The Astrophysical Journal, 584:385–389, 2003 February 10

EMISSION LINES OF [Cl II] IN THE OPTICAL SPECTRA OF GASEOUS NEBULAE

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Received 2002 September 16; accepted 2002 October 14

ABSTRACT

Recent ***R***-matrix calculations of electron impact excitation rates among the $3s^2 3p^4$ levels of Cl II are used to derive the nebular emission-line intensity ratios $R_1 = I(6161.8\ \text{Å})/I(8578.7\ \text{Å})$ and $R_2 = I(6161.8\ \text{Å})/I(9123.6\ \text{Å})$ as a function of electron temperature (T_e) and density (N_e). The ratios are found to be very sensitive to changes in T_e but not N_e for densities lower than 10^5 cm^{-3}. Hence, they should, in principle, provide excellent optical T_e diagnostics for planetary nebulae. The observed values of R_1 and R_2 for the planetary nebulae NGC 6741 and IC 5117, measured from spectra obtained with the Hamilton echelle spectrograph on the 3 m Shane Telescope, imply temperatures in excellent agreement with those derived from other diagnostic lines formed in the same region of the nebula as [Cl II]. This provides some observational support for the accuracy of the [Cl II] line ratio calculations and hence the atomic data on which they are based. The [Cl II] 8578.7 and 9123.6 Å lines are identified for the first time (to our knowledge) in a high-resolution spectrum of the symbiotic star RR Telescopii, obtained with the University College London Echelle Spectrograph on the 3.9 m Anglo-Australian Telescope. However, the 6161.8 Å feature is unfortunately too weak to be identified in the RR Telescopii observations, consistent with its predicted line strength.

Subject headings: atomic data — binaries: symbiotic — H II regions — planetary nebulae: general — stars: individual (RR Telescopii)

1. INTRODUCTION

Emission lines arising from transitions among the $3s^2 3p^4$ levels of S-like Ar III are frequently observed in the spectra of gaseous nebulae (Hyung et al. 2001). Several papers have been published on the calculation of diagnostic emission-line intensity ratios for this ion and comparisons made between theory and observation (Keenan & Conlon 1993 and references therein). By contrast, there has been little work on S-like Cl II. Krueger & Czyzak (1970) and Mendoza & Zeippen (1983) calculated electron impact excitation rates and Einstein *A*-coefficients, respectively, for this ion. However, to our knowledge there has been no subsequent determination of diagnostic line ratios and a comparison with nebular observations.

Very recently, Wilson & Bell (2002) calculated electron impact excitation rates for transitions among the $3s^2 3p^4$ levels of Cl II using the ***R***-matrix method and found results significantly different from those of Krueger & Czyzak (1970). For example, at an electron temperature of $T_e = 5000$ K, Wilson & Bell derive an effective collision strength (Υ) for the $^3P_2$–$^3P_1$ transition of $\Upsilon = 4.98$, compared to the Krueger & Czyzak value of $\Upsilon = 2.17$, while for the $^3P_2$–$^1D_2$ transition the results are $\Upsilon = 4.69$ (Wilson & Bell) and $\Upsilon = 2.14$ (Krueger & Czyzak).

In this paper, we use the Wilson & Bell (2002) atomic data to derive electron temperature and density sensitive emission-line ratios for [Cl II]. These calculations are subsequently compared with available high-resolution optical observations of gaseous nebulae to investigate (for the first time) the usefulness of [Cl II] line ratios as plasma diagnostics.

2. THEORETICAL LINE RATIOS

The model ion for Cl II consisted of the three energetically lowest LS states, namely $3s^2 3p^4\ ^3P$, ^1D, and ^1S, making a total of five levels when the fine-structure splitting was included. Energies for these levels were obtained from Kelly (1987). Test calculations including higher terms such as $3s3p^5\ ^3P$ and $3s^2 3p^3 4s\ ^5S$ were found to have a negligible effect on the $3s^2 3p^4$ level populations at the nebular electron temperatures and densities considered in the present paper and, hence, these states were not included in the analysis.

