Emission lines of [K v] in the optical spectra of gaseous nebulae

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Recent R-matrix calculations of electron impact excitation rates in K v are used to derive the nebular emission line ratio $R = I$(4122.6 Å)/I(4163.3 Å) as a function of electron density (N_e). This ratio is found to be very sensitive to changes in N_e over the density range 10^3 to 10^6 cm^{-3}, but does not vary significantly with electron temperature, and hence in principle should provide an excellent optical N_e diagnostic for the high-excitation zones of nebulae. The observed value of R for the planetary nebula NGC 7027, measured from a spectrum obtained with the Hamilton Echelle spectrograph on the 3-m Shane Telescope, implies a density in excellent agreement with that derived from [Ne iv], formed in the same region of the nebula as [K v]. This observation provides observational support for the accuracy of the theoretical [K v] line ratios, and hence the atomic data on which they are based. However, the analysis of 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, reveals that the [K v] 4122.6 Å line in this object is badly blended with Fe ii 4122.6 Å. Hence, the [K v] diagnostic may not be used for astrophysical sources that show a strong Fe ii emission line spectrum.

Emission lines arising from transitions among the $3s^23p^3$ levels of P-like ions are frequently observed in the optical spectra of gaseous nebulae (1, 2). Of particular importance are the nebular ^{4}S–^{2}D$_{3/2}$ and ^{4}S–^{2}D$_{5/2}$ lines, which can provide an excellent electron density (N_e) diagnostic for the emitting plasma by means of their intensity ratio (3). However, to calculate reliable theoretical line ratios, accurate atomic data must be used, especially for electron impact excitation rates (4).

Previously, we have derived theoretical ratios for P-like [S II] (5), [Cl III] (6), and [Ar IV] (7) applicable to the spectra of gaseous nebulae, by using electron impact excitation rates calculated with the **R**-matrix code (8). Very recently, Wilson and Bell (9) have extended this work by performing **R**-matrix calculations for P-like K V, which are a significant improvement over the earlier results of Butler *et al.* (10), because of the inclusion of more levels and the delineation of additional resonances in the collision cross sections (see ref. 9 for more details).

In this paper we use the Wilson and Bell (9) atomic data for K V to derive density-sensitive line ratios for this ion involving the nebular transitions at 4122.6 Å and 4163.3 Å. These data are subsequently compared with high-resolution optical observations to investigate the usefulness of the [K V] line ratio as a density diagnostic. We note that the [K V] nebular ratio is potentially a very important density indicator. As the [K V] lines arise in a region where K IV is ionized, and the ionization potential (IP) of this species is 60.9 eV (1 eV = 1.602×10^{-19} J), the [K V] emission zone will lie in a very high-excitation part of a nebula. Most density diagnostic line ratios for high-excitation regions of nebulae lie at UV or infrared wavelengths, such as those for [Ne IV] (11) and [O IV] (12). Some high-excitation species, including Fe VII and Ar IV, have emission lines in the optical, but their intensity ratios are sensitive to both density and temperature (7, 13). Hence, if reliable values of N_e could be derived from [K V], this would mean that densities could be determined for the high-excitation zones of nebulae on the basis of optical observations alone.

Adopted Atomic Data and Theoretical Line Ratios

The model ion for K V consisted of the three LS states within the $3s^23p^3$ ground configuration, namely ^{4}S, ^{2}D, and ^{2}P, making a total of five fine-structure levels. Energies of all these levels were taken from Sugar and Corliss (14). Test calculations, including the higher-lying $3s3p^4$ terms, were found to have a negligible effect on the $3s^23p^3$ level populations at the electron temperatures and densities typical of gaseous nebulae, and hence these states were not included in the analysis.

