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Determination of temperature of the ionizing stars of H II regions

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Abstract. The determination of temperature ($T_{\rm eff}$) of the ionizing stars of H II regions was considered. In this work we used photoionization models for H II regions ionized by a single star to show that the index $R = \log$([O II]$\lambda\lambda$3726+3729/[O III]λ5007) can be used to estimate $T_{\rm eff}$. The relation R vs. $T_{\rm eff}$ proved to be rather independent of the chemical abundances, but strongly dependent on the ionization parameter of the nebula. In order to check the reliability of using R for temperature determination, we compared the values of $T_{\rm eff}$ obtained via the index R for a sample of H II regions with data available in the literature with independent estimations.

Key words. ISM: H II regions – stars: fundamental parameters – stars: early-type

1. Introduction

Since the pioneer work by Zanstra (1931) many methods based on the nebular emission have been proposed and used to estimate the temperature $T_{\rm eff}$ of the ionizing stars of H II regions. However most of them require the observation of faint lines or the stellar continuum. A recent study of the limitations and advantages of some of the most used methods was presented by Kennicutt et al. (2000). Although the recent advances in astronomical equipment and techniques have made possible the observation of more distant and fainter objects, only the strongest emission lines can still be measured. Among all methods to determine $T_{\rm eff}$ already proposed, the original suggestion by Gurzadyan (1955), later discussed by Köppen & Tarafdar (1978), of using the ratio of strong [O II] and [O III] emission lines would be the most widely applicable.

In this paper, we investigated the use of the index $R = \log$([O II]$\lambda\lambda$3727+3729/[O III]λ5007) to estimate the temperature of ionizing stars of H II regions. As a check, we have compared the estimates of $T_{\rm eff}$ of the stellar constituents of some H II regions of the Milky Way, Magellanic Clouds and M 101 obtained with the use of the R line ratio with those derived from other indexes. We also reassess the gradient of star temperature in the M 101 galaxy.

2. The theoretical models

We employed the photoionization code Cloudy /95.03 (Ferland 2002) to produce a series of models of H II regions. In these a single star was considered responsible for the ionization of the nebula, which is essentially the case of small H II regions. In giant H II regions the ionization is caused by OB associations composed of stars with different temperatures. However the spectrum of an H II region depends mainly on the temperature of the hottest star of the ionizing cluster (Shields & Tinsley 1976; Shields 1986). So, the ionizing source in each model was admitted to be a star with $T_{\rm eff}$ ranging from 30 000 to 50 000 K. The corresponding luminosity (L) have been taken from the L vs. $T_{\rm eff}$ relation proposed by Tout et al. (1996). Since the predicted nebular emission line ratios depend on the atmosphere model adopted, we used three different sets of models, namely the plane-parallel LTE models with line blanketing of Kurucz (1991) for abundances $Z_\odot$ (already incorporated into Cloudy), $3 \times Z_\odot$ and $Z_\odot/3$ (taken from the website `http://cfaku5.havard.edu/`), the non-LTE CoStar models (Schaerer et al. 1996a, 1996b; Schaerer & de Koter 1997), which contemplate the effects of stellar winds and line blanketing, for $Z_\odot$ and $Z_\odot/5$ (from `http://webast.ast.obs-mip.fr/sfr/`), and the non-LTE models for dwarf stars by the Munich group (Pauldrach et al. 1998), which take into account radiation from shock-heated matter and a consistent calculation of line blocking and blanketing, for $Z_\odot$ and $Z_\odot/2$ (from `http://www.usm.uni-muenchen.de/people/adi/adi.html`).

In order to build more realistic models the metallicity of the stellar atmosphere was matched with the one of the nebula. The nebula was considered as a static sphere with filling factor $\epsilon = 0.3$, inner radius of 10^{17} cm and outer radius defined as the point where the electron temperature reaches 1000 K. The electron density was considered constant along the nebula.

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The presence of silicate grains was considered. We adopted the grain abundances of Orion (Baldwin et al. 1991) linearly scaled with the abundance of the gas Z.

In the following subsections we discuss the influence of some parameters of the nebula, as the chemical abundances, ionization parameter, electron density and filling factor, and the evolutive effects on the relation R vs. $T_{\rm eff}$.