Electron impact excitation rates for transitions in Cl II were taken from Wilson & Bell (2002). However, we note that there is a typographical error in their Table 3, with all of the values for the $^1D_2$–$^1S_0$ transition being a factor of 10 too small. This error is clearly apparent from an inspection of Figure 10 in Wilson & Bell and has been confirmed by the authors. For Einstein *A*-coefficients, the calculations of Mendoza & Zeippen (1983) were adopted. As discussed by Seaton (1964), excitation by protons may be important for transitions with small excitation energies, i.e., fine-structure transitions. However, test calculations for Cl II setting the proton rates for $^3P_2$–$^3P_1$, $^3P_2$–$^3P_0$, and $^3P_1$–$^3P_0$ equal to the equivalent electron excitation rates or 10 times these values had a negligible effect on the level populations, showing that this atomic process is unimportant, at least under conditions prevalent in gaseous nebulae.

Using the above atomic data in conjunction with the statistical equilibrium code of Dufton (1977), relative Cl II level populations and, hence, emission-line intensity ratios were derived for a range of electron temperatures (T_e) and densities (N_e). Details of the procedures involved and approximations made may be found in Dufton et al. (1978). Given

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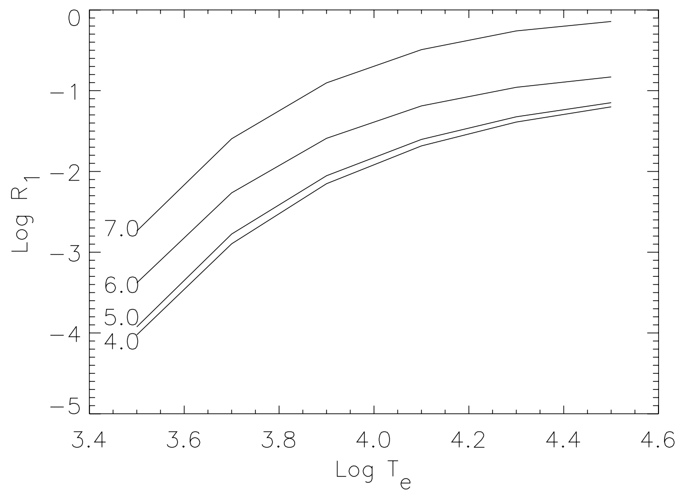

FIG. 1.—Theoretical [Cl II] line intensity ratio $R_1 = I(3s^23p^4\ ^1D_2\text{–}3s^23p^4\ ^1S_0)/I(3s^23p^4\ ^3P_2\text{–}3s^23p^4\ ^1D_2) = I(6161.8\ \text{Å})/I(8578.7\ \text{Å})$, where I is in energy units plotted as a function of logarithmic electron temperature (T_e in K) for several values of logarithmic electron density (N_e in cm^{-3}) in the range $\log N_e = 4.0\text{–}7.0$. Values of R_1 for $N_e < 10^4$ cm^{-3} are coincident with those at $N_e = 10^4$ cm^{-3}.