Electron impact excitation rates for transitions in K V were obtained from Wilson and Bell (9), whereas for Einstein A coefficients, the calculations of Mendoza and Zeippen (15) were adopted. As discussed by, for example, Seaton (16), excitation by protons may be important for transitions with small excitation energies, i.e., fine-structure transitions. However, test calculations for K V setting the proton rates for ^{2}D$_{3/2}$–^{2}D$_{5/2}$ and ^{2}P$_{1/2}$–^{2}P$_{3/2}$ 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 atomic data discussed above in conjunction with the statistical equilibrium code of Dufton (17), relative K V level populations and hence emission line strengths were derived for a range of electron temperatures and densities. Details of the procedures involved and approximations made may be found in Dufton (17) and Dufton *et al.* (18). Given uncertainties of typically ±10% in both the adopted electron excitation rates and A values, we estimate that our derived theoretical line ratios should be in error by at most ±15%.

In Fig. 1 we plot the [K V] nebular emission line ratio

$$R = I(^4\mathrm{S} - {^2\mathrm{D}_{5/2}})/I(^4\mathrm{S} - {^2D_{3/2}}) = I(4122.6\,\mathring{A})/I(4163.3\,\mathring{A})$$

as a function of logarithm of electron density at electron temperatures of T_e = 10,000 and 20,000 K. An inspection of the figure reveals that R is very density sensitive, changing by a factor of 13 between $N_e = 10^3$ and 10^6 cm^{-3} at T_e = 10,000 K. However, the ratio does not vary significantly with temperature, with for example changing T_e from 10,000 to 20,000 K leading to only a 3% variation in R at $N_e = 10^3$ cm^{-3}, and 7% at $N_e = 10^4$ cm^{-3}. Hence, in principle, the ratio should provide an excellent density diagnostic for the higher-excitation zones of gaseous nebulae.

Abbreviations: IP, ionization potential; FWHM, full width half maximum; RR Tel, RR Telescopii.

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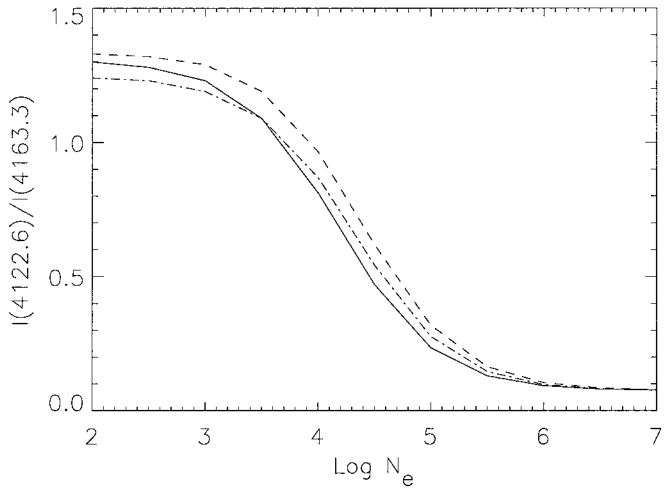

Fig. 1. Plot of the theoretical [K V] nebular emission line ratio $R = I(3s^23p^3\ ^4S - 3s^23p^3\ ^2D_{5/2})/I(3s^23p^3\ ^4S - 3s^23p^3\ ^2D_{3/2}) = I(4122.6\ \text{Å})/I(4163.3\ \text{Å})$, where I is in energy units, as a function of logarithm of electron density (N_e in cm^{-3}). Shown in the figure are line ratios calculated with the electron impact excitation rates of Wilson and Bell (9) at electron temperatures of T_e = 10,000 K (solid line) and 20,000 K (dashed-dotted line), plus those derived by using the atomic data of Butler *et al.* (10) at T_e = 10,000 K (dashed line).

Also shown in Fig. 1 are the theoretical values of R for T_e = 10,000 K derived by using the electron impact excitation rate calculations of Butler *et al.* (10). There are significant differences between these results and the present more accurate line ratios, with for example at T_e = 10,000 K the latter being 19% lower at $N_e = 10^4$ cm^{-3}, and 36% lower at $N_e = 10^5$ cm^{-3}.

