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High Resolution Spectroscopy of the Semi-regular Variable LR Sco

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Abstract. A detailed spectroscopic investigation of LR Sco which was earlier misclassified as R CrB star is made. Atmospheric parameters and elemental abundances are determined using detailed depth-dependent model atmospheres and line synthesis technique. Most of the elements show near solar abundances.

The strength of circumstellar components seen in Na D lines are used to derive the mass loss rate. Another independent estimate of mass loss rate is made using the observed infrared flux from 1–100μm. These two approaches lead to nearly the same value of mass loss rate when M_v is assumed to be – 4.5 for this star.

Key words: Semi-regular variables—abundances—infrared flux—mass loss

1. Introduction

LR Sco has been listed as an SR variable in the *General Catalogue of Variable Stars* by Kukarkin *et al.* (1969). This classification is based on photometric observations of Shapley & Swope (1934) who estimated a period of 104.4 days using 202 observations covering 145 epochs. Stephenson (1978) examined a low dispersion (580 Å mm^{-1}) objective prism spectrum of this star in the blue spectral region and remarked that the spectrum resembled that of R CrB stars at light minimum. His remarks appear to have persuaded Bidelman (1979) to list this star with other R CrB stars.

Feast (1979) showed that the observed infrared excess of LR Sco is very similar to that of other R CrB stars i.e. the location of LR Sco in (J–H) vs (H–K), and (H–K) vs (K–L) diagrams is similar to that of other R CrB stars; J, H, K and L photometry of LR Sco was published by Carter, Roberts & Feast (1979). Later IRAS observations showed the infrared excess as prominent at 12, 25, 60 and 100 μm indicating that cold dust surrounds the star (Table 1). The infrared photometry lent further support to the classification of LR Sco as R CrB type star (Walker 1986). Drilling & Hill (1986) included this star in their list of cool hydrogen deficient stars. However, our high resolution spectra reveals that LR Sco is not a R CrB type star but a normal yellow supergiant of spectral type near G0Ib (Giridhar *et al.* 1991).

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Table 1. Basic observational data for LR Sco.

R.A. = 17:24:17	
Dec = − 43:50.9	
Radial velocity − 12 ± 3 km s^{-1}	
V = 9.72(B − V) = 0.55	
Infrared magnitudes	
J	8.20
H	7.48
K	6.52
L	4.73
Infrared flux (Jy)	
12 μm	10.72
25 μm	7.75
60 μm	3.41
100 μm	7.06:

J, H, K, L magnitudes are from Carter *et al.* (1979)
The IRAS fluxes are from Walker (1986)
Radial velocity from Giridhar *et al.,* (1990)

2. Observation and data analysis

High resolution spectra with a GEC CCD detector were obtained using the cassegrain echelle spectrometer of the 4-m reflector of the Cerro-Tololo-Inter-American-Observatory. The spectral regions covered are 4200–4900 Å and 5450–6850 Å. The instrumental profile in the adopted configuration has a width (FWHM) of 0.34 Å in red and 0.32 Å in the blue spectral region. Three exposures were taken for each region to get better S/N ratio and identify cosmic ray hits. The exposure times were 20 minutes both in the red and in the blue. A xenon lamp was used for the flatfield images.

Our spectra were reduced using the spectroscopic data reduction package RESPECT (Prabhu, Anupama & Giridhar 1987) in its upgraded version (Prabhu & Anupama 1991). The extraction of the echelle spectrum follows the algorithm of Home (1986, 1988). The background level due to thermal noise and mean scattered light in the spectrograph is estimated using the counts in interorder rows after removing the effect of cosmic ray hits. Flatfielding was done using a normalized flatfield image. A Th + A hollow cathode lamp was used for wavelength calibration. The extracted spectrum orders were linearized in wavelength using a third degree polynomial for wavelength as a function of position. The standard error of the fit was around 0.02 Å. The pseudocontinuum for each order was determined using the highest points in spectrum known to be free of stellar lines. The spectra were then reduced to normalized continuum using spline interpolated values between these points. The accuracy of equivalent widths measured here are of the order of 10% for weak lines in equivalent width range 10–30 mÅ, 5–10% for lines in 50–200 mÅ range and 5% for lines in 200–350mÅ range. The S/N ratio was in the range of 60–80.

3. Description of the spectrum

LR Sco was observed alongwith 12 R CrB type stars and 5 Hdc stars during an observing run from 17–18 July, 1989, When the spectrum of LR Sco was compared with well known R CrB stars like RY Sgr it was obvious that LR Sco did not belong to R CrB group (Giridhar, Rao & Lambert 1990). The CI lines that are a principal characteristic of R CrB stars are conspicuous by their absence. We could measure a few very weak CI lines at, for example, 4770 Å and 6587 Å, but these lines are seen at comparable strength in the spectra of normal F-G supergiants. Other differences were also striking. R CrB stars have numerous NI lines in 6400-6700 Å region but LR Sco spectra does not show them.

By contrast, the line spectrum of LR Sco is very similar to that of a normal supergiant of spectral type near G0. We have compared the equivalent widths of unblended FeI and FeII lines with those of μ Per (G0Ib) measured by Harris & Pilachowski (1984) and with δ C Ma (F8Ia) measured by Castley and Watson (1980). It is apparent from this comparison that LR Sco is slightly hotter than μ Per ($T_{\rm eff}$ 5500, log g = 1.5, as estimated by Luck 1982), but marginally cooler than δ C Ma ($T_{\rm eff}$ = 6250K, log g = 0.6, as estimated by Luck & Lambert 1985).

