Astronomical and Astrophysical Transactions, 1998,
Vol. 15, pp. 281–289
Reprints available directly from the publisher
Photocopying permitted by license only

INTERPRETATION OF ANOMALOUS HELIUM ABUNDANCE DERIVED FROM RADIO RECOMBINATION LINE OBSERVATIONS OF NEBULAE

D. ERSHOV[1], S. A. GULYAEV[1], A. IVANCHIK[2], D. A. VARSHALOVICH[2]
and A. TSIVILEV[3]

[1] *Ural State University, Ekaterinburg, Russia*
[2] *A. F. Ioffe Institute of Physics and Technology, St. Petersburg, Russia*
[3] *P. N. Lebedev Physical Institute, Moscow, Russia*

(Received September 23, 1996)

We solve the ionization and thermal balance problem for homogeneous and inhomogeneous models of gaseous nebulae. The relative intensities of helium to hydrogen radio recombination lines (RRL) are calculated for these models at various positions and widths of the antenna beam. A class of inhomogeneous models of nebulae is found in which, due to the hardening of the spectrum in the periphery of the H II–He II region, the ratio of the integral intensities of the He and H RRLs, y^+, can reach relatively high values near the nebula boundary ($y^+ \geq 20\%$ in spite of the relative He abundance $y_0 = 8\%$). This maximum observed value of y^+ decreases with increasing width of the antenna beam. New calculations of the interstellar extinction curve in the wavelength range 100–3500Å are employed. Contrary to previous studies, we conclude that the presence of dust can enhance the effect of hardening.

KEY WORDS Nebulae, radio recombination lines, helium abundance

1 INTRODUCTION

The relative helium abundance y_0 is one of the key parameters in cosmology and astrophysics that can be determined from observations.

The most reliable method to determine y_0 is in measuring the radio recombination lines (RRL) in nebulae (e.g., Mezger, 1980; Schmid–Burgk, 1981). These observations allow one to evaluate the quantity $y^+ = \int T^{\mathrm{He}} d\nu / \int T^{\mathrm{H}} d\nu$, the ratio of the He and H integral intensities of RRLs.

The observations may yield key information on the possible gradient of the He abundance in the Galaxy (Thum *et al.*, 1980; Shaver *et al.*, 1983). Gradient detection would enable one to estimate the contribution of stellar nucleosynthesis to the observed He abundance, and compare it with the initial He abundance that had been formed in "the first three minutes".

The He II abundance in the galactic H II regions has been determined from a number of RRL observations. Recent observations have revealed an exciting fact: there are variations of y^+ inside the H II-regions (Sgr B2, W10, W3A, etc.). These variations imitate the dependence of y^+ on the angular distance, Θ, from the ionizing star (as a rule, y^+ increases with Θ).

An anomalously high apparent He abundance was found in W3A. High resolution mapping of W3A in the RRLs 110α and 77α made by Roelfsema and Goss (1991) show variations of y^+ from 10% in the nebula centre up to 40% at the periphery. The same behaviour of y^+ was found in W3B: a growth of y^+ from 15% in the centre to 25% at the boundary. Later these authors confirmed their results (Roelfsema *et al.*, 1992). A detailed analysis of these results has been performed recently by Gulyaev *et al.* (1996).

A similar situation was found in Sgr B2 (Roelfsema *et al.*, 1987) and in DR21 (Tsivilev, 1991).

The measurements of y^+ (Θ) in the Orion Nebula performed by several authors are contradictory. For instance, the radio mapping of Ori A at 6 cm shows that $y^+(\Theta)$ decreases from the centre of the nebula to its periphery (Pankonin *et al.*, 1980). On the contrary, at higher frequencies, y^+ shows a minimum in the centre and increases with Θ (Tsivilev *et al.*, 1986; Gordon, 1989). Optical observations are also contradictory. According to Peimbert and Torres-Peimbert (1977), y^+ decreases with Θ. More recent observations of Baldwin *et al.* (1991) show that $y^+(\Theta)$ remains constant up to $\Theta = 5$ arcmin.