Results and Discussion

The [K V] 4122.6 Å and 4163.3 Å emission lines would be expected to be very weak in a nebular spectrum, given the low cosmic abundance of K. Indeed, normally only the stronger 4163.3 Å feature is detected, and even then, high spectral resolution and signal-to-noise observational data are required (1). However, we have been able to measure both lines in the spectrum of the high-excitation planetary nebula NGC 7027. This object was observed with the Hamilton Echelle Spectrograph at the coudé focus of the 3-m Shane Telescope at the Lick Observatory on August 29, 2001. A slit width of 640 μm (1.16 arc seconds) and a slit length of 4 arc seconds were adopted, giving a spectral resolution of ≈0.2 Å (full width at half maximum; FWHM). Our basic observing and reduction procedures are described in detail by Keyes *et al.* (19) and Hyung (20).

Emission line intensities in the NGC 7027 spectrum have been corrected for interstellar extinction by using the extinction curve of Seaton (21), in conjunction with the interstellar extinction coefficient C = 1.47E(B − V) = 1.37 (19). In Figs. 2 and 3, we show portions of the Hamilton Echelle Spectrograph spectrum containing the [K V] lines, to illustrate the quality of the observational data. The measured [K V] line ratio is R = 0.36, which implies log $N_e \simeq 4.8 \pm 0.3$ from the present diagnostic calculations in Fig. 1, irrespective of the adopted electron temperature.

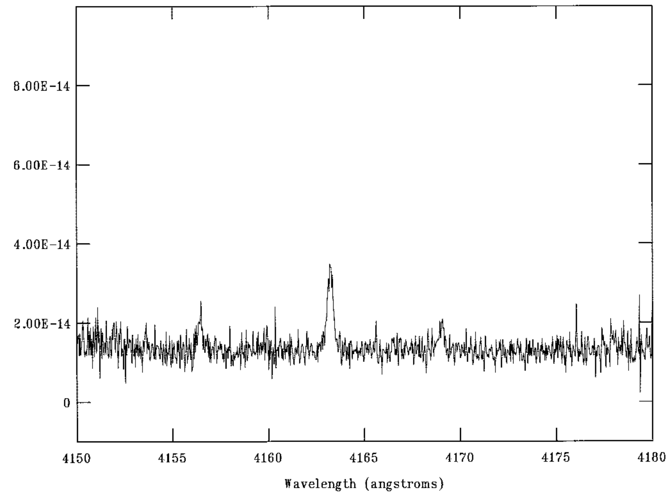

Fig. 3. Portion of the Hamilton Echelle spectrum of the planetary nebula NGC 7027, obtained on August 29, 2001, where the flux is in units of erg·cm^{-2}·sec^{-1}·Å^{-1}. The [K V] 4163.3-Å line is clearly visible in the figure, as are the C III 4156.3-Å and He I 4168.9-Å transitions.

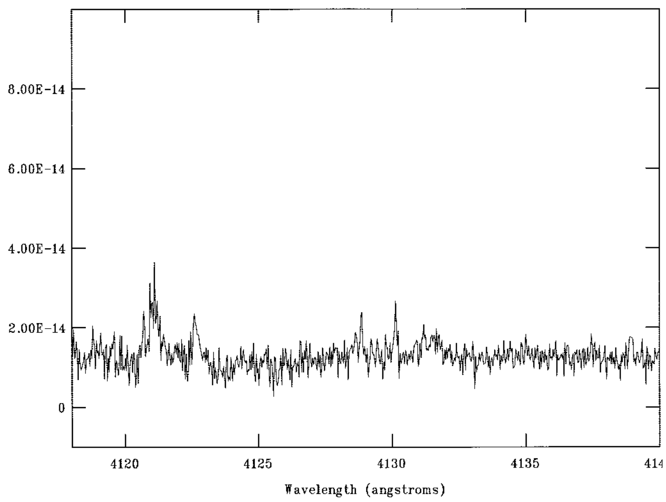

Fig. 2. Portion of the Hamilton Echelle spectrum of the planetary nebula NGC 7027, obtained on August 29, 2001, where the flux is in units of erg·cm^{-2}·sec^{-1}·Å^{-1}. The [K V] 4122.6-Å line is clearly visible in the figure, as is the He I 4120.7-Å transition.

