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RADIO RECOMBINATION LINES AND ANOMALOUS BALMER LINE INTENSITIES

Two problems concerning hydrogen recombination in gaseous nebulae have recently been discussed. One of these involves the high members of the Balmer series (up to H35) that are too bright compared with Hβ in some nebulae by factors of 2 and greater (Kaler 1966). The anomaly is similar for He I and He II. The other problem involves transitions which take place between very high levels ($n \rightarrow n - 1$, where $n > 90$) which have recently been observed in the radio spectrum (Höglund and Mezger 1965; Lilley, Menzel, Penfield, and Zuckerman 1966). The ratio of line flux to continuum intensity can be used to measure the electron temperature of a nebula by a formula developed by Kardashev (1959). This technique has been used by Mezger and Höglund (1967; hereinafter cited as "MH") to measure the electron temperatures of a large number of diffuse nebulae by observing the $n = 110 \rightarrow n = 109$ transition, referred to as the 109α line. In nearly all cases they find that the temperatures are lower than what one would generally expect. For example MH measure an average electron temperature of $T_e = 5360°$ K for the Orion Nebula, whereas Kaler (1966) gives $T_e = 9200°$ K using all available optical data. Goldberg (1966) has ascribed this result as due to stimulated emission in the high levels.

We believe that the two problems outlined above stem from the same mechanism and are closely related to turbulence within the nebula.

Figure 1 shows the electron temperatures measured by MH plotted against the Doppler temperatures derived from the line width, which they call T_D. The latter are, of course, not true temperatures, as they include the effects of both thermal and turbulent broadening and should always be greater than the electron temperatures. As can be seen, the relationship is nearly linear; T_e decreases as T_D increases. If we assume a linear relation, we find a correlation coefficient of 0.71.

Osterbrock, Miller, and Weedman (1965) have recently measured the line profiles of a number of planetary nebulae at high dispersion. The observations easily separate the two components produced by nebular expansion. They also give a Doppler temperature appropriate to the width of the individual components which we shall also call T_D. Three of these nebulae (NGC 7009, NGC 7662, and NGC 6572) are included in Kaler's (1966) study so that we can compare the H30 anomaly with T_D. We can also estimate T_D for four other nebulae included in Kaler's (1966) list, as described below.

D. E. Osterbrock and D. W. Weedman have kindly furnished us with Hα, [O III] and [N II] line profiles of NGC 7027. Although the turbulent motions within the nebula are so high that the expansion components are not resolved for hydrogen we can at least bracket T_D. If we ignore nebular expansion $T_D = 54000°$ K. The hydrogen-line profile is somewhat asymmetrical, and the [O III] profile shows that the red component is at least twice as strong as the blue. If we try to make the profile symmetrical, we find $T_D = 40000°$ K. The true value probably lies somewhere in between.

MH quote a remark by Goldberg in which he states that the most probable velocity of the atoms in the Orion Nebula is 23.5 km/sec, a number derived from the observations of Kaler, Aller, and Bowen (1965). With $T_e = 9200°$ K we convert this figure to a Doppler temperature of 34300° K. This value of the turbulence should be used rather than others in the literature as it is appropriate to the region in which the optical observations were made.

Finally, we are able to add the planetary nebulae IC 418 and IC 4997 with the aid of tracings of Mount Wilson plates kindly supplied to us by L. H. Aller. We have measured the true half-widths of the hydrogen lines in these objects by using the comparison spectrum to find the instrumental profile. Unfortunately, the dispersion is too low (20 Å/mm) to separate the expansion components so that we must further correct the half-widths to find T_D. Wilson's (1950) observations of IC 418 give a separation for the [S II] lines of 35 km/sec and zero for the hydrogen lines, as these are not separated. From his print of the spectrum we estimate a separation of about 20 km/sec for hydrogen. We then find $T_D = 42000°$ K for IC 418. The expansion velocity of IC 4997 is unknown, so that we can place only upper and lower limits on T_D. If there is no expansion, $T_D = 49000°$ K. The lower limit must obviously equal the electron temperature, $T_D = 22700°$ K (Kaler 1966).

