Mon. Not. R. astr. Soc. (1986) **219**, 479–494

The chemical composition of algol systems – III. Beta Lyrae–nucleosynthesis revealed

Suchitra Balachandran, David L. Lambert and Jocelyn Tomkin *Department of Astronomy, The University of Texas, Austin, Texas 78712, USA*

M. Parthasarathy *Indian Institute of Astrophysics, Bangalore, 560034, India*

Accepted 1985 September 24. Received 1985 September 24; in original form 1985 July 26

Summary. We have used high signal-to-noise ratio Reticon observations of visible and near-infrared lines of He, C, N, O, Ne and Fe to determine the abundances of these elements in the B8 primary of the eclipsing binary β Lyr.

A direct estimate of the He abundance, based on measurements of weak He I lines, shows a definite He enrichment: N(H)=0.4, N(He)=0.6. An indirect estimate of the He abundance, which assumes that the initial CNO abundances were cosmic and that the sum of the CNO abundances has not changed during the evolution of β Lyr, demands the same He enrichment. It is supported by similar indirect estimates based on Ne and Fe and the assumption that the Ne and Fe abundances have not altered during the evolution of β Lyr.

Nitrogen is extremely overabundant. With a microturbulence of $10\,\mathrm{km\,s^{-1}}$, determined from the Fe II lines, and the He-rich model atmosphere, we find that it is 20 times more abundant than in the Sun. Carbon and O are very underabundant relative to N; we find C/N$\leq$0.011 and O/N=0.025 (factor of 2 uncertainty for both ratios). These ratios, which are drastically different from the solar C/N and O/N ratios of 5 and 8, respectively, are sufficiently close to the equilibrium ratios of the CNO cycle as to leave little doubt that the material has been fully processed by the CNO cycle.

In single stars these changes of composition associated with the burning of H to He are hidden from view by the unprocessed outer layers; even during red giant evolution they are only partially revealed. However, in β Lyr, which is unusual in that the phase of rapid mass transfer has been very recent, the original primary is still the primary in an observational sense, even though it is now much less massive than the secondary ($\sim 2\,m_\odot$ versus $\sim 12\,m_\odot$), and its processed core is exposed to view. The spectroscopic evidence of He enrichment and extreme CNO cycling confirms the major compositional changes demanded by the theory of nuclear burning and, thereby, supports the modern picture of β Lyr.

From a comparison of the observed H, He, C, N, and O abundances with the calculated interior abundances of evolved stellar models, we conclude that the $2\,m_\odot$ primary is the remnant of a $12\,m_\odot$ star that has lost $10\,m_\odot$ by Roche lobe overflow.

1 Introduction

Evolution of stars in a close binary is often drastically modified by mass exchange between the components and mass loss from the system. If one star experiences a severe loss of mass, its core may be exposed and reveal spectroscopic evidence of the changes in chemical composition wrought by nucleosynthesis. Furthermore, if the other star accepts the bulk of the mass stripped from the first star, its spectrum may also reflect the effect of nucleosynthesis.

The well-known eclipsing binary β Lyr is a dramatic example of such a system. The modern interpretation of β Lyr demands that the B8 II primary be substantially less massive than the secondary, whose spectrum has not been detected. The large mass function

$$f(m)=\frac{m_{\rm sec}^3 \sin^3 i}{(m_{\rm pri}+m_{\rm sec})^2}=8.5\,m_\odot$$

which is reliably determined from the well-defined velocity curve of the primary, is the main piece of evidence leading to this conclusion. This mass function and the known inclination, $i=85°$, require an implausibly large mass for the primary, $m_{\rm pri}\geqslant 35\,m_\odot$ for a mass ratio less than, or equal to, 1. (The mass ratio, q is defined in the sense $q=m_{\rm sec}/m_{\rm pri}$.) Only if the mass ratio is greater than one, i.e. the primary is *less* massive than the secondary, does the mass of the primary become compatible with the absolute visual magnitude $M_{\rm v}=-4$ (Abt *et al.* 1962; Dobias & Plavec 1985). The conclusion that the primary is the less massive component leads to the further conclusion that it must be filling its Roche lobe and transferring mass to the secondary, because the very rapid increase of the $12.^{\rm d}9$ period means that the less massive component is losing mass. Because there is no sign of the secondary spectrum, the exact value of q is unknown, but various indirect arguments suggest $3<q<8$. Wilson & Lapasset (1981) adopt $q=6$ which leads to $m_{\rm pri}=2\,m_\odot$ and $m_{\rm sec}=12\,m_\odot$, The secondary is most probably an early B main-sequence star surrounded by a geometrically thick, opaque disc (Huang 1963; Wilson 1974) which completely hides the star, as seen from Earth.

If the mass exchange has been conservative, the primary's initial mass must have exceeded one-half of the present $14\,m_\odot$ total mass of the system in order for it to have evolved first and become the mass-losing star. So the present $2\,m_\odot$ primary is the remnant of a star that originally was at least $7\,m_\odot$, i.e. we are looking at a star that is a mass fraction $f\leqslant 0.29$ of what was a much more massive star. If, as is likely, the mass exchange has been non-conservative, the mass loss has been even more severe and this prediction for f is an even looser upper limit.

By inspection of Iben's (1966a, b) models for massive main sequence stars near the exhaustion of the H core we find that the initial composition is preserved from the surface down to $f\sim 0.6$ where ^{12}C is depleted with a concommitant increase in the ^{14}N abundance. Further towards the centre, $f\sim 0.3$ marks the beginning of the H shell burning layers in which ^{16}O is partially depleted to cause a further rise in the ^{14}N abundance. H is partially depleted in the H shell burning region but a near-total conversion to He does not occur until $f\sim 0.2$ is reached.

The estimated upper limit for f suggests that the present atmosphere should clearly betray spectroscopic evidence of H burning at an earlier time. Specifically, we expect a significant depletion of ^{12}C and a matching ^{14}N enhancement. Reductions of the ^{16}O abundance and the H/He ratio are also likely. Although specific predictions would depend on the applicability of

Iben's models to a member of a close-binary system, the general sense of the predictions is surely correct.

The observational evidence bearing upon these predictions is far from conclusive. Boyarchuk's (1959) curve of growth analysis led to a large He overabundance: He/H~25 by number of atoms, a roughly 250 fold enhancement relative to the standard Population I composition. This pioneering study has not been confirmed by more recent line profile analyses. Leushin *et al.*'s (1977) model atmosphere analysis of He I and Balmer lines provided a more modest He enrichment: He/H=1.55 (see also Hack & Job 1965). With Bahýl''s (1982) line profile study suggesting that the abundance He/H=0.125 (i.e. the Pop. I abundance) provides a satisfactory fit to Balmer line profiles, evidence for a He enrichment is perhaps best described as 'uncertain'.

The CNO-tricycle of H burning reactions can induce gross changes in the C/N and possibly the O/N ratios as minor increases in the He/H ratio are created. Hence, spectroscopic confirmation of the idea that the primary is an exposed interior of a main sequence star should be most apparent from photospheric lines of carbon, nitrogen and oxygen. Leushin *et al.* (1979) made the first model atmosphere analysis of the absorption line spectrum in the blue including several multiplets attributed to C II, N II and O II. [See Boyarchuk (1959), and Hack & Job (1965) for curve of growth analyses involving just one or two lines of each species.] Later, Leushin & Snezhko (1980) extended the model atmosphere analysis to a few lines of C I, N I and O I in the red and near-infrared. The results of the two studies are in violent disagreement. We confine the comparison to the ratios C/N and O/N for which the solar ratios are 4.8 and 8.5, respectively (Lambert 1978). The ionized lines in the blue gave C/N=0.6, but O/N=20 (Leushin *et al.* 1979). By contrast, a similar model atmosphere analysis of the neutral lines in the red and near-infrared gave C/N=0.3 and O/N=0.04. Although the C/N ratios are in fair agreement, the presence of C in the primary's atmosphere is at odds with the, possibly naïve, expectation that the primary has been stripped down to the C-depleted layers. This surprising presence of C and the unexplained change by a factor of 500 in the O/N ratio prompted our re-examination of β Lyr.