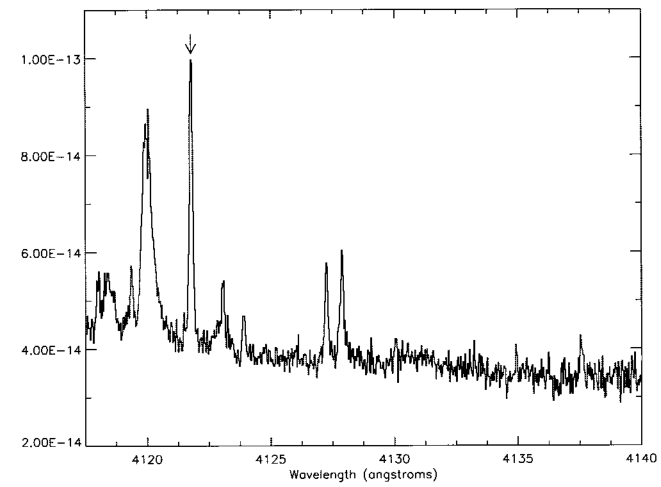

Fig. 4. Portion of the University College London Echelle spectrum of the symbiotic star RR Tel, obtained on July 13, 2000, where the flux is in units of erg·cm^{-2}·sec^{-1}·Å^{-1}. The spectrum shows a feature, indicated by an arrow, identified by Crawford *et al.* (22) as the [K V] nebular line at 4122.6 Å. Many other emission features are also clearly visible in the spectrum (see ref. 22 for a detailed line list).

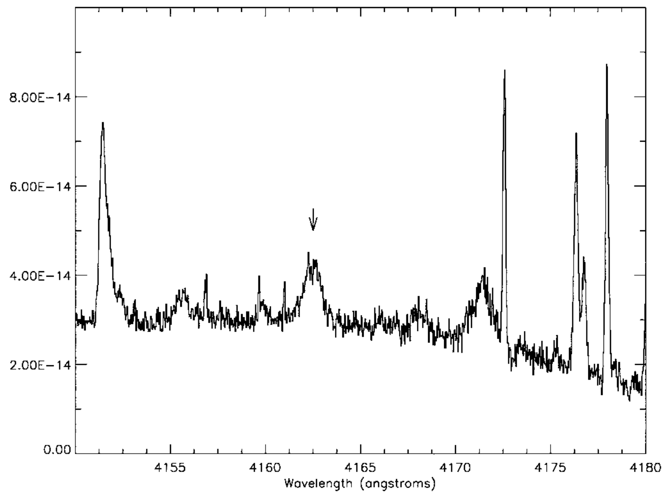

Fig. 5. Portion of the University College London Echelle Spectrum of the symbiotic star RR Tel, obtained on July 13, 2000, where the flux is in units of erg·cm^{-2}·sec^{-1}·Å^{-1}. The [K V] 4163.3-Å line is indicated by an arrow, and many other emission features are also clearly visible in the spectrum (see ref. 22 for a detailed line list).

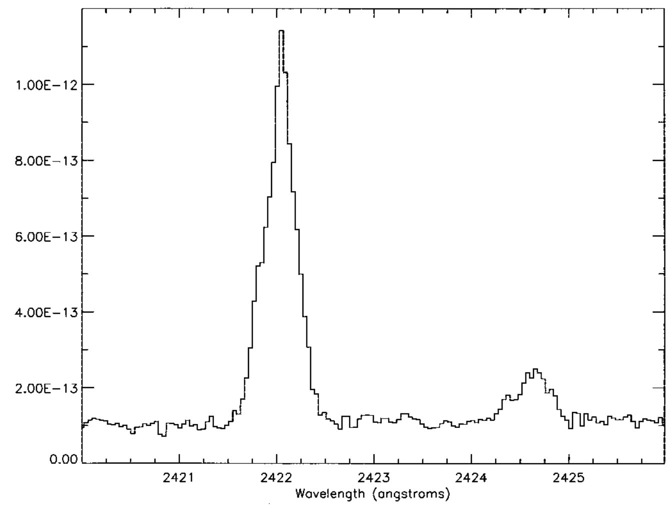

Fig. 6. Portion of the high-resolution spectrum of RR Tel obtained with the Space Telescope Imaging Spectrograph on October 18, 2000, where the flux is in units of erg·cm^{-2}·sec^{-1}·Å^{-1}. The observations were taken with the E230M grating, yielding a spectral resolution of ≈0.08 Å (FWHM). Clearly visible in the figure are the [Ne IV] 2422- and 2424-Å lines.

