentioned above tasks require the abundances of the chemical elements determined correctly and as precisely as possible. For example, to determine the chemical abundances in high-metallicity H II regions it is necessary to use the so-called calibrating methods [24], because the weak auroral emission lines required for the determination of abundances of the corresponding chemical elements using the T_e -method [25] (e.g. the auroral line [O III] $\lambda 4363$ in the case of O/H determination) are absent in most of the observed emission spectra of high-metallicity H II regions. Calibrating methods are often based on the photoionisation modelling [7, 31].

In the case of usage of the diagnostic methods, which are based on method of the crossing curves of $n_e - T_e$ dependences [4], it is possible to determine the chemical abundances for the observed ionisation

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stages. To take into account the unobserved ionisation stages the ionisation-correction factors (ICFs) method is usually used. The derivation of expressions for ICFs in most cases is also based on the photoionisation modelling of H II regions [5, 6, 17, 31].

Thus, photoionisation modelling plays the crucial role during determination of the chemical elements abundance in H II regions. Therefore, such modelling should be performed in the most correct way available at present day.

In our previous papers [13–18, 23] we developed the multicomponent photoionisation modelling (MPhM) method, which takes into account the presence and evolution of a superwind region (SWR). In the last (newest) version of our method we used the model of Chevalier and Clegg [2] to define the temperature distribution in the SWR free expansion region (it is the first component in our simulations). The second SWR component in our MPhM contains the hot rarefied gas thermalised by the reverse shock. The physical conditions (density and temperature distributions) and their evolution in this region in our models are described using the theory by Weaver & Castor [33]. Density within the third component containing the gas compressed by the direct shock of SWR is determined during MPhM using the constant pressure condition at boundary between the second and third components. The fourth component contains the hydrodynamically undisturbed nebular environment. The physical conditions are determined using the ordinary photoionisation modelling. The presence of dust grains is taken into account in our MPhM. Our models of the low-metallicity H II regions reproduce the intensities of strong emission lines within the observed range (see e.g. [17]). Also, they explain the presence of high excitation lines He II 4686 Å and [Ne V] 3626 Å in the observed spectra of H II regions in the blue compact dwarf galaxies (BCDGs) [32].

In this work we present the MPhM results for high-metallicity H II regions.

DESCRIPTION OF MODELS

The detailed description of our method for MPhM of H II regions surrounding star-forming regions can be found in our previous work [17]. Here we enumerate only the differences between the grid input parameters in this work and in [17], respectively: (i) The metallicity of H II regions in this work is within the following range: $Z = 0.003\text{--}0.012$, $12 + \lg(\text{O}/\text{H}) = 8.2\text{--}8.67$; (ii) The total fixed mass M_* of stars in a star-forming region used in evolutionary population synthesis by the code **Starburst99** [19] was assumed to be $(10^4, 10^5, 10^6, 10^7, 10^8, 10^9, 10^{10}) M_\odot$. The metallicity of stars Z_* used in the **Starburst99** code has next values: 0.002, 0.008, 0.014; (iii) The density n_0 in the fourth component (outer component in our multicomponent photoionisation modelling) has the following values: (0.05,

1, 10, 50) cm^{-3} ; (iv) The modelling spectra were compared with the relative intensities of strong emission lines of the observed spectra for H II regions of the blue compact dwarf, spiral and irregular galaxies from [12, 26–28].

Exponents of the Kroupa initial mass functions (IMF) of stars are 1.3 and 2.3 in the range of stellar masses $(0.1 \dots 0.5) M_\odot$ and $(0.5 \dots 100) M_\odot$, respectively.

The calculation of our models was stopped in the case of pressure balance at boundary of the third and fourth components. The outer radius of the third component and the age at which it occurs are called the stagnation radius and stagnation age, respectively. Simultaneously, the bubble expansion stops, and later, probably, the third component is fragmented with the further decay of the adopted SWR structure due to the hydrodynamic instabilities [17]. Thus, we calculated the evolutionary sequences of such models for ages from 1 Myr until reaching the stagnation radius (or in other words the stagnation age) [17]. These models take into account the evolution of internal structure of the high-metallicity H II regions due to the presence of superwind from the central star-forming region. *Lyc*-spectra of the star-forming region and their evolution were obtained using the **Starburst99** code.