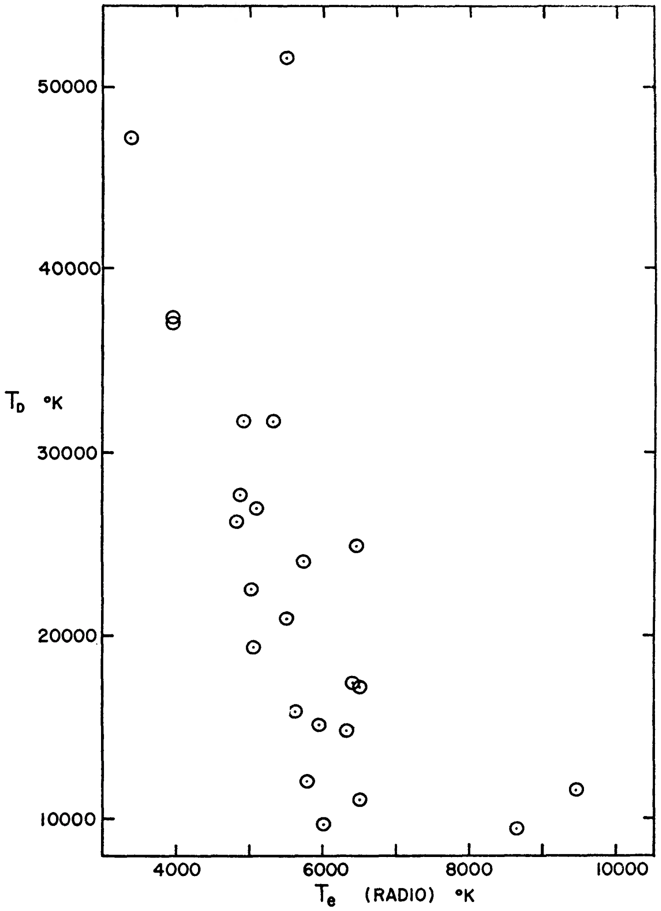

FIG. 1.—Mezger and Höglund's 109α line data. The Doppler temperatures T_D are plotted against their measured electron temperatures.

The circles in Figure 2 plot the values of

$$\log d = \log\left[\frac{I(\mathrm{H30})}{I(\mathrm{H}\beta)}\right]_{\text{observed}} - \log\left[\frac{I(\mathrm{H30})}{I(\mathrm{H}\beta)}\right]_{\text{theoretical}} \tag{1}$$

taken from Kaler (1966) against the values of T_D for the seven nebulae given above. The value of log d for NGC 7009 has been corrected for a reddening constant of 0.28 instead of 0.82. Note that again there is a correlation, with the deviation at H30 (log d) increasing with T_D.

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It is of particular interest to look at the Orion Nebula, which is the only nebula observed in both the radio and optical studies. We refer to MH's equation (2a):

$$\Delta\nu_L\left(\frac{T_L}{T_C}\right)=2.036\times10^4\,\frac{1}{a\,(\nu,T_e)}\,\nu_L{}^{2.1}T_e{}^{-1.15} \qquad (2)$$

where $\Delta\nu_L$ is the line width, T_L and T_C are the line and continuum brightness temperatures, respectively, and a is related to optical depth. If we now reverse their procedure and assume the optical value of T_e we find that the average T_L is 1.9 times larger than it should be for that temperature, or that the 109α line is 1.9 times stronger than it should be in comparison with the value predicted by recombination theory. This figure is similar to the value of the deviation of H30, which is 2.3 times brighter than theoretically predicted. We could interpret this result as meaning that $n = 30$ and $n = 110$ are both overpopulated with respect to a Boltzmann distribution by factors of about 2.