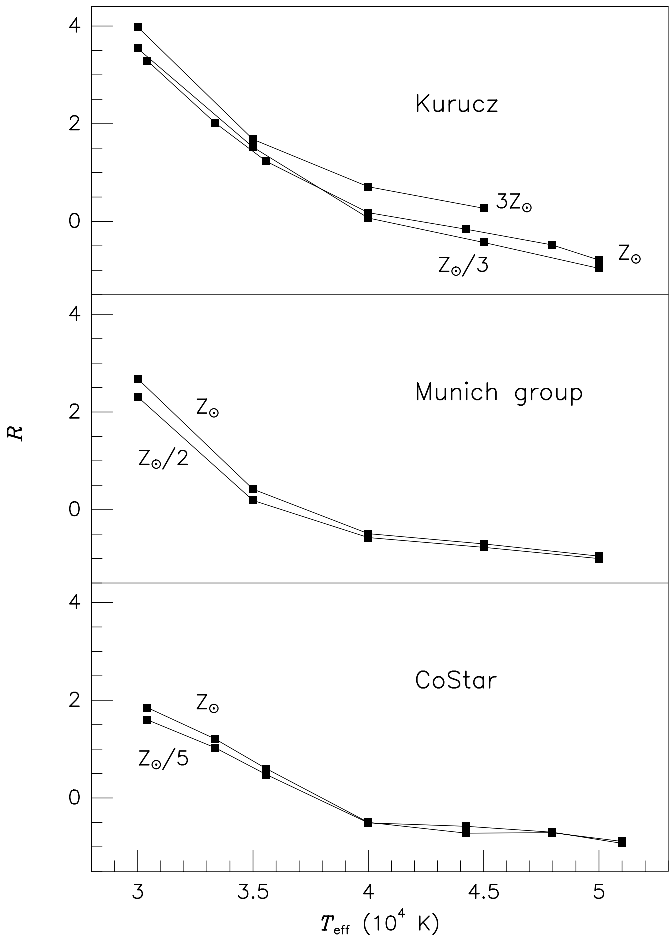

Fig. 1. The relation R vs. $T_{\rm eff}$ for chemical abundances varying from $Z_{\odot}/5$ to $3\times Z_{\odot}$ according to the three different stellar atmosphere models adopted and for an electron density of $N_{\rm e}$ = 500 cm^{-3}.

2.1. The metallicity

Figure 1 shows the relation R vs. $T_{\rm eff}$ for a series of models with chemical abundances varying from $3\times Z_{\odot}$ to $Z_{\odot}/5$. For all models the electron density was considered to be $N_{\rm e}$ = 500 cm^{-3}.

The results obtained for each of the three sets of atmosphere models indicate that the relation R vs. $T_{\rm eff}$ is little dependent on Z. However, as can be seen in Fig. 1, the estimates of $T_{\rm eff}$ derived from R using any of the non-LTE models (CoStar and Munich) are appreciably lower than those obtained from the LTE models of Kurucz (1991). A similar result was found by Stasińska & Schaerer (1997), who reported that $T_{\rm eff}$ determined from an ionic ratio would be lower using the CoStar models than using the Kurucz models. The same trend was also found by Rubin et al. (1995) when comparing photoionization models constructed using the non-LTE atmospheres of Kunze (1994) with those based on the Kurucz ones.