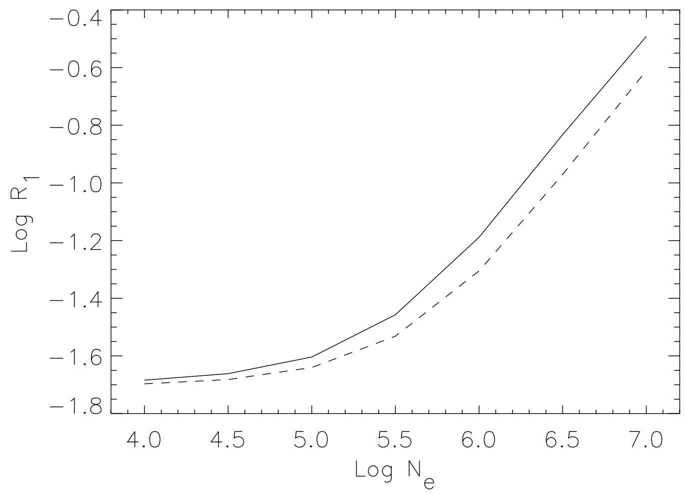

FIG. 2.—Theoretical [Cl II] line intensity ratio $R_1 = I(3s^23p^4\ ^1D_2\text{–}3s^23p^4\ ^1S_0)/I(3s^23p^{4\,3}P_2\text{–}3s^23p^4\ ^1D_2) = I(6161.8\ \text{Å})/I(8578.7\ \text{Å})$, where I is in energy units plotted as a function of logarithmic electron density (N_e in cm^{-3}) at an electron temperature of $T_e = 10^{4.1}$ K. *Solid line*: Calculations with the electron impact excitation rates of Wilson & Bell (2002). *Dashed line*: Calculations with the atomic data of Krueger & Czyzak (1970).

uncertainties of typically ±10% in both the adopted electron excitation rates and A-values (see above references), we estimate that our derived theoretical line ratios should be in error by at most ±15%.

In Figure 1, we plot the [Cl II] emission-line intensity ratio $R_1 = I(^1D_2\text{–}^1S_0)/I(^3P_2\text{–}^1D_2) = I(6161.8\ \text{Å})/I(8578.7\ \text{Å})$ as a function of electron temperature for several values of the electron density. An inspection of the figure reveals that for $N_e \leq 10^5$ cm^{-3}, the ratio is density insensitive but varies strongly with electron temperature, changing by a factor of 32 between $T_e = 5000$ and 20,000 K. Hence, in principle, R_1 should provide an excellent T_e diagnostic at low electron densities. However, for values of $N_e > 10^5$ cm^{-3}, the ratio does become very density dependent and, hence, the density (or temperature) of the [Cl II]-emitting region of a nebula would need to be known before R_1 could be used to derive the other plasma parameter.

We note that the theoretical ratios $R_2 = I(^1D_2\text{–}^1S_0)/I(^3P_1\text{–}^1D_2) = I(6161.8\ \text{Å})/I(9123.6\ \text{Å})$, $R_3 = I(^3P_1\text{–}^1S_0)/I(^3P_2\text{–}^1D_2) = I(3677.9\ \text{Å})/I(8578.7\ \text{Å})$, and $R_4 = I(^3P_2\text{–}^1S_0)/I(^3P_2\text{–}^1D_2) = I(3586.0\ \text{Å})/I(8578.7\ \text{Å})$ have the same temperature and density dependence as R_1 due to common upper levels, but with $R_2 = 3.79 \times R_1$, $R_3 = 1.07 \times R_1$, and $R_4 = 0.0164 \times R_1$.

In Figure 2, we plot the current R_1 ratios as a function of electron density at $T_e = 10^{4.1}$ K as well as the results when we adopt the electron impact excitation rate calculations of Krueger & Czyzak (1970). An inspection of the figure reveals that the two sets of ratios agree very well at low densities, which might be surprising given the large differences in the Wilson & Bell (2002) and Krueger & Czyzak electron excitation rates (see § 1). However, at low densities, the $^1D_2\text{–}^1S_0$ and $^3P_2\text{–}^1D_2$ emission lines in the R_1 ratio are in the coronal approximation (Elwert 1952), and the intensities of these transitions therefore depend only on the electron excitation rate from the ground state to the relevant upper level, i.e., on the $^3P_2\text{–}^1S_0$ and $^3P_2\text{–}^1D_2$ rates. Although the Wilson & Bell results are over a factor of 2 larger than the Krueger & Czyzak atomic data, the ratio of the $^3P_2\text{–}^1S_0$ and $^3P_2\text{–}^1D_2$ excitation rates is about the same for the two sets of calculations, hence leading to similar theoretical values of R_1. As the density increases, excitation among the excited levels starts to play a significant role in the Cl II level populations and, hence, emission-line intensities, and the differences in the Wilson & Bell and Krueger & Czyzak data then lead to increasing discrepancies between the resultant line ratio calculations. For example, at $N_e = 10^6$ cm^{-3}, the present values of R_1 in Figure 1 are about 30% larger than those derived using the Krueger & Czyzak rates.