This paper presents a model atmosphere analysis of neutral and ionized lines of C, N and O in the spectra of β Lyr and a standard star of similar spectral type, and concludes with a discussion of the present composition and its relationship to the predicted nucleosynthesis in a main sequence star.

2 Observations

The McDonald Observatory 2.7-m telescope and coudé Reticon (Vogt, Tull & Kelton 1978) were used to make the majority of the observations. A few additional observations were made with the McDonald Observatory 2.1-m telescope and coudé Reticon. Wavelength intervals, each approximately 100 Å long, were chosen so as to include the various neutral and once ionized lines of C, N and O in the visible and near-infrared. Most of the observations had a resolution of 0.4 Å and a few – mostly those in the blue – had a resolution of 0.2 Å. This resolution (0.4 Å corresponds to 20 km s^{-1} at 6000 Å) ensured that the instrumental broadening was much less than the rotational broadening of β Lyr, which, from the widths of the N II and Ne I lines on our spectra, we determine as $v \sin i = 65 \pm 6$ km s^{-1}. The signal-to-noise ratios of the observations varied between 300 and 500. Such large signal-to-noise ratios were easily achieved thanks to the brightness of β Lyr and, thanks to the large rotational broadening, were also essential for the identification and measurement of the weak lines. All the observations were made at phases between 0.4 and 0.6. These phases are well outside of primary eclipse – phase 0.0 is mid-primary eclipse – when the view of the primary is unobstructed.

The observations were accompanied by observations of Fe Ne comparison spectra. In those wavelength regions affected by telluric lines, such as the 9100 Å C I lines, a hot, rapidly-rotating star at a similar airmass was also observed, and used to divide out the telluric lines. (The very large smearing of the lines in the rapid rotator was such that in the divided spectrum the profiles of the lines of interest were not significantly affected by the presence of the same lines in the spectrum of the rapid rotator.) The standard star γ Lyr, whose B9 III spectral type is similar to that of β Lyr was also observed at the same wavelengths, and with the same resolution and signal-to-noise ratios as the β Lyr observations.

Figs 1, 2 and 3 show the dramatic differences between the strengths of the C I, N II and O I lines in the cases of the C I, N II and O I lines these differences are mostly a consequence of the unusual completely absent from β Lyr. In Fig. 2 the 3994.9 Å N II line is present in β Lyr, but not in γ Lyr, and in Fig. 3, the 6156 Å O I line is much weaker in β Lyr than in γ Lyr. In Fig. 3, it may also be seen that the Ne I lines are present in β Lyr, but are completely absent from γ Lyr. We will see that in the cases of the C I, N II and O I lines these differences are mostly a consequence of the unusual CNO abundances of β Lyr, while in the case of the Ne I lines the difference is not an abundance effect, but is due to a combination of the fact that β Lyr is about 3000 K hotter than γ Lyr and that, as a result of its He rich composition, all lines (except H lines) in β Lyr are stronger than they would otherwise be.

Table 1 gives details of the lines measured and their equivalent widths in β Lyr and γ Lyr. Information for the Ne I and Fe II lines included in the observations is also given.

3 Analysis

As mentioned earlier, the secondary spectrum has not been detected. The Reticon spectra, also, do not show any sign of secondary features; in particular, there is no evidence that the profiles or equivalent widths of the measured primary lines are distorted by the presence of secondary counterparts. The large rotational velocity of the secondary – Wilson & Lapasset (1981) estimate the rotational velocities of the secondary disc and photosphere of the secondary are ~350 and ~800 km s^{-1}, respectively – means that such counterparts, even if present, would be so smeared out as to be practically indistinguishable from the continuum.

The equivalent widths in Table 1 are with respect to the observed continuum which is the sum of the primary and secondary continua. Before they were analysed they were multiplied by a correction factor to transform them into equivalent widths with respect to the continuum of the primary alone.

This correction is a function of both wavelength and phase. Wilson & Lapasset (1981) estimate monochromatic flux ratios $F_{\rm pri}/(F_{\rm pri}+F_{\rm sec})$ of 0.70 and 0.65 at 4375 and 5525 Å, respectively. (Note that these are the flux ratios seen from Earth; because of aspect effects they are quite different from the luminosity ratios.) The corresponding correction factors by which the equivalent widths must be multiplied are 1.43 and 1.54 at 4375 and 5525 Å, respectively. For intermediate wavelengths we interpolated with respect to wavelength, and for shorter and longer wavelengths we used the correction factors for 4375 and 5525 Å, respectively. The shortest wavelength in question (3900 Å) is not far removed from 4375 Å and observations in the red and near-infrared [see Fig. 7 of Plavec (1985) and the 1.2 μ light curve of Jameson & Longmore (1976)] show that the depths of primary and secondary eclipses are not very different from those at 5525 Å, so these short and long wavelength approximations should be adequate. The observations were all made at phases between 0.4 and 0.6, i.e. during the progress of secondary eclipse. The decrease of brightness during secondary eclipse is due to the eclipse of the secondary disc by the primary and ellipsoidal variation of the tidally distorted primary. Estimates, based on Wilson's (1974) model, show that the eclipse of the secondary disc and the ellipsoidal variation of the primary cause similar percentage decreases of $F_{\rm sec}$ and $F_{\rm pri}$, so the flux ratio is roughly