The main problem is whether these fluctuations are associated with the real gradient of the He abundance in a nebula, or are they an apparent effect due to the underionization of hydrogen caused by the hardening of the radiation field.

The results of many numerical simulations of the ionization structure of gaseous nebulae are also contradictory.

According to Osterbrock (1989), the boundary of the He II zone is usually situated inside the H II zone. If, however, an ionizing star is very hot (of spectral type earlier than O7), the outer boundaries of both ionization zones approximately coincide, and there appears a unified H II–He II region. In the latter case one usually treats an observed value of y^+ as a real He abundance y_0.

Osterbrock (1989) did not consider the detailed structure of the boundary layer of the coupled H II–He II region, but showed that the critical effective temperature of the ionizing star (above which both ionization zones coincide) was about 40 000 K.

Earlier Aller (1984) showed that if the star was sufficiently hot the hardening led to the inversion of the He and H Strömgren spheres. He considered the nebula model with $T_{\rm eff} = 48\,000$ K and $N_{\rm H} = 11\,000$ cm^{-3} and found that the H II zone was smaller than the corresponding He II zone (Figure 6-1 from Aller, 1984). If so, even in the case of constant relative He abundance throughout the nebula, a solution can be obtained with a positive gradient of y^+ as a function of Θ, at least near the boundary.

On the other hand, Roelfsema *et al.* (1992) have studied several H II region models with the effective temperatures of the ionizing stars in the range from 40 000 to 60 000 K. An ambient density of 10 H atoms cm^{-3} has been used, and a He abundance by number, y_0, of 10% has been adopted. The authors have solved the same equations as Osterbrock (1989) and they have taken into account the same mechanisms of He and H ionization as Osterbrock (1974, 1989) and Aller (1984). Nevertheless, they have obtained the opposite result: if $T_{\rm eff} = 50\,000$ K, then the He II zone lies within the H II zone. As seen from Figure 5 of their article, in this case they have $\Delta r_{1/2}/r_{1/2} = 20\%$, where $\Delta r_{1/2}$ is the difference between the radius of the H II zone, r_1/r_2, and the radius of He II zone defined for the ionization degree $x = 1/2$. Even if $T_{\rm eff} = 60\,000$ K (Figure 6 from Roelfsema *et al.*, 1992), the boundary of the He II zone does not go beyond that of the H II zone: $\Delta r_{1/2}/r_{1/2} = 8\%$. Thus, Roelfsema *et al.* (1992) explain the observed high values of y^+ in W3A by the local enhancement of the He abundance at the nebula boundary due to the enrichment of the local ISM by WR stars.

The goal of the present article is to answer the main question: is it possible to explain the above observations by choosing certain ionization structures of the nebulae? We have solved the ionization and thermal balance problem (Osterbrock, 1989) for homogeneous and inhomogeneous models of gaseous nebulae. The relative intensities of helium to hydrogen RRLs have been calculated at different positions and widths of the antenna beam. The influence of dust is discussed based on the latest achievements in this field.

2 MODEL SIMULATIONS AND RESULTS

Let us consider the ionization state of H and He around a hot star taking into account the hardening of stellar radiation. The hardening of radiation, propagating to the outer boundary of the nebula, is caused by the very strong frequency dependence of the bound–free absorption coefficient: ν^{-3} for hydrogen and ν^{-2} for helium. The most efficient absorption occurs near the ionization threshold.

According to Aller (1984), the hardening of radiation from a rather hot star ($T_{\rm eff} = 48\,000$ K) can invert the boundaries of the He and H Strömgren spheres: the fraction of ionized He near the nebula boundary may be higher than that of hydrogen (then the H II zone is smaller than the He II zone). Aller (1984) notes also a rapid temperature rise towards the outer nebula boundary in spite of the increase of number densities of N^+, O^+ and S^+ ions which provide efficient cooling. The hardening of the radiation field, as the nebula boundary is approached, has an even stronger effect than the rise in the number densities of cooling agents.