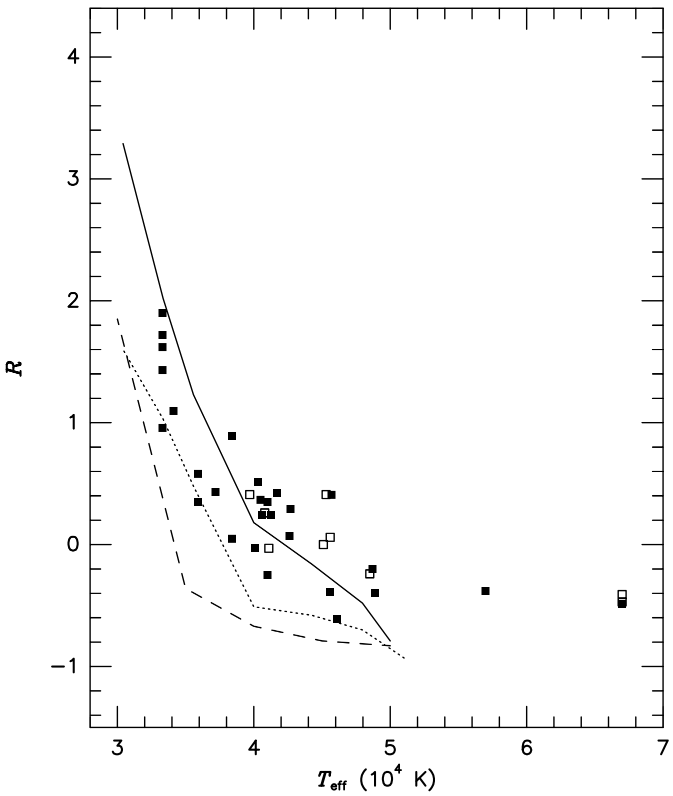

Fig. 2. R vs. $T_{\rm eff}$ from data by Kennicutt et al. (2000) for H II regions in the Milky Way (filled square) and in the LMC (open squares). The solid, dotted and long dashed lines represent the Kurucz, CoStar and Munich models taken from Fig. 1 for $Z_{\odot}$ respectively.

Figure 2 shows the R index against $T_{\rm eff}$ of the hottest stars in some H II regions of the Galaxy and the LMC. Both the observational data for calculating R and the temperature estimates, obtained from the calibration of $T_{\rm eff}$ with spectral type by Vacca et al. (1996) and the stellar ionizing fluxes calculated by Schaerer & de Koter (1997), were taken from the paper by Kennicutt et al. (2000). In this figure the H II regions in the LMC can not be distinguished from the Galactic ones despite the difference in abundances, which also indicates that the dependence of the R vs. $T_{\rm eff}$ relation on the abundances is small. Also in this plot we can see that the index R saturates for $T_{\rm eff}$ > 50 000 K, so R can not be used as temperature indicator above this limit. All four objects with temperatures over 50 000 K are Wolf-Rayet stars. In addition, Fig. 2 shows that R is essentially dependent on the temperature of the hottest star in the ionizing cluster, once the R value depends on the shape of the integrated ionizing continuum emitted by the ionizing stars while $T_{\rm eff}$ was derived from the spectral analysis of the hottest star of the cluster. With the goal of comparing the observational data with our model predictions we superimposed in Fig. 2 the models for $Z_{\odot}$ shown in Fig. 1. It seems that Kurucz models agree better with the observational data than the non-LTE ones. However, the spectral calibration by

