1988JApA....9..161S

J. Astrophys. Astr. (1988) **9**, 161–172

Study of the Wolf-Rayet Members of the Cluster NGC 6231

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Received 1987 November 17; revised 1988 June 3; accepted 1988 June 21

Abstract. Two Wolf-Rayet members of the cluster NGC 6231 are studied spectrophotometrically. HD 151932, a suspected variable, shows variations in the emission line flux as well as continuum magnitude measurements. An attempt is made to understand this variation as due to the asymmetric atmospheric structure. The other, HD 152270, a (WC7 + O) binary, shows variation of emission line flux for C III and C IV lines only. This variation is studied as a possible phenomenon of atmospheric eclipses.

Key words: stars, emission-line—stars, Wolf-Rayet—open clusters, NGC 6231.

1. Introduction

The open cluster NGC 6231 is considered to belong to the Sco OB1 Association. Many detailed investigations like the determination of the H-R diagram, the distance modulus and the reddening have been carried out extensively (Struve 1944; Schild, Hiltner & Sanduleak 1969, 1971; Graham 1965; Crawford *et al.* 1971; Garrison & Schild 1979; Lundstrom & Stenholm 1980). There are two Wolf-Rayet (WR) stars in this cluster: HD 152270 (WC 7 + O) which is in the central region of the cluster, and HD 151932 (WN 7), which is situated 22 arcmin west of the centre. The membership of these two to the cluster has been discussed in detail (Seggewiss 1974 a, b; Seggewiss & Moffat 1979; Lundstrom & Stenholm 1980).

HD 152270 (MR 65, WR 79) is one of the six binaries with a WC component (Moffat *et al.* 1986) and was established as a spectroscopic binary with O-type companion by Struve (1944). Radial velocity curves were studied by Seggewiss (1974b), who improved the period to 8.893 days. Proper motion measures (Braes 1967) and radial velocity (RV) measures of the interstellar lines (Seggewiss 1974b) have confirmed the membership to the cluster. Line profiles have the absorptions due to the companion, as well as the violet-shifted absorptions moving with the WC component (Seggewiss 1974b). The profile of the C III line at λ 5696 has been particularly studied in great detail (Schumann & Seggewiss 1975; Schmidt & Seggewiss 1976; Neutsch, Schmidt & Seggewiss 1981; Neutsch & Seggewiss 1985), and a cone model explanation has been offered for the double-peaked profile. Polarimetric observations (Luna 1982) have been used for deriving the angle of inclination of the orbit to be $35° \pm 8°$. Recent observations by St Louis *et al.* (1987) have improved this value to $45° \pm 5°$.

HD 151932 (MR 64, WR 78) was classified as WN 7A by Hiltner & Schild (1966) because of the narrow emission lines. Its membership in the cluster itself has been debated about not only because of its location 22 arcmin west of the centre, but also

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because of the large reddening it displays. Based on the interstellar line velocities and interstellar diffuse-band equivalent widths, Seggewiss & Moffat (1979) have included it in the cluster. Recent photometric investigations of the cluster (Heske & Wendker 1985) puts it as a post-main-sequence member.

Schild, Hiltner & Sanduleak (1969) studied the radial velocity measures of Struve (1944) and suspected that there is an unseen companion with an orbital period of about 3.3 d. Bappu (1973) attributed the excess reddening to a late-type companion. Seggewiss (1974a) studied the RV curves and found that the 3.3d periodicity was spurious because even the interstellar lines showed the same period. Hill, Kilkenny & Van Breda (1974) also did not find any orbital motiòn. A further detailed investigation by Seggewiss & Moffat (1979) showed that the excess reddening can be explained by normal interstellar reddening and an unseen companion need not be invoked. Recently the variability of the Si IV line also has been reported (Vreux *et al.* 1987).

These two objects are important for the following reasons:

1. Although HD 152270 is not an eclipsing binary, based on the previous studies of CQ Cep and HD 50896 (Shylaja 1986a, b) we may expect to see atmospheric eclipses, which by virtue of the relatively low angle of inclination, may be partial.
2. In the case of HD 151932 any similar effect of flux variation may throw some light on the possibility of a companion.