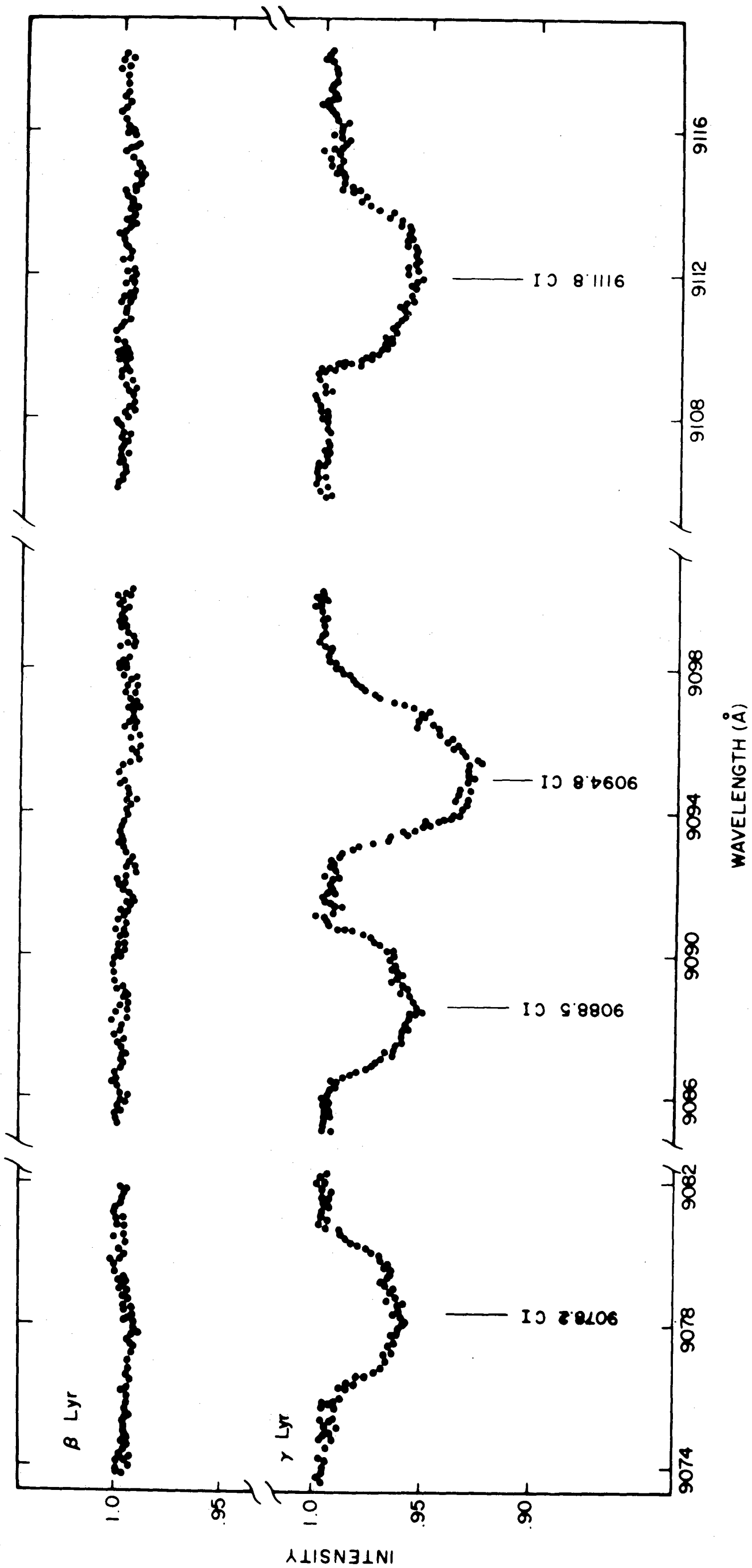

Figure 1. The 9100 Å C I lines in β Lyr and γ Lyr; note their absence in β Lyr, In order to remove the telluric water lines both the β Lyr and γ Lyr spectra have been divided by the spectrum of a hot, rapidly-rotating star observed at similar airmass.

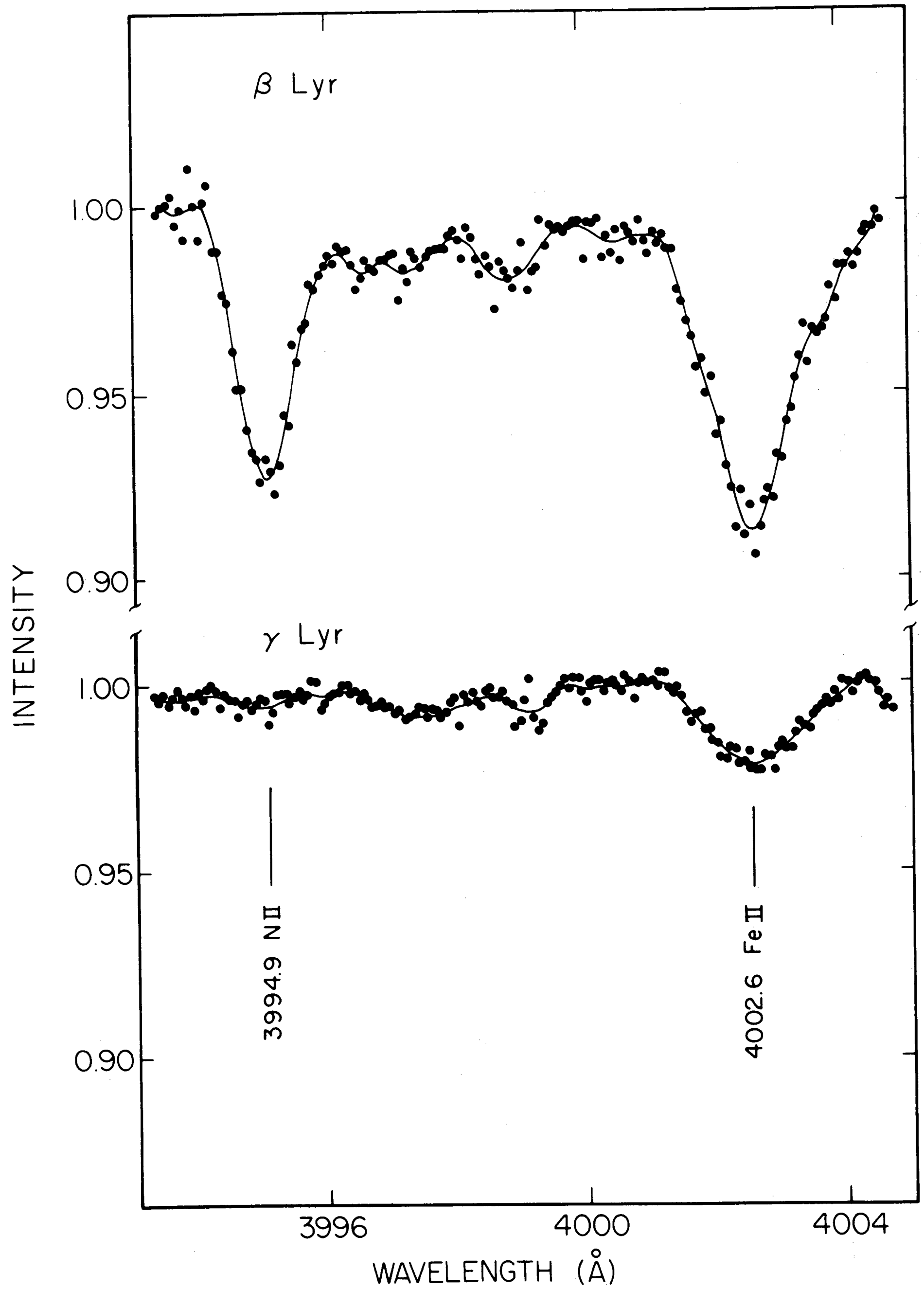

Figure 2. The 3995 Å N II line in β Lyr and γ Lyr; note its complete absence in γ Lyr.

preserved and we made the approximation that the equivalent width correction is unaffected by secondary eclipse.

The following effective temperatures and gravities were adopted for the model atmosphere analysis:

	T(K)	log g
β Lyr	13 300	2.5
γ Lyr	10 000	3.5

The temperature of β Lyr is set by the requirement that the N I and N II lines yield the same N abundance. As Table 2 shows, this temperature depends on the degree of He enrichment of the model atmosphere. The 13 300 K adopted temperature is that required by the N(H)=0.4, N(He)=0.6 model, which, as we will see, is appropriate for β Lyr. We used the weak 6440 Å N I line to set the N I based N abundance. The other six N I lines (see Table 1) are much stronger and yield much higher, and much less reliable, abundances. The 4654 Å N II line was measured, but was not used for abundance determination because the oscillator strength of this intercombination line is poorly determined; all the other N II lines (see Table 1) have reliable oscillator strengths (Dufton & Hibbert 1981). The $\pm$800 K error estimate for the temperature arises from the uncertainties of the N II and N I based N abundances. For the N II lines, the uncertainty is taken to be the 0.3 dex standard deviation of the individual line abundances; for the 6440 Å N I line a 0.18 dex abundance uncertainty, corresponding to an estimated 50 per cent possible error in the equivalent width of this weak line, is adopted.

