IUE observations of the shells of RR Pic and GK Per*  

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SUMMARY  
We present ultraviolet observations of the resolved shells of the old novae RR Pic (1925) and GK Per (1901). On the assumption that the RR Pic nebula is photoionized by the ultraviolet continuum emitted by the stellar remnant, we conclude that nitrogen is overabundant relative to solar in both the 'equatorial ring' and 'polar blob' regions; there are steep gradients in the C/O ratio, however. We also find possible evidence for emission by molecular hydrogen in the 'blob'. There is, in addition, some evidence for abundance gradients in the GK Per nebula, in which excitation is likely to be by shocks rather than by the weak ultraviolet emission of the stellar remnant. The existence of abundance gradients in old nova shells is consistent with the infrared behaviour of recent novae, and must arise during the thermonuclear runaway itself.  

Key words: stars: abundances – circumstellar matter – stars: individual: GK Per – stars: individual: RR Pic – novae, cataclysmic variables – ultraviolet: stars.
2.2 GK Per

GK Per (1901) with its associated remnant is unique amongst classical novae in that it is the only nova remnant associated with a non-thermal radio source (Reynolds & Chevalier 1984; Bode, Seaquist & Evans 1987); a full discussion of the GK Per remnant may be found in Seaquist et al. (1989). The material ejected in the 1901 eruption was resolved in 1916 and, again unusually for a nova shell, is still relatively bright. Optical spectroscopy of the resolved remnant, described by Williams (1981), suggests an electron temperature \( \geq 2.5 \times 10^4 \) K and an overabundance of nitrogen. Optical spectroscopy of the nebula where \([\text{N} \text{ ii}]\lambda 6584\) emission is strongest has been briefly described by Bode et al. (1988) and will be discussed more fully elsewhere. These observations suggest differing degrees of hydrogen underabundance in different locations in the nebula.

3 IUE OBSERVATIONS

The observations to be described here were carried out over the period 1987–90 and were all obtained at low resolution through the IUE large (20 \( \times \) 10 arcsec\(^2\)) aperture. For both nova acquisition was by blind offset from the stellar remnant. A log of IUE observations is given in Table 1, in which \( \theta \) is the angular distance from the stellar remnant to the centre of the IUE large aperture.

The south-eastern equatorial ring of the RR Pic nebula (hereafter ‘the ring’) was observed with both SWP and LWP cameras; however, no signal was obtained in the long-wavelength range. The south-western polar blob region (hereafter ‘the blob’) was observed with the SWP camera only. Plate 1 shows the locations of the IUE large aperture at the times of the observations. The stellar remnant was also observed at low resolution, through the large aperture, with both SWP and LWP cameras.

In the case of GK Per the brightest regions of the nebula, as seen at \([\text{N} \text{ ii}]\lambda 6584\), were selected for IUE observation, and in each case the position angle of the long axis of the large aperture was again chosen so as to include as much of the optical flux as possible while avoiding any contamination by stars in the field. In the case of GK Per, the offset was determined by careful measurement of Palomar Sky Survey (POSS) plates and allowance made for the (known) decelerated motion of the shell. Plate 2 shows a \([\text{N} \text{ ii}]\) image of the GK Per nebula, on which are superimposed the locations of the IUE large aperture for each observation. Location ‘A’ includes the strongest (optical) emission around the ‘northern pole’ of the nebula; locations ‘B’ and ‘C’ include the ‘bar’ which forms part of the ‘equatorial belt’ (see Plate 2). From fig. 11 of Seaquist et al. (1989) it can be seen that location A is also bright in \([\text{O} \text{ ii}]\lambda 5007\), whereas locations B and C are virtually devoid of such emission.

4 DATA REDUCTION

The data were reduced using the Starlink iuedr program (Giddings 1983). In view of the fact that only a weak emission-line spectrum was anticipated, with negligible continuum, both short- and long-wavelength spectra were tracked along the dispersion using a template track previously created by the extraction of a well-exposed stellar image. At short wavelengths the width of the track used to extract the spectrum was defined by the size of the IUE large aperture, which was obtained from the geocoronal Ly\( \alpha \) emission; the same channel width was also used in the extraction of the long-wavelength spectra. The background was extracted in two channels having the same width as the dispersion channel. After spectrum extraction the IUE photowrite images were carefully examined to ensure that any spectral features that emerged from the data reduction were real and not associated with camera ‘flares’ etc. Two SWP spectra were obtained at the blob of the RR Pic nebula and these spectra have been co-added.

