O STAR EFFECTIVE TEMPERATURES AND H II REGION IONIZATION PARAMETER GRADIENTS IN THE GALAXY

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ABSTRACT

Extensive photoionization model grids are computed for single-star H II regions using stellar atmosphere models from the WM-Basic code. Mid-IR emission-line intensities are predicted, and diagnostic diagrams of [Ne III/II] and [S IV/III] excitation ratios are built, taking into account the metallicities of both the star and the H II region. The diagrams are used in conjunction with Galactic H II region observations obtained with the Infrared Space Observatory to determine the effective temperature $T_{\text{eff}}$ of the exciting O stars and the mean ionization parameter $\bar{U}$, where $T_{\text{eff}}$ and $\bar{U}$ are found to increase and decrease, respectively, with the metallicity of the H II region represented by the Ne/Ne$\equiv$ ratio. No evidence is found for gradients of $T_{\text{eff}}$ or $\bar{U}$ with Galactocentric distance $R_{\text{Gal}}$. The observed excitation sequence with $R_{\text{Gal}}$ is mainly due to the effect of the metallicity gradient on the spectral ionizing shape, upon which the effect of an increase in $T_{\text{eff}}$ with $Z$ is superposed. We show that not taking properly into account the effect of metallicity on the ionizing shape of the stellar atmosphere would lead to an apparent decrease of $T_{\text{eff}}$ with $Z$ and an increase of $T_{\text{eff}}$ with $R_{\text{Gal}}$.

Subject headings: Galaxy: stellar content — H II regions — infrared: ISM — stars: atmospheres — stars: fundamental parameters — supergiants

1. INTRODUCTION

The determination of the stellar distribution (especially of the hottest stars) and physical characteristics of Galactic H II regions are of primary importance to the evaluation of star formation theories and to our understanding of the chemical evolution of galaxies.

Shields & Tinsley (1976) used the equivalent width of the H$\beta$ emission line from H II regions in spiral galaxies to determine the existence of a radial gradient in the effective temperature ($T_{\text{eff}}$) of the hottest stars, associated with a decrease in metal abundance. Campbell (1988) determined $T_{\text{eff}}$ and the ionization parameter $U$ for various H II galaxies and concluded that the $T_{\text{eff}}$ of the hottest star decreases with increasing oxygen abundance.

On the other hand, Evans & Dopita (1985) have computed extensive photoionization models using Hummer & Mihalas (1970) atmosphere models and have determined from optical observations of H II regions that the ionization temperature of the exciting stars is approximately constant (41 kK, independent of the metallicity $Z$ and $U$). They concluded that the $T_{\text{eff}}$ of the hottest star decreases with increasing oxygen abundance.

More recently, Martin-Hernández et al. (2002a) used Infrared Space Observatory (ISO) spectral observations of Galactic H II regions to show that the gas excitation increases with the Galactocentric distance $R_{\text{Gal}}$. They concluded that the stellar spectral energy distributions (SEDs) are softer at higher metallicities, that is, toward the Galactic center, and that the SED changes can explain the observed gradient. Giveon et al. (2002b) similarly used ISO observations but suggested that the increase in excitation corresponds instead to a decrease in stellar effective temperature. Morisset et al. (2003, hereafter MSBM04) showed that excitation gradients are partly due to changes in the ionizing spectral shape of O stars with metallicity. They concluded that the excitation scatter is probably mainly due to randomization of both the stellar $T_{\text{eff}}$ and the nebular mean ionization parameter $\bar{U}$.

No attempt was made by Giveon et al. (2002b), Martin-Hernández et al. (2002a), or MSBM04 to determine $T_{\text{eff}}$ and $U$ for individual H II regions.

Dors & Copetti (2003) used optical observations of Galactic and Magellanic H II regions to determine $T_{\text{eff}}$ from optical diagnostic line ratios. They also found an increase of $T_{\text{eff}}$ with Galactocentric distance.

The aim of the present work first is to build diagnostic diagrams for the determination of $T_{\text{eff}}$ and $U$, based on mid-IR emission lines. The diagrams are derived from an extensive grid of photoionization models that populate the $T_{\text{eff}}$-$U$-$Z$ grid and use the WM-Basic (Pauldrach et al. 2001) code to compute the ionizing atmosphere models. In a second step, $T_{\text{eff}}$ and $U$ are determined for the ISO H II regions using the new diagnostic diagrams.