The 13 300$\pm$800 K adopted effective temperature of β Lyr is close to the 13 500 K effective temperature of a B6 III–II star (Böhm-Vitense 1981), which is two subclasses earlier than the B8 II spectral type of β Lyr. In view of β Lyr's spectral peculiarities – the stronger H and He lines are in emission – and its abnormal composition, this spectral type inconsistency is probably not significant.

The temperature of γ Lyr is a mean of the temperatures derived from its B9 III spectral type and its energy distribution (Schild *et al.* 1971).

The gravity of β Lyr follows from the $2 m_\odot$ mass (see Introduction) and $14 R_\odot$ radius of the primary. The adopted mass ratio, q=6, gives a $55 R_\odot$ separation between the centres of the components which, with the fractional primary radius of 0.25 obtained for the q=6 light-curve

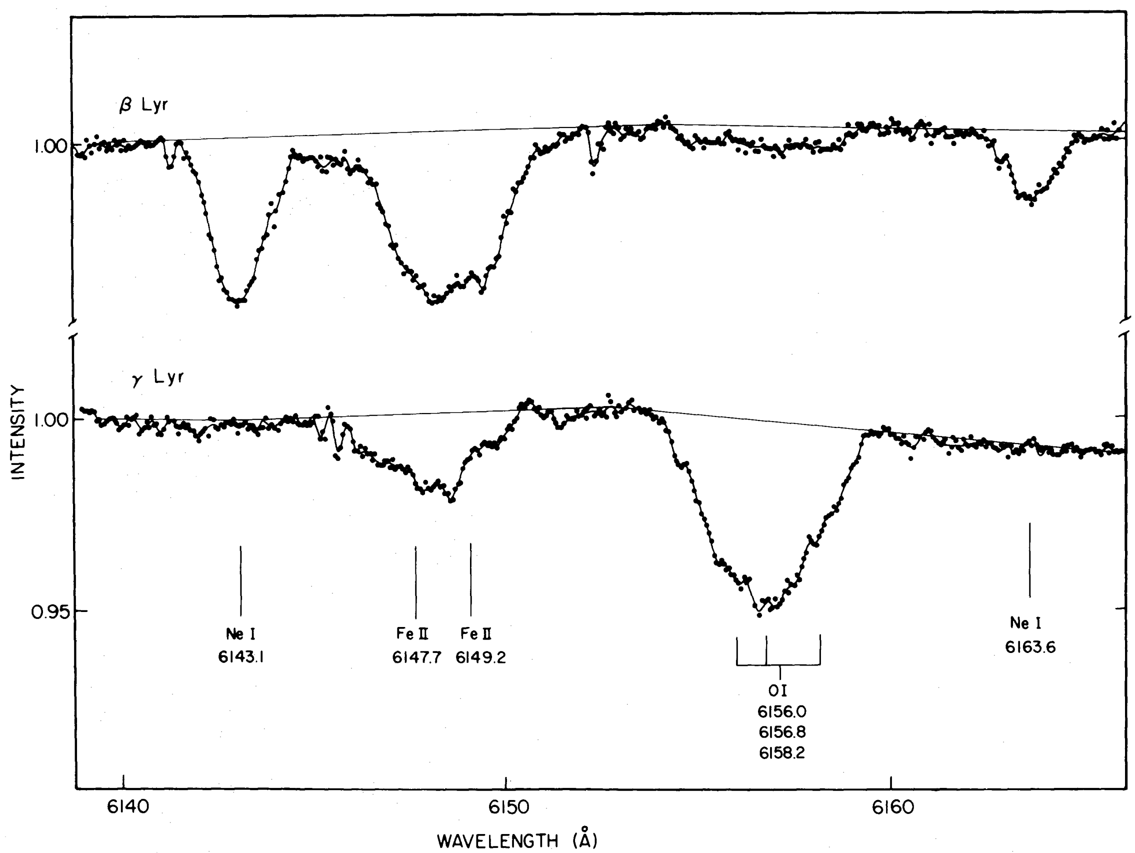

Figure 3. The 6156 Å O I line and some Ne I and Fe II lines in β Lyr and γ Lyr. Note the weakness of the O I line in β Lyr and that the Ne I lines are present in β Lyr, but absent in γ Lyr. The plots, which are on an expanded intensity scale, are affected by some residual slope so the continuum level is indicated.