Also, such MPhM of H II regions accounts for the radiative transfer through SWR components. Therefore, we suggest that such modelling approach describes the ionisation structure of H II regions more correctly than the ordinary photoionisation models.

Despite the fact that galaxies with the high-metallicity H II regions are characterised by continuous star-formation we used the starburst model of the central star-forming region for these high-metallicity H II regions assuming that the star-forming process with continuous rate always can be theoretically approximated as a sequence of instantaneous bursts.

RESULTS, THEIR ANALYSIS AND CONCLUSIONS

The following four types of the *Lyc*-spectra shape transformation due to the transfer of ionising quanta through the SWR components are shown in Fig. 1:

- (1) Output from the SWR bubble *Lyc*-spectrum at the photon energies $> 5 \text{ Ryd}$ is characterised by the higher number of ionising quanta than the original one from stars. It means that at such photon energies the SWR components emit the ionising quanta additional to ones emitted by stars and not absorbed by these components, and as results at the output from SWR we have obtained in this photon energy range the higher number of ionising quanta than of ones emitted by stars. The input parameters of models with this type of the *Lyc*-spectra shape were

as follows: Age = 5, 6 Myr, $n_0 = 0.05 \text{ cm}^{-3}$, $M_* = 10^4 M_\odot$, $Z_* = 0.002$. It means that such situation can occur in the case when SWR is surrounded by the rarefied gas (component four), and as result the SWR is large, after the age (4-5 Myr) of supernovae explosions, when the mechanical energy from these explosions was transformed into the thermal energy of the rarefied gas in SWR cavern that emits the UV and soft X-ray photons.

- (2) This type is characterised by the lack of quanta (in comparison with the *Lyc*-spectrum from stars) at the energies $\geq 4 \text{ Ryd}$ (ionisation potential for He^+). This lack of quanta is due to the absorption of ionising radiation within the third component. The input parameters of models with this type of *Lyc*-spectra shape were as follows: Age = 1-6 Myr, $n_0 = 1\text{--}50 \text{ cm}^{-3}$, $M_* = 10^5\text{--}10^7 M_\odot$, $Z_* = 0.002, 0.008, 0.014$. It can be seen that the higher values of n_0 than in the previous case are required to form the sufficiently dense third component.
- (3) This type is characterised by the lack of quanta at the energies $\geq 1 \text{ Ryd}$ (ionisation potential of H^0) and then we see the additional ‘jump down’ of spectrum at $\geq 1.8 \text{ Ryd}$ (ionisation potential of He^0). This lack of quanta is due

to the absorption of ionising radiation by H^0 and He^0 . The input parameters of models with this type of *Lyc*-spectra shape were as follows: Age = 4, 5 Myr, $n_0 = 1 \text{ cm}^{-3}$, $M_* = 10^4\text{--}10^6 M_\odot$, $Z_* = 0.008, 0.014$. This is a typical case when the third component causes the lack of quanta in *Lyc*-spectra. In this case we obtain a compact, entirely formed cavern limited from the outside by a thin compressed layer with high density. Under certain conditions, such layer really causes the change of the *Lyc*-spectrum shape influencing the appearance of so-called spectral lack of quanta in the photon energy range of 1-1.8 Ryd. The physical cause of the appearance of such lack of quanta is the peculiarity of energy dependence of the effective cross-sections of photoionisation σ_v for the Hydrogen-like ions having the sharp maximum for ionisation potential that decreases rapidly with the increase of photon energy. As the length of free path of photon in the medium with density n is determined as $l_v = 1/(\sigma_v n)$, while transferring through the thin layer of high density, the quanta with energy close to the ionisation potential will be absorbed more efficiently than the quanta with higher energies, the most of which will penetrate the ambient inward part of H II region non-perturbed by the wind [16].