Section 2 describes the ISO observations of H II regions, and § 3 the grid of photoionization models. The location of ISO observations in the model grids, the process to determine $T_{\text{eff}}$, and the mean ionization parameter $\bar{U}$ for every object are presented in § 4, using two different methods. Section 5 describes the resulting gradients of $T_{\text{eff}}$ and $U$. In § 6 we discuss the effect of the stellar metallicity in the determination of $T_{\text{eff}}$, in particular, the influence of the changes in the stellar SEDs with metallicity. The conclusions are presented in § 7.

2. ISO OBSERVATIONS OF H II REGIONS

Mid-IR fine-structure line intensities obtained from observations of H II regions with ISO SWS (Martin-Hernández et al.

| Year | Reference | Description |
|------|-----------|-------------|
| 1985 | Evans & Dopita | Use of H$\beta$ emission line to determine $T_{\text{eff}}$ and $U$. |
| 1988 | Campbell | Determined $T_{\text{eff}}$ and $U$ for various H II galaxies. |
| 1976 | Shields & Tinsley | Use of H$\beta$ emission line to determine a radial gradient in $T_{\text{eff}}$. |
| 1985 | Evans & Dopita | Computed extensive photoionization models. |
| 2002a | Martin-Hernández et al. | Used ISO observations to show that gas excitation increases with $R_{\text{Gal}}$. |
| 2002b | Giveon et al. | Used ISO observations but suggested an increase in excitation instead. |
| 2003 | Dors & Copetti | Used optical observations to determine $T_{\text{eff}}$. |

Note: The mean ionization parameter $\bar{U}$ is defined, following Evans & Dopita (1985), as the value of $U$ evaluated at a distance from the ionizing star $r = r_{\text{empty}} + \Delta R/2$, where $r_{\text{empty}}$ is the size of the empty cavity and $\Delta R$ is the thickness of the uniform-density H II shell.
were computed with spectral distributions from supergiant atmosphere models that (Morisset et al. 2002) has been calculated using ionizing only an upper limit) are removed, 42 usable sources remain.

of the line intensities used in this work is not defined (or have only an upper limit) are removed, 42 usable sources remain.

3. GRID OF PHOTOIONIZATION MODELS
A grid of photoionization models using the NEBU code (Morisset et al. 2002) has been calculated using ionizing spectral distributions from supergiant atmosphere models that were computed with WM-Basic version 2.112 (Pauldrach et al. 2001). The current grid of photoionization models is similar to the one used in MSBM04 (see MSBM04 for details). It has been extended further to encompass the full range of values expected within the three-dimensional parameter space $T_{\text{eff}}$-U-Z, where $T_{\text{eff}}$ ranges from 30 to 50 kK by 5 kK steps, log ($U$) is $-2.6, -1.5, -0.8, -0.1, 0.5$, and the metallicity $Z$ of both the ionizing star and the nebular gas is 0.5, 0.75, 1.0, 1.5, and 2.0 times the solar value (as defined in WM-Basic). In total, 125 models have been computed from which mid-IR line intensities were derived.

4. DETERMINATION OF $T_{\text{eff}}$ AND $U$
Three mid-IR line ratios could in principle be used as excitation diagnostics, namely, [Ar III]/[Ar II], [Ne III]/[Ne II], and [S IV]/[S III]. We note, however, that [Ar III]/[Ar II] is overestimated in photoionization models, as pointed out in MSBM04. It is not clear whether the latter is due to an improper determination of the ionizing flux near 24 eV or simply to incomplete atomic physics used within photoionization codes (e.g., missing accurate dielectronic recombination rates). For these reasons, despite its low dependence on $U$, the [Ar III]/[Ar II] ratio proves to be useless for determining $T_{\text{eff}}$. On the other hand, while the alternative excitation ratios [Ne III]/[Ne II] and [S IV]/[S III] are both sensitive to $T_{\text{eff}}$ and $U$, it turns out that the effect of either parameter on both ratios is somewhat different, and a way to determine $T_{\text{eff}}$ and $U$ using these excitation diagnostics can be extracted. Even though the direct use of [Ne III]/[Ne II] and [S IV]/[S III] or other combinations of these line ratios would provide equivalent constraints, we prefer to adopt $\eta_{\text{Ne-Ne}}$ defined following Vilchez & Pagel (1988) as $\eta_{\text{Ne-Ne}} = [\text{S IV}/\text{S III}]/[\text{Ne III}/\text{Ne II}]$, in combination with [Ne III]/[Ne II]. The determination of $T_{\text{eff}}$ and $U$ turns out to be clearer and easier to read off when using $\eta_{\text{Ne-Ne}}$.