The RRL intensities depend on the ion number density of a given element. Then, if the inversion takes place, a high apparent He abundance, y^+, near the nebula boundary can be observed.

The question is – can this effect be strong enough to explain the observed behaviour of y^+?

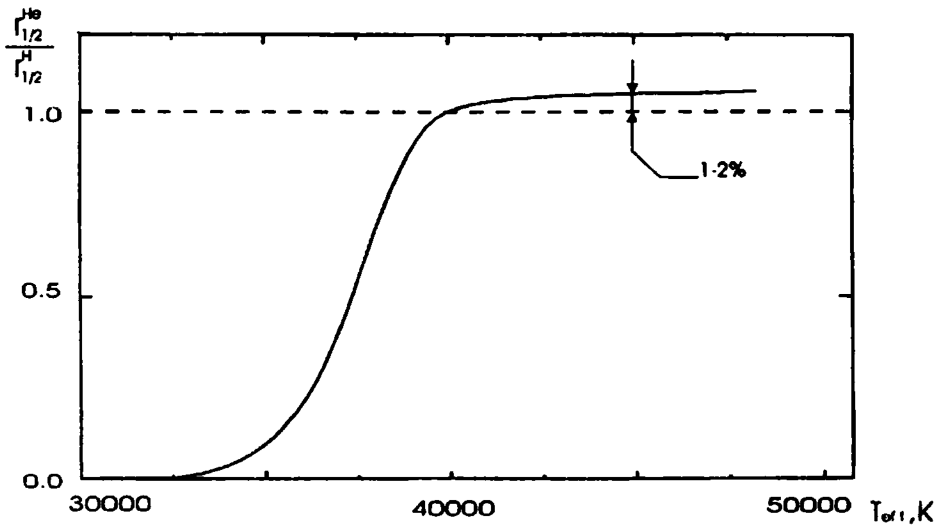

Figure 1 Relative radius of He II zone $r_{1/2}^{He}/r_{1/2}^{H}$ as a function of the effective temperature of a central star. If $T_{eff} > 40\,000$ K, the difference $\Delta r_{1/2}$ is about 1–2% of the nebula radius.

We have constructed several ionization models of a hydrogen–helium nebula. We have tried to find under which conditions the thickness of the transition zone (where the fraction of ionized He is higher than that of hydrogen) is a maximum.

First, we have considered a number of homogeneous models with various (but constant through the nebula) He abundances y_0 (from 4% to 12%), different gas densities and effective temperatures of the ionizing star. The stellar fluxes have been taken from Mihalas (1972). The output parameter is the ionization degree as a function of distance r from the central star: $x^{He}(r)$ for helium and $x^{H}(r)$ for hydrogen. We have also found the radii of Strömgren spheres at the $x = 1/2$ level: $r_{1/2}^{He}$ for helium and $r_{1/2}^{H}$ for hydrogen.

The results are presented in Figure 1. If T_{eff} is lower than 40 000 K, we have $r_{1/2}^{He} < r_{1/2}^{H}$, in accordance with Osterbrock (1989). If T_{eff} is higher than 40 000 K, the situation is reversed: $r_{1/2}^{He} > r_{1/2}^{H}$. We have obtained a class of homogeneous models with a very thin transition zone – the difference $r_{1/2}^{He} - r_{1/2}^{H} = \Delta r_{1/2}$ is about 1–2% of the nebula radius (Figure 1). The presence of helium provides an additional opacity and affects also the ionization structure: the ground-state recombinations and bound–bound transitions in He produce photons which are able to ionize hydrogen. Thus, the He and H ionizations become coupled. The quantity $\Delta r_{1/2}/r_{1/2}$ shows a weak dependence on the hydrogen density and the helium abundance; in models with low values of these parameters it can reach 2–2.5%.