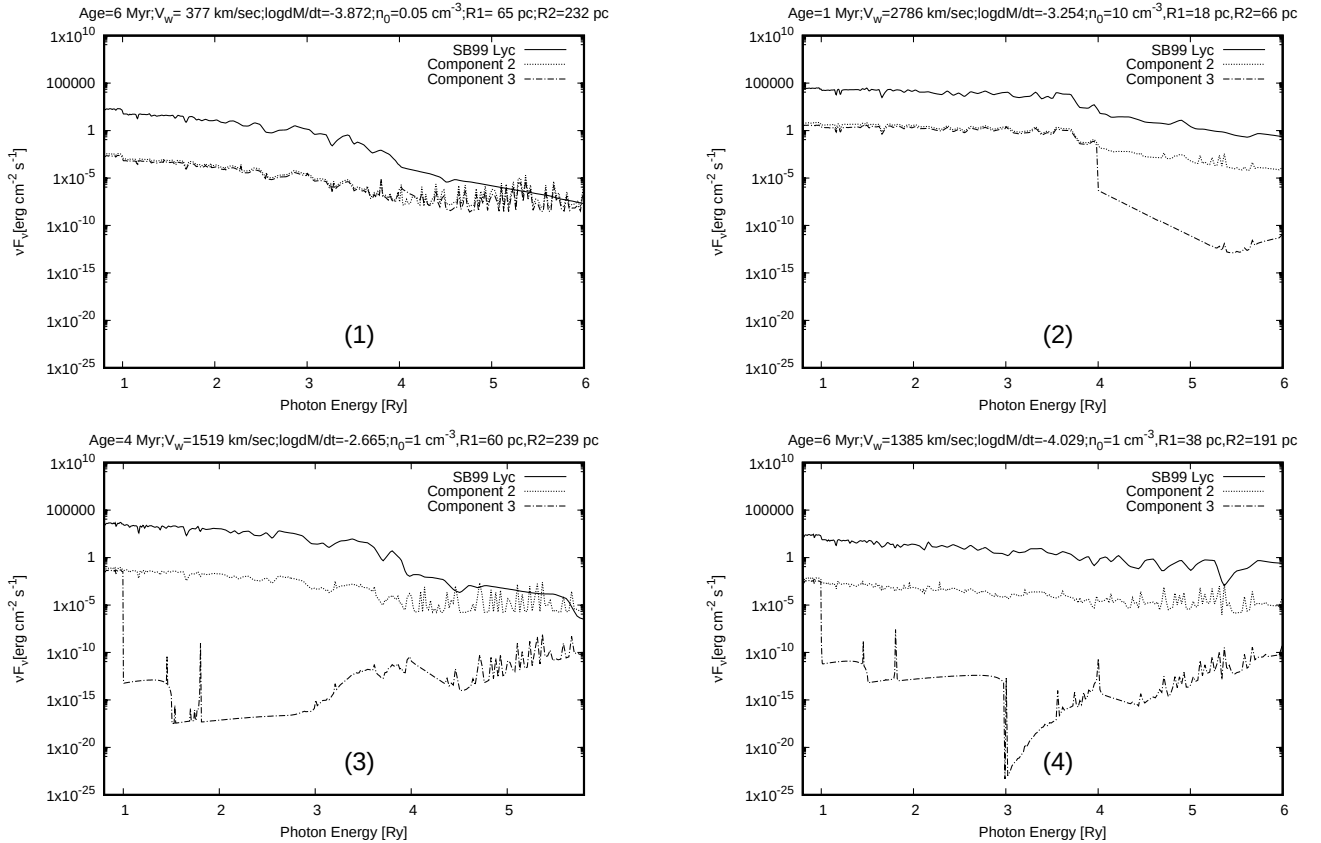


Fig. 1: Different types of the shape of output *Lyc*-spectra.

- (4) This type is characterised by the lack of quanta at the energies ≥ 3 Ryd (ionisation potential of some ions of C or Ne). Also the ionisation potentials of S^{++} and O^+ are close to this energy boundary. The input parameters of models with this type of *Lyc*-spectra shape were as follows: Age = 5, 6 Myr, $n_0 = 1 \text{ cm}^{-3}$, $M_* = 10^4 - 10^7 M_\odot$, $Z_* = 0.008, 0.014$.

