1996

Theoretical HeI Line Intensities in Gaseous Nebulae: NGC 1976, 6572 and IC 4997

J. B. Kingdon
Space Telescope Science Institute

Gary J. Ferland
University of Kentucky, gary@uky.edu

Mon. Not. R. Astron. Soc. **282,** 723–725 (1996)

Theoretical He I line intensities in gaseous nebulae: NGC 1976, 6572 and IC 4997

J. B. Kingdon[1] and G. J. Ferland[2]

[1]*Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*
[2]*Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA*

Accepted 1996 April 24. Received 1996 April 19; in original form 1995 November 3

ABSTRACT

Smits has recently calculated theoretical He I intensities for a large number of lines for conditions appropriate to gaseous nebulae. These are likely to remain the definitive calculations for some time to come. A comparison of these line ratios with observed values in three nebulae reveals some discrepancies. We show that these discrepancies are reduced when collisional effects from the metastable 2^3S level are included, and that it is not necessary to invoke an unknown depopulation mechanism for the He I 2^3S level.

Key words: ISM: abundances – planetary nebulae: general.

1 INTRODUCTION

Accurate He abundances are important for a wide range of astrophysical problems, ranging from galactic chemical evolution to the determination of the primordial He abundance (Pagel 1996). The calculation of He I line intensities is complicated by the metastability of the 2^3S level, which affects the intensities in two ways: (1) through collisional excitation from 2^3S (Clegg 1987), and (2) through self-absorption and subsequent cascading of lines in the 2^3S–n^3P series (Robbins 1968).

There has been some controversy over the magnitude of the collisional effects, which are important due to the large population of the 2^3S level. Early observations of He I λ10830 (2^3S–2^3P) indicated that this line was only half as strong as predicted by theory (cf. Osterbrock 1964). This could be interpreted as either being due to poor collisional data, or as an indication of some unknown process affecting the atom. Peimbert & Torres-Peimbert (1987) also concluded that the 2^3S level was underpopulated by roughly a factor of 2, based on discrepancies among abundances derived from different optical lines. Kingdon & Ferland (1991, 1993) argued that the λ10830 discrepancy could be explained by a combination of telluric absorption, dust destruction, and observational uncertainty, which reduces the observed intensity from its theoretical value. The Peimbert & Torres-Peimbert (1987) results were biased by λ7065, whose intensity had been incorrectly calculated by Brocklehurst (1972). An examination of optical lines in the planetary nebulae (PNe) NGC 7027 and 7026 by Kingdon & Ferland (1995, hereafter KF95), which utilized updated recombination (Smits 1996, hereafter S96) and collisional (Sawey & Berrington 1993) data, found no evidence for any unknown depopulation mechanism. In addition, an examination of several Type I PNe by Peimbert, Luridiana & Torres-Peimbert (1995) concluded that He I abundances derived from different lines agreed to within the observational uncertainties, without the need of invoking depopulation of 2^3S. The question of the reliability of the theoretical He I spectrum is central if accurate He abundances are to be obtained.

S96 has recently revised his earlier 1991 paper, and has calculated theoretical intensities for numerous He I lines at several densities and temperatures. His work now stands as the definitive treatment of He I. S96 compares observed line ratios in Orion and two PNe to his predicted values. He finds several discrepancies, and discusses theoretical and observational uncertainties in an attempt to explain them.

The S96 calculations are for Baker & Menzel (1938) case B conditions (with case A also considered for the singlets). Case B ignores the ground and lowest excited states. Therefore collisional excitation from 2^3S is not included in the line intensities (with the partial exception of λ10830), although it can be added as a perturbation (cf. KF95; Peimbert et al. 1995). It is essential that this process be included when high accuracy is required.

In this paper, we examine how collisions from the 2^3S level affect the discrepancies noted by S96. We find that including collisional excitation from 2^3S brings the predicted line intensities into better agreement with the observations.

