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# THE [O III] LINES AS A QUANTITATIVE INDICATOR OF NEBULAR CENTRAL-STAR TEMPERATURE

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## ABSTRACT

New and revised blackbody temperatures ($T_s$) for exciting stars of nebulae are calculated by Stoy's method. In low-excitation optically thick nebulae the $I(\lambda5007)$[O III]/$I(\text{H}\beta)$ ratio correlates well enough with $T_s$ to be used alone as an accurate indicator of the calculated blackbody temperature. For nebulae for which λ4686 He II is weak [less than 0.05 $I(\text{H}\beta)$] or absent, for which $T_s \leqslant 68{,}000$ K, it is found that $\log T_s = 4.426 + 4.827 \times 10^{-4} I(\lambda5007) - 1.374 \times 10^{-7} I^2(\lambda5007)$, where $I(\text{H}\beta) = 100$. A similar correlation exists for $I(\lambda3868)$[Ne III].

*Subject headings:* nebulae: general — nebulae: planetary

Kaler (1976*a*) recently published a list of the effective temperatures ($T_s$) of the exciting stars of low-excitation planetary and diffuse nebulae, calculated by a modification of Stoy's (1933) method. This method uses the ratio of the total flux in the forbidden lines to that of Hβ, taking into account the measured electron temperature ($T_e$) of the nebula and allowing for absorption of starlight by helium. Physically, the method is used to determine the temperature that the central star must have for the cooling rate in the nebula to equal the heating rate at the measured $T_e$ and He/H. In this paper the method is restricted to the assumption that the stars radiate as blackbodies (see Kaler 1976*a*). $T_s$ is then the equivalent blackbody temperature required to give the above ratio.

This paper presents both new values, based upon new data, and improvements to the earlier list, based upon better predictions of flux from the fine-structure states. New observational data were taken from Torres-Peimbert and Peimbert (1977) and Lutz (1977), and were combined with the data presented in Kaler's (1976*b*) catalog. The details of the calculations are found in Kaler (1976*a*). New fine-structure fluxes were calculated for $Ne^+$, $Ne^{2+}$, $O^{2+}$, and $N^{2+}$. The contribution from other ions was negligible. In calculating the fine-structure contributions, it was assumed that Ne/O = 0.23 (Kaler 1978) and that $N^{2+}/N^+ = O^{2+}/O^+$. Of these four ions, $N^{2+}$ was the least important. Target areas and transition probabilities were taken from Osterbrock (1974), Garstang (1968), and Nussbaumer (1971). The new and revised values of temperatures are presented in Table 1, where the columns give the name of the nebula, the Perek and Kohoutek (1976, PK) number, and $10^{-3}T_s$. The last column gives an estimate of the quality of the results, where A denotes an error in $T_s$ of $\sim \pm 10\%$; C, $\sim \pm 25\%$. Generally, only the lowest-excitation nebulae needed revision.

The major difficulty with this method is that it requires fairly complete observation of the nebular spectrum; all the major forbidden lines must be accounted for, and an electron temperature must be derived. In Figure 1 the intensity of λ5007[O III] [on scale $I(\text{H}\beta) = 100$] is plotted against $\log T_s$ for

TABLE 1

TEMPERATURES OF EXCITING STARS

| Nebula | PK | $10^{-3}T_s$ | Qual. |
|---|---|---|---|
| *a*) Planetary Nebulae | | | |
| NGC 5315*† | 309−4°2 | 56 | A |
| NGC 5882*† | 327+10°1 | 61 | A |
| NGC 6543 | 96+29°1 | 45 | A |
| NGC 6826 | 83+12°1 | 47 | A |
| IC 418 | 215+24°1 | 32 | A |
| IC 2149 | 166+10°1 | 36 | A |
| IC 2501† | 281−5°1 | 51 | A |
| IC 4593 | 25+40°1 | 43 | A |
| IC 5117*† | 89−5°1 | 77 | B |
| IC 5217*† | 100−5°1 | 68 | A |
| BD +30°3639 | 64+5°1 | 27 | A |
| Cn 3-1† | 38+12°1 | 25 | C |
| He 2-108† | 316+8°1 | 29 | B |
| He 2-131† | 315−3°1 | 26 | B |
| He 2-138† | 320−9°1 | 22 | B |
| Hu 2-1 | 51+9°1 | 36 | B |
| M 1-14† | 235−1°1 | 35 | B |
| M 1-59 | 23−2°1 | 42 | B |
| M 1-73 | 51−3°1 | 39 | B |
| Me 2-2 | 100−8°1 | 46 | B |
| Ps1 | 65−27°1 | 27 | B |
| Vy 2-2† | 45−2°1 | 56 | C |
| *b*) Diffuse Nebulae | | | |
| NGC 1976 | ... | 34 | A |
| NGC 3576 | ... | 35 | B |
| NGC 6523 | ... | 35 | A |
| NGC 6618 | ... | 36 | A |
| IC 1470 | ... | 34 | B |
| η Car | ... | 29 | B |

* λ4686 He II present in nebular spectrum.