To be sure that our models correspond to the observed data for the H II regions surrounding star-forming regions we have compared the synthetic spectra with the observed ones. The comparison of the following strong emission line intensities obtained from the selected MPhMs with the ones obtained during the spectroscopic observations are shown in Fig. 2–5. The line intensities are defined as follows:

$$R_2 = ([O \text{ II}] 3727 + [O \text{ III}] 3729)/H_\beta;$$

$$R_3 = ([O \text{ III}] 4959 + [O \text{ III}] 5007)/H_\beta;$$

$$N_2 = ([N \text{ II}] 6548 + [N \text{ II}] 6584)/H_\beta;$$

$$S_2 = ([S \text{ II}] 6717 + [S \text{ II}] 6731)/H_\beta.$$

Models with the masses of a central star-forming region of 10^8 , 10^9 and $10^{10} M_\odot$ are not shown in these figures because they don't reproduce the observed data. All comparisons show the same trend: the increases of the mass of inner star-forming region and the metallicity in our models lead to the worse reproduction of the observed data. It can be explained by the fact that at higher masses of star-forming region as well as at higher metallicities the internal structure of H II regions becomes more complex than the template of our models. In particular, the hydrodynamics can be more complicated due to the angular momentum presence and/or more complex structure of the interstellar medium in spiral galaxies in comparison with the dwarf ones (our models can reproduce the spectra of low-metallicity H II regions in BCDGs with the small-mass starburst inside [17]). At the higher metallicities the hydrodynamic instabilities can play more important role, which we did not take into account in our models. Also, we adopted in present work the burst model of central star-forming region, not the continuous one. But in the spiral galaxies and even in the dwarf ones the star-forming processes are often in the continuous mode characterised by various values of the stars formation rate (SFR). Therefore, in our next works we are going to perform our MPhM of the high-metallicity H II regions for the non-zero values of SFR. After that we plan to account for the hydrodynamical instabilities and deviations from the spherical symmetry caused by the H II region rotation using the Pluto hydrodynamical code¹.

Also, we have investigated the impact of bubble structure on the reproduction quality of the observed

emission line fluxes. We have calculated the evolutionary grid of models without the bubble structure (pure photoionisation models: instead of four components in such models only the component 4 is present extending from the star-forming region to the ionisation front). The comparison of such types of models with the observed data was also done². It should be noticed that the *Lyc*-spectra in pure photoionisation models evolve in the same way as in models with the bubble, but the bebular structure does not evolve there (it is constant and homogeneous). It can be concluded from the mentioned above comparison that the MPhMs show much better reproduction of the observed data than the models without SWR bubble structure. While in the cases of R_2 , N_2 and S_2 intensities the pure photoionisation models underestimate the corresponding observed data only at high metallicities ($12 + \lg(O/H) \geq 8.6$), in the case of R_3 the underestimation of the corresponding observed data can be seen within the whole considered range of metallicities ($8.2 \leq 12 + \lg(O/H) \leq 8.7$). The exception is the low-mass star-formation region ($10^4 M_\odot$), where the mentioned underestimation is sufficient at $12 + \lg(O/H) \geq 8.4$.

Thus, we can conclude that the method of comparison of the modelling results with the corresponding observed data is sensitive to the adopted structure of H II region and MPhMs, which account for the SWR structure and its evolution, reproduce the observed strong emission lines of these objects much better than the pure photoionisation models (without the bubble, only the evolution of *Lyc*-spectrum is taken into account).

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¹<http://plutocode.ph.unito.it/>