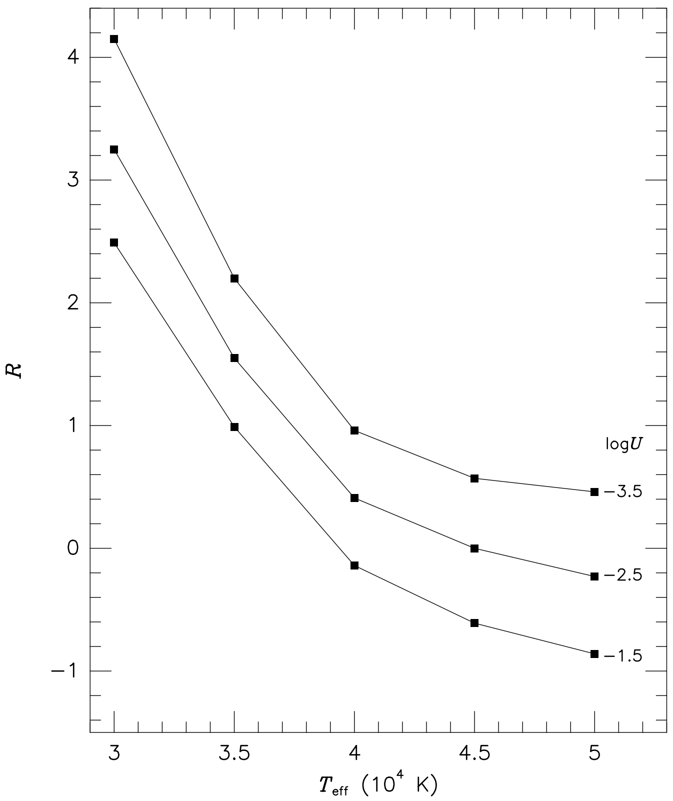

Fig. 3. R vs. $T_{\rm eff}$ for $\log U$ from −1.5 to −3.5. Solar abundances and the Kurucz atmosphere models were adopted.

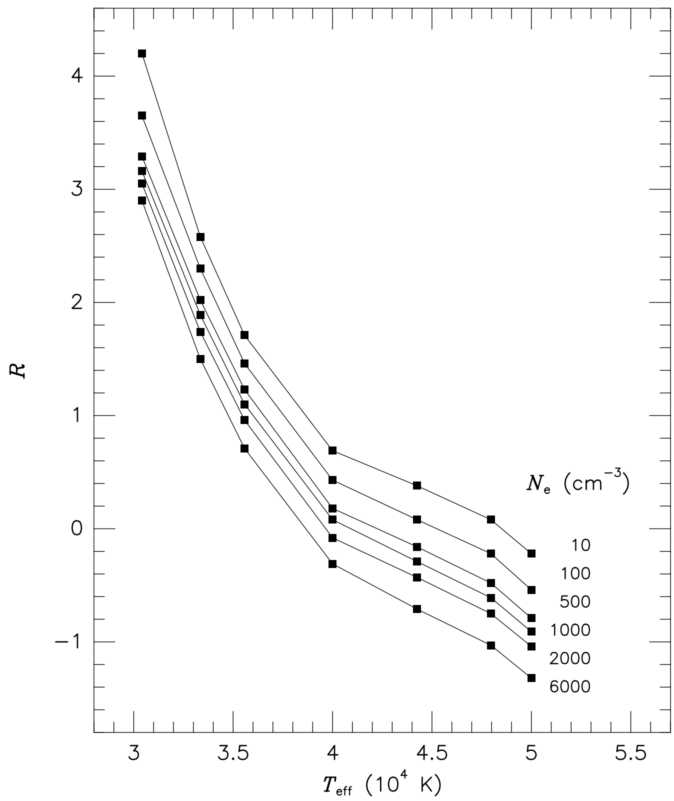

Fig. 4. R vs. $T_{\rm eff}$ for electron densities from 10 to 6000 cm^{-3}. Solar abundances and the Kurucz atmosphere models were adopted.

Vacca et al. (1996) is based on a compilation of values obtained from pure H^+ and He models known to overestimate $T_{\rm eff}$ values for hot stars. Recent works (Bianchi et al. 2003; Martins et al. 2002) based on non-LTE models with full blanketing and hydrodynamics consistently indicate a $T_{\rm eff}$ scale up to 20% lower, which would reconcile the observational points with the non-LTE models in Fig. 2.

2.2. The ionization parameter

It is well known that the line ratio [O II]$\lambda\lambda$3726+3729/[O III]λ5007 is very sensitive to the ionization parameter, defined by $U = Q_{\rm H^o}/4\pi R_{\rm s}^2 nc$; where $Q_{\rm H^o}$ is the number of hydrogen ionizing photons emitted per second by the star, $R_{\rm s}$ is the Strömgren radius, n is the hydrogen density ($\approx N_{\rm e}$), and c is the light speed. However, we should bear in mind that a large fraction of the variation of U is due to differences in temperature of the ionizing stars. Bresolin et al. (1999) have rewritten the ionization parameter as $U = A(Q_{\rm H^o} n \epsilon^2)^{1/3}$, where ϵ is the filling factor and $A \propto T_{\rm e}^{-2/3}$. According to Kennicutt et al. (2000), the ionization parameter of most of the H II regions lies in the range $-3.5 < \log U < -1.5$, whereas the brightest extragalactic H II regions are found in the narrow range from −3.5 to −2.5. In Fig. 3 a series of models with $\log U = -1.5, -2.5$ and -3.5 produced with different combinations of $Q_{\rm H^o}$, $N_{\rm e}$ and ϵ is shown. The index R is subject to variations of the order of 1.0 dex for $-3.5 < \log U < -1.5$ and 0.5 dex for $-3.5 < \log U < -2.5$, corresponding to errors in $T_{\rm eff}$ of about 8000 K and 3000 K respectively.