The underlying hypothesis/assumptions made here are the following: (1) The ISO H II regions are excited by a single star (i.e., the presence of other less luminous stars does not affect the results). (2) The H II regions are ionized by stars of comparable surface gravity $\log (g)$ at a given $T_{\text{eff}}$ [see MSBM04 for the effects of $\log (g)$]. (3) The Ne abundance determined from the H II region is a reliable estimator of the ionizing star metallicity. (4) The presence of dust in the H II regions does not affect the $T_{\text{eff}}$ and $U$ gradients. Dust would decrease the global amount of ionizing photons, but also increase the hardness of the ionizing SED, increasing the excitation of the gas depicted by the IR excitation diagnostics. (3) Using a nebular geometry consisting of a simple shell does not affect the diagnostic diagrams. (6) the WM-Basic atmosphere models describe well the ionizing flux between 35 and 41 eV (or at least the relative changes that occur when the parameters $T_{\text{eff}}$ or Z are varied).

4.1. S-Method: Using only Solar-Metallicity Atmosphere Models
In a first step, we use only the results of the photoionization models obtained with the solar-abundance atmosphere models.

Figure 1 shows the values taken by $\eta_{\text{Ne-Ne}}$ and [Ne III]/[Ne II] when $T_{\text{eff}}$ and $U$ are varied in locked steps. For each H II region, two-dimensional interpolations within this grid are performed and used to determine $T_{\text{eff}}$ and $U$. All the observed values lie inside the grids; no extrapolation is needed. The $T_{\text{eff}}$ and $U$ obtained with solar-metallicity atmosphere models are presented in § 5.

From Figure 1, we can determine the effects of uncertainties in line intensities on $T_{\text{eff}}$ and $U$: a factor of 2 in the excitation diagnostics leads to a shift in $T_{\text{eff}}$ by 1 kK and in $U$ by 0.5 dex.

4.2. Z-Method: $T_{\text{eff}}$ and $U$ Obtained Using Z-dependent Atmosphere Models
The chemical composition of a star strongly affects its radiation, especially in the extreme ultraviolet, where the ionizing photons are emitted. For the same $T_{\text{eff}}$, changing the stellar luminosity by a factor of 4 can affect the excitation diagnostic line ratios by up to 2 orders of magnitude (MSBM04). The determination of $T_{\text{eff}}$ and $U$ need then be performed using grids of photoionization models with various stellar metallicities, as described in § 3. Making the assumption that the metallicity of the ionized region reflects the metallicity of the ionizing star, we can use adapted diagnostic grids, corresponding to the H II regions’ metallicities, to...
determine $T_{\text{eff}}$ and $\bar{U}$. The metallicity of an H II region is hereafter given by the abundance ratio $\frac{\text{Ne}}{\text{Ne}_\odot} = \frac{[\text{Ne}/\text{H}]/[\text{Ne}/\text{H}]_\odot}$, where $[\text{Ne}/\text{H}]$ is obtained from Giveon et al. (2002a). The solar abundance used, $[\text{Ne}/\text{H}]_\odot = 1.4 \times 10^{-4}$, is defined as the value of the abundance gradient $[\text{Ne}/\text{H}]$ ($R_{\text{Gal}}$) found by Giveon et al. (2002a), evaluated at 8.5 kpc. The Ne abundances as a measure of $\frac{Z}{Z_\odot}$ are preferred to a combination of Ne, Ar, and S abundances, since for these two last elements, the abundances are not reliable when the excitation is extreme (MSBM04). For each H II region, we extract from the $T_{\text{eff}}$-$\bar{U}$-Z photoionization model grid the $T_{\text{eff}}$-$\bar{U}$ plane, whose metallicity lies closest to the $\frac{\text{Ne}}{\text{Ne}_\odot}$ of the H II region. Figure 2 shows, for the five metallicities used in the photoionization model grid, the values taken by $\frac{\text{S}}{\text{Ne}}$ and $\frac{[\text{Ne}^\text{iii}]/[\text{Ne}^\text{ii}]}{[\text{Ne}^\text{iii}]/[\text{Ne}^\text{ii}]_\odot}$. The effect of increasing the metallicity of the atmosphere models (and consequently of the nebular gas) is clearly to increase the value of $T_{\text{eff}}$ for a given $[\text{Ne}^\text{iii}/\text{Ne}^\text{ii}]$ ratio, as already pointed out in MSBM04. The observed values for the H II regions are also plotted in the diagram corresponding to their metallicities. All the observed values lie inside the grids. Two-dimensional interpolations are performed to determine $T_{\text{eff}}$ and $\bar{U}$ for each H II region.