2. Observations

Spectrophotometric observations were carried out at the Cassegrain focus of the 102 cm reflector at the Vainu Bappu Observatory with the automated spectrum scanner (Bappu 1977). The wavelength range was 4000–6000 Å in the first order (later this was extended to 8500 Å for measuring the continuum distribution only). The standards from the list of Hayes (1970), Breger (1976) and Kuan & Kuhi (1976) were used for estimating the instrumental corrections. Sample scans are shown in Fig. 1.

The monochromatic magnitudes at 5560 Å (mainly continuum) derived from the energy distributions are tabulated in Table 1.

3. Results

3.1 *HD 152270*

The phases have been calculated from an initial epoch of JD 2441796.233 and a period of 8.8908 d, following St Louis *et al.* (1987). Although the photometric results at 5560 Å show a small dip near phase 0.1 (Fig. 2) there is too much scatter to be attributed to an eclipse effect.

Spectrophotometric results were used to derive the line flux of the broad features like (C III/C IV + He II) near λ4650, C IV λ5470, (C IV λ5808 + He I λ5876) and also C III/C IV λ5696; all these measurements are listed in Table 2 and indicated in Fig. 2.

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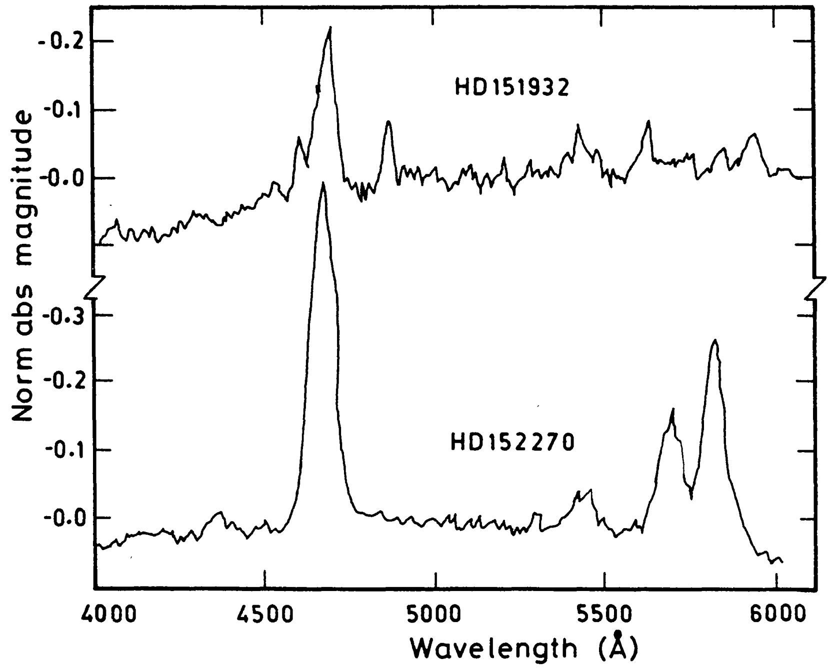

Figure 1. Sample scans of HD 152270 and HD 151932 uncorrected for reddening. The ordinate is magnitude normalized at 5000 Å.

3.2 *HD 151932*

The photometric data of HD 151932 were searched for any possible periodicities by the method of least squares (Raveendran, Mohin & Mekkadan 1982) between 1 and 10d. This showed that there is an indication of a period of about 6 d, but the amplitude of variation is very small, 0.05 mag (Fig. 3). However, such a period determination is not completely free of alias effects and further continuous monitoring only can establish this. The light curve of Seggewiss & Moffat (1979) also shows similar scatter. The scanner observations were used for estimating the flux values of N IV λ4058, N V λ4603, C IV λ5808, He II λ4860, 5410, 4686, He I λ5876 and the blend of λ4540. The line of N III could not be resolved to measure the flux accurately. All the measured fluxes are listed in Table 3 and variations may be seen in Fig. 4.