Scattered light from the stellar remnants may contribute to the nebular flux. This is particularly the case for RR Pic, as the star was \( \sim 10 \) arcsec away from the centre of the aperture and some scattered light from the star is expected. We have attempted to allow for this using the formulae given by de Boer & Cassatella (1986). The extracted SWP spectrum of the RR Pic ring, together with the contribution from scattered light from RR Pic itself, is shown in Fig. 1. Lines of \( \text{N} \text{ v} \lambda 1240\), \( \text{O} \text{ iv} \lambda 1400\), \( \text{N} \text{ v} \lambda 1486\), \( \text{C} \text{ iv} \lambda 1550\), \( \text{He} \text{ ii} \lambda 1640\) and \( \text{N} \text{ iii} \lambda 1750\) are clearly visible. However, it is evident that most of the \( \text{C} \text{ iv} \lambda 1550\) line seems to be contributed by scattered light from the star. In the case of GK Per \( (\theta \approx 30 \) arcsec), the effect of scattered light is negligible. The spectra displayed in the following section have been smoothed with a 3-Å Gaussian filter and ‘binned’ into 5-Å bins. Where emission lines are present, the integrated flux has been determined by fitting a Gaussian to the line profile.

5 RESULTS AND DISCUSSION

5.1 RR Pic

In the case of RR Pic there is no evidence of an absorption feature around \( \lambda 2200\) in the spectrum of the stellar remnant, suggesting that \( E(B-V) < 0.05 \); Krautter et al. (1981) found \( E(B-V) = 0.01 \). We shall assume a value of \( E(B-V) = 0 \).

The SWP spectra of the RR Pic nebulousy, with scattered stellar light removed, are displayed in Fig. 2; Fig. 2(a) shows

Table 1. Log of IUE observations.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>P.A. (deg.)</th>
<th>( \theta ) ((^{\circ}))</th>
<th>Image</th>
<th>Exp. (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR Pic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18-Jun-89</td>
<td>S-E ring</td>
<td>62</td>
<td>10</td>
<td>SWP36550</td>
<td>372</td>
</tr>
<tr>
<td>19-Jun-89</td>
<td>Star</td>
<td>–</td>
<td>–</td>
<td>SWP36558</td>
<td>20</td>
</tr>
<tr>
<td>19-Jun-89</td>
<td>Star</td>
<td>–</td>
<td>–</td>
<td>LWP15758</td>
<td>15</td>
</tr>
<tr>
<td>19-Jun-89</td>
<td>S-E ring</td>
<td>62</td>
<td>10</td>
<td>LWP15759</td>
<td>317</td>
</tr>
<tr>
<td>18-Sep-89</td>
<td>S-W blob</td>
<td>151</td>
<td>13</td>
<td>SWP37070</td>
<td>362</td>
</tr>
<tr>
<td>19-Sep-89</td>
<td>S-W blob</td>
<td>152</td>
<td>13</td>
<td>SWP37086</td>
<td>334</td>
</tr>
<tr>
<td>19-Sep-89</td>
<td>Star</td>
<td>–</td>
<td>–</td>
<td>SWP37087</td>
<td>17</td>
</tr>
<tr>
<td>GK Per</td>
<td>B</td>
<td>10</td>
<td>29</td>
<td>LWP12305</td>
<td>60</td>
</tr>
<tr>
<td>18-Dec-87</td>
<td>B</td>
<td>10</td>
<td>29</td>
<td>SWP32555</td>
<td>330</td>
</tr>
<tr>
<td>20-Dec-87</td>
<td>A</td>
<td>7</td>
<td>37</td>
<td>SWP32565</td>
<td>404</td>
</tr>
<tr>
<td>12-Dec-88</td>
<td>B</td>
<td>17</td>
<td>29</td>
<td>LWP14637</td>
<td>410</td>
</tr>
<tr>
<td>28-Jan-90</td>
<td>C</td>
<td>337</td>
<td>35</td>
<td>SWP38091</td>
<td>356</td>
</tr>
</tbody>
</table>
the spectrum of the ring, while Fig. 2(b) shows that of the blob. Although the spectrum is weak, it is clear that there are similarities and important differences between the spectra in the ring and blob regions. The nitrogen lines N v λ 1240, N iv λ 1486 and N iii λ 1750 are present in both locations, although in the ring the partially forbidden N iv λ 1486 and N iii λ 1750 lines seem to be relatively weaker by comparison with the N v λ 1240 resonance line (cf. the optical [N ii] lines). He ii λ 1640 is also present in both locations, and is comparable in strength to N v λ 1240. Fluxes, which have been determined by fitting Gaussians to the line profiles, are listed in Table 2; errors in the fluxes are typically 20–30 per cent and arise mainly in the Gaussian fitting procedure.

The major differences between the ring and blob lie in the carbon and oxygen lines. In the ring spectrum the feature at 1400 Å is presumably due to O iv λ 1400, although Si iv λ 1400 may also contribute; there is no strong evidence for any carbon lines in this region. In the blob, however, the C iv λ 1550 and C iii λ 1909 lines are present and there is no evidence for the 1400-Å line.