In addition, through the use of minimization techniques, we find that the observed data are consistent with the 2^3S population predicted by theory.

2 CALCULATIONS

Consider the intensity ratio I_1/I_2 of any two He I lines. We can think of each line as being comprised of two parts: a 'recombination' component R (which will also include l-mixing collisions), and a collisional component C due solely to collisions from 2^3S. Then we may write

$$\frac{I_1}{I_2}=\frac{R_1+\gamma C_1}{R_2+\gamma C_2}. \tag{1}$$

Here we have introduced the depopulation factor γ, which is equal to the ratio of the true population of 2^3S to the predicted population. In the absence of any unknown depopulation mechanism, $\gamma=1$.

In his table 4, S96 lists ratios of observed to predicted line intensities for three nebulae: NGC 1976 (Orion), NGC 6572 and IC 4997. S96 obtained the observed intensity ratios from the literature. These will be given by equation (1). The predicted intensity ratios used by S96 come from the calculations in that paper. Since these calculations utilize case B, which does not include collisions from 2^3S for any of the lines considered in this table, his predicted line intensity ratios will simply be equal to R_1/R_2. Therefore, while the observed intensities used by S96 in his table 4 include contributions due to the metastable 2^3S level, the predicted intensities do not. In terms of the quantities R and C defined above, the ratio of observed to predicted intensities listed by S96 is given by

$$\frac{(I_1/I_2)_{\rm Obs}}{(I_1/I_2)_{\rm Pred}}=\frac{1+\gamma(C/R)_1}{1+\gamma(C/R)_2}. \tag{2}$$

Note that this ratio will not be equal to unity unless (1) $\gamma=0$, i.e., no collisional effects, or (2) the C/R values for the two lines considered are equal. This is due to the fact that the predicted intensities of S96 do not include collisions from 2^3S as discussed above. Therefore the fact that the entries in table 1 of S96 are not equal to unity is not in itself cause for concern.

We are now ready to examine how the inclusion of collisional processes affects the agreement between theory and observation. Of the numerous lines given in table 1 of S96, seven have C/R values calculated by KF95: $\lambda\lambda$4026, 4387, 4471, 4922, 5876, 6678 and 7281. We will exclude λ7281 from our analysis, since it can be strongly affected by both telluric absorption and self-absorption. Self-absorption effects, which we do not consider here, should be negligible for the remaining lines.

We present the results of our calculations for each of the three objects in Table 1, with column 1 giving the wavelength. Columns 2, 4, and 6 give the ratio of the observed to predicted line intensities, ignoring collisions from 2^3S. These values are taken directly from table 1 of S96. All intensities considered here are with respect to λ4471. Columns 3, 5 and 7 list the result obtained by evaluating the right-hand side of equation (2), where we have used the C/R values from KF95, calculated using the temperature and density for each object listed by S96, and have taken $\gamma=1$. For perfect agreement between observation and theory, the values in the two columns for each object should be identical. For each of the three nebulae, we have determined two root-mean-square (RMS) values of the residuals between the values in the two columns. The first RMS considers all five line ratios, while the second excludes $\lambda\lambda$4026 and 4387. These two lines both arise from $n=5$, and should therefore be relatively weak and thus have the greatest observational uncertainty, as well as the largest uncertainty in their collisional rates (see KF95 for a discussion). We note here that this approach is essentially identical to comparing the direct observed line ratios with the predicted values from S96, corrected for collisional effects. As is readily seen, the agreement for Orion and NGC 6572 is good, while that for IC 4997 is poorer.

We may use the observational data to check whether there is any evidence for an unknown depopulation mechanism for 2^3S, i.e., whether γ is not equal to 1. Our method is similar to that discussed above. We use the data in the first of the two columns for each object in Table 1, and evaluate the expression on the right-hand side of equation (2). However, this time we treat γ as an unknown parameter. Our goal is to determine the value of γ which minimizes the RMS for each object.