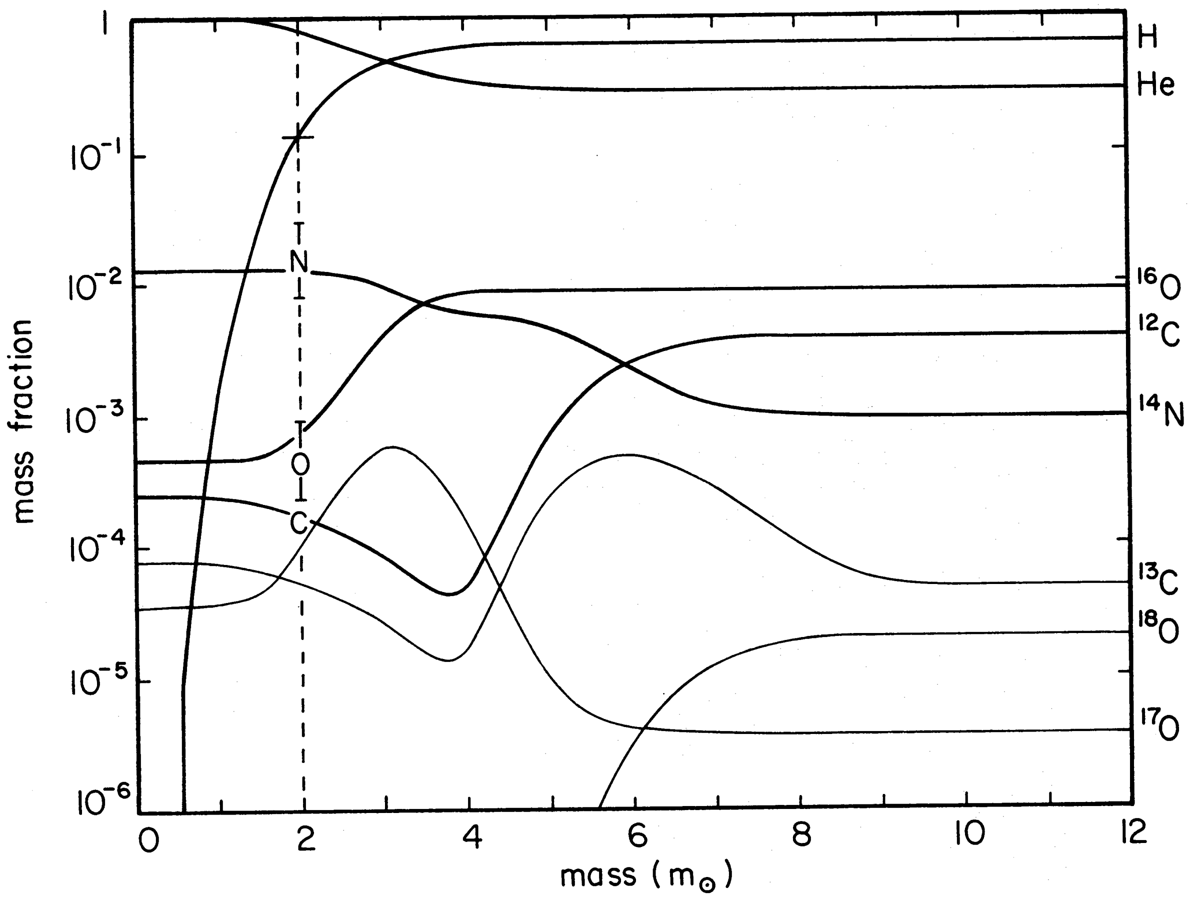

Figure 4. The composition of a 12 $m_\odot$ star after ignition of the H burning shell and before its first crossing of the HR gap. (^{15}N is not shown; it is below 10^{-5} in the envelope and below 10^{-6} interior to 6 $m_\odot$.) The dashed vertical line marks the present surface of β Lyr; it is identified as the point where the H abundance matches the observed $x=0.14$ abundance. Mass loss by Roche lobe overflow has removed the 10 $m_\odot$ exterior to the dashed line. The letters C, N and O along the dashed line show the upper limit on the C abundance (factor of 2 estimated error bar not shown) and the observed N and O abundances with factor of 2 estimated error bars. The observed and predicted abundances agree, within the errors. The model was calculated for $z=0.02$, which is almost identical to the solar z. Use of a metal-rich $z=0.025$ model, more appropriate for β Lyr (see text), would raise the calculated curves for C, N and O by a factor of 1.25 and would not alter their shape significantly.

solution (Wilson 1974) leads to the 14 $R_\odot$ radius for the primary. The mass ratio is known only within wide limits; Wilson (1974, 1982) allows a range $3<q<8$. If we had adopted $q=3$, instead of $q=6$, then the corresponding 5.1 $m_\odot$ mass and 19 $R_\odot$ radius of the primary would have meant a log g of 2.6 instead of 2.5. Evidently, the gravity is surprisingly well-determined, even though q is not. The gravity of γ Lyr is from its B9 III spectral type and Sinnerstad's (1980) Hβ index-based estimate of a log g of 3.5 for luminosity class III B stars.

The analysis of the equivalent widths to determine abundances was carried out with the program WIDTH 6 (R. L. Kurucz, private communication) and selected model atmospheres from Klinglesmith's (1971) grid of flux constant models. This grid of models is well suited to our purpose; it spans $10\,000 \leqslant T \leqslant 20\,000$ K, $2.5 \leqslant \log g \leqslant 4.5$ and includes moderately He enriched [N(H)=0.4, N(He)=0.6], and extremely He enriched [N(H)=0.06, N(He)=0.94], models as well as normal [N(H)=0.9, N(He)=0.1] composition models. In order to investigate the He enrichment of β Lyr its equivalent widths were analysed with models of all three compositions.

The oscillator strengths (Table 1) of the C I lines are from Kurucz & Peytremann (1975); their good agreement with those of Lambert (1968) suggests that they are reliable. The N I line

Table 1. Equivalent widths of lines measured in β Lyr and γ Lyr.

	λ(Å)	χ(eV)	log *gf*	Equivalent width (mÅ)		Abundance	
				β Lyr	γ Lyr	β Lyr	γ Lyr
He I	4437.5	21.22	−2.03	112	–	12.04	–
	5047.7	21.22	−1.60	88	–	11.74	–
C I	9078.3	7.48	−0.45	<28	146	<8.13	9.05
	9088.6	7.48	−0.43	<28	119	<8.11	8.68
	9094.9	7.49	0.12	<28	192	<7.56	9.10
	9111.9	7.49	−0.51	<28	128	<8.19	8.87
C II	6578.0	14.45	−0.03	<23	<43	<7.61	<10.31
N I	6440.9	11.71	−1.14	24	–	9.51	–
	7423.6	10.33	−0.76	176	66	(10.29)	9.09
	7442.3	10.33	−0.33	218	115	(10.36)	9.45
	7468.3	10.34	−0.16	275	102	(10.96)	9.07
	8703.2	10.33	−0.29	272	132	(10.26)	9.16
	8711.7	10.33	−0.34	296	126	(10.56)	9.11
	8718.8	10.34	−0.26	225	117	(9.77)	8.93
N II	3994.9	18.50	0.30	80	–	9.07	–
	4613.9	18.47	−0.59	40	–	9.53	–
	4643.1	18.48	−0.37	44	–	9.34	–
	4654.5	18.50	–	27	–		–
	5676.0	18.48	−0.38	41	–	9.91	–
	5679.6	18.48	0.25	58	–	9.65	–
O I	6156.0	10.74	−0.70				
	6156.8	10.74	−0.48	20	160	7.90	9.04
	6158.2	10.74	−0.33				
	7771.9	9.15	0.33				
	7774.2	9.15	0.19	476	523	–	–
	7775.4	9.15	−0.03				
Ne I	6143.1	16.62	−0.35	71	–	9.02	–
	6163.6	16.72	−0.59	26	–	8.83	–
	6334.4	16.62	−0.31	76	–	9.04	–
	6382.9	16.67	−0.26	50	–	8.64	–
	6402.3	16.62	0.36	142	–	8.96	–
Fe II	3906.0	5.57	−1.67	133	60	8.16	–
	3935.9	5.57	−1.67	118	–	8.02	–
	4002.6	5.96	−2.03	114	45	8.52	–
	4258.2	2.70	−3.49	107	36	8.34	7.60
	4278.1	2.69	−3.89	73	–	8.46	–
	4296.6	2.70	−2.86	124	61	7.83	7.45
	4303.2	2.70	−2.53	160	78	7.78	7.47
	4351.8	2.70	−2.21	–	88	–	7.71
	4583.8	2.81	−2.10	–	99	–	7.59
	4629.3	2.81	−2.50	148	96	7.74	7.92
	4657.0	2.89	−3.64	74	29	8.33	7.72
	4663.7	2.89	−3.80	–	30	–	7.90
	4666.8	2.83	−3.43	89	–	8.22	–
	6175.2	6.22	−2.19	36	–	8.22	–
	6179.4	5.57	−2.73	17	–	8.06	–
	6416.9	3.89	−2.91	69	–	8.17	–
	6432.7	2.89	−3.89	55	–	8.50	–
	6446.4	6.22	−2.21	24	–	8.04	–
	6456.3	3.90	−2.26	149	87	8.25	8.26

Note: The measured β Lyr equivalent widths are given. They were multiplied by a wavelength dependent correction of 1.43 to 1.54 to adjust them to be with respect to the continuum of the primary. See text for details. Abundances of β Lyr and γ Lyr are on a scale such that $\log \Sigma(\mathrm{N})$ for all elements is 12.0.

Table 2. β Lyr abundances.