2.3. The electron density

A series of models with electron densities varying from 10 to 6000 cm^{-3} is presented in Fig. 4. The stellar atmosphere models of Kurucz (1991) were adopted. We can note a systematic decrease of R with the increase of $N_{\rm e}$ at fixed $T_{\rm eff}$, which may be understood as due to the dependence of the R index on the ionization parameter ($U \propto N_{\rm e}^{1/3}$ and $R \propto U^{-1}$). If this dependence is not taken into account errors in the estimation of $T_{\rm eff}$ from R of the order of 3000 to 10 000 K may be produced. However, the values of electron density usually found in Galactic and extragalactic nebulae lay in much narrower range. For instance, Copetti et al. (2000), in a study of internal variation of electron density in 15 Galactic H II regions, have found that all observed objects have mean densities of the order of $N_{\rm e} \approx$ 20–360 cm^{-3}. In a similar work, Castañeda et al. (1992) have found at the brightest knots of a sample of extragalactic H II regions densities below 400 cm^{-3}. So, for electron densities in the range of 10 to 400 cm^{-3} the error in $T_{\rm eff}$ would be of the order of 2 000 for $T_{\rm eff} < 40\,000$ K and up to 7000 K for higher temperatures.

2.4. Evolutive effects

With the aim of analyzing the evolutive effects on the R vs. $T_{\rm eff}$ relation, we built models of nebulae having ionizing stars with different ages (see Fig. 5). We used the CoStar atmosphere models (the only available for many ages) with solar metallicity, stellar masses of 120, 85, 60, 40, 25 and 20 $M_{\odot}$ and ages

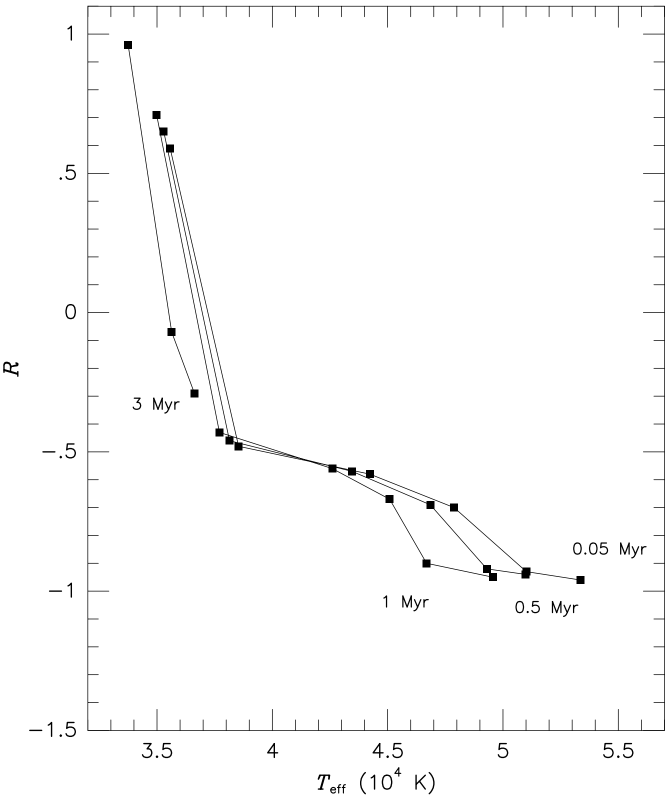

Fig. 5. R vs. $T_{\rm eff}$ for stellar ages from 5×10^4 to 3×10^6 years. From right to left, the squares represent models with stellar masses of 120, 85, 60, 40, 25 and 20 $M_\odot$ for ages of 0.05, 0.5 and 1 Myr and 20, 25 and 40 $M_\odot$ for the age of 3 Myr.

of 5×10^4, 5×10^5, 1×10^6 and 3×10^6 years. The interior models were calculated with the Geneva stellar evolution code with the same input physics (reaction rates, opacities, etc.) as in Meynet et al. (1994). We can see that the evolutive effects on the R vs. $T_{\rm eff}$ relation are small for evolution close to the main sequence. However, massive stars in a Wolf-Rayet phase may reach temperatures much higher than those of main sequence stars.