²http://physics.lnu.edu.ua/wp-content/uploads/Images_AASP2019.pdf

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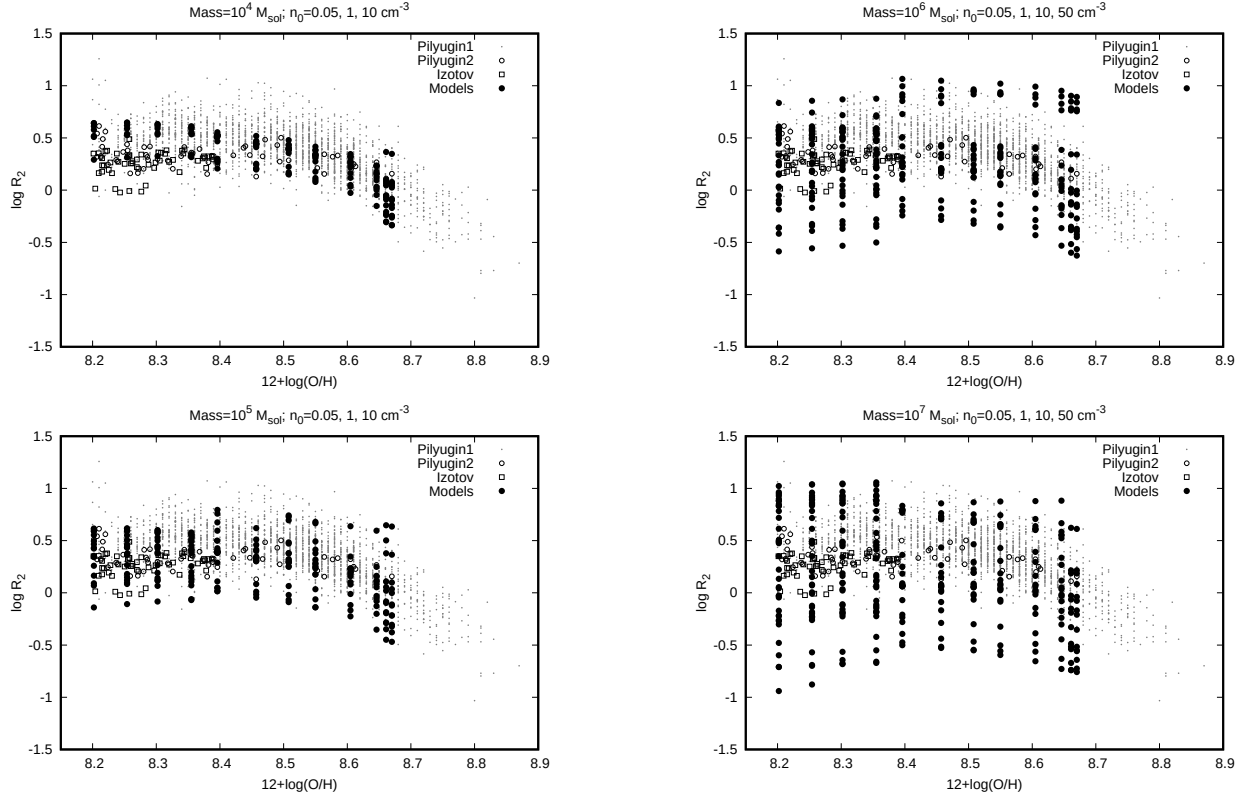


Fig. 2: Comparison of the obtained from modelling (filled circles) and observations (grey dots – the data compilation without the line $[\text{O III}] \lambda 4363 \text{ \AA}$ from [26–28], empty circles – the data compilation with the line $[\text{O III}] \lambda 4363 \text{ \AA}$ from [26–28]; empty squares – the data from [12]) values of the relative intensities of strong emission lines R_2 (see in the text) as the functions of $12 + \lg(\text{O}/\text{H})$.