3.3 *Interstellar Reddening*

For a study of the colour excesses of the various members of the cluster, previous investigators have pointed out that the interstellar reddening across the face of the cluster is not very smooth and therefore a single value of $E(B-V)$ is not applicable for all the members of the cluster (Schild, Neugebauer & Westphal 1971; Garrison & Schild 1979). This aspect is made clear in Fig. 5 which shows the observed (normalized at 5000 Å) energy distributions of a few cluster members. Therefore, it was necessary to derive the colour excesses separately for the two WR stars (Shylaja & Bappu 1983).

The excess red light, which was attributed to a possible late-type companion by Bappu (1973) was explained as a consequence of interstellar reddening (Seggewiss &

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Table 1. Monochromatic magnitudes of HD 151932 and HD 152270, at λ5560.

JD 2440000+	Magnitudes HD 151932	Phase	Magnitudes HD 152270	Phase	JD 2440000+	Magnitudes HD 151932	Phase	Magnitudes HD 152270	Phase
4711.331	0.731	0.481	—	—	4740.317	0.710	0.317	—	—
4711.396	0.739	0.492	—	—	4740.300	—	—	0.819	0.136
4711.475	0.718	0.505	—	—	4740.330	—	—	0.823	0.140
4711.383	—	—	0.815	0.884	4740.356	—	—	0.814	0.143
4711.454	—	—	0.820	0.892	5065.426	—	—	0.831	0.705
4711.480	—	—	0.829	0.895	5065.436	0.714	0.499	—	—
4712.325	0.714	0.647	—	—	5068.443	0.702	0.000	—	—
4712.349	0.727	0.651	—	—	5068.454	0.711	0.002	—	—
4712.475	0.722	0.672	—	—	5068.466	0.705	0.004	—	—
4712.350	—	—	0.822	0.993	5068.434	—	—	0.826	0.044
4712.425	—	—	0.829	0.001	5068.461	—	—	0.815	0.047
4712.461	—	—	0.826	0.005	5068.476	—	—	0.822	0.048
4713.335	0.708	0.815	—	—	5069.446	—	—	0.821	0.157
4713.366	0.717	0.821	—	—	5069.466	—	—	0.819	0.160
4713.373	—	—	0.827	0.108	5069.450	0.719	0.168	—	—
4713.443	—	—	0.816	0.116	5069.475	0.708	0.172	—	—
4739.386	0.705	0.157	—	—	5070.426	—	—	0.824	0.268
4739.446	0.716	0.167	—	—	5070.450	—	—	0.817	0.270
4739.459	0.725	0.169	—	—	5070.474	—	—	0.822	0.273
4739.393	—	—	0.822	0.034	5070.434	0.735	0.332	—	—
4739.419	—	—	0.815	0.037	5070.456	0.729	0.336	—	—
4739.468	—	—	0.812	0.043	5070.478	0.732	0.339	—	—
4740.308	0.718	0.310	—	—	5071.348	0.724	0.484	—	—
4740.313	0.728	0.313	—	—	5071.359	—	—	0.821	0.373

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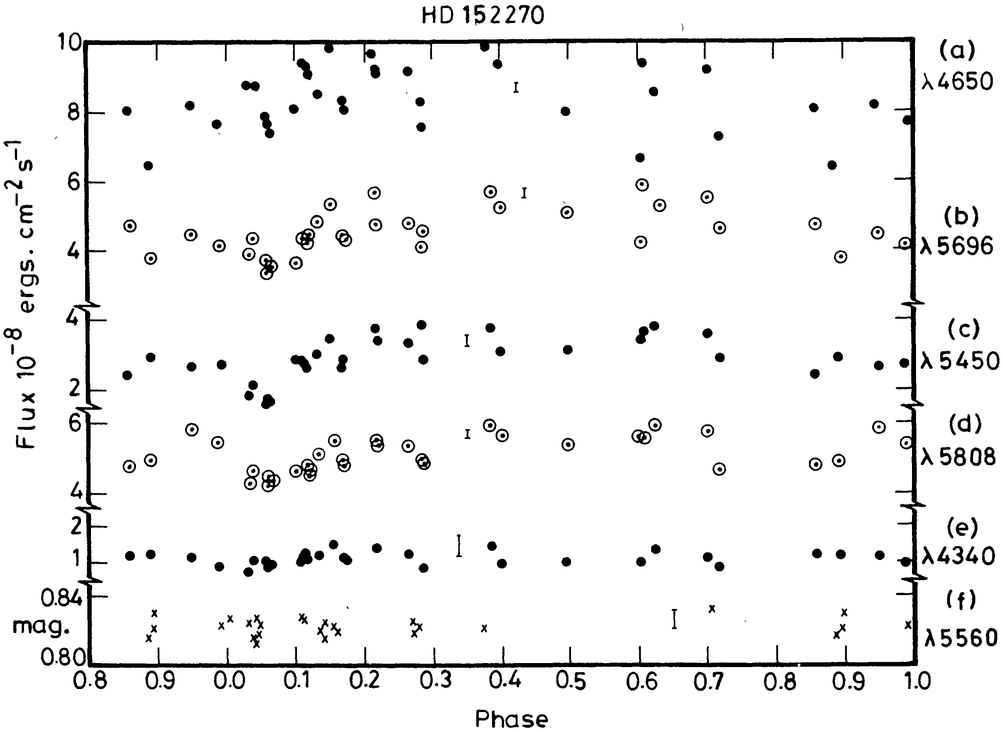