Let us determine S, the thickness of the zone, where the transition occurs from the ionized to the neutral state. Figure 2*a* shows schematically the difference bet-

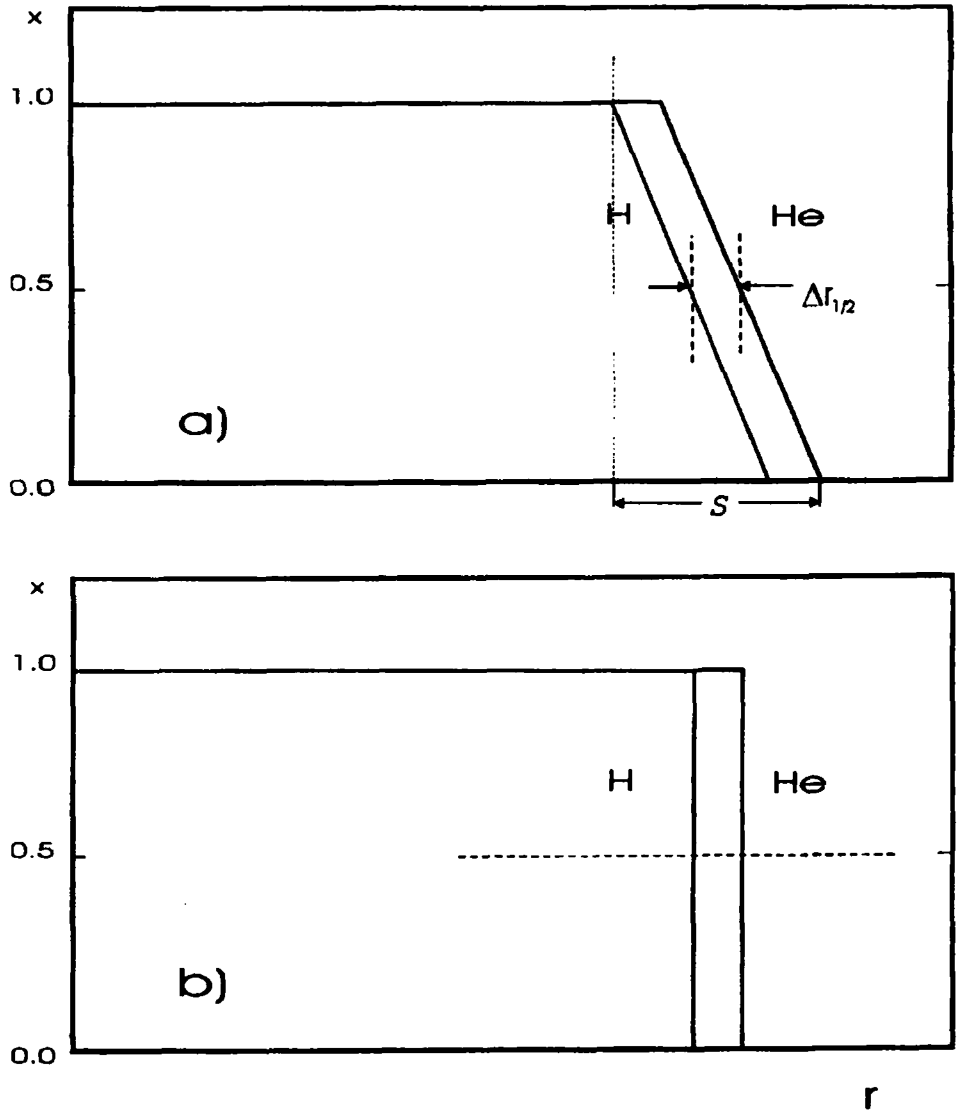

Figure 2 Ionization degree vs distance from the central star: (a) an illustration of the difference between S (the thickness of the transition zone) and $\Delta r_{1/2}$; (b) the homogeneous nebula models; the ionization degree decreases very abruptly, and S is actually equal to $\Delta r_{1/2}$.

ween S and $\Delta r_{1/2}$. In this figure we plot the ionization degree as a function of distance r from the central star.