As noted earlier, the [K V] emission lines arise in a high-excitation region of the nebula where K IV is ionized, and this species has an IP of 60.9 eV. Similarly, the [Ne IV] emission region will occur where Ne III is ionized, and the IP of this species is 63.5 eV, very close to that of K IV. Hence, one would expect the [Ne IV] and [K V] emission regions to have similar spatial distributions and hence physical conditions, including electron density. Keenan *et al.* (11) have derived log N_e = 4.7 for NGC 7027 from the I(2424 Å)/I(2422 Å) ratio of [Ne IV], in excellent agreement with the [K V] density. This finding provides support for the [K V] results, and indicates that reliable densities in the high-excitation regions of planetary nebulae may be derived from optical spectra, provided high spectral resolution and signal-to-noise observations are used. For example, we can see from Fig. 2 that at lower spectral resolution the [K V] 4122.6-Å feature would be blended with He I 4120.7 Å.

Crawford *et al.* (22) have identified the [K V] 4122.6 Å and 4163.3 Å lines in a spectrum of the symbiotic star RR Telescopii (RR Tel), obtained on July 22, 1996, by using the University College London Echelle Spectrograph (UCLES) on the 3.9-m Anglo-Australian Telescope (AAT). The spectral resolution of these observations is ≈0.08 Å (FWHM). However, on July 13, 2000, we obtained a superior UCLES/AAT spectrum of RR Tel, at a resolution of ≈0.03 Å (FWHM). These data have been reduced and flux calibrated by using methods discussed in detail by Crawford *et al.* (22); in Figs. 4 and 5 we plot regions of the spectrum containing the [K V] emission features.

The measured [K V] line ratio for RR Tel is R = 0.72, which implies log $N_e \simeq 4.2 \pm 0.3$ from the present diagnostic calculations in Fig. 1. However, the [Ne IV] I(2424 Å)/I(2422 Å) ratio for RR Tel is 0.15, derived from a Hubble Space Telescope spectrum obtained on October 18, 2000 (see Fig. 6), quite close in time to the UCLES/AAT observations. From the diagnostic calculations of Keenan *et al.* (11), this [Ne IV] ratio indicates log N_e = 5.8, much larger than that deduced from [K V]. This finding implies that the [K V] density is too low, and hence, that the measured R ratio is too large (by about a factor of 6), probably because of severe blending of the [K V] 4122.6-Å feature.

An inspection of Figs. 4 and 5 reveals that the two features identified as [K V] by Crawford *et al.* (22) have very different values of FWHM, with the 4122.6-Å line having FWHM = 0.16 Å and the 4163.3-Å transition a FWHM = 1.1 Å. Crawford (23) has noted a correlation between the FWHM of a line in the spectrum of RR Tel and the IP of the relevant species. The FWHM of the 4163.3-Å line is consistent with that expected for [K V], but the small FWHM for 4122.6 Å implies that the feature arises from a low-IP species. A search of line lists reveals the presence of the Fe II $3d^64s$ $^4P_{5/2}$–$3d^64p$ $^4F_{5/2}$ transition at 4122.6 Å (24), and other ^{4}P-^{4}F lines are also detected in the spectrum of RR Tel (22). We therefore conclude that the 4122.6-Å feature in RR Tel is in fact due to Fe II and not [K V]. However, we also point out that none of the Fe II ^{4}P–^{4}F transitions is detected in the spectrum of NGC 7027 (19), so that the measured [K V] line ratio for this object should be secure. Indeed, our results indicate that the [K V] lines may be used as a reliable density diagnostic, but only for objects that do not show a strong Fe II emission line spectrum.

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