Figure 2. Flux variations of HD 152270: (a) λλ4650+4686, (b) λ5696, (c) λλ5410+5470, (d) λ5808, (e) λ4340, and (f) λ5560 magnitude.

Moffat 1979). In Fig. 5 it may be noticed that HD 151932 and HD 152003, which are located 20 arcmin away from the nucleus of the cluster, have similar energy distributions and somewhat different from the other members of the cluster. Therefore, it may be inferred that there is some source of excess reddening in this region. The recent photometric investigation by Heske & Wendker (1984, 1985) also shows that the reddening is not uniform in this region.

3.4 *The Possibility of a Companion to HD 151932*

The evolutionary calculations of de Loore (1980) for the WR phase in a binary show that a late-type companion is not possible. Therefore, in the light of the explanation of anomalous reddening near HD 151932, the possibility of another type of companion may be sought.

The detailed spectroscopic investigation by Seggewiss (1974a) has clearly shown that there is no apparent RV variation. Based on the 6d period derived from the photometry, an attempt was made to fold the absorption line RV measures of Seggewiss & Moffat (1979), which did not yield any meaningful RV curve for any line. The other emission lines show smooth RV variation and therefore it is unlikely that any compact companion, if present, can be detected by such velocity curves.

The existence of a compact companion would imply a very high mass ratio of $q = m_{WR}/m_c > 10$, assuming the WN 7 to be $\sim 20\,M_\odot$ and the compact star to be about $2\,M_\odot$. However, in the case of CQ Cep, another binary with WN 7, the mass derived

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Table 2. Flux ($\times 10^{-11}$ erg cm^{-2} s^{-1}) of emission lines of HD 152270.

JD 240000+	Phase	Blend λ4340	C IV λ5808	Blend λ5450	Blend λ4650	C III λ5696
4663.468	0.495	93.0	530.0	305.0	795.0	506.0
4664.442	0.604	95.0	558.0	330.0	655.0	418.0
4665.458	0.718	82.0	460.0	286.0	722.0	457.0
4684.467	0.857	119.0	475.0	238.0	797.0	465.0
4711.429	0.889	106.0	492.0	285.0	642.0	371.0
4712.332	0.991	89.0	544.0	272.0	758.0	408.0
4713.336	0.104	97.0	461.0	280.0	801.0	362.0
4714.344	0.217	135.0	550.0	372.0	983.0	565.0
4739.397	0.035	65.0	422.0	182.0	835.0	382.0
4740.281	0.134	115.0	506.0	297.0	852.0	483.0
4780.208	0.625	130.0	590.0	375.0	849.0	520.0
5065.392	0.701	110.0	570.0	352.0	907.0	545.0
5068.421	0.042	98.0	462.0	210.0	875.0	430.0
5069.417	0.154	146.0	545.0	342.0	982.0	535.0
5070.399	0.265	115.0	536.0	315.0	915.0	470.0
5071.478	0.386	140.0	587.0	368.0	995.0	561.0
5405.461	0.951	109.0	585.0	262.0	815.0	440.0
5406.441	0.061	95.0	412.0	150.0	785.0	370.0
5406.462	0.064	78.0	445.0	168.0	760.0	335.0
5406.476	0.065	84.0	430.0	155.0	735.0	348.0
5407.427	0.172	110.0	490.0	255.0	830.0	435.0
5407.437	0.173	96.0	465.0	283.0	797.0	407.0
5408.429	0.285	76.0	487.0	382.0	753.0	396.0
5408.440	0.286	82.0	481.0	285.0	827.0	456.0
5409.448	0.399	88.0	562.0	300.0	930.0	516.0
5451.369	0.114	110.0	490.0	275.0	938.0	430.0
5451.404	0.118	102.0	475.0	262.0	900.0	415.0
5451.415	0.120	113.0	453.0	248.0	927.0	442.0
5452.325	0.222	120.0	530.0	335.0	910.0	470.0
5811.393	0.608	107.0	558.0	361.0	927.0	590.0