Element	Solar abundance		Abundance	
		N(H)=0.9 N(He)=0.1 T=12 700	N(H)=0.4 N(He)=0.6 T=13 300	N(H)=0.06 N(He)=0.94 T=13 900
			By log number	
He	(11.0)	12.35±0.25	11.89±0.21	11.10±0.31
C I	8.69	<7.88	<7.56	<7.04
C II	8.69	<7.86	<7.61	<7.07
N	7.99	9.86±0.32	9.50±0.27	8.82±0.24
O	8.91	8.24	7.90	7.23
Ne	(8.0)	9.28±0.16	8.90±0.13	8.03±0.13
Fe	7.67	8.35±0.24	8.16±0.30	7.57±0.24
	1.25×solar abundance by mass		By mass	
C+N+O	0.018	0.08	0.016	0.0024
Ne	0.0018	0.029	0.006	0.0006
Fe	0.0023	0.010	0.0029	0.0005

Note: Temperatures with the model compositions are the effective temperatures required by condition that N I and N II lines yield the same N abundance. Abundances by number are on a scale such that log Σ(N) for all elements is 12.0. Solar abundances are on customary log N(H)=12.0 scale and are from Grevesse (1984). Because of non-LTE effects not included in the analysis, the tabulated β Lyr Ne abundances are probably too large by order of a factor 5; see text. The adopted abundances are those for the N(H)=0.4, N(He)=0.6 model (column 4).

oscillator strengths are the same as those used by Lambert (1978) and the O I line oscillator strengths are from Wiese *et al.* (1966). The 6578 Å C II line oscillator strength (Wiese & Martin 1980) has a 'C' uncertainty rating, i.e. it is accurate to within 25 per cent. The N II oscillator strengths are from Dufton & Hibbert (1981) who estimated that their calculations should be accurate to 10 per cent or better; they are supported by Kurucz & Peytremann's (1975) earlier, independent results. The Ne I and Fe II line oscillator strengths are from Kurucz & Peytremann (1975), and Phillips (1979), respectively.

The 6156 Å O I feature is a triplet of lines at 6156.0, 6156.8 and 6158.2 Å blended into a single feature by the rotational broadening. To account for this the equivalent width was analysed by a spectrum synthesis program (Sneden 1973). The difference between the oxygen abundances derived by this program and WIDTH from the equivalent width of a hypothetical single O I line was used to normalize the results to the abundances WIDTH would have given if it had spectrum synthesis. (The 7770 Å O I feature is also a triplet and should have been treated in the same way but it was not analysed because its great strength makes it subject to large non-LTE effects.)

The microturbulences are derived from the Fe II lines; Fe II is the only species represented by a large number of lines that also covers a sufficient range of equivalent width to define the saturation of the curve of growth. The microturbulences of β Lyr and γ Lyr are 10±3 and 2±1 km s^{-1}, respectively. (Note that the relatively light C, N and O atoms have a high thermal velocity – at 11 000 K the thermal velocity of C is 3.9 km s^{-1} – so for microturbulences of less than ~4 km s^{-1} their abundances are not sensitive to the precise value of the microturbulence.)

Leushin *et al.* (1979) include a number of C II and O II line identifications in their study of the blue spectrum of β Lyr. Inspection of our spectra, which include Leushin *et al.* (1979)

identifications of three C II and seven O II lines, shows that, with the exception of the 4267 Å C II line, there is no evidence of any of these lines; they are either absent or the lines that are present are due to other species, such as N II and Fe II. A well-defined line, with an observed wavelength of 4267.39 Å and an equivalent width of 66 mÅ, is present near the location of the 4267 Å C II line, which has an effective wavelength of 4267.14 Å. (It is a blend of two nearly equal components at 4267.02 and 4267.27 Å). The wavelength agreement is not particularly good, but neither is it so bad as to exclude, by itself, a possible C II line identification. The main reason this line is probably an unidentified line, rather than 4267 Å C II, is because its strength is inconsistent with the absence of the 6578.0 and 6582.9 Å C II lines, which are the strongest available C II lines in the visible and near-infrared. (Note that the 23 mÅ entry for the equivalent width of the 6578 Å line in Table 1 is an upper limit.) Also, identification of the 4267 Å line as C II would require a C abundance 1.3 dex greater than the upper limit set by the complete absence of the 9100 Å C I lines; see Fig. 1.

4 Results

The abundances for β Lyr and the standard star, γ Lyr, are given in Tables 2 and 3, respectively. For β Lyr we give results for the normal composition model and the moderate, and extreme, He enrichment models. The most striking results are the He enrichment, the very high abundance of N and the very low abundances of C and O in β Lyr.

Before we discuss the results further we note that the C abundance in β Lyr is an upper limit set by the absence of the 9100 Å C I lines. It is confirmed by the absence of the 6578 Å C II line, which, it so happens, sets an upper limit that is only slightly higher than the C I based limit. The N and O abundances are based on the 6440 Å N I, N II and 6156 Å O I lines. The N I lines at 7400 and 8700 Å are present, but because of their great strength (see Table 1) they are probably affected by non-LTE so the LTE abundances they provide are unreliable. The 7770 Å O I line was rejected for the same reason.

The two He I lines demand the moderately He rich composition. Table 2 shows that for this composition the derived He abundance, log N(He)=11.89, is consistent, within observational error, with the log N(He)=11.78 abundance of the N(H)=0.4, N(He)=0.6 model. Neither of the other two models gives self-consistent He abundances; for the N(H)=0.9, N(He)=0.1 normal composition model the derived log N(He)=12.35 abundance is much greater than the log N(He)=11.00 model abundance, while for the N(H)=0.06, N(He)=0.94 extremely He rich model the derived log N(He)=11.10 abundance is much less than the log N(He)=11.97 model abundance.

The He abundance may also be inferred as the He abundance of the model which yields cosmic abundances of the heavy elements. The assumption is that the initial composition of β Lyr was

Table 3. γ Lyr abundances.

Element	Abundance γ Lyr	Solar
C	8.97	8.69
N	9.17	7.99
O	9.08	8.91
Ne	–	(8.0)
Fe	7.78	7.67

Note: The γ Lyr and solar abundances are on the log N(H)=12.0 scale.

Table 4. Dependence of abundances on T and $\log g$.

Species	Change of abundance (dex) $\Delta T=1000\,\mathrm{K}$	$\Delta \log g=0.2$
C I	0.14	−0.02
C II	−0.39	0.10
N I	0.10	−0.01
N II	−0.39	0.10
O I	0.10	−0.01
Ne I	−0.30	0.08
Fe II	0.23	0.03

cosmic and that its evolution has not altered the abundances of the heavy elements. (For C, N and O we assume that the sum of their abundances has not changed and we consider this rather than the individual abundances of C, N and O.)

The results for γ Lyr (see Table 3), which range from 0.1 dex greater than solar for Fe to 0.3 dex greater than solar for C, provide our estimate of the cosmic abundances. The large 1.2 dex enhancement of N shows that γ Lyr is a nitrogen-rich B star. We think this result is probably reliable because the N I lines in γ Lyr are much weaker than in β Lyr and are much more consistent with each other; for γ Lyr the standard deviation of the individual N I line abundances (see Table 1) is 0.17 dex, while for β Lyr, for N I lines only, it is 0.48 dex. No abundance is available for Ne in γ Lyr because of the absence of the Ne I lines. We will assume that 0.1 dex greater than solar, i.e. 1.25×solar, is a simple and adequate representation of the cosmic abundances.

Thus, we look for the model composition which yields approximately 1.25×solar abundances of the heavy elements in β Lyr. Inspection of the abundances by mass (lower part of Table 2) shows that the moderately He rich model satisfies this requirement for both the sum of the CNO abundances and the Fe abundance, whereas the other two models do not. The Ne abundance suggests an even larger He enrichment but is unreliable because departures from LTE affect the Ne I lines. Auer & Mihalas (1973) found that the Ne abundance deduced from LTE analyses of B-star Ne I spectra are systematically too large by about a factor of 5. Reduction of the tabulated 0.006 LTE Ne abundance by mass for the moderately He rich model by this factor brings it into agreement, within observational error, with the 0.0018 cosmic Ne abundance. Thus, although the Ne abundance is less reliable than the abundances of the other elements, it, too, is consistent with a moderate He enrichment of β Lyr.

This second, independent and indirect, method confirms the moderate He enrichment indicated by the He I lines. We also confirm the result of Leushin *et al.* (1979), who determined an identical He enrichment.