The observed (B–V) given in Table 1 corresponds to spectral type G0I (Fitzgerald 1970; Flower 1977). When this colour is compared with the colours computed from model atmospheres of Kurucz (1979) it indicates a $T_{\rm eff}$ = 6000K.

4. Abundance analysis

Since we had a large spectral coverage, we could measure equivalent widths for a large number of lines and therefore estimate abundances for several elements. We have calculated theoretical equivalent widths for lines of interest using model atmospheres based on the usual assumption of local thermodynamic equilibrium (LTE) in a plane parallel atmosphere in hydrostatic equilibrium. A model atmosphere grid calculated using the MARCS code (Gustafsson *et al.* 1975) was kindly supplied by R. E. Luck. Since the line spectrum is very similar to normal population I supergiants, we have used solar abundance models. The line equivalent widths are calculated using a program originally written by Sneden (1973) and revised by us. Details of our method of deriving abundances are described in Giridhar (1983). We have proceeded by first determining the atmospheric parameters $T_{\rm eff}$ (effective temperature), g (gravity) and V_t (microturbulence) using a set of iron lines comprising of 189 FeI and 26 FeII lines. The sample of FeI lines covering a range in excitation potential of (0.8–5.5 eV) and in equivalent widths of 20–450mÅ was used to determine $T_{\rm eff}$ and V_t. The comparison of FeI and FeII lines then gives the gravity. The atmospheric parameters could be estimated with an accuracy of 200 K in $T_{\rm eff,}$ 0.5 in log g, and 0.5 km s^{-1} in microturbulence velocity.

Oscillator strengths used in the present analysis were taken mostly from Führ, Martin & Wiese (1988) and Martin, Führ & Wiese (1988) for Fe-peak elements. For CI lines the gf values were taken from Luo & Pradhan(1989).

The gf values for the remaining elements were taken from the complilation of Luck (1991). We have used solar abundances tabulated by Grevesse (1984) to estimate relative abundances. The atmospheric parameters estimated for LR Sco are given below.

$$T_{eff} = 5500\text{K}$$

$$g = 10^{0.5}\ \text{cms}^{-2}$$

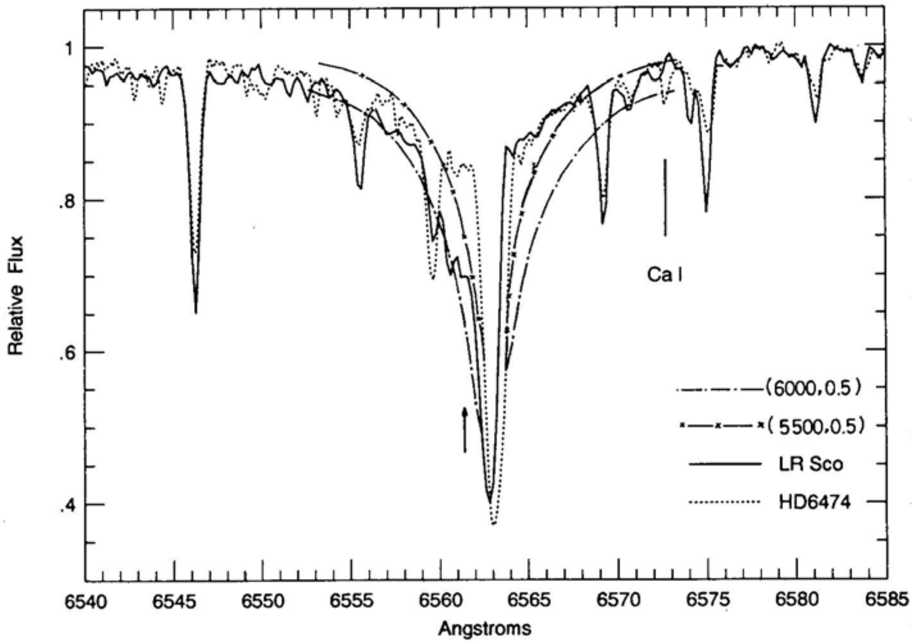

Figure 1. Hα line profile of LR Sco (shown by continuous line) with that of a G0 supergiant HD 6474 (shown by dotted line). The figure also contains Hα profiles calculated by Kurucz (1979) for model atmospheres with ($T_{\rm eff}$ = 5500K, log g = 0.5) and ($T_{\rm eff}$ = 6000K, log g = 0.5) shown by dash-cross and dash-dot pattern respectively.

$$V_t\text{=5.5 km s}^{-1}$$

The red wing of the observed Balmer alpha profile is consistent with the red wings of the profile computed by Kurucz (1979) for the model with $T_{\rm eff}$ = 5500K and *log* g = 0.5 as demonstrated in Fig. 1. The sensitivity of the abundances to the changes in the model parameters are as follows. A change of $T_{\rm eff}$ = 300 K results in a change of 0.3 in log (abundance) (eg. Fe), a change of V_t= 1 kms^{-1} results in a change of 0.3 in log (abundance) (effects the singly ionised metals), a change in log g of 0.5 results in a change of 0.15 in log (abundance).

4.1 *C, O Abundances*

Our abundances of light elements C, and O are based on very few lines. In the case of C, we could measure and use 5 lines and the gf values of Luo & Pradhan (1989) were used. All the five lines give a consistent value. In case of oxygen, the