for the WN7 component is about 35 $M_\odot$ (Stickland *et al.* 1984; Leung, Moffat & Seggewiss, 1983). Therefore, the mass ratio in this case with a compact companion can be higher than 10. To estimate the approximate amplitude of the RV curve, we may assume $q=10$ and period 6d. Then the amplitudes will be less than 30 km s^{-1}. Such small amplitudes have not been detected even with high-dispersion spectra. The polarization data does not show significant periodicity (Drissen *et al.* 1987). The polarization vector is fairly aligned with that of other stars in the area indicating that a large fraction of the polarization is interstellar.

The presence of a compact companion represents the second WR phase in the evolution of a massive binary, which in other cases, like HD 50896, has many other characteristics like the associated nebulosity. HD 151932 being a member of the relatively young cluster does not fit into this scheme.

4. Line-emitting regions in HD 151932

The violet-shifted absorptions clearly indicate an expanding envelope, following the excitation potential versus velocity relation like other systems (Seggewiss, 1974a).

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Therefore, it is implied that higher excitation lines like He II, N V, N IV and C IV originate closer to the photosphere. The variations shown by the observed flux may be interpreted with this criterion. The He I lines, which are formed in the outermost regions of the atmosphere show large scatter of flux (Figs 3 and 4). Their RV curves also show a large scatter (Seggewiss 1974a) compared to other lines. Such RV variations were attributed to fluctuations in the particle density by Seggewiss & Moffat (1979). They have shown that small changes in particle density (the source for this is

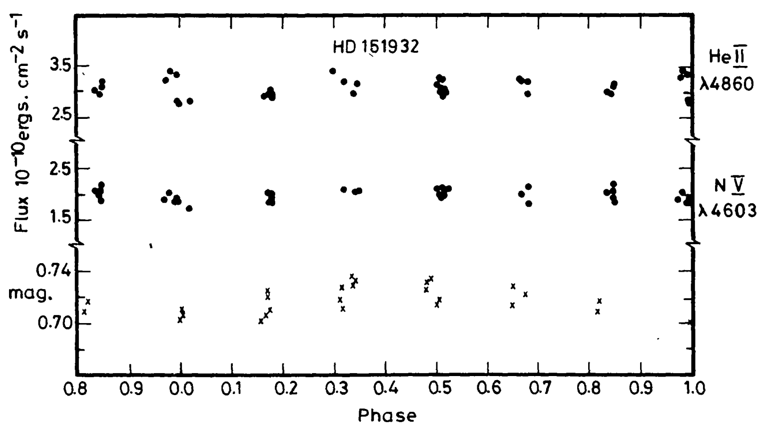

Figure 3. The photometric variations of HD 151932 at λ5560 folded over a period of 6 days, taking JD 24445068.443 as epoch. The flux variations also are included for some lines.

