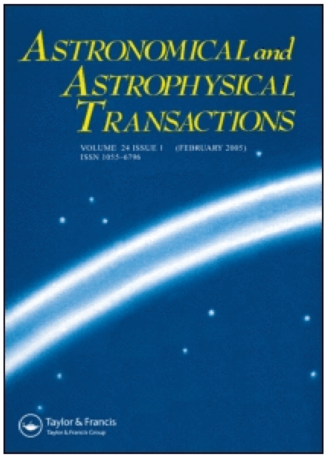

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

THE RADIO CONTINUUM EVOLUTION IN THE PLANETARY NEBULAE

O. I. Sharova [a]
[a] Radiophysical Research Institute, Bolshaya Pecherskaya 25, Nizhny Novgorod, 603950, Russia.

Online Publication Date: 01 January 2002
To cite this Article: Sharova, O. I. (2002) 'THE RADIO CONTINUUM EVOLUTION IN THE PLANETARY NEBULAE', Astronomical & Astrophysical Transactions, 21:4, 271 - 277
To link to this article: DOI: 10.1080/10556790215602
URL: http://dx.doi.org/10.1080/10556790215602

Astronomical and Astrophysical Transactions, 2002, Vol. 21(4–6), pp. 271–277 Taylor & Francis
Taylor & Francis Group

THE RADIO CONTINUUM EVOLUTION IN THE PLANETARY NEBULAE

O. I. SHAROVA

Radiophysical Research Institute, Bolshaya Pecherskaya 25, Nizhny Novgorod, 603950, Russia

(Received 9 April 2002)

The radio continuum variations from galactic planetary nebulae in the process of the central star evolution without helium flashes are considered. On the base of our distance scale we obtained empirical evolutionary dependences for the ionized mass and the hydrogen atom concentration. The parameters of a theoretical model of the interacting stellar winds (ISW) are determined to reach an agreement between empirical and theoretical dependences. In this model the time dependences are obtained for the intrinsic flux density at 15 GHz and for the critical frequency. The flux density may increase with rate of several percents until the kinematic age does not exceed 1000 years.

Keywords: Planetary nebulae, ISW model, radio continuum spectrum, evolution

1 INTRODUCTION

According to present-day knowledge planetary nebulae are a transitive stage stellar evolution from red giants to white dwarfs. The electromagnetic spectrum of radiation from a planetary nebula reflects specific features of an exiting star: its very high temperature which often exceeds 10^5 K, and small size. Changes in the parameters of a central star manifest by changes in the spectrum of radiation from planetary nebulae. Variations are found in optical lines (Kostyakova, 1999).

Continuum radiation from planetary nebulae is most intensive at radio waves and in infrared range. The radio emission is not absorbed by the interstellar medium, it carries the information about physical conditions of a nebula and a central star. In this range there is no problem to separate radiation of a nebula and a central star. In this connection a search of changeability in a radio continuum is of great interest. Non-stationary changes of radio flux density were found out (Sharova, 1987) from planetary nebula IC 418 in centimetre range.

In the present work changes of radio continuum are considered in the process of evolution of central star without helium flashes. The question on change of a radio spectrum is closely connected to a question of evolutionary changes of the ionized mass.

ISSN 1055-6796 print; ISSN 1476-3540 online

DOI: 10.1080/1055679021000034179

2 THE EMPIRICAL EVOLUTIONARY RELATIONSHIPS FOR THE IONIZED MASS AND THE HYDROGEN ATOM CONCENTRATION

Discussions about the value of the ionized gas mass and its change with nebula radius have a rich history and still are continuing. The importance of this question is caused by the fact that ionized mass is the lower estimate of the total outflowing mass. It is also important for determining the central star temperatures.