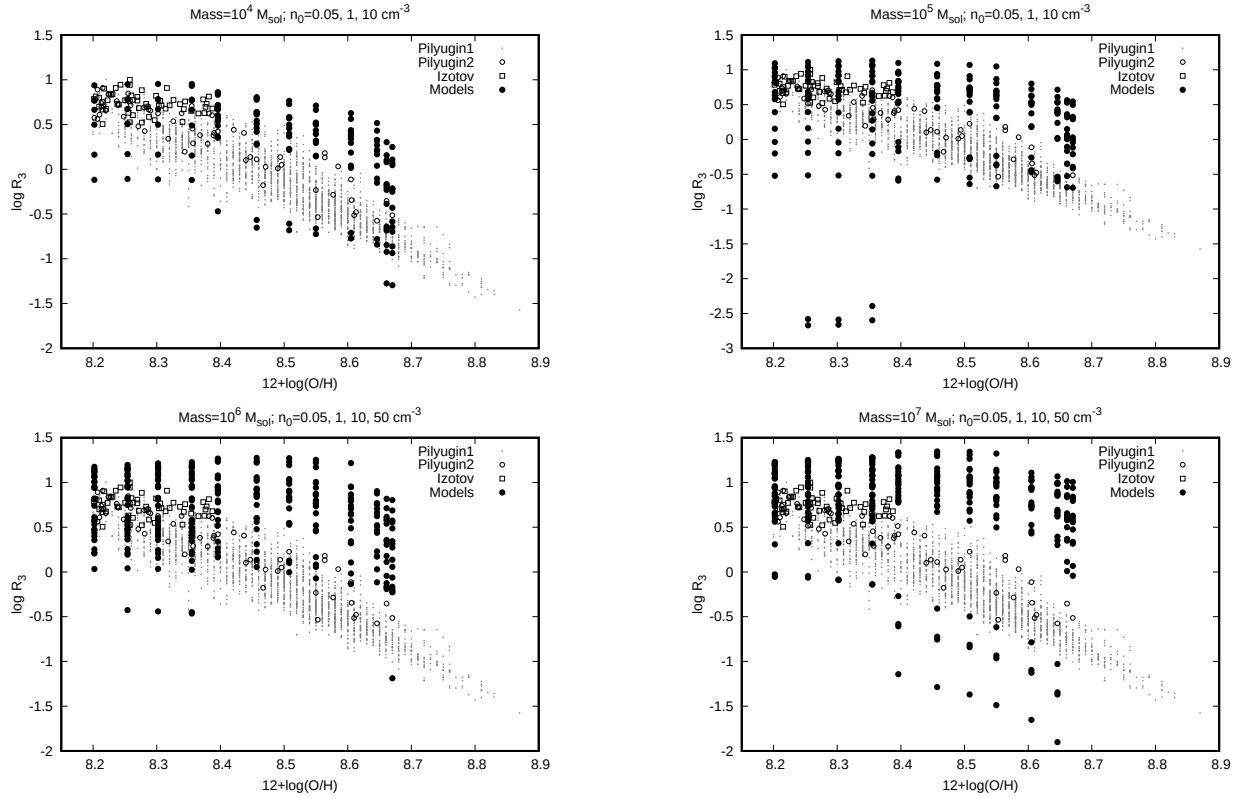


Fig. 3: The same as in Fig. 2 for R_3 .