5. RESULTS

Table 1 presents the characteristics of the 42 H II regions used in this work: $R_{\text{Gal}}$, $\frac{\text{Ne}}{\text{Ne}_\odot}$ (with a symbol corresponding to the grid used within the Z-method (§ 4.2), $[\text{Ne}^\text{iii}/\text{Ne}^\text{ii}]$, $[\text{S}^\text{iv}/\text{S}^\text{iii}]$, and the $T_{\text{eff}}$ and $\bar{U}$ obtained using the Z-method. The values of $T_{\text{eff}}$ range from 34 to 50 kK, and $\log (\bar{U})$ ranges from $-1.5$ to 0.5, with mean values of 40.5 kK and $-0.60$, respectively. Such ranges for $T_{\text{eff}}$ and $\bar{U}$ are in agreement with the results found by Evans & Dopita (1985). For the three sources for which two independent observations are available, the results obtained lead to a coherent determination of $T_{\text{eff}}$, while the values of $\bar{U}$ can differ by up to a factor of 5.

The set of inferred values for $T_{\text{eff}}$ and $\log (\bar{U})$ versus the Galactocentric radius $R_{\text{Gal}}$ and the abundance ratio $\frac{\text{Ne}}{\text{Ne}_\odot}$ are shown in Figure 3 for the S-method (§ 4.1) and in Figure 4 for the Z-method (§ 4.2). Linear fits to the data are also presented in all the figures.

Fig. 2.—Same as Fig. 1 but with stellar and nebular metallicities 0.5, 0.75, 1.0, 1.5, and 2.0 times solar, from top left to bottom right. Solid (dotted) lines connect iso-$\bar{U}$ (iso-$T_{\text{eff}}$) models, where $T_{\text{eff}}$ and $\log (\bar{U})$ take values of 30, 35, 40, 45, and 50 kK and $-2.6, -1.5, -0.8, -0.1$, and 0.5, respectively. All the observations of the H II regions are distributed in the diagrams according to their nearest values of $\frac{\text{Ne}}{\text{Ne}_\odot}$ (Z-method). The H II regions are symbolized by X, W, +, 0, and = for $\frac{\text{Ne}}{\text{Ne}_\odot} = 0.5, 0.75, 1.0, 1.5$, and 2.0, respectively. See Table 1 for the correspondence between the sources and the diagram used.
The results obtained for $T_{\text{eff}}$ with S- and Z-methods are very different (Figs. 3 and 4, top). While the S-method leads to an increase (decrease) of $T_{\text{eff}}$ with $R_{\text{Gal}}$ (Ne/Ne$_{\odot}$), the use of the Z-method leads to rather different results: no clear correlation is found to exist between $T_{\text{eff}}$ and $R_{\text{Gal}}$, while a correlation is present between $T_{\text{eff}}$ and Ne/Ne$_{\odot}$. The distribution of $T_{\text{eff}}$ versus Ne/Ne$_{\odot}$ obtained with the Z-method can also be described as $T_{\text{eff}}$ increasing strongly with Ne/Ne$_{\odot}$ for Ne/Ne$_{\odot} < 1.2$ and a quasi-constant value (~43 K) for higher Ne/Ne$_{\odot}$, coupled with a higher dispersion.

The dispersion of Ne/Ne$_{\odot}$ with position in the Galaxy is relatively high (see the dispersion of the symbols along $R_{\text{Gal}}$ in the left panels of Fig. 4). The absence of correlation between $T_{\text{eff}}$ and $R_{\text{Gal}}$ obtained with the Z-method might be the result of this high dispersion. Note that for H II regions with $R_{\text{gal}} < R_{\text{gal,0}}$, the determination of $R_{\text{Gal}}$ is degenerate (Martin-Hernández et al. 2002b), and the errors are also important.

Virtually no changes are observed for log ($\bar{U}$) between the S- and the Z-method (Figs. 3 and 4, bottom). This gives insights into the robustness of our results concerning $\bar{U}$, whatever the method used. This can be understood as follows: the main effect of changing $Z$ on the diagnostic diagrams (Fig. 2) is to shift horizontally ([Ne iii/n] axis) the grids of models, while the determination of $\bar{U}$ is mainly dependent on...
the vertical position along the $\eta$-[Ne] axis, which is not affected by the stellar metallicity. No clear correlation is found between $\tilde{U}$ and $R_{\text{Gal}}$, but an inverse correlation between $\tilde{U}$ and Ne/Ne$_{\odot}$ is present (see Fig. 4, bottom).

Figure 5 shows the distribution of $T_{\text{eff}}$ versus the [Ne m/\n] excitation ratio. The softening of the stellar emission when the metallicity increases (even if $T_{\text{eff}}$ does not change) is enough to cover the whole observed range of [Ne m/\n] (over 2.5 dex). This Figure 5 illustrates one more time the illusion of determining $T_{\text{eff}}$ from only one excitation diagnostic. On the other hand, a global increase of $T_{\text{eff}}$ with [Ne m/\n] is also present (the hottest stars are associated with the most highly excited H $\alpha$ regions).