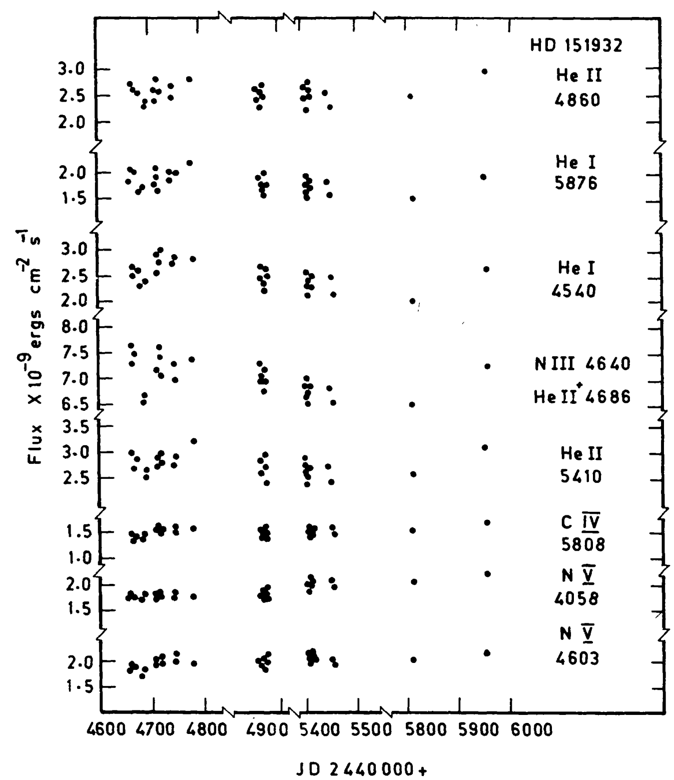

Figure 4. The variation of emission flux of HD 151932. The lines and the wavelengths of emission are indicated.

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Table 3. Flux of emission lines of HD 151932.

JD 2440000+	N V λ4603	N IV λ4058	C IV λ5808	He II λ4860	He II λ5411	He II λ4686	Blend λ4540	He I λ5876
4663.430	190.0	182.0	146.0	324.0	298.0	724.0	249.0	174.0
4663.461	198.0	177.0	143.0	308.0	279.0	717.0	236.0	163.0
4664.435	182.0	174.0	135.0	318.0	272.0	769.0	268.0	212.0
4665.451	186.0	178.0	141.0	307.0	284.0	748.0	258.0	203.0
4684.467	172.0	174.0	135.0	281.0	241.0	641.0	222.0	151.0
4685.403	183.0	182.0	152.0	294.0	263.0	669.0	241.0	172.0
4685.428	180.0	177.0	143.0	286.0	256.0	658.0	236.0	164.0
4711.406	205.0	181.0	156.0	327.0	268.0	707.0	249.0	170.0
4711.436	209.0	170.0	168.0	306.0	274.0	725.0	268.0	186.0
4712.441	212.0	185.0	155.0	291.0	289.0	758.0	292.0	192.0
4713.424	196.0	174.0	141.0	308.0	275.0	741.0	297.0	214.0
4714.333	192.0	176.0	146.0	332.0	296.0	707.0	276.0	168.0
4739.383	202.0	172.0	154.0	294.0	271.0	695.0	213.0	206.0
4740.277	211.0	184.0	1[illegible]	319.0	289.0	727.0	285.0	177.0
4780.200	191.0	178.0	164.0	325.0	327.0	746.0	291.0	211.0
4780.236	206.0	162.0	147.0	341.0	311.0	728.0	276.0	237.0
5065.370	208.0	196.0	147.0	311.0	289.0	684.0	241.0	176.0
5066.353	197.0	181.0	159.0	319.0	265.0	709.0	268.0	192.0
5068.353	184.0	174.0	138.0	276.0	247.0	651.0	218.0	159.0
5069.416	194.0	170.0	149.0	309.0	275.0	674.0	231.0	172.0
5070.380	207.0	176.0	138.0	294.0	299.0	695.0	242.0	199.0
5071.454	191.0	184.0	145.0	299.0	286.0	676.0	259.0	175.0
5405.428	190.0	176.0	140.0	291.0	296.0	681.0	257.0	176.0
5406.431	207.0	199.0	154.0	315.0	280.0	694.0	232.0	195.0
5407.411	195.0	186.0	147.0	274.0	265.0	658.0	241.0	162.0
5407.419	211.0	212.0	144.0	299.0	257.0	645.0	211.0	149.0
5408.419	200.0	207.0	155.0	326.0	249.0	676.0	250.0	168.0
5409.456	217.0	195.0	149.0	311.0	274.0	668.0	227.0	184.0
5451.360	203.0	207.0	155.0	302.0	276.0	675.0	245.0	177.0
5452.317	187.0	192.0	141.0	277.0	245.0	646.0	212.0	151.0
5811.434	201.0	203.0	152.0	295.0	260.0	641.0	198.0	142.0
5964.125	212.0	215.0	163.0	342.0	311.0	717.0	257.0	185.0