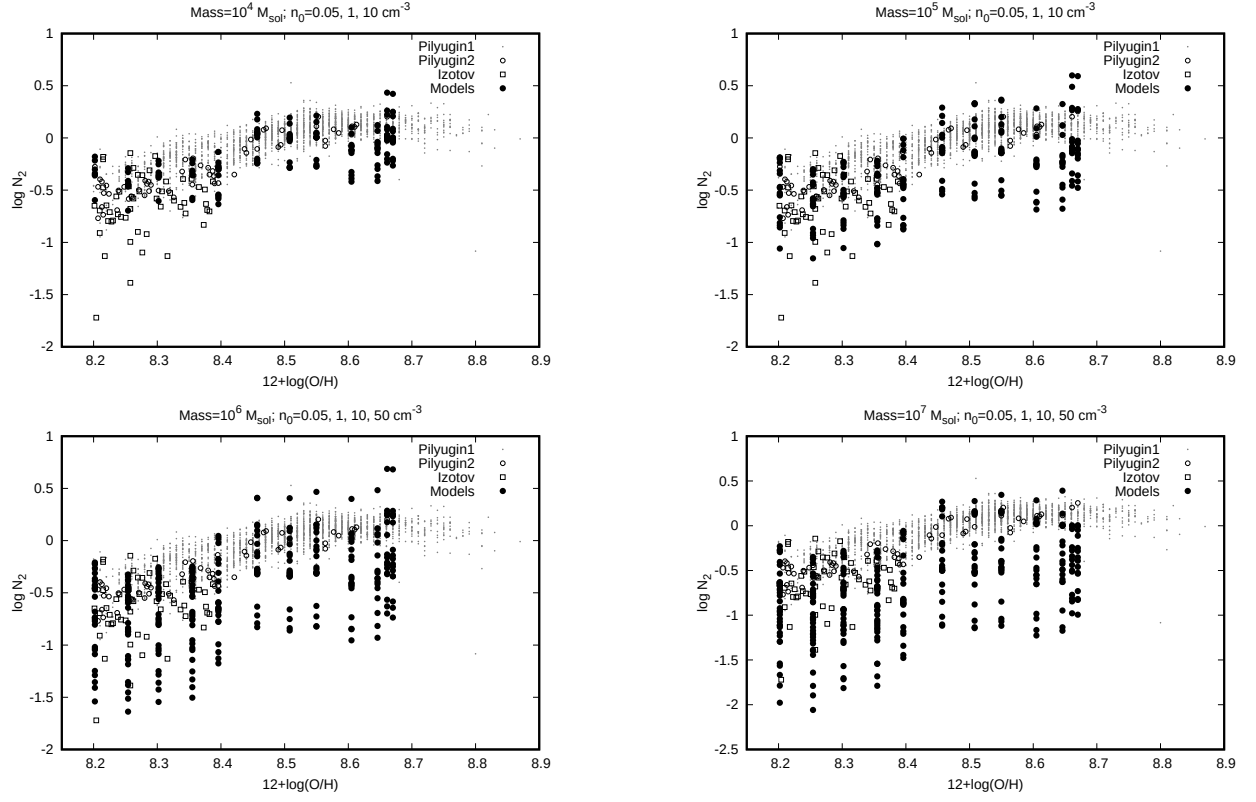


Fig. 4: The same as in Fig. 2 for N_2 .

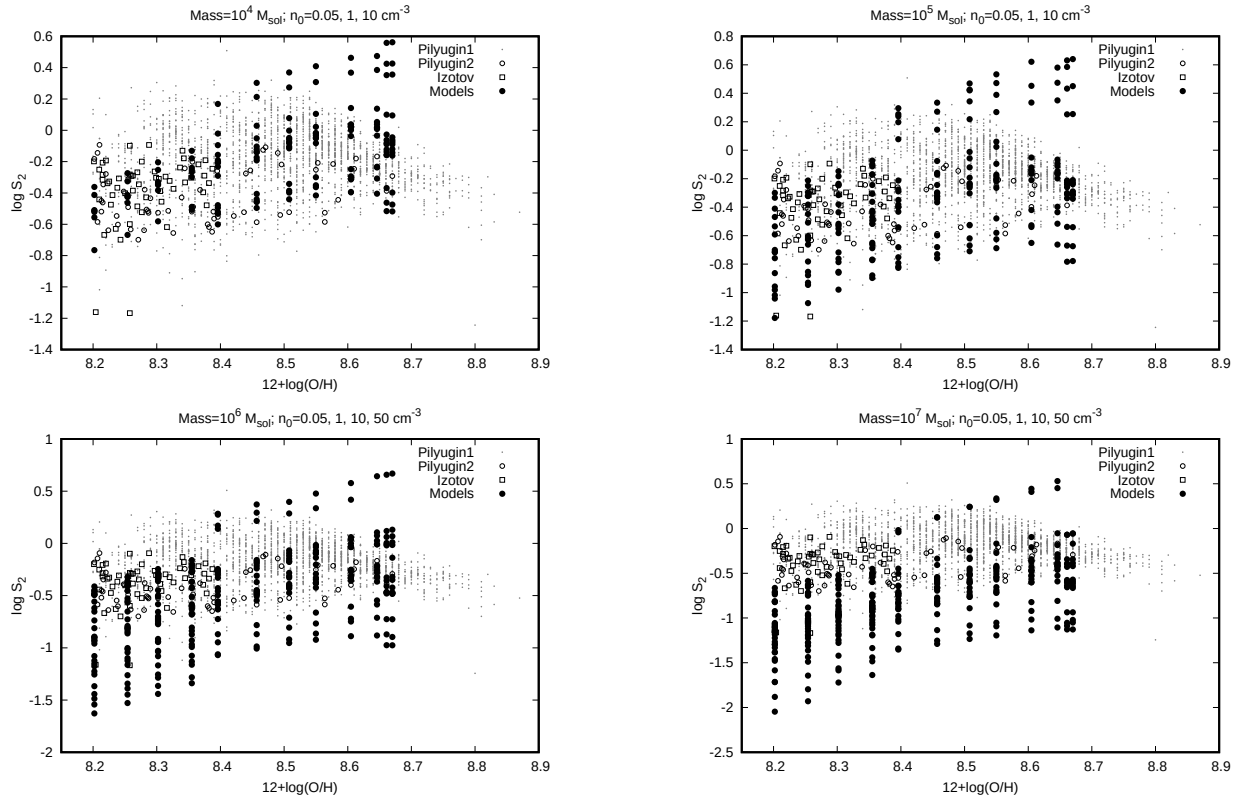


Fig. 5: The same as in Fig. 2 for S_2 .