† New value.

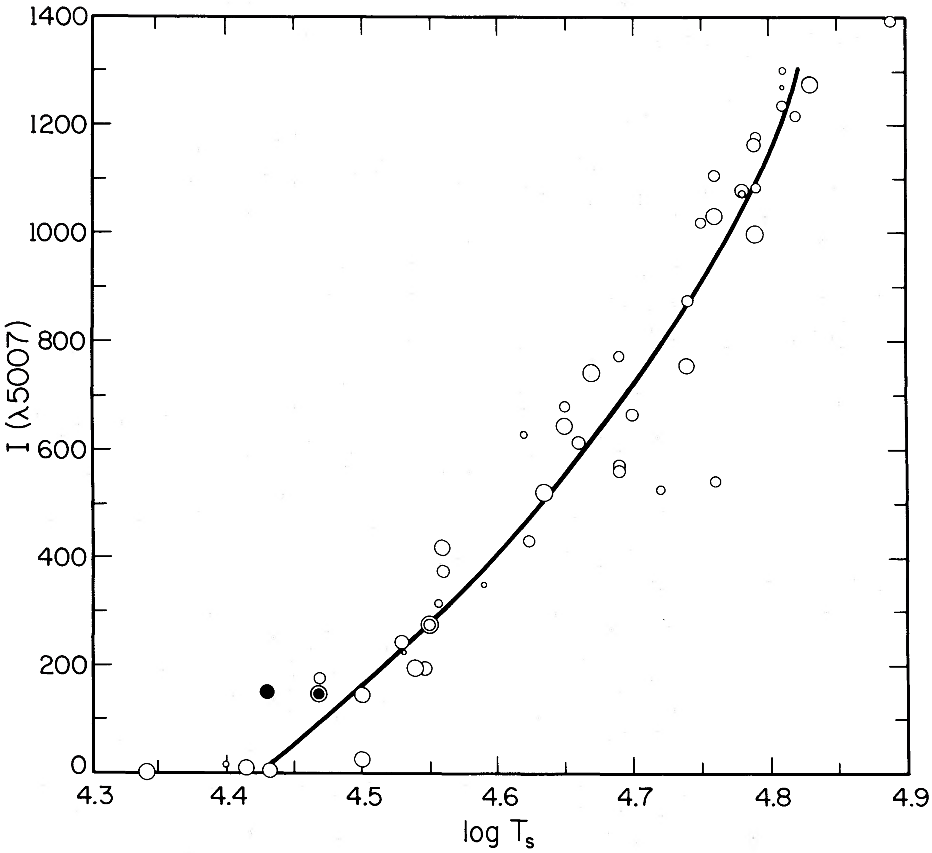


FIG. 1.—$I(\lambda5007)$[O III], for $I(H\beta) = 100$, plotted against log $T_s$. The solid line is the quadratic least-squares fit given by eq. (1), and the dotted symbols are excluded points.

all the nebulae (including those in Kaler 1976*a*). The size of the symbol reflects a subjective estimate of the weight of the point. The correlation is clearly good enough for $T_s$ to be estimated from $I(\lambda5007)$ alone. Thus a large number of exciting-star temperatures can be measured for nebulae for which observational data are incomplete.

A least-squares, weighted, quadratic fit to the data presented in Figure 1 (on the assumption that all the error is in log $T_s$) yields

$$\log T_s = 4.426 + 4.827 \times 10^{-4} I(\lambda5007) - 1.374 \times 10^{-7} I^2(\lambda5007)\,. \quad (1)$$

The curve from this equation is drawn in Figure 1. The equation is valid only for low-excitation nebulae—that is, when $I(\lambda4686)$He II $< 0.05 I(H\beta)$, for which $T_s \lesssim 68{,}000$ K, and when the nebula is optically thick.