3. OBSERVATIONAL DATA

The [Cl II] emission lines would be expected to be very weak in a nebular spectrum, given the low cosmic abundance of Cl. Indeed, normally only the stronger 8578.7 and 9123.6 Å features are detected and, even then, high spectral resolution and signal-to-noise observational data are required (Aller & Hyung 1995). However, we have been able to identify the 6161.8, 8578.7, and 9123.6 Å lines in the spectra of the planetary nebulae NGC 6741 and IC 5117. These objects were observed with the Hamilton echelle spectrograph (HES) at the coudé focus of the 3 m Shane Telescope at the Lick Observatory. The echelle grating, which is ruled with 316 grooves cm^{-1} to achieve the best possible match with a 2048 × 2048 TI CCD detector, permits coverage of the wavelength range 3700–10300 Å. Each order contains only a small portion of spectrum, and these are separated with the aid of a pair of low-dispersion prisms that serve as cross dispersers. The data we have utilized here were secured in the context of a spectral survey of several planetaries of high surface brightness. For nebular observations, a slit width of 640 μm (1″.16) and a slit length of 4″ were adopted, giving a spectral resolution of ∼0.2 Å (FWHM). These choices were imposed by constraints on spectral purity (for slit width) and overlapping orders, especially in the red (for slit length). The total area accepted by the slit is generally much smaller than the whole nebular image. In addition to the usual exposures on laboratory arcs and appropriate

TABLE 1
Summary of [Cl II] Observations

Object	Observation Date	I(6161.8 Å)[a]	I(8578.7 Å)	I(9123.6 Å)	C[b]
NGC 6741...	1995 Aug 19	0.11 ± 0.03	9.7 ± 1.0	3.4 ± 0.5	1.10
IC 5117.......	1995 Aug 18	0.17 ± 0.04	4.7 ± 0.5	1.6 ± 0.2	1.40
RR Tel........	2000 Jul 13	<0.6	8.0 ± 0.8	2.5 ± 1.3	0.12

[a] Line intensities (corrected for interstellar extinction) are in units of 10^{-14} ergs cm^{-2} s^{-1}.
[b] Interstellar extinction coefficient $C = 1.47\ E(B-V) = \log[I^i(\mathrm{H}\beta)/I^o(\mathrm{H}\beta)]$, where $I^i(\mathrm{H}\beta)$ and $I^o(\mathrm{H}\beta)$ are the intrinsic and observed Hβ line intensities, respectively.

References.—Sources of C are NGC 6741: Hyung & Aller 1997; IC 5117: Hyung et al. 2001; RR Tel: Jordan, Mürset, & Werner 1994.

comparison stars, one also needs a diffuse continuous source to allow for pixel-to-pixel sensitivity variations. Our basic observing and reduction procedures are described in Keyes, Aller, & Feibelman (1990) and Hyung (1994).

In Table 1, we list the planetary nebulae considered in the present analysis, their date of observation, and the intensities (I) of the [Cl II] 6161.8, 8578.7, and 9123.6 Å lines measured using the spectral synthesis package DIPSO (Howarth, Murray, & Mills 1994). The [Cl II] line intensities in the table have been corrected for interstellar extinction using the extinction curve of Seaton (1979) in conjunction with the interstellar extinction coefficient $C = 1.47E(B-V) = \log[I^i(\mathrm{H}\beta)/I^o(\mathrm{H}\beta)]$, where $I^i(\mathrm{H}\beta)$ and $I^o(\mathrm{H}\beta)$ are the intrinsic and observed Hβ line intensities, respectively. Values of C listed in Table 1 have been taken from the references given as footnotes to the table.