6. DISCUSSION

The results presented in § 5 are sensitive to the changes of the stellar SED with metallicity for a given atmosphere model code. The gradients in $T_{\text{eff}}$ as a function of Ne/Ne$_{\odot}$ and $R_{\text{Gal}}$ derived from a single-solar-metallicity set of stars (S-method) are very different from the gradients obtained with coherent metallicity for the stellar atmosphere model (Z-method).

The results obtained with the S-method agree with those of Campbell (1988) and Dors & Copetti (2003), who similarly did not take into account the Z-dependence of the stellar emission. This confirms that the trends seen in the top panels of Figure 4, when the Z-dependence is properly considered, are mainly due to the changes in the stellar SEDs when the metallicity decreases (an effect that has to be present, but whose magnitude might depend on the family of atmosphere models used). Dors & Copetti (2003) checked the effect of metallicity on the excitation of the ionized gas, but did not find a strong effect; the metallicity range they test is only a factor of 2 for WM-Basic models, they used a low value for the ionization parameter, the effect of Z being reduced in this case, and they used dwarf WM-Basic models, for which the effect of Z is lower than for supergiants. The $T_{\text{eff}}$ values obtained by Campbell (1988) and Dors & Copetti (2003) are derived using an S-method, and the apparent decrease of $T_{\text{eff}}$ with $Z$ and increase of $T_{\text{eff}}$ with $R_{\text{Gal}}$ that they respectively found are likely to be the result of not considering Z-dependent stellar models (the excitation of the gas is not a valid $T_{\text{eff}}$ indicator, as shown by Fig. 5). Note also that the maximum $T_{\text{eff}}$ obtained with the S-method is 45 kK, while the $T_{\text{eff}}$ values from the Z-method get as high as 50 kK.

The results shown in this paper concerning $T_{\text{eff}}$ and $\tilde{U}$ are strongly dependent on the kind of atmosphere model used to compute the photoionization grid of models. In MSBM04, we discuss in detail the major differences between, for instance, WM-Basic and CMFGEN (Hillier & Miller 1998), insofar as the determination of $T_{\text{eff}}$ is concerned. Using the CMFGEN instead of WM-Basic atmosphere models would certainly lead to a globally lower $T_{\text{eff}}$ (MSBM04) and perhaps different gradients.

The increase of $T_{\text{eff}}$ with $Z$ found here is in contradiction with the theoretical predictions of, e.g., Schaller et al. (1992), and if confirmed, it might have profound implications for the study of the upper-mass end of the initial mass function.

However, more extensive studies will be needed to check whether the use of different atmospheres codes will confirm the gradients found here or generate genuine gradients. Our results, nevertheless, show the importance of taking properly into account the variation in the stellar SEDs with metallicity in any attempt to determine a reliable $T_{\text{eff}}$ from H $\alpha$ regions.
7. SUMMARY AND CONCLUSION

Using WM-Basic atmosphere models, we have computed a large set of photoionization models. From these models we have built excitation diagnostic diagrams based on \([\text{Ne}^{\text{iii}}/\text{ii}]\) and \([\text{S}^{\text{iv}}/\text{iii}]\) (mid-IR lines) excitation ratios. ISO observations of Galactic \(H\ II\) regions are superposed on these diagrams. According to their metallicity, \(T_{\text{eff}}\) and \(\bar{U}\) are determined for every \(H\ II\) region.

A correlation between \(T_{\text{eff}}\) and \(\text{Ne}/\text{Ne}_\odot\) and an anti-correlation between \(\bar{U}\) and \(\text{Ne}/\text{Ne}_\odot\) have been found, without evidence of any correlation between \(T_{\text{eff}}\) and \(\bar{U}\) with \(R_{\text{Gal}}\). The determination of \(T_{\text{eff}}\) is strongly dependent on the changes in stellar SEDs because of the radial metallicity gradient within the Galaxy, while the results found concerning the behavior of \(\bar{U}\) are globally insensitive to this effect. The gaseous excitation sequence is therefore mainly driven by the effects of metallicity on the stellar SEDs. A global increase of \(T_{\text{eff}}\) with metallicity appears nevertheless to be present. More investigation using different atmosphere codes will be needed to confirm that our conclusions are not unduly biased toward the use of WM-Basic models. Comparison with \(T_{\text{eff}}\) determined from direct observations of ionizing stars can also help to evaluate the robustness of the method presented in this work.

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