We have established the N(H)=0.4, N(He)=0.6 composition of β Lyr and we therefore adopt the abundances provided by this model (column 4 of Table 2). The C/N and O/N ratios of β Lyr are <0.011 and 0.025, respectively. The scatter in the N abundances from individual lines suggests a factor of 2 uncertainty in these ratios due to observational error. The ratios are not very dependent on the adopted microturbulence, effective temperature, or gravity. For example, a change of the adopted microturbulence from 10 to 7 $\mathrm{km\,s^{-1}}$ causes 0.08 and 0.05 dex increases of the N and O abundances, respectively, and a negligible 0.03 dex change in the O/N ratio. The uncertainties of the effective temperature and $\log g$, which were discussed earlier, are ±800 K and ±0.2 dex; the corresponding abundance uncertainties may be estimated from the temperature and gravity dependences given in Table 4. The C I, N I and O I based abundances have very similar temperature sensitivities so their ratios are relatively insensitive to temperature changes and the gravity related uncertainties are insignificant. An exception is the upper limit on

Table 5. β Lyr abundances.

Element	Abundance Leushin *et al.* (1979)	Leushin & Snezhko (1980)	Present work
H	11.60	11.60	11.60
He	11.78	11.78	11.78
C	8.2	9.00	<7.56
N	8.4	9.60	9.50
O	9.7	8.20	7.90
Ne	7.3	8.13	8.90
Fe	7.4	–	8.16

Note: 0.33 dex has been added to the tabulated abundances of Leushin *et al.* (1979) and Leushin & Snezhko (1980) in order to put all abundances on a scale such that $\log \Sigma(\mathrm{N})$ for all elements is 12.0. The Leushin *et al.* (1979) Ne abundance is not the tabulated value, but is from a note added in proof.

the C/N ratio in the case of a temperature increase. Then the upper limit on the C abundance is set by the absence of the C II lines, instead of the C I lines. An 800 K upward change of temperature or a change of microturbulence from 10 to 7 km s^{-1} would both lower the C/N ratio upper limit by about a factor of 2. (A decrease of microturbulence causes the adopted temperature to increase because the N I and N II based N abundances have different microturbulence dependences and we set the temperature by the condition that the N I and N II lines yield the same N abundance.) Thus, a factor of 2 observational error dominates the uncertainty of the C/N and O/N ratios and, in the case of the C/N ratio, admissible increases of temperature or decreases of microturbulence could lower the upper limit on this ratio by as much as a factor of 2.

In Table 5 we compare our abundances for β Lyr with those of Leushin *et al.* (1979, table 5), and Leushin & Snezhko (1980, table IV); all three investigations use the same N(H)=0.4, N(He)=0.6 composition and we have added 0.33 dex to the two earlier investigations' tabulated abundances in order to put them on the same $\log \Sigma(\mathrm{N})=12.0$ scale that we employ. We also note that Leushin *et al.* (1979), and Leushin & Snezhko (1980) adopted an effective temperature of 12 000 K for β Lyr, which compares with the 13 300 K we adopt, and that all three investigations adopt the same $\log g=2.5$ gravity. The table shows that the Leushin *et al.* (1979) results are not supported either by those of Leushin & Snezhko (1980), or our own. Leushin & Snezhko (1980) remark that their abundances differ markedly from those of Leushin *et al.* (1979), but do not comment further, except to say that the lines used in the earlier investigation are very weak. We do not confirm (see above) the C II and O II line identifications of Leushin *et al.* (1979) and, therefore, suspect that these lines are, in fact, non-existent. With the exception of C, our results and Leushin & Snezhko's (1980) are not in violent disagreement. For C, Leushin & Snezhko determine $\log \mathrm{N(C)}=9.00$ whereas we estimate an upper limit $\log \mathrm{N(C)}<7.56$. Allowance for the difference between the adopted effective temperatures of β Lyr widens the gap further; if Leushin & Snezhko had used the 13 300 K temperature of the present investigation then their C I line based C abundance would increase to $\log \mathrm{N(C)}=9.18$ which is 1.6 dex greater than our upper limit. The absence of the 9100 Å C I lines – see Fig. 1 – which are stronger than the three C I lines (6587, 6828 and 8335 Å) Leushin & Snezhko use, casts doubt on their C I line identifications. Furthermore, the 8335 Å line, which is the strongest of Leushin & Snezhko's C I lines, is in a part of the spectrum populated with numerous telluric water lines, but although it would not have been easy to disentangle the C I line from the water lines on 28 Å mm^{-1} photographic plates, Leushin &

Snezhko do not mention this complication. These considerations suggest that Leushin & Snezhko's C I line identifications may be incorrect and, therefore, their C abundance may be spurious.

5 Discussion

The observed He enrichment and C, N and O abundances are compared here with the composition to be expected if the primary of β Lyr is the exposed core of an originally much more massive star. The He enrichment means the primary must have overflowed its Roche lobe during the shell hydrogen burning stage of its evolution (case B mass exchange). As Wilson (1974) remarks: '. . . computations of conservative mass transfer predict that the helium-enriched core of the mass-giving component is uncovered in case B mass exchange, but not in case A (Roche lobe reached during the first slow evolution from the zero-age main sequence during core hydrogen burning).' The small separation of the components, which in the past was even smaller, and the fact that the present state of rapid mass transfer is a very short-lived evolutionary phase have prevented the evolution of the primary across the HR gap to become a red giant and, in particular, mean that core He burning has not yet started. From discussion of β Lyr's properties as a binary, we have seen that 7 $m_\odot$ is a lower limit to the initial mass of the primary and that the present primary and secondary masses are estimated to be 2 and 12 $m_\odot$, respectively. Thus, we compared the observed composition of the primary with the predicted core composition of 9, 12 and 15 $m_\odot$ models, kindly provided by Dr David S. P. Dearborn (private communication), shortly after the start of shell hydrogen burning. The models include recent CNO-cycle reaction rates (Fowler *et al.* 1975; Harris *et al.* 1983).

It should be noted that, thanks to the rapidity of the mass loss – for a conservative model of mass transfer, Ziółkowski (1976) has estimated that the Roche lobe overflow of the primary started 6500 yr ago – it is almost instantaneous compared to the primary's $\sim 10^7$ yr nuclear-evolution time-scale so that direct comparison of the observed abundances with the calculated interior abundances of the models is probably valid.

The present surface of β Lyr is the point in the model where the H abundance matches the observed $x=0.14$ abundance and the appropriate model is that for which the mass interior to this point matches β Lyr's present estimated mass of 2 $m_\odot$. The 12 $m_\odot$ model satisfied these requirements. Fig. 4 shows the abundances of H, He, C, N and O as a function of mass from the centre out to the surface of this model. The figure also shows the good agreement of the observed C, N and O abundances, and the calculated abundances at the point in the model where $x=0.14$. Thus, the C, N and O abundances confirm the conclusion that the present atmosphere of the primary once belonged to the core of a much more massive star.

Evidently the primary's original mass was 12 $m_\odot$ and it has lost all but 2 $m_\odot$ of this by Roche lobe overflow. This large fractional mass loss of 83 per cent is not very dependent on the exact value of the primary's present mass. For example, if a value of 3 $m_\odot$ was used instead of 2 $m_\odot$, then the estimated original mass of the primary would be 15 $m_\odot$ rather than 12 $m_\odot$ and the estimated fractional mass loss would be 80 per cent.