In the homogeneous nebula models, the gradient of the ionization degree $|dx/dr|$ is very high, from 10^3 to 10^6 pc^{-1}, depending on the input parameters of the nebula model. The ionization degree decreases very abruptly, and S is actually equal to $\Delta r_{1/2}$ (Figure 2b).

For the homogeneous models, we have determined the intensities of hydrogen and helium RRLs. Because of the narrow transition zone $S = \Delta r_{1/2} =$ 1–2% and very high gradients $|dx/dr|$ of the ionization degree, the contribution of the transition zone to the integral RRL intensities is negligible, even if the antenna beam is narrow.

We have analysed a class of inhomogeneous models with a negative density gradient. We have considered several models with different density–distance relations: r^{-1}, r^{-2}, $\exp(-r/r_0)$, etc. We have found that, for the inhomogeneous models, the H II and He II zones coincide at $T_{\rm eff} = 40\,000$ K as in the case of the homogeneous models.

The main result is that the transition zone can be relatively thick for this class of model, so that $S \gg \Delta r_{1/2}$ (a situation similar to that in Figure 2*a*). This is very important because the observed quantity y^+ depends more strongly on S than on $\Delta r_{1/2}$. The same is true in the interval 1–2% of $r_{1/2}$ which is explained by the coupling of the H II and He II zones.

Figure 3 presents the nebula model where the density varies as r^{-1}. We adopt the density $N_{\rm H} = 100\,000$ cm^{-3} in the centre, and 200 cm^{-3} near the boundary; the relative He abundance, y_0, is constant throughout the nebula. We plot the following quantities:

(a) ionization degree $x^{\rm He}(r)$ for helium and $x^{\rm H}(r)$ for hydrogen vs r;

(b) local value of $y^+(r) = y_0 x^{\rm He}(r)/x^{\rm H}(r)$ vs r;

(c) relative RRL integral intensities He 60α/H 60α for three antenna beam widths (5%, 10%, 20% of nebula diameter) as functions of position of the centre of the antenna beam r.

We arrive at the conclusion that it is a possible to obtain a very high local $y^+(r)$ near the nebula boundary – up to 50%.

The observed values of y^+ are certainly lower because of the integration over the antenna beam. If the antenna beam width is about several percent of the nebula diameter, the apparent y^+ can reach relatively high values near the nebula boundary (more than 20% for $y_0 = 8\%$). This maximum value of the observed y^+ decreases with increasing width of the antenna beam.

The H II regions are expected to contain dust which can influence the ionization structure (Aller, 1984). Dust particles absorb and scatter light selectively. To allow for the effect of dust on the ionization structure, one must solve the radiative transfer problem more accurately, expecially near the ionization thresholds of He and H. In the article of Voshchinnikov and Il'in (1993), the optical properties of silicate and graphite dust grains of various sizes were calculated in the wavelength range 100–3500Å (the proposed working range of the Spectrum-UV project). The authors computed the interstellar extinction curve for a silicate-graphite mixture with a power-law size distribution. In addition to the well-known bump near 2200Å, they discovered a strong maximum near 700Å. Behind this maximum, the extinction decreases with decreasing λ, and reaches a plateau at $\lambda < 300$ Å.