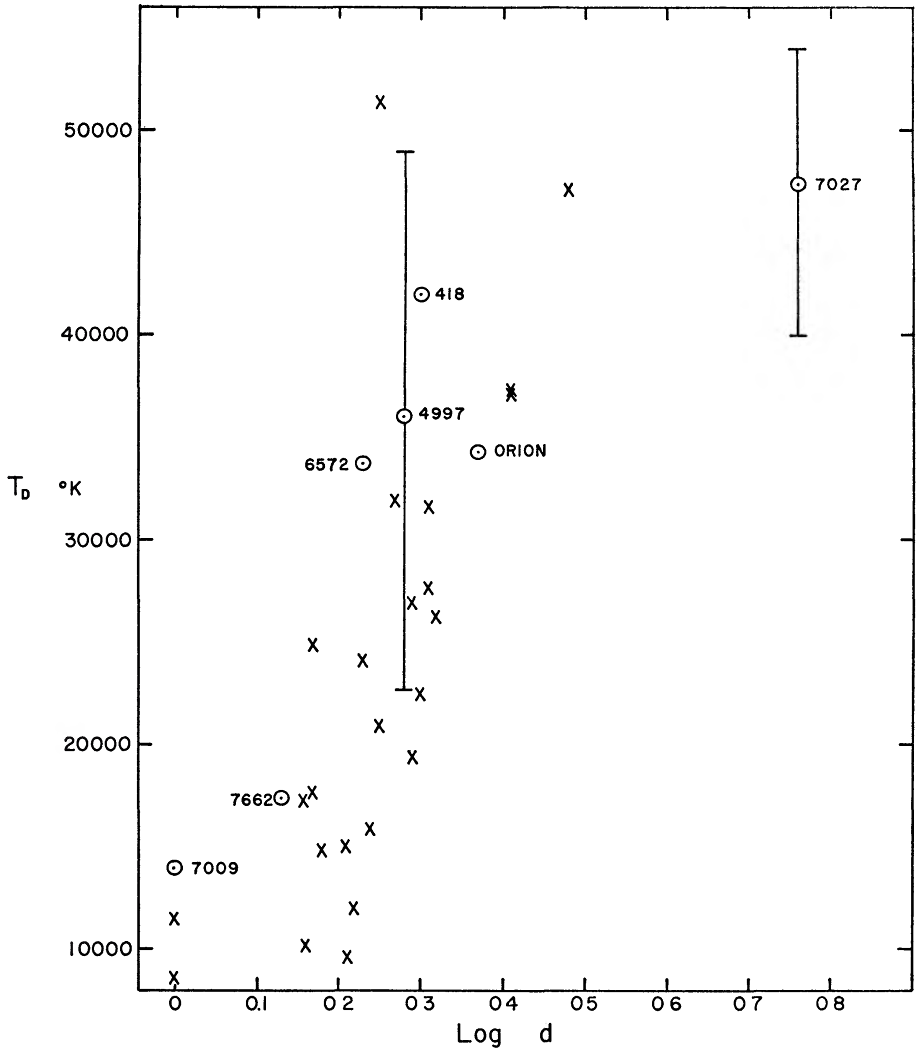

FIG. 2.—The H30 deviation, log d, plotted against T_D. The circles represent the optically observed points and measured log d. The crosses represent the diffuse nebulae observed at the 109α line and computed values of log d based on measured radio T_e and the assumption of a true electron temperature of 9000° K. The optically observed points are labeled with the NGC or IC number.

It can be shown that the H30 deviation is not due to a 2.3 times underpopulation of $n = 4$ as the ratio of forbidden line intensities to Hβ yields a black-body temperature of 38000° K for θ^1 Ori C from Stoy's method (Kaler 1967). If $n = 4$ were underpopulated by a factor of 2.3, the measured temperature would fall to about 24000° K, which is too low for an O6 star. This argument is even more convincing when applied to NGC 7027; in this case $\log d = 0.76$. If $n = 4$ were underpopulated, the central star temperature would be only 40000° K, which is far too low to produce the observed excitation.

Kaler (1966) finds that in many nebulae the ratio of observed to theoretical line intensity increases to about H26 where it levels off. We suggest that the anomaly continues at this same factor to at least $n = 110$.

On the above assumption we can predict from equation (2) what the H30 deviation (or the $n = 110$) deviation should be on the basis of the observed radio electron temperature:

$$\log d = \log\left[\frac{T_e(\text{true})}{T_e(\text{radio})}\right]^{1.15} . \tag{3}$$

Unfortunately, very few diffuse nebulae have had their electron temperatures measured. We therefore adopt a mean of $\langle T_e \rangle = 9000°$ K, which should at least be statistically valid, and compute the value of $\log d$ for all the nebulae in MH's Table 2. These are plotted against T_D as the crosses in Figure 2. The value of $\log d$ is set equal to zero in the two cases where T_e (radio) is greater than 9000° K.

The actual values of $\log d$ for the diffuse nebulae require a knowledge of the true electron temperature. Some of the scatter is probably due to the assumption of a mean electron temperature. It is consequently of importance to measure the temperatures of these nebulae using the forbidden lines. We might mention here that the values of T_D derived from the radio objects include the effect of nebular expansion, whereas the planetary nebulae do not. This would not seem to be an important problem, however, as doubling of lines due to nebular expansion is not seen in the Orion Nebula (Wilson, Münch, Flather, and Coffeen 1959), and the optical and radio line profiles are the same (Weedman 1966).

Figure 2 shows the agreement between the radio and optical data. The two sets have nearly the same slope and fall on nearly the same line.

We thus find that (1) there is a good correlation between the optically observed hydrogen and helium line intensity anomalies and the Doppler temperature measured from line width; and (2) a similar correlation exists between the electron temperatures of diffuse nebulae, as measured by radio recombination lines, and the Doppler temperature. The similarity between the two correlations and the agreement between the optical and radio data from the Orion Nebula lead us to believe that the radio electron temperatures are probably not correct and that they reflect the same peculiarity observed in the optical hydrogen and helium lines. The anomalies appear to be related in some way to turbulence within the nebula.

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James B. Kaler
Paul D. Lee

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University of Illinois Observatory
Urbana, Illinois

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