The resultant values of R_1 and R_2 are given in Table 2. To illustrate the quality of the observational data, in Figures 3, 4, and 5, we plot portions of the HES spectrum of IC 5117 that contain the [Cl II] emission lines.

4. RESULTS AND DISCUSSION

In Table 2, we list the plasma parameters, denoted (T_e, $\log N_e)_{\rm other}$, determined from other line ratios in NGC 6741 and IC 5117 that have similar ionization potentials and, hence, similar spatial distributions to [Cl II] such as I(6717 Å)/I(6730 Å), and I(4068 + 4076 Å)/I(6717 + 6730 Å) in [S II]. These T_e and N_e estimates have been deduced from diagnostic diagrams constructed using the same HES data as those employed for the [Cl II] observations. Hence, the values of (T_e, $\log N_e)_{\rm other}$ should apply to the region of the planetary nebula for which the [Cl II] observations were obtained so that the [Cl II] results are directly comparable to these. Plasma parameters from the literature, on the other hand, often refer to the whole nebular image. The sources of the diagnostic diagrams used to derive (T_e, $\log N_e)_{\rm other}$ are listed as footnotes to Table 2.

Also listed in Table 2 are the values of T_e derived from the observed R_1 and R_2 ratios in conjunction with Figure 1, where we have adopted the electron density value from (T_e, $\log N_e)_{\rm other}$. However, we note that changing the adopted density by even an order of magnitude would not lead to a significant variation in the derived value of T_e.

For both NGC 6741 and IC 5117, the derived electron temperatures are in very good agreement with those deduced from other line ratios in the HES observations, with discrepancies that average only 700 K. This agreement indicates that R_1 is a reliable temperature diagnostic for planetary nebulae and also provides support for the accuracy of the adopted atomic physics data, at least in terms of the reliability of the ratio of the electron impact excitation rates (see § 2).

The symbiotic star RR Telescopii (RR Tel) is a well-known source of narrow emission lines at both optical and ultraviolet wavelengths, which are very useful in providing line identifications and testing diagnostic calculations (Harper et al. 1999; Keenan et al. 1999 and references therein). Previous high-resolution studies of RR Tel have failed to identify the [Cl II] emission lines (McKenna et al. 1997; Crawford et al. 1999; Selvelli & Bonifacio 2000). However, very recently, we have obtained a spectrum of RR Tel using the University College London Echelle Spectrograph (UCLES) on the 3.9 m Anglo-Australian Telescope (AAT) at a spectral resolution of ~0.03 Å (FWHM), superior to previous observations. These data have been reduced and flux calibrated using methods discussed in detail by Crawford et al. In Figures 6–8, we plot regions of the spectrum covering the [Cl II] 6161.8, 8578.7, and 9123.6 Å lines and also indicate the predicted positions of these features.

We have measured the intensities of the lines at the predicted positions of the [Cl II] 8578.7 and 9123.6 Å transitions using DIPSO and these are listed in Table 1, corrected for interstellar extinction using $C = 0.12$ (Jordan, Mürset, & Werner 1994). However, for the 6161.8 Å line, we have been able to determine only an upper limit to the intensity, which is also given in Table 1.

The observed I(8578.7 Å)/I(9123.6 Å) intensity ratio for RR Tel is 3.2 ± 1.7, which is in agreement with the theoretical value of 3.8 (§ 2), albeit with a large error bar. This

TABLE 2
[Cl II] Emission-Line Ratios and Derived Electron Temperatures (in K)

Object	R_1	R_2	$T_e(R_1)$	$T_e(R_2)$	(T_e, $\log N_e)_{\rm other}$
NGC 6741...	0.011 ± 0.003	0.032 ± 0.010	9500 ± 1000	9200 ± 1300	9800, 3.7
IC 5117.......	0.036 ± 0.009	0.11 ± 0.03	$16{,}500 \pm 1500$	$15{,}200 \pm 2000$	15,000, 4.4

References—Sources of (T_e, $\log N_e)_{\rm other}$ are NGC 6741: Keenan et al. 1996; IC 5117: Hyung et al. 2001.