What will β Lyr's next escapade be? For systems in which the first episode of mass exchange is of type B and the initial primary mass is $\leqslant 15\, m_\odot$, Kippenhahn & Thomas (1980) have pointed out that after a period as a helium-burning star on the helium main sequence, the primary again fills its Roche lobe and starts a second episode of mass exchange in which almost pure helium is transferred to the secondary, which is still on the main sequence. Very likely, this will be the next stage in the β Lyr story. Delgrado & Thomas (1981) christen this second episode of mass exchange case BB and have followed the evolution of a model with initial masses of 9 and 6 $m_\odot$ and an initial period of 2.4 days through to case BB mass exchange. The model is remarkably similar to β Lyr.

Following the first episode of mass exchange, the primary and secondary have masses of 2 and 13 $m_{\odot}$, respectively, and the period has lengthened to 21 days. Currently, β Lyr is near the end of this phase of its evolution. After 3×10^6 yr, the second mass-exchange episode starts, and when it is over, the primary and secondary have masses of 1 and 14 $m_{\odot}$, respectively, and the period has lengthened still further to 140 days. It is now a wide system consisting of a hydrogen-burning star of 14 $m_{\odot}$ with a carbon-oxygen white dwarf companion. The further evolution of the system is shrouded in uncertainty, although more interaction between the components is probable. Delgrado & Thomas (1981) speculate about a third episode of mass exchange which they label the 'BBC' case.

The effects of nuclear processing in stellar interiors are normally veiled by the overlying unprocessed layers. Even in red giants, in which the processed material is convectively mixed to the surface, the interpretation of the observed composition is complicated by its being a mixture of processed and unprocessed material. However, in close binaries, such as β Lyr, the severe mass loss draws the veil of unprocessed material completely aside and reveals the processed core. In β Lyr we find substantial observational confirmation of the helium enrichment and the CNO cycle abundances predicted by stellar evolution theory.

Roche lobe overflow in an interacting binary is not the only mechanism capable of removing the unprocessed outer layers. In the Wolf–Rayet stars, mass loss by stellar winds also reveals the processed core (e.g. Maeder 1983). The WN Wolf–Rayet stars show the N enrichment caused by the CNO cycle, while in the WC stars, the mass loss has gone even further and revealed the C enrichment due to He burning. An advantage of binaries, such as β Lyr, is that their lines are mostly in absorption and are sufficiently narrow to permit measurement of weak lines so their abundances should be inherently more reliable than those of Wolf–Rayet stars, in which the lines are in emission and are also so broad that weak lines are smeared beyond recognition.

Acknowledgments

We thank Dr Douglas Gies for making some critical observations of β Lyr, and Dr David S. P. Dearborn for sending us the results of his stellar model calculations. This work has been supported, in part, by the National Science Foundation through grants AST 81-17485 and 83-16635 and by the Robert A. Welch Foundation of Houston, Texas.

References

Abt, H. A., Jeffers, H. M., Gibson, J. & Sandage, A. R., 1962. *Astrophys. J.,* **135,** 429.
Auer, L. H. & Mihalas, D., 1973. *Astrophys. J.,* **184,** 151.
Bahýl', V., 1982. In: *Be Stars, IAU Symp. No. 98,* p.205, eds Jaschek, M. & Groth, H. G., Reidel, Dordrecht, Holland.
Böhm-Vitense, E., 1981. *A. Rev. Astr. Astrophys.,* **19,** 295.
Boyarchcuk, A. A., 1959. *Astr. Zh.,* **36,** 766.
Delgrado, A. J. & Thomas, H.-C., 1981. *Astr. Astrophys.,* **96,** 142.
Dobias, J. J. & Plavec, M. J., 1985. *Astr. J.,* **90,** 773.
Dufton, P. L. & Hibbert, A., 1981. *Astr. Astrophys.,* **95,** 24.
Fowler, W. A., Caughlan, G. R. & Zimmerman, B. A., 1975. *A. Rev. Astr. Astrophys.,* **13,** 69.
Grevesse, N., 1984. *Physica Scripta,* **T8,** 49.
Hack, M. & Job, F., 1965. *Z. Astrophys.,* **62,** 203.
Harris, M. J., Fowler, W. A., Caughlan, G. R. & Zimmerman, B. A., 1983. *A. Rev. Astr. Astrophys.,* **21,** 165.
Huang, S., 1963. *Astrophys. J.,* **138,** 142.
Iben, I. Jr, 1966a. *Astrophys. J.,* **143,** 505.
Iben, I. Jr, 1966b. *Astrophys. J.,* **143,** 516.
Jameson, R. F. & Longmore, A. J., 1976. *Mon. Not. R. astr. Soc.,* **174,** 217.

Kippenhahn, R. & Thomas, H.-C., 1980. In: *9th Texas Symp. on Relativistic Astrophys.*, p. 579, eds Ehlers, J. *et al.*, The New York Academy of Sciences, New York.
Klinglesmith, D. A., 1971. *Hydrogen Line Blanketed Model Stellar Atmospheres,* NASA SP-3065, Scientific and Technical Information Office, NASA, Washington, D.C.
Kurucz, R. L. & Peytremann, E., 1975. *A Table of Semiempirical gf Values,* Smithsonian Astrophys. Obs. Special Report 362.
Lambert, D. L., 1968. *Mon. Not. R. astr. Soc.,* **138,** 143.
Lambert, D. L., 1978. *Mon. Not. R. astr. Soc.,* **182,** 249.
Leushin, V. V., Nevskii, M. Yu. & Snezhko, L. I., 1979. *Bull. Spec. Astrophys. Obs. – N. Caucasus,* **11,** 34.
Leushin, V. V., Nevskii, M. Yu., Snezhko, L. I. & Sokolov, V. V., 1977. *Bull Spec. Astrophys. Obs. – N. Caucasus,* **9,** 1.
Leushin, V. V. & Snezhko, L. I., 1980. *Soviet Astr. J. Lett.,* **6,** 94.
Maeder, A., 1983. *Astr. Astrophys.,* **120,** 113.
Phillips, M. M., 1979. *Astrophys. J. Suppl.,* **39,** 377.
Plavec, M. J., 1985. *Interacting Binaries, (Proceedings of the NATO Advanced Study Institute on Interacting Binaries; Cambridge, U.K.; 31 July–13 August 1983),* p. 155, eds Eggleton, P. P. & Pringle, J. E., Reidel, Dordrecht, Holland.
Schild, R., Peterson, D. M. & Oke, J. B., 1971. *Astrophys. J.,* **166,** 95.
Sinnerstad, U., 1980. *Astr. Astrophys. Suppl.,* **40,** 395.
Sneden, C., 1973. *PhD thesis,* University of Texas.
Vogt, S. S., Tull, R. G. & Kelton, P., 1978. *Applied Optics,* **17,** 574.
Wiese, W. L. & Martin, G. A., 1980. *Wavelengths and Transition Probabilities for Atoms and Atomic Ions,* Part II, NSRDS-NBS 68.
Wiese, W. L., Smith, M. W. & Glennon, B. M., 1966. *Atomic Transition Probabilities, Vol. I Hydrogen Through Neon,* NSRDS-NBS 4.
Wilson, R. E., 1974. *Astrophys. J.,* **189,** 319.
Wilson, R. E., 1982. *Binary and Multiple Stars as Tracers of Stellar Evolution,* p. 261, eds Kopal, Z. & Rahe, J. Reidel, Dordrecht, Holland.
Wilson, R. E. & Lapasset, E., 1981. *Astr. Astrophys.,* **95,** 328.
Ziołkowski, J., 1976. *Astrophys. J.,* **204,** 512.