We present our results graphically in Figs. 1(a)–(c) for Orion, NGC 6572 and IC 4997, respectively. Each figure shows the RMS of the fit as a function of γ. The solid line shows our preferred value of the RMS (excluding $\lambda\lambda$4026 and 4387), while the dashed line is the RMS including all five line ratios. A cursory inspection of the figures shows that the RMS for the lines in Orion is only weakly dependent on γ, while the RMS for the other two objects shows a much stronger dependence. We should clarify here that Fig. 1 does not depict the dependence of the line ratios themselves on γ, but rather the dependence of the RMS on this parameter. Thus, while the effect of the metastable 2^3S level is strongest in IC 4997 due to its high density, the RMS for this object does not have the strongest dependence on γ. The value of γ is best determined from the curves that have the strongest dependence on this parameter. Using the three-line RMS for NGC 6572 we obtain a value of $\gamma=1.1$,

Table 1. Fits to observed line intensity ratios.

	Orion		NGC 6572		IC 4997	
λ	Smits	Pred.	Smits	Pred.	Smits	Pred.
4026	1.04	0.99	0.99	0.97	1.04	0.96
4387	0.91	0.98	1.00	0.95	0.91	0.94
4922	0.91	0.99	0.98	0.96	0.86	0.95
5876	1.04	1.04	1.11	1.09	0.99	1.11
6678	0.97	1.00	0.96	0.99	0.73	0.99
	RMS(5)=5.59%		RMS(5)=3.38%		RMS(5)=13.79%	
	RMS(3)=4.95%		RMS(3)=2.39%		RMS(3)=17.29%	

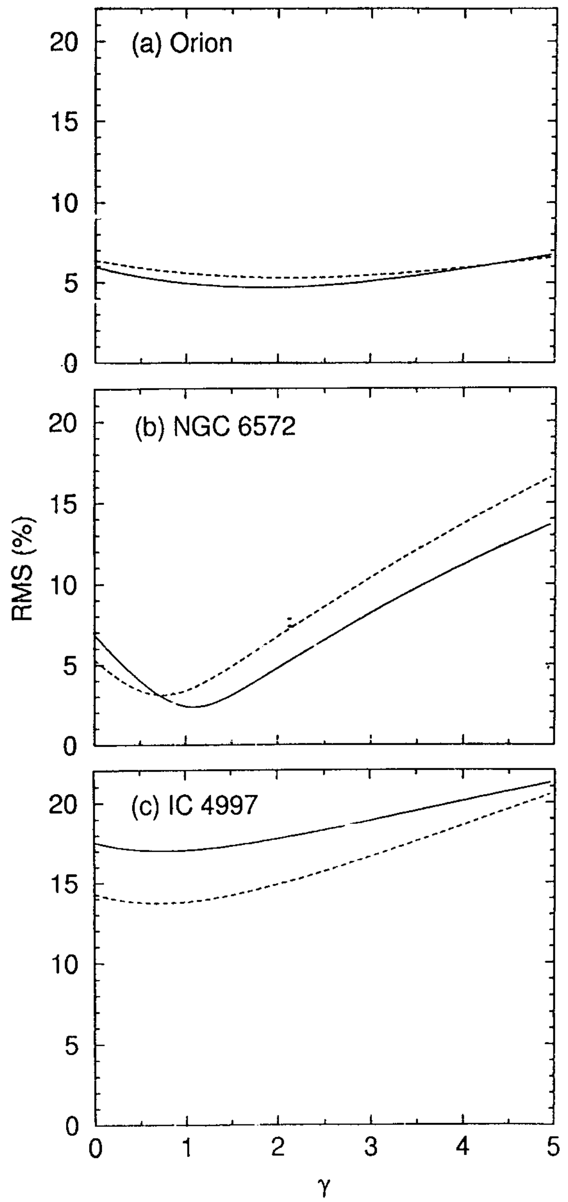

Figure 1. Plot of root-mean square of fit versus the depopulation factor γ. The solid line corresponds to the RMS considering three line ratios, while the dashed line gives the RMS for all five line ratios. (a) Orion, (b) NGC 6572 and (c) IC 4997.