The relative fluxes for lines emitted by a nebula photoionized by a power-law continuum have been calculated in detail by Staśniska (1984). For present purposes we express fluxes relative to He ii λ 1640 for a solar-abundance gas photoionized by a continuum $f_\lambda \propto \lambda^{-1.3}$ and having an electron density $10^4 \text{ cm}^{-3}$ (the nearest to RR Pic available in Staśniska's tabulation); the mean $T_e$ for these models is in the range $(10–18) \times 10^3 \text{ K}$. In the case of the blob the fluxes listed in Table 2 are consistent with the results of Staśniska if nitrogen is overabundant relative to solar by a factor of $\sim 5$, although a substantial amount of the N iv emission must arise as a result of the recombination of N v rather than as a result of collisional excitation. Carbon is underabundant relative to solar by a factor of 10 and most of the C iii emission must arise as a result of collisional excitation rather than by recombination of C iv; oxygen is underabundant relative to solar by a factor of at least 5.

In the ring the fluxes listed in Table 2 are consistent with Staśniska if nitrogen is overabundant relative to solar by a factor of 5–10, while the abundance of oxygen is essentially solar, although the absence of O iv λ 1665 (expected flux $\geq 0.1$) is surprising. An alternative identification would be Si iv λ 1400, which would require a silicon overabundance relative to solar of a factor of $\sim 10$; the Si iii line at 1883 Å (expected flux $\geq 0.1$) is absent. Carbon, on the other hand, is underabundant by a factor of at least 100.

If the electron temperature were lower than the above value, recombination would dominate the excitation. If this were the case then the carbon abundance in the blob would be enhanced relative to solar by a factor of $\sim 10$, while nitrogen would be overabundant by a factor of $\sim 30$. In the ring nitrogen would be overabundant by a factor of $\sim 20$. We should stress, however, that all our conclusions regarding abundances are tentative, direct comparison with solar-abundance models providing only a first approximation to relative abundances. Relative fluxes need to be rigorously recalculated for a gas having abundances typical of a nova.

While the differing relative intensities of the resonance and forbidden nitrogen lines in the ring and blob regions can be ascribed to different physical conditions in the two regions, the only way of understanding the oxygen and
Figure 2. (a) SWP spectrum of the southern equatorial ring of the RR Pic nebula with the stellar component subtracted as described in the text. The data have been smoothed and binned into 5-Å bins. (b) SWP spectrum of the western polar blob of the RR Pic nebula with the stellar component subtracted as described in the text. The data have been smoothed and binned into 5-Å bins. Vertical lines represent expected relative fluxes of H$_2$ lines, the curve the wavelength dependence of free-bound H$_2$ emission. See text for details.
Table 2. UV emission-line fluxes in the RR Pic nebula.

<table>
<thead>
<tr>
<th>Line</th>
<th>S-E ring Flux (10^{-14} erg s^{-1} cm^{-2})</th>
<th>S-W blob</th>
</tr>
</thead>
<tbody>
<tr>
<td>NVλ1240</td>
<td>47</td>
<td>25</td>
</tr>
<tr>
<td>Ovλ1400</td>
<td>3.3</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>NVλ1485</td>
<td>7.3</td>
<td>4.1</td>
</tr>
<tr>
<td>Cuλ1550</td>
<td>&lt; 1</td>
<td>27</td>
</tr>
<tr>
<td>Hελ1640</td>
<td>7.1</td>
<td>23</td>
</tr>
<tr>
<td>Niiλ1750</td>
<td>8.8</td>
<td>41</td>
</tr>
<tr>
<td>CIIIλ1909</td>
<td>&lt; 1</td>
<td>7.7</td>
</tr>
</tbody>
</table>

5.2 GK Per

In location A only one emission line was detected at long wavelengths, namely Mg ii λ2798 (see Fig. 3a); the feature is just visible on the IUE photowrite. The peak flux density is (5.8 ± 1.3) × 10^{-15} erg s^{-1} cm^{-2} Å^{-1}; the integrated flux, dereddened by an amount corresponding to A_v = 0.7 (cf. Wu et al. 1989), is (2.7 ± 1.1) × 10^{-13} erg s^{-1} cm^{-2}. No lines were detected in the short-wavelength range to a 2σ upper limit of 3.6 × 10^{-15} erg s^{-1} cm^{-2} Å^{-1}; in the long-wavelength range the corresponding upper limit is 1.4 × 10^{-13} erg s^{-1} cm^{-2} Å^{-1}. The upper limit on the integrated flux in any other line is 10^{-13} erg s^{-1} cm^{-2} at both long and short wavelengths.