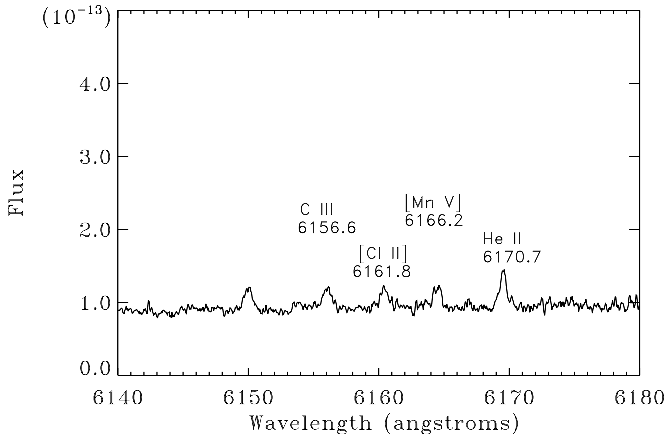

FIG. 3.—Portion of the HES spectrum of the planetary nebula IC 5117, where the flux is in units of ergs cm^{-2} s^{-1} $Å^{-1}$, showing the [Cl II] 6161.8 Å emission line. Also labeled in the figure are the C III 6156.6 Å, [Mn V] 6166.2 Å, and He II 6170.7 Å transitions, while there is an unidentified feature at 6150.1 Å. Radial velocity and interstellar extinction corrections have not been applied to this spectral scan.

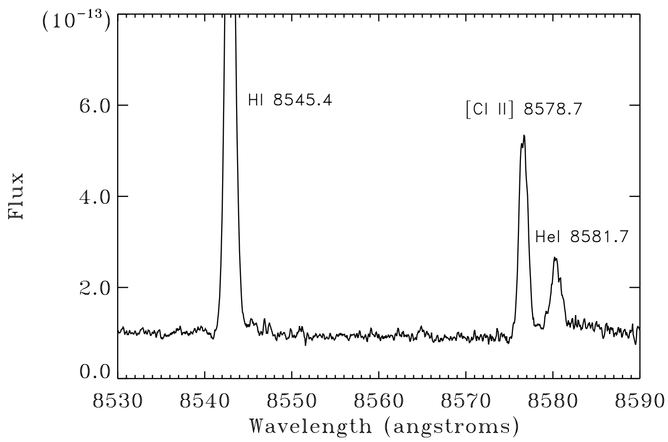

FIG. 4.—Portion of the HES spectrum of the planetary nebula IC 5117, where the flux is in units of ergs cm^{-2} s^{-1} $Å^{-1}$, showing the [Cl II] 8578.7 Å emission line. Also labeled in the figure are the H I 8545.4 Å and He I 8581.7 Å transitions. Radial velocity and interstellar extinction corrections have not been applied to this spectral scan.

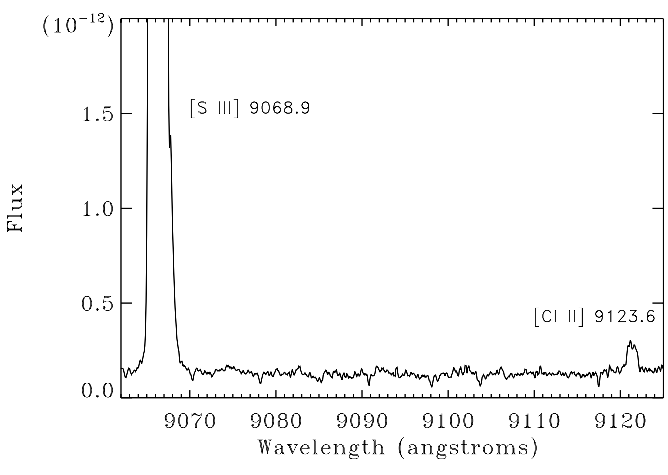

FIG. 5.—Portion of the HES spectrum of the planetary nebula IC 5117, where the flux is in units of ergs cm^{-2} s^{-1} $Å^{-1}$, showing the [Cl II] 9123.6 Å emission line. Also labeled in the figure is the [S III] 9068.9 Å transition. Radial velocity and interstellar extinction corrections have not been applied to this spectral scan.