A correlation between the ionized mass and its radius is established for nebulae near the galactic centre (Gathier *et al.*, 1983), in the galactic bulge (Zijlstra, 1990; Stasińska *et al.*, 1991), and for galactic planetary nebulae with well-known individual distances (Boffi and Stanghellini, 1994). The influence of observational selection cannot be excluded because of the limited number of objects. The distance scale based on empirical dependences between parameters of nebulae, beforehand predetermines behaviour of ionized mass with increase of nebula radius. Using of the theoretical evolutionary tracks of the central stars for determination of distances results in an absolute consent of the empirical data with concrete theoretical model.

Our distance scale (Sharova, 1995) is based on regression dependence between the central star temperature T_* and radius R_* (Sharova, 1992). Comparison of our scale was carried out with 18 other scales (Sharova, 1997). In four of them the central stars parameters are also used for determination of distances (Mendez *et al.*, 1988; Mendez *et al.*, 1992; Zhang, 1995; Mal'kov, 1997), but with theoretical evolutionary tracks. Our scale on the average better than others agrees with independent estimates of individual distances. In our scale we did not use theoretical evolution tracks of the central stars, and nebulae angular radii and filling factors. Based on the newly obtained distances we have estimated the electron concentration and the ionized mass in 186 nebulae (Sharova, 1999). The hydrogen atom concentrations N_H are in a wide interval from $30\,\mathrm{cm}^{-3}$ to $2.6 \times 10^5\,\mathrm{cm}^{-3}$. These estimates are in good agreement with electron densities obtained from forbidden lines in the spectra, without using distances of almost all the nebulae. The ionized masses M_i are in the interval from 10^{-3} $M_\odot$ to 1.87 $M_\odot$. The ionized masses are larger in the nebulae with larger dimensions and lower electron densities. For 132 planetary nebulae with the known expansion velocities (Acker, 1992) we obtained estimates of the kinematical ages

$$\tau = 4,74\frac{D\theta}{V_S}\,\mathrm{yr},$$

where D is the distance to a nebula (in pc); θ is angular radius (*in arcseconds*); V_S is expansion velocity (in km s^{-1}).

The oldest planetary nebula is NGC 6072, its kinematic age is 49,700 years, the lowest age is 210 years for Hb 12. The hydrogen atom concentrations decrease with the age more slowly than in case of constant mass. The regression relationship between the kinematical ages τ and N_H is

$$\lg N_H(\mathrm{cm}^{-3}) = 8,51(\pm 0,25) - 1,49(\pm 0,07) \cdot \lg \tau(\mathrm{yr}), \tag{1}$$

with the correlation coefficient 0.87.

We obtained also the regression relationship between the ages and the ionized masses

$$\lg M_i(M_\odot) = -6,23(\pm 0,28) + 1,42(\pm 0,08) \cdot \lg \tau(\mathrm{yr}), \tag{2}$$

with the correlation coefficient 0.84.

The unlimited growth of ionized mass can be interpreted as follows: planetary nebulae are surrounded with clouds of neutral hydrogen through which passes the ionization front. The total mass of a nebula must be not less than $2M_\odot$. The concentration of HI atoms depends on age much weaker, than in the assumption of constant mass and full ionization of the nebula.

3 COMPARISON WITH THEORETICAL EVOLUTIONARY DEPENDENCES

Let us compare the obtained regression dependences with the theoretical ones in the interacting stellar winds (ISW) model. In this model formation of a nebula starts at the stage when the red giant is on the asymptotic giants branch (AGB). This period of evolution is accompanied by high mass losses up to $10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$, with the stellar wind velocity from $3\ \mathrm{km\ s}^{-1}$ up to $15\ \mathrm{km\ s}^{-1}$, and cold circumstellar envelopes being formed. The lifetime of a red giant at AGB is estimated as 10^5 years, hence the star may lose up to $10\ M_\odot$.