In location B the N v λ1240 line was detected and is also visible on the IUE photowrite; the dereddened flux is (8.9 ± 4.0) × 10^{-13} erg s^{-1} cm^{-2}. The spectrum in this region is displayed in Fig. 3(b). No other lines were detected to a limit of 6.1 × 10^{-15} erg s^{-1} cm^{-2} Å^{-1} at short wavelengths, and 4.3 × 10^{-15} erg s^{-1} cm^{-2} Å^{-1} in the long-wavelength range. The upper limit on the integrated flux in any other line is 4 × 10^{-13} erg s^{-1} cm^{-2} at short wavelengths and 10^{-13} erg s^{-1} cm^{-2} at long wavelengths. We note in particular that the Mg ii λ2798 line was not detected. No emission lines were detected in the short-wavelength spectrum obtained in location C to a limit of 4.9 × 10^{-15} erg s^{-1} cm^{-2} Å^{-1}.

There are major disparities in the N v and Mg ii fluxes between locations A and B; in the former N v/Mg ii < 0.4, whereas in the latter N v/Mg ii > 15. In nova shells the excitation of ions generally occurs via photoionization and recombination (see Williams 1990 for a recent review). The stellar remnant of GK Per is, however, unlike other nova remnants, a weak UV source. As noted by Bianchini & Sabadin (1983), the optical–UV flux distribution peaks at ≈ 3600 Å, whereas for most old novae it rises steeply towards shorter wavelengths. For example, at 2000 Å the spectral power of GK Per is only ~0.05 of that of RR Pic.

It is known from radio and other observations that the ejected shell of GK Per is interacting strongly with its environment (Seaquist et al. 1989), and we consider the possibility that excitation is by radiative shocks. Cox & Raymond (1985) have computed the relative intensities of optical and UV emission lines arising in radiative shocks in a gas having solar abundances. The N v λ1240 line is prominent only in location B. According to Cox & Raymond the N v λ1240 line is strong only for shocks having velocities ≥ 180 km s^{-1}. Furthermore, for a solar-abundance gas the C iv line is expected to be stronger than N v and so the non-detection of the C iv line in this region is consistent with the results of Cox & Raymond (1985) if carbon is depleted relative to nitrogen in location B; this would also be consistent with the non-detection of the C iii/λ1909 line. We also note that, at shock velocities ≥ 180 km s^{-1}, the O iv/λ1400 line is expected to have strength comparable with N v, but we see no evidence for a feature at this wavelength; we also note that there is no evidence for the O iii/λ1666 line. The non-detection of oxygen lines implies that oxygen is depleted relative to nitrogen as well. Alternatively, nitrogen is overabundant relative to both carbon and oxygen. However, as in the case of RR Pic, there is a need to recalculate rigorously the relative UV line intensities for a shocked gas having abundances typical of novae.
Figure 3. (a) LWP spectrum around the northern pole of the GK Per nebula. (b) SWP spectrum of the equatorial bar in the GK Per nebula. For both (a) and (b), the fluxes have been dereddened by an amount corresponding to $A_V = 0.7$. The data have been smoothed and binned into 5-Å bins.
The situation at location A is different. There is no evidence of the N v λ1240 line but the Mg II λ2798 line is present. The limit on the ratio N v/Mg II implies a shock velocity significantly lower (≤140 km s⁻¹) than in location B, or that the relative abundances of N and Mg are inverted relative to location A. It should be noted that the optical imaging of the shell reported in Seaquist et al. (1989) implied higher shock velocities in the vicinity of location A. A full understanding of emission from the nebula therefore needs detailed investigation of the effects of both differing shock velocities and relative abundances. An overabundance of Mg would be consistent, on TNR grounds, with the prominence of Ne lines in the optical during outburst (e.g. Payne-Gaposchkin 1957) – GK Per was a ‘neon nova’. As already noted in the context of RR Pic, chemical inhomogeneities in the ejected material may have arisen early during the eruption, possibly even during the TNR itself.

6 CONCLUDING REMARKS

We have presented UV observations of the resolved shells of the old novae GK Per and RR Pic. Our conclusions may be summarized as follows.

(i) There are significant differences in the abundances in different locations in the nebular remnant of RR Pic. The C/O ratio is inverted in the southern equatorial ring relative to that in the western polar blob.

(ii) There is broad-band emission in the 1400–1700 Å region of the western polar blob of RR Pic, which we tentatively attribute to emission by molecular hydrogen.

(iii) There are also chemical inhomogeneities in the shell of GK Per; excitation in this case is likely to be by shocks rather than by photoionization.

(iv) Line strengths are consistent with non-solar abundances, and substantial overabundance of nitrogen relative to solar; there is a need, however, to calculate rigorously the expected line strengths for abundances typical of novae.

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