3. Estimation of $T_{\rm eff}$ from R and comparison with other methods

3.1. Nebulae in the Galaxy and Magellanic Clouds

In Table 1 the $T_{\rm eff}$ of the ionizing stars of some H II regions in the Milky Way and Magellanic Clouds obtained via the index R (using Fig. 1) are compared with the values found by Kennicutt et al. (2000) based on the spectral classification of the ionizing stars and also with those derived from the line ratio He I λ5876/Hβ and the index η' introduced by Vilchez & Pagel (1988) as

$$\eta' = \frac{[\mathrm{O\,II}]\lambda 3727/[\mathrm{O\,III}]\lambda\lambda 4959, 5007}{[\mathrm{S\,II}]\lambda\lambda 6717, 6731/[\mathrm{S\,III}]\lambda\lambda 9069, 9532}. \quad (1)$$

All the emission lines ratios used in this comparison were taken from Kennicutt et al. (2000). From this same paper (Figs. 6 and 9 therein) we also used the calibration of $T_{\rm eff}$ with the He I ratio and with the index η'.

In general, the temperature estimates based on R are consistent with those obtained with the other methods with the exception of five objects. For RCW 5, N 138DB N 57C and RCW 48 which are ionized by early-type Wolf-Rayet stars, the temperatures based on spectral classification are much higher than those derived from nebular emission line ratios. Once the relation R and $T_{\rm eff}$ was derived using models of H II regions ionized by main sequence stars, it is not surprising that the index R fails to predict the appropriate temperatures for these objects. For the hottest star in N 66 nebula, we obtained using Kurucz models a value for $T_{\rm eff}$ about 8000 K higher than the one based on spectral classification. This is the brightest nebula in the SMC, ionized by a rich star cluster. Kennicutt et al. (2000) suspected that the associated temperature might be underestimated due to the presence of the luminous Wolf-Rayet star HD 5980. The median deviations between the estimates of $T_{\rm eff}$ derived from R and those based on the spectral classification, η' and He I/Hβ ratio are respectively 3000, 2000 and 3000 K assuming the Kurucz models and 6000, 3500 and 2000 K for the non-LTE atmospheres. As already discussed in Sect. 2.1, the temperatures derived from a calibration $T_{\rm eff}$ vs. R based on the LTE Kurucz atmospheres are systematically higher (by 12% on average) than those obtained from the non-LTE models.

3.2. Radial gradient of $T_{\rm eff}$ in M 101

Shields & Tinsley (1976) concluded that the spatial variations of Hβ equivalent width of H II regions in spiral galaxies discovered by Searle (1971) were due to gradients in the temperature of the exciting stars. For M 101 they found that $T_{\rm eff}$ increases by $\triangle \log (T_{\rm eff}) = 0.02$–$0.13$ K from the intermediate to the outermost H II regions. This temperature gradient has been reassessed by many other author (e.g. Evans 1986; Vilchez & Pagel 1988; Henry & Howard 1995).

We have determined the temperature of the ionizing stars of H II regions in M 101 from the index R with the observational data taken from Kennicutt & Garnett (1996) adopting an electron density of 500 cm^{-3} and using the LTE stellar atmosphere models of Kurucz (1991) and the non-LTE models (Fig. 1). In Fig. 6 we show the radial distribution of temperature obtained and, for comparison, the results of other authors. The discrepancy between the estimations of $T_{\rm eff}$ based on LTE and non-LTE atmosphere models is clearly seen in this figure. Our estimates using the Kurucz models are in good agreement with those of Evans (1986) based on the LTE models of Hummer & Mihalas (1970), while the temperatures we have obtained using the CoStar and the Munich group non-LTE models agree with those by Vilchez & Pagel (1988) and Henry & Howard (1995), also based non-LTE atmosphere models.