not known) can lead to large changes of ion density in the outermost regions where the He I lines are formed. Any atmospheric eclipse effect is not evident on the emission lines (Fig. 3).

The observed photometric variations of period ~6 d, which reflect the asymmetry in the envelope, also can be explained by the variable density hypothesis. Further, the intrinsic variations of WRs are not uncommon, which, in the present study, might have produced the observed apparent periodic variation. Only continuous photometry with simultaneous spectroscopic measurements can establish this aspect.

5. Possible atmospheric eclipses in HD 152270

This is one of the 6 stars with WC component, and has an established period of about 8.89 d. Seggewiss (1974b) obtained the RV curves with high resolution and noticed the central absorption of the λ5696 line of C III. The absorption lines of the companion

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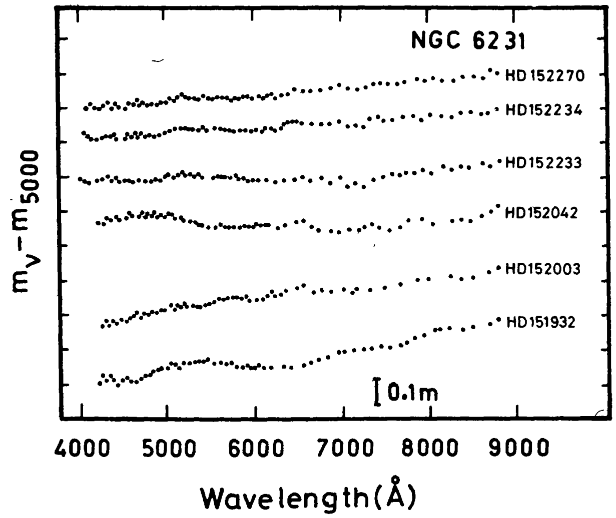

Figure 5. Observed energy distributions of some members of the cluster NGC 6231, normalized at 5000 Å.

also were easily detectable because of the phase difference of 0.5 relative to the emission lines at λλ5696, 5808 and 5471. Therefore it was possible to improve the period to 8.893d. The velocities and the amplitudes of the RV curves show different values corresponding to different emission lines. Based on the RV curve of the unblended line of C IV λ5471, which shows the systemic velocity, Seggewiss (1975b) obtained the masses of the components.

The violet-displaced absorptions have also been studied by Seggewiss (1974b); they all follow the behaviour of the emission lines. Higher excitation lines like C IV have smaller velocities compared to He I lines. However, the relation of the EP versus velocity is not as strong as in the case of WN systems. Further, the RV amplitudes of He I λ5876 and C III λ4650 are nearly same, implying that they both have similar motion in at least some binary systems.

The origin of gas streams in this star has also been discussed in detail (Seggewiss 1974b). Further detailed investigations by Schmidt & Seggewiss (1976) have clearly shown the effect of central absorption with phase. This was attributed to a 'hole' near the Lagrangian point by Neutsch & Seggewiss (1977) and Neutsch *et al.* (1985).

The polarization studies by St Louis *et al.* (1987) have improved the period to 8.8908 ± 0.0005 days and the angle of inclination to $44°.8 \pm 5°$. Consequently the masses of the components are $M(\mathrm{WR}) = 5 \pm 2 M_\odot$ and $M(\mathrm{O}) = 14 \pm 5 M_\odot$. The flux measures in Fig. 3 show a dip at phase 0.1 for some lines. The zero phase corresponds to the WC in front and the angle of inclination is 45°. Therefore, one may assume that at phase 0.1 part of the line-emitting region is covered only for some lines. Then this would represent the case of an atmospheric eclipse, since at the corresponding phase there is no change in the continuum (Fig. 2).