in excellent agreement with $\gamma=1$. We maintain that all the curves in Figs 1(a)–(c) are consistent with $\gamma=1$ within observational and theoretical uncertainties. Note that for all six curves shown, the value of the RMS at $\gamma=1$ is less than that at $\gamma=0$. This implies that in all three objects considered, a better fit to the observations is obtained when collisional excitation from 2^3S is included.

Since the *C/R* values have a strong temperature dependence, it is interesting to examine to what extent uncertainties in the temperature can affect the collisional corrections, and thus the predicted line intensity ratios. We performed calculations similar to that done above, except that γ was set equal to unity and the temperature was varied in order to obtain the minimum RMS. If we consider all five line ratios, the value of the minimum RMS obtained in this way differed by only 0.86 per cent (Orion), 0.37 per cent (NGC 6572), and 0.33 per cent (IC 4997) from the value obtained using $\gamma=1$ and the temperatures given by S96. Therefore, for the three objects considered here, uncertainties in temperature have a negligible effect on the collisional corrections (note that we have considered only the collisional component here, and *not* the recombination component). This result can be explained as being due to two factors. First, if the *C/R* values are much smaller than unity, as is usually the case, the term $1+C/R$ will depend only weakly on changes in *C/R*. Secondly, since each line intensity ratio involves a ratio of $1+C/R$ terms, the temperature effects will be further suppressed, unless the two lines considered have very different temperature dependences. We therefore conclude that small uncertainties in the temperature will have a negligible effect on collisional corrections, except in cases where collisional effects are very strong.

3 CONCLUSIONS

In this paper, we have demonstrated that when collisional effects are included, the S96 theoretical line intensities for Orion and NGC 6572 agree with observation to within the theoretical and observational uncertainties. However, while inclusion of collisional effects improves the fit for IC 4997, there remain significant discrepancies. One possible explanation for these discrepancies lies in the fact that this object has a dust-to-gas ratio of 0.02, some three times larger than that for the general intestellar medium (ISM). It is conceivable that this dust follows a different extinction law than the general ISM. An examination of the two columns for IC 4997 in Table 1 shows a clear correlation between the size of the discrepancy and the wavelength difference of the two lines in the ratio (recall that all intensities are with respect to λ4471). This strongly suggests that the cause of the discrepancies for this object is uncertainties in the extinction corrections. Clearly, this object merits further careful observational study.

ACKNOWLEDGMENT

This work was supported by grants from NSF (AST 93-19034), NASA (NAGW-3315), and STScI.

REFERENCES

Baker J. G., Menzel D. H., 1938, ApJ, 88, 52
Brocklehurst M., 1972, MNRAS, 157, 211
Clegg R. E. S., 1987, MNRAS, 229, 31P
Kingdon J., Ferland G. J., 1991, PASP, 103, 752
Kingdon J., Ferland G. J., 1993, ApJ, 403, 211
Kingdon J., Ferland G. J., 1995, ApJ, 442, 714 (KF95)
Osterbrock D. E., 1964, ARA&A, 2, 95
Pagel B., 1996, in Münch, G., Mampaso A., eds, Key Problems in Astronomy. Cambridge Univ. Press, Cambridge, in press
Peimbert M., Torres-Peimbert S., 1987, Rev. Mex. Astron. Astrofis., 14, 540
Peimbert M., Luridiana V., Torres-Peimbert S., 1995, Rev. Mex. Astron. Astrofis., 31, 147
Robbins R. R., 1968, ApJ, 151, 511
Sawey P. M. J., Berrington K. A., 1993, Atomic Data Nucl. Data Tables, 55, 81
Smits D. P., 1996, MNRAS, 278, 683 (S96)