We have also calculated $T_{\rm eff}$ using the empirical fit for extragalactic H II regions $T_{\rm eff} = 50819 - 16485x + 3778x^2$ K, with $x = \log \eta'$, proposed by Kennicutt et al. (2000) and the necessary data from Kennicutt & Garnett (1996). With this approach, no gradient of temperature can be perceived in M 101.

Table 1. Comparison between estimates of T_{eff} derived from the emission line ratios R, η' and He I λ5871/Hβ, and from the spectral classification (SC) of the stars by Kennicutt et al. (2000).

ID	R	log(η')	He I/Hβ	$T_{eff}(R)$			T_{eff}(SC)	$T_{eff}(\eta')$	T_{eff}(He I/Hβ)
				Kurucz	CoStar	Munich			
Galaxy									
S 212	0.24	0.93	0.13	39 800	36 500	36 000	40 600	40 000	≥40 000
S 237	–	–	0.00	–	–	–	32 900	–	≤30 000
M 42	−0.03	0.76	0.11	42 500	37 700	37 600	40 100	42 000	38 500
S 255	1.43	1.36	0.05	35 000	31 300	32 800	33 300	36 000	34 800
S 257	1.10	1.10	0.05	36 000	32 900	33 600	34 100	37 500	34 800
S 271	1.72	1.38	0.02	34 200	≤30 000	32 200	33 300	35 000	31 000
S 275	0.07	0.43	0.11	41 500	37 300	36 900	42 600	48 000	38 500
S 288	0.35	0.90	0.10	39 300	36 200	35 400	35 900	40 000	37 500
RCW 6	0.29	0.75	0.13	39 400	36 300	35 800	42 700	42 000	≥40 000
RCW 5	−0.49	−0.08	0.16	48 200	≥40 000	40 100	67 000	–	≥40 000
RCW 8	1.90	1.99	0.03	33 700	≤30 000	31 800	33 300	33 000	32 000
S 307	0.96	1.20	0.06	36 700	33 600	33 800	33 300	36 000	35 500
RCW 16	−0.20	0.77	0.12	44 600	38 700	38 600	48 700	40 000	39 000
RCW 34	0.43	1.08	0.11	38 900	35 600	35 000	37 200	38 000	38 500
RCW 40	0.89	1.35	0.10	37 000	34 000	34 100	38 400	35 500	37 500
RCW 48	−0.38	–	0.10	46 600	39 400	39 200	57 000	–	37 500
RCW 53	0.41	0.87	0.10	39 200	35 800	35 200	45 700	39 000	37 500
NGC 3603	−0.40	0.89	0.12	47 000	39 500	39 700	48 900	39 000	39 000
RCW 62	0.42	1.25	0.10	39 000	35 700	35 100	41 700	36 000	37 500
M 8	0.35	1.10	0.11	39 300	36 200	35 400	41 000	38 000	38 500
M 16	0.37	0.72	0.12	39 250	36 000	35 300	40 500	42 000	39 000
M 17	−0.39	0.44	0.14	46 900	39 450	39 600	45 600	49 000	≥40 000
S 99	0.05	0.65	0.14	41 800	37 500	37 100	38 400	43 000	≥40 000
S 100	−0.61	0.44	0.16	48 900	≥40 000	43 000	46 100	49 000	≥40 000
S 148	1.62	0.99	0.05	35 000	30 000	32 400	33 300	38 000	34 800
S 152	0.58	1.17	0.11	38 300	35 200	34 600	35 900	36 000	38 500
S 156	0.51	1.16	0.12	38 700	35 500	34 700	40 300	36 000	39 000
S 158	−0.25	0.48	–	45 400	38 800	38 800	41 000	50 000	–
S 162	0.24	0.99	–	39 800	36 500	36 000	41 250	38 000	–
LMC									
N11B	0.00	0.55	0.11	42 300	37 600	37 300	45 100	37 500	≥40 000
N44	0.26	0.54	0.08	39 700	36 400	35 900	40 800	37 500	37 000
N138D,B	−0.41	−0.04	0.13	47 600	39 600	39 800	67 000	44 000	≥40 000
N51D	0.41	0.56	0.12	39 200	35 800	35 200	39 700	37 500	≥40 000
N144	−0.03	0.37	0.09	42 500	37 700	37 600	41 100	38 300	39 000
N57C	−0.47	−0.23	0.14	48 000	≥40 000	39 900	67 000	–	≥40 000
30 Dor	−0.24	0.39	0.11	45 300	38 750	38 700	48 500	38 000	≥40 000
N70	0.41	0.33	0.12	39 200	35 800	35 200	45 300	39 100	≥40 000
N180	0.06	0.42	0.11	41 700	37 400	37 000	45 600	38 000	≥40 000
SMC									
N66	−0.66	−0.17	0.09	49 200	≥40 000	≥43 000	41 900	50 000	37 000