Since it is known that the O-type companion can contribute to some line profiles (as central absorption) an effect of this may be seen on the measured total flux as well. It is a difficult task to determine this contribution because the He II and He I lines appear as blends. The brightest line λ4686 has been studied at high dispersion (Seggewiss 1974b) and no central absorption could be detected. It is also possible that this line is formed

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in an extended region and therefore has a peculiar behaviour as in case of WN binaries (Shylaja 1987). In other cases, because of the line blends it is not possible to isolate the He II or He I lines. Therefore it may be assumed that such central absorptions do not contribute significantly to the total flux.

Following the type of stratification with ionization potential, we may expect to see deeper eclipses for higher excitation lines like C IV and He II compared to C III or He I. This is partly true in Fig. 2—C IV $\lambda 5808$ has larger depth, which is similar to that of $\lambda 5450$ (blend of He II and C IV) and $\lambda 4650$ (C III/C IV and He II). The blend at $\lambda 4340$ has smaller dip since the possible contributors are He II & He I. This stratification can be ascertained by individually resolving the various contributors of the blends and studying their flux variation.

5.1 *Line-Emitting Regions in HD 152270*

The masses derived by St Louis *et al.* (1987) as $14 M_\odot$ for the O star and $5 M_\odot$ for the WC star, may be used for estimating the distance of L_1, the inner Lagrangian point, following the tables of Plavec & Kratochvil (1964). For a separation of about $14 R_\odot$, this will be about $9 R_\odot$ from the centre of mass. Since the angle of inclination is about 45°, and since the observed eclipse is very broad, quantitative derivations are not possible. The Roche surface calculations probably may not be valid for these stars with strong winds. The eclipse effects on C IV lines imply that they are formed closer to the photosphere than the He I lines. Since the line profiles do not reflect the asymmetry directly as seen in V 444 Cyg (Ganesh, Bappu & Natarajan 1967) and θ Mus (Moffat & Seggewiss, 1977), the extension of the He II and C IV line-emitting material may be taken as the inner Roche surface itself.

From the interferometric measurements of the (WC8 + O9 I) binary γ^2 Vel ($P = 78$ d), Brown *et al.* (1970) found that the extension of the C III line-emitting region is five times larger than the continuum-emitting region. However, the dimensions derived by them cannot be used directly here because of the difference in the WC subgroup.

The large velocities associated with the violet absorptions of emission lines indicate that the winds in the envelopes are strong enough to complicate the structure of He I lines, which are probably formed in the outermost parts of the envelope. Very-high-dispersion spectra only can reveal this aspect, since it is known that, even in a well separated binary like γ^2 Vel the line profiles are affected by the presence of the companion (Ganesh 1966).

6. Conclusions

This spectrophotometric study of the two Wolf-Rayet members of NGC 6231 shows that the reddening is not smooth across the face of the cluster. This leads to an observable excess reddening for HD 151932. There is a variation of total flux from the emission lines which could be a consequence of variable particle density or an unseen companion. Considering that there is a variation in the continuum the latter possibility cannot be completely eliminated, because a compact companion may show barely observable RV variations less than $25\ \mathrm{km\,s^{-1}}$. Further, the total flux of

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emission lines do not show atmospheric eclipse effect. However, other characterstic features of WR + compact systems are yet to be established, which necessitates a rethinking concerning the membership to the cluster.

In the case of the established binary HD 152270, the total flux variation shows possible atmospheric eclipses of some higher excitation lines like C IV. Although C III λ5696 shows a variable line profile, the measured total flux shows atmospheric effects clearly.

Thus this study shows that the measurement of the variation of flux in binaries can be used as an effective tool to understand the atmospheric structure of binaries.

Acknowledgements

The author wishes to thank Prof. J. C. Bhattacharyya for continued encouragement, Prof. N. K. Rao for a critical reading of the manuscript and Prof. Seggewiss for very helpful discussions. Thanks are also due to Prof. A. F. J. Moffat and other referees for helpful suggestions.

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