It is assumed, that mass losses and velocities of stellar winds do not depend on time. If all kinetic energy of the wind from the central star surface transforms to work of forces of pressure, the expansion velocity of a nebula is constant and is defined by the equation (Kwok 1982)

$$\left(\frac{\dot{M}}{V} - \frac{\dot{m}}{v}\right)V_S^3 - \left(\dot{M} - \dot{m}\right)V_S^2 = \frac{1}{2}\dot{m}v^2, \tag{3}$$

where $\dot{M}$ is the mass loss rate of the red giant; $\dot{m}$, the mass loss rate of the central star; V, the velocity of stellar wind from the red giant; v, the velocity of stellar wind from the central star. Then the nebula radius is $R_S = V_S t$. Let us consider the dependence of observable parameters of the planetary nebula on its kinematical age. During the evolution the observed radius of the nebula $R_N = V_S\tau$ gets the value

$$R_N = \begin{cases} R_0, & R_0 < R_S, \\ R_S, & R_0 > R_S. \end{cases}$$

The radius of the ionization zone of hydrogen R_0 is determined by the temperature and radius of central star and hydrogen density in the nebula (Sharova, 1992). The dependences of the central star parameters on the age t are taken from the evolutionary tracks (Schönberner, 1981; Schönberner, 1983; Blöcker and Schönberner, 1990).

It is assumed, that stellar wind from the red giant stops at the moment $t = 0$, and at the same moment mass loss from the central star initiates. The total mass of the nebula grows proportionally to evolutionary time t. In the considered theoretical models the mass loss rate from the central star in the form $\dot{m} \propto L^{+1.86}$ is accepted. But we assumed it constant on the time interval $\Delta t \le M_e/2\dot{m}$, where $M_e \approx 10^{-3}\ M_\odot$ is the mass of an envelope with the layered source of hydrogen and helium burning around degenerated nucleus of the central star. We accept

$$\dot{m} = 10^{-8} i, \quad i = 1, 2, \ldots, 5$$

for the central stars with masses 0.546, 0.565, 0.6, 0.64, 0.836 $M_\odot$, accordingly. Then the estimations of Δt are from 10^5 to 10^4 years. Later on the total mass of the nebula remains constant.

Empirical evolutionary dependences agree with the theoretical ones if one accepts the following parameters for stellar winds

$$\dot{M} = 5 \times 10^{-5}\ M_\odot \mathrm{yr}^{-1}, \quad V = 5\ \mathrm{km\ s}^{-1}, \quad v = 2500\ \mathrm{km\ s}^{-1},$$

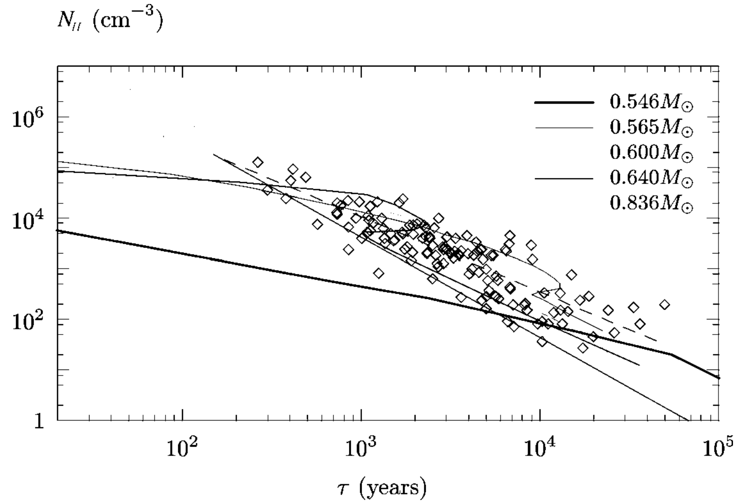

FIGURE 1 Evolutionary changes of the hydrogen atom concentration.

The corresponding expansion velocities of nebulae are from 16 km s^{-1} to 27 km s^{-1}, and the rate of the total mass increase are from 1.15×10^{-4} $M_\odot$ yr^{-1} to 1.5×10^{-4} $M_\odot$ yr^{-1}. The empirical and theoretical evolution dependences are plotted in Figure 1 and Figure 2 , the empirical relationships (1) and (2) are shown by dashed line. The parameters of examined nebulae are also shown. The dependence of the average hydrogen density on kinematical age has more complex character, than its dependence on evolutionary age of the central star ($N_H \propto t^{-2}$): it changes with the mass of central star. The largest total mass (3.45 $M_\odot$) is obtained in model with the smallest star core (0.546) $M_\odot$ for kinematical age of 55,000 years. At this time the observed radius of the nebula is equal to 0.9 pc, the ionized mass is 1.64 $M_\odot$, and the concentration of hydrogen is the 20 cm^{-3}. It is close to the limiting values obtained earlier for our list of planetary nebulae (Sharova, 1999). As the age further increases the nebula becomes fully ionized, while hydrogen density falls down to 1 cm^{-3}.

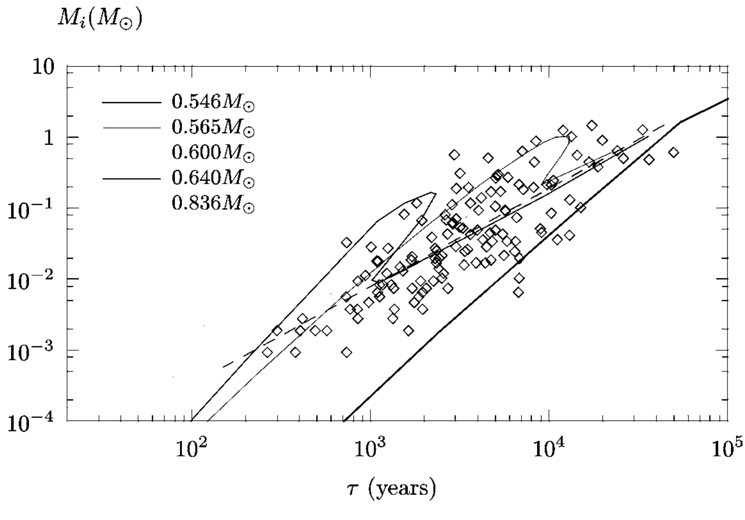

FIGURE 2 Evolutionary changes of the ionized mass of planetary nebulae.

The accepted velocity of stellar wind at the AGB stage is close to the minimal value, and the mass loss rates for central stars are close to the maximal values.

4 TIME VARIATIONS OF RADIO SPECTRUM FROM PLANETARY NEBULAE

The radio emission of planetary nebulae in continuum is thermal. It is generated by free–free transitions of electrons. Theoretical thermal radio spectrum of a nebula with homogeneous density may be represented as

$$S_\nu = A \cdot y^2[0.5 - y^{4.2} + \exp(-y^{-2.1})(y^{2.1} + y^{4.2})], \tag{4}$$

where S_ν is the flux density (Jy) at frequency ν (GHz), $y = \nu/\nu_c$, ν_c is the critical frequency (GHz), $A = 4.53 \times 10^{-2}\theta^2\nu_c^2 t_e$ (Jy), $t_e = 10^{-4}T_e$, T_e is the electron temperature; we assume t_e=1. At critical frequency the optical thickness of a nebula is equal to one. At the frequency $2,646\nu_c$ radio flux density reaches maximum equal to $0,288A$ (Jy). In the limit $\nu \gg \nu_c$ the flux density is proportional to N_iN_e and depends on frequency only through Gaunt factor. At frequencies $\nu \ll \nu_c$ its dependence on frequency is determined by density distribution in the nebula. For a homogeneous nebula $S_\nu \propto \nu^2$, and does not depend on densities of electrons and ions.

Using parameters of the best fit ISW model we calculated critical frequency ν_c and parameter A as a function of kinematic age of a nebula shown in Figure 3.

The critical frequency strongly depends on the mass of star nucleus. For the nucleus mass 0.546 $M_\odot$ it is always lower than 1 GHz. Apparently it cannot be a single-valued evolutionary parameter, since lower critical frequency may be a consequence of smaller nucleus mass. If critical frequency is higher than 10 GHz, the nebula has an age less than 100 years and a massive exiting star. If critical frequency is lower than 1 GHz, a central star has lower mass or the nebula age is greater than 1000 years.

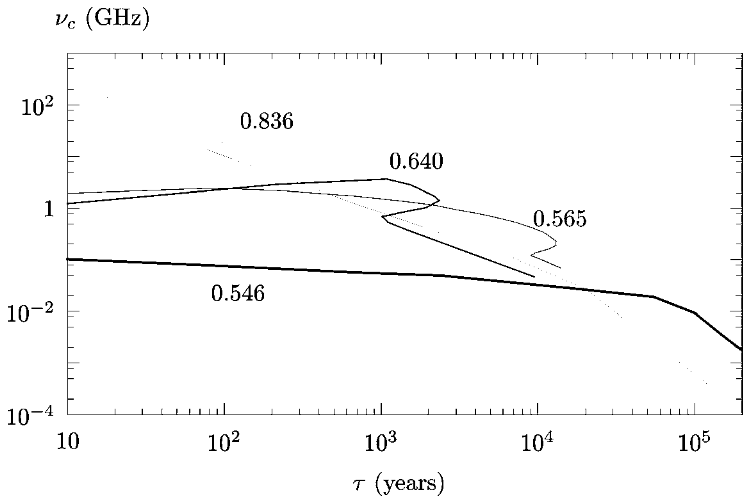

FIGURE 3 The critical frequency as a function of kinematical age of nebula.

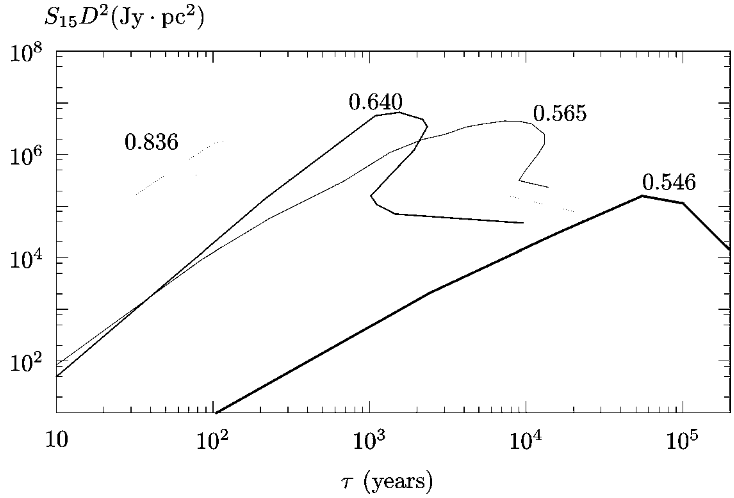

FIGURE 4 The intrinsic flux density at 15 GHz as function of kinematic age of nebula.

Critical frequency in models with nucleus masses 0.600 $M_{\odot}$ and 0.640 $M_{\odot}$ grows very slowly,with rate not higher than 0.4% yr^{-1}, when the kinematical age is less than 1000 years. In model with nucleus mass 0.565 $M_{\odot}$ in the interval from 0.6 years till 86 years critical frequency grows with rate 0.05% yr, and falls afterwards with a rate not above 0.02% yr^{-1}. In other models critical frequency monotonously decreases. In model with nucleus mass 0.836 $M_{\odot}$ the rate is maximal: for kinematic age less than 1170 years it reaches 0.46% yr^{-1}.

The time variations of the intrinsic flux density $S_{15}D^2$ are shown in Figure 4 at 15 GHz. At this frequency the nebula remains optically thick up to kinematic age of 100 years if the central star mass is $0.836M_{\odot}$. During this time maximum of radio emission is at very high frequency (≥ 30 GHz). The intrinsic flux density changes in a wide interval of values in some orders of power. Radio flux continues to increase up to kinematical age of 1000 in the model with nucleus mass 0.640 $M_{\odot}$; up to 10,000 years in the model with 0.565 $M_{\odot}$; up to 100 years in the model with 0.846 $M_{\odot}$; up to 5×10^4 years in the model with 0.546 $M_{\odot}$. The maximal growth rate of the flux density of 8% yr^{-1} increase is obtained for the model with 0.640 $M_{\odot}$ in the interval from 200 to 1100 years. Further the flux density falls down with the rate 0.8% per year.

5 CONCLUSIONS

Based on new distances empirical evolutionary relationships have been obtained for the ionized mass and hydrogen densities. In the framework of the ISW model theoretical dependences have been calculated between kinematical age and these parameters of nebula. Empirical and theoretical dependences are close to each other in the energy-conserving case if the mass loss rate from central star is kept constant at $1 \div 5 \times 10^{-8}\,M_{\odot}\,\mathrm{yr}^{-1}$. Time variations of radio continuum has been predicted. The critical frequency and the intrinsic flux density at 15 GHz have been calculated as a function of kinematical age of the planetary nebula. They vary in wide ranges and strongly depend on the mass of central star. If critical frequency is higher than 10 GHz, a nebula younger than 100 years and has a massive exiting star. Low critical frequency does not indicate that the nebula is old. Flux density may increase with rate about 8% per year. There is an actual problem to find time variations of radio continuum from planetary nebulae by observations.

Acknowledgements

This work is partly supported by a grant from FNTP within the project "Researches of mechanisms of energy generation in astrophysical objects and behaviour of substance in extreme conditions."

References

Acker, A., Ochsenbein, F., Stenholm, B., Tylenda, R., Marcout, J. and Schohn, C. (1992). *Strasbourg-ESO Catalogue of Galactic Planetary Nebulae*, Publ. ESO.
Blöcker, T. (1995). *Astron. Astrophys.*, **299**, 755.
Gathier, R. (1987). *Astron. Astrophys. Suppl. Ser.*, **71**, 245.
Kostyakova, E. B. (1999). *Pis'ma v Astron. Z.*, **25**, 457.
Kwok, S. (1982). *Astrophys. J.*, **258**, 280.
Mal'kov, Yu. F. (1997). *Astron. Zurn.*, **74**, 853.
Mendez, R. H., Kudritzki, R. P., Herrero, A., Husffeld, D. and Groth, H.G. (1988). *Astron. Astrophys.*, **190**, 113.
Mendez, R. H., Kudritzki, R. P. and Herrero, A. (1992). *Astron. Astrophys.*, **260**, 329.
Sharova, O. I. (1999). *Thesis.*
Sharova, O. I. (1987). Galactic and extragalactic radioastronomy. *XIX Radioastronomy Conference*, Tallin, p. 159.
Sharova, O. I. (1992). *Astron. Zurn.*, **69**, 38.
Sharova, O. I. (1995). *Radiophysics and Quantum Electronics*, **38**, 344.
Schönberner, D. (1981). *Astron. Astrophys.*, **103**, 119.
Schönberner, D. (1983). *Astrophys. J.*, **272**, 708.
Blöcker, T. and Schönberner, D. (1990). *Astron. Astrophys.*, **240**, L11.
Stasińska, G., Tylenda, R., Acker, A. and Stenholm, B. (1991). *Astron. Astrophys.*, **247**, 173.
Zhang, C. Y. (1993). *Astrophys, J.*, **410**, 239.
Zijlstra, A. A. (1990). *Astron. Astrophys.*, **234**, 384.