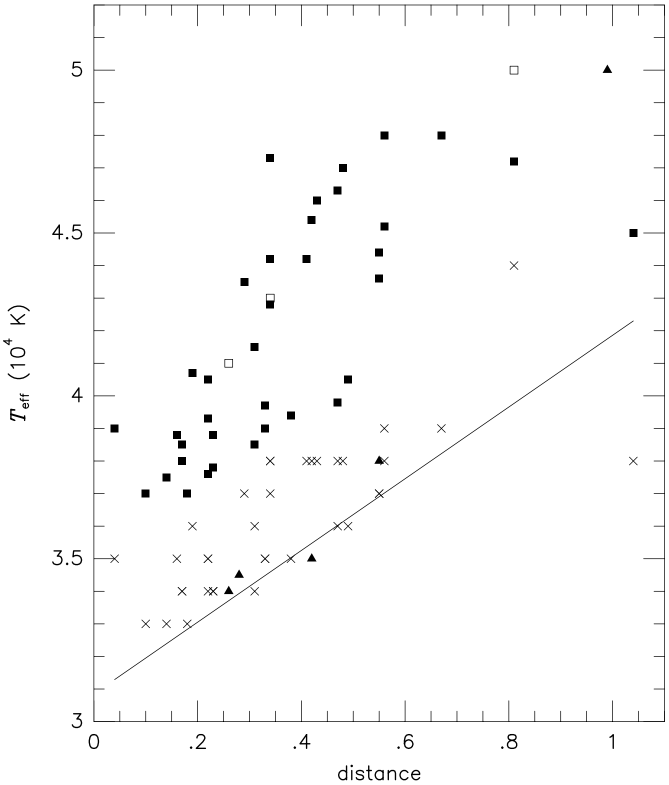

Fig. 6. Star temperature vs. the galactocentric distance (in units of Holmberg radius) for H II regions in M 101. $T_{\rm eff}$ from (■) R via Kurucz models, (×) R via CoStar and Munich atmospheres, (□) Evans (1986), (▲) Vilchez & Pagel (1988). The solid line represents the gradient by Henry & Howard (1995).

Bresolin et al. (1999) have already pointed out the difficulty of revealing temperature gradients from the index η'.

4. Conclusions

We have shown that the temperature of the ionizing stars of H II regions can be estimated from the line ratio $R = \log([\mathrm{O\,II}]\lambda\lambda3726{+}3729/[\mathrm{O\,III}]\lambda5007)$ despite the strong dependence of this index on the ionization parameter, electron density, and on the stellar atmosphere model adopted. The temperature estimates from R based on LTE atmosphere models are significantly higher (by 12% on average) than those obtained from non-LTE models.

The needed emission lines are among the strongest in the spectra of H II regions, what makes this temperature indicator specially useful for statistical studies of distant objects. We have shown that the values of $T_{\rm eff}$ obtained from the index R are, in general, consistent with those derived from other methods, mainly if the electron density is known. However, the index R tends to be less sensitive at higher temperatures and can not predict the correct temperatures of early-type Wolf-Rayet stars with $T_{\rm eff} > 50\,000$ K. Owing to the weak dependence of the index R on the chemical abundances, it is a useful tool for unveiling temperature gradients in the disks of spiral galaxies.

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