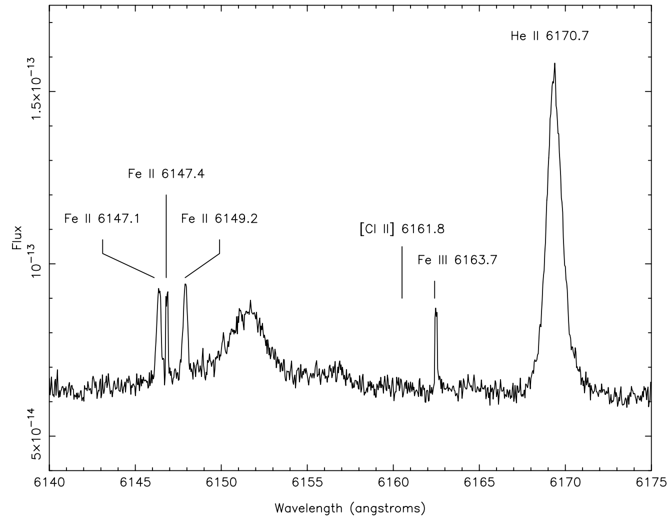

FIG. 6.—Portion of the UCLES spectrum of the symbiotic star RR Telescopii, where the flux is in units of ergs cm^{-2} s^{-1} $Å^{-1}$, with the expected position of the [Cl II] 6161.8 Å emission feature (*line*). Also labeled in the figure are the Fe II 6147.1 Å, Fe II 6147.4 Å, Fe II 6149.2 Å, Fe III 6163.7 Å, and He II 6170.7 Å transitions, while there is an unidentified feature at 6150.1 Å. Radial velocity and interstellar extinction corrections have not been applied to this spectral scan.

provides support for our identification of the [Cl II] features in the RR Tel spectrum. The electron temperature and density of the emission zone in RR Tel responsible for lowly ionized species are around $T_e = 13,000$ K and $N_e = 10^6$ cm^{-3} (Keenan et al. 1999 and references therein). From Figure 1, we would therefore expect a [Cl II] line ratio of $R_1 = 0.06$ that combined with the observed I(8578.7 Å) line intensity of 8×10^{-14} ergs cm^{-2} s^{-1} indicates that the 6161.8 Å feature should have $I \simeq 4.8 \times 10^{-15}$ ergs cm^{-2} s^{-1}. This is just below our detection limit of 6×10^{-15} ergs cm^{-2} s^{-1} (Table 1) and is hence consistent with our inability to identify the line. Clearly, better signal-to-noise observations of RR Tel in this wavelength region are required in order to