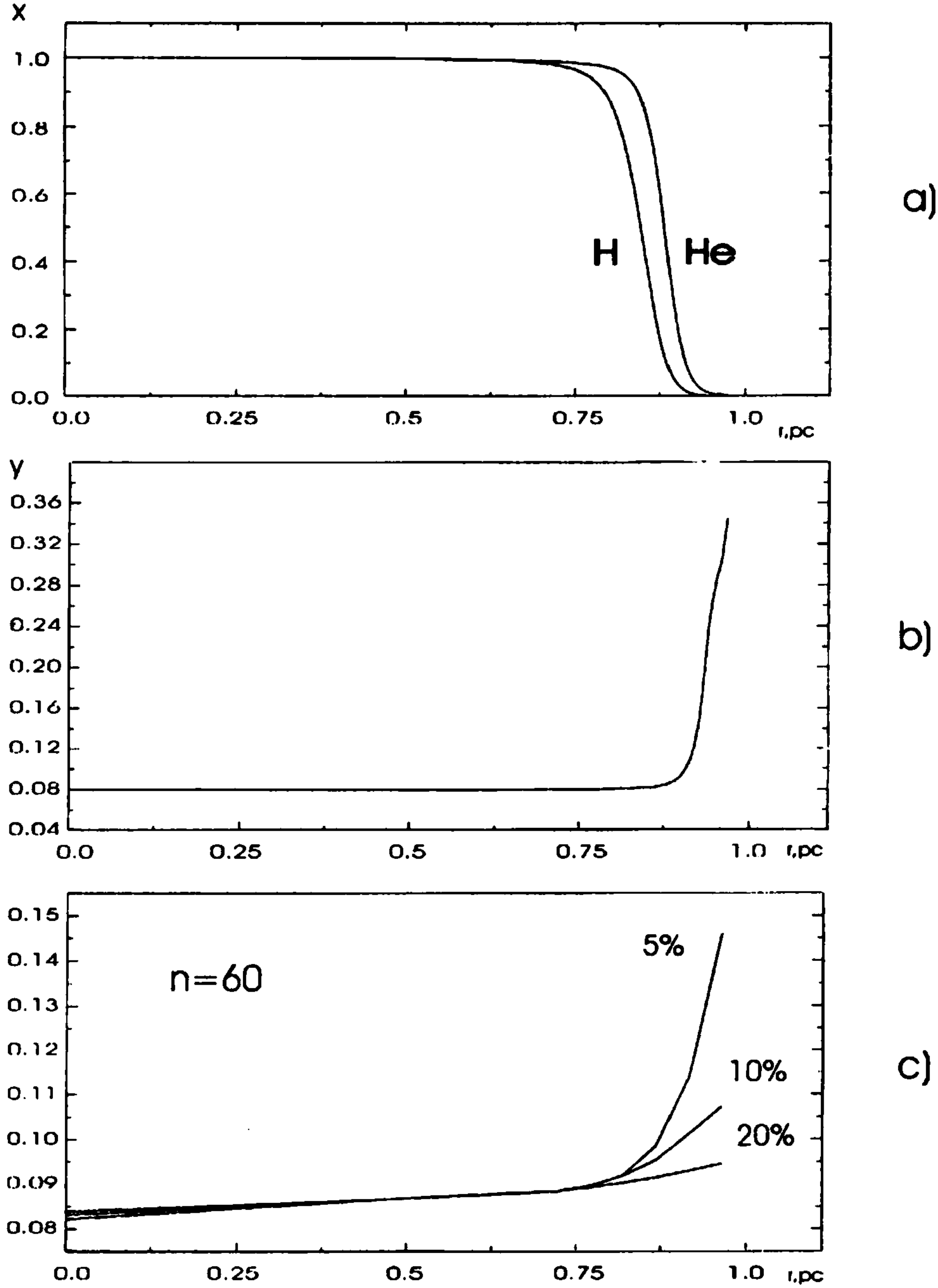

Figure 3 A model in which the density N_H decreases as r^{-1} ($N_H = 100\,000$ in the centre and 200 cm^{-3} near the boundary), and the He abundance is $y_0 = 8\%$: (*a*) ionization degrees $x^{He}(r)$ and $x^H(r)$ vs r, (*b*) local variable $y^+(r) = y_0 x^{He}(r)/x^H(r)$ vs r, (*c*) relative line intensity He 60α/H 60α vs r if the antenna beam width is 5%, 10%, and 20% of the nebula diameter.