The nebulae Ps1 and He 2-108 were excluded from this analysis, because they are probably optically thin; therefore, $T_s$ is a lower limit. These points are marked with dots inside their symbols in Figure 1. From equation (1), we find that log $T_s$ is 4.50 and 4.49, respectively, for Ps1 and He 2-108, still too low for their high observed He/H ratio (Kaler 1978). One must keep in mind that the nebula must be optically thick in order that the method work.

An analysis of the $\lambda3868$[Ne III] intensity gives a result very similar to that for [O III]. $I(\lambda3868)[I(H\beta) = 100]$ is plotted against log $T_s$ in Figure 2. A least-squares quadratic fit gives

$$\log T_s = 4.490 + 4.484 \times 10^{-3} I(\lambda3868) - 1.548 \times 10^{-5} I^2(\lambda3868)\,, \quad (2)$$

which is drawn in the figure as a solid line. The quadratic fit does not appear as good for $\lambda3868$ as it does for $\lambda5007$. A linear least-squares fit gives

$$\log T_s = 4.522 + 2.617 \times 10^{-3} I(\lambda3868)\,, \quad (3)$$

which is plotted in the figure as a dashed line. The quadratic fit is better for log $T_s < 4.6$. An average of the two fits would probably make a good compromise for $T_s > 4.6$.

To understand Figures 1 and 2, consider that $T_s$ controls the nebular heating rate and that the total flux in the forbidden lines, $\sum F$, reflects the cooling rate. For a given $T_s$, $\sum F$ must be fairly independent of the chemical composition of the nebula. If the abundance of cooling ions were to decrease, the elec-

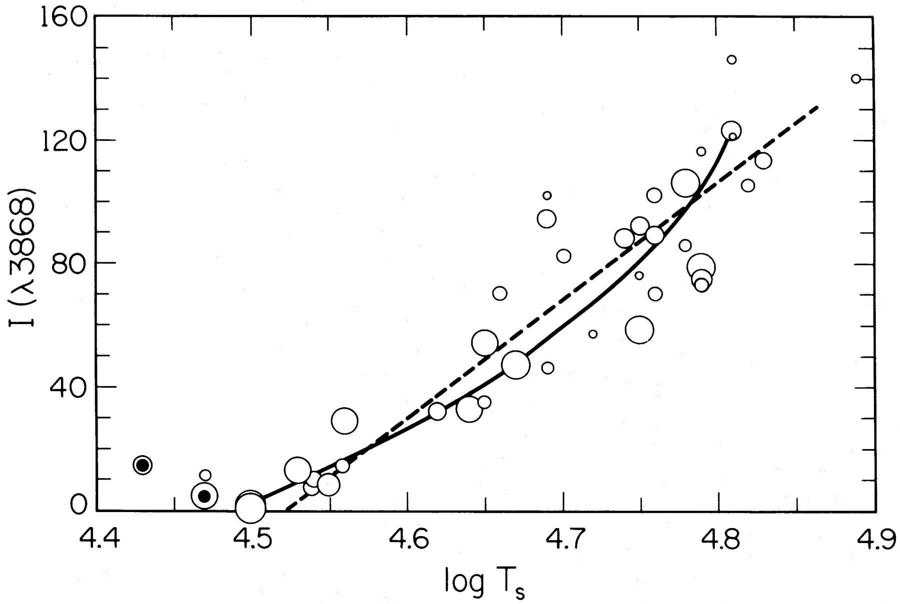


FIG. 2.—$I(\lambda3868)$[Ne III], plotted against log $T_s$, with the same symbolism as that of Fig. 1. The solid line is given by eq. (2) (quadratic fit), and the dashed line by eq. (3) (linear fit).

tron temperature would rise in compensation, so that the cooling rate would be equal to the heating rate; thus $\sum F$ would remain constant. Since [O III] dominates the forbidden lines and since the ratios of most important cooling atoms to oxygen (in particular, Ne and Ar) are generally constant (see, e.g., Kaler 1978), the λ5007 intensity will generally be proportional to $\sum F$. This effect accounts for the low scatter in Figure 1. The scatter that does exist is produced by observational error, by erroneous allowance for unobserved lines, by the variable N/O ratio (see, e.g., Peimbert and Torres-Peimbert 1971), by the variable λ10830 He I contribution, and by variation in ionization levels, e.g., $O^{2+}/O^{+}$.

The low scatter in Figure 2 again reflects the constancy of the Ne/O ratio and the smooth transition from $Ne^{2+}$ to $Ne^{+}$ as a function of $T_s$. Note that $I(\lambda3868)$ goes to zero at a higher temperature than does $I(\lambda5007)$, a reflection of the higher ionization potential of $Ne^{2+}$.

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