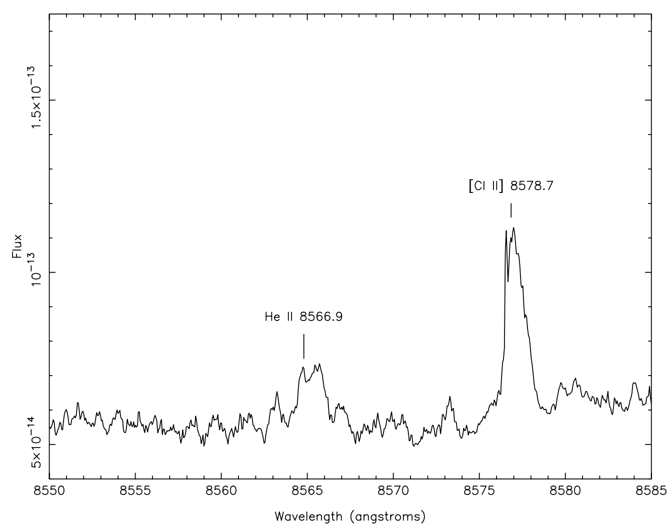

FIG. 7.—Portion of the UCLES spectrum of the symbiotic star RR Telescopii, where the flux is in units of ergs cm^{-2} s^{-1} $Å^{-1}$, with the [Cl II] 8578.7 Å emission feature (*line*). Also labeled in the figure is the He II 8566.9 Å transition. Radial velocity and interstellar extinction corrections have not been applied to this spectral scan.

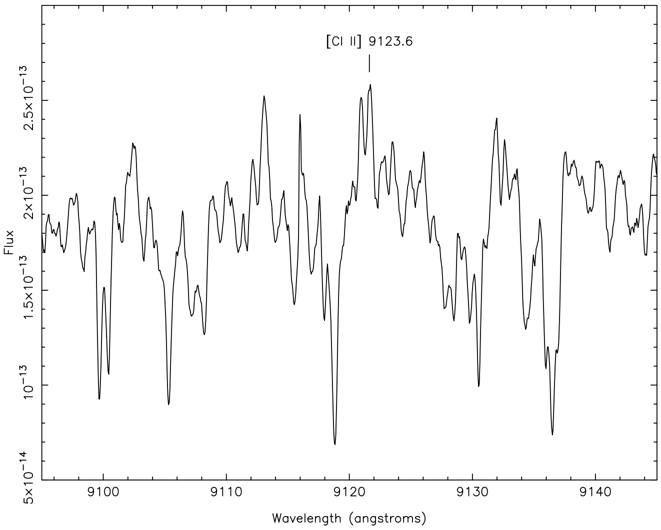

FIG. 8.—Portion of the UCLES spectrum of the symbiotic star RR Telescopii, where the flux is in units of ergs cm^{-2} s^{-1} Å^{-1}, with the [Cl II] 9123.6 Å emission feature (*line*). Radial velocity and interstellar extinction corrections have not been applied to this spectral scan.

reliably identify the [Cl II] 6161.8 Å line and estimate a value for R_1. This, in turn, will allow us derive the temperature/density of the [Cl II] emission zone and compare with values deduced from other diagnostics.

Finally, we note that the 3586.0 and 3677.9 Å lines of [Cl II] should provide useful T_e diagnostics when ratioed against the 8578.7 and 9123.6 Å transitions. In addition, both features share a common upper level with the 6161.8 Å line and, hence, the intensity ratios have the constant values $I(3586.0\ \text{Å})/I(6161.8\ \text{Å}) = 0.0164$ and $I(3677.9\ \text{Å})/I(6161.8\ \text{Å}) = 1.07$ (§ 2). Simultaneous observations of these lines would therefore allow a check of the intensity calibration of a nebular spectrum over the 3586–6162 Å wavelength range. Unfortunately, existing high-resolution nebular observations at near-ultraviolet wavelengths, including our current HES and UCLES data, are of insufficient sensitivity to detect the [Cl II] lines. Hopefully, better quality spectra will be forthcoming in the future, especially given the continued development of blue-sensitive CCDs. In particular, we note that the 3677.9 Å line is predicted to be similar in strength to the 6161.8 Å feature and provides the best chance for detection.

K. M. E. is grateful to the Particle Physics and Astronomy Research Council of the United Kingdom for financial support. This research was supported by National Science Foundation grants AST 90-14133, AST 93-13991, and AST 94-16985 and Space Telescope Science Institute grant AR-06372.01-95A to the University of California, Los Angeles. S. H. gratefully acknowledges the support provided by grants KRF 2000-015-DP0445 and the Korean Science Foundation (KOSEF) R01-1999-000-00022-0.

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