This behaviour of the extinction in the far UV changes critically our understanding of the role of dust. Contrary to previous results, dust *enhances* the effect of hardening of stellar spectra. Thus the presence of dust does not reduce the difference between the boundaries of the He and H ionization zones as thought previously (Mathis, 1971; Roelfsema *et al.*, 1992). On the contrary, dust weakens the coupling of the zones.

3 CONCLUSION

We have solved the ionization and thermal balance problems for homogeneous and inhomogeneous models of gaseous nebulae. The relative intensities of helium to hydrogen RRLs for these models have been calculated at different positions and widths of the antenna beam. We have determined physical conditions in inhomogeneous nebula models which yield a relatively high apparent y^+ near the nebula boundary (more than 20% if $y_0 = 8\%$) due to the effect of hardening. This maximum value of the observed y^+ decreases with increasing the width of the antenna beam.

We have taken into account the advanced theoretical interstellar extinction curve in the wavelength range 100–3500Å (Voshchinnikov and Il'in, 1993). The curve approaches a maximum at $\lambda = 700$Å and then decreases with decreasing λ, reaching a plateau at $\lambda < 300$Å. After inclusion of these new data, we find that the presence of dust can enhance the effect of hardening, contrary to previous results.

In the introduction we formulated the goal of this article as follows: is it possible to explain anomalously high values of y^+, observed in the direction of some nebula boundaries, by a particular ionization structure of the nebulae? We believe the answer is affirmative.

Acknowledgment

This work was performed as part of the Cosmion project.

References

Aller, L. H. (1984) *Physics of Thermal Gaseous Nebulae*, Reidel Publishing Company, Dortrecht.
Baldwin, J. A. *et al.* (1991) *Astrophys. J.* **374**, 580.
Gordon, M. A. (1989) *Astrophys. J.* **337**, 782.
Gulyaev, S. A., Sorochenko, R. L., and Tsivilev, A. P. (1996) *Sov. Astron. Letters* (in press).
Mathis, J. S. (1971) *Astrophys. J.* **167**, 261.
Mezger, P. G. (1980) Radio Recombination Lines, *Proc. Workshop, Ottava*, (Aug. 24–25, 1979), P. A. Shaver (ed.), Dortrecht **80**, p. 8.
Mihalas, D. (1972) Non-LTE model atmospheres for B and AO stars. National Center for Atmospheric Research, Boulder, Colorado, NCAR-TN/STR-76.
Osterbrock, D. E. (1989) *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei, University Science Books*, Mill Valley, CA.
Pankonin, V., Walmsley, C. M., and Thum, C. (1980) *Astron. Astrophys.* **89**, 173.
Peimbert, M. and Torres-Peimbert, S. (1977) *Mon. Not. R. Astr. Soc.* **179**, 217.

Roelfsema, P. R., Goss, W. M., Whiteoak, J. R., Gardner, F. F., and Pankonin, V. (1987) *Astron. Astrophys.* **175**, 219.

Roelfsema, P. R. and Goss, W. M. (1991) *Astron. Astrophys. Suppl. Ser.* **87**, 177.

Roelfsema, P. R., Goss, W. M., and Malnik, D. C. (1992) *Astrophys. J.* **394**, 188.

Schmid–Burgk, J. (1981) Nuclear astrophysics, *Proc. Int. School of Nuclear Phys.*, D. H. Wilkinson (ed.), Pergamon Press, Oxford, p. 625.

Shaver, P. A., McGee, K. X., Newton, L. M., Danks, A. C., and Pottash, S. R. (1983) *Austral. J. Phys.* **204**, 53.

Thum, C., Mezger, P. G., and Pankonin, V. (1980) *Astron. Astrophys.* **87**, 269.

Tsivilev, A. P., Ershov, A. A., Smirnov, G. T., and Sorochenko, R. L. (1986) *Sov. Astron. Letters* **12**, 848.

Tsivilev, A. P. (1991) *Sov. Astron. Letters* **17**, 3.

Voshchinnikov, N. V., Il'in, V. B. (1993) *Sov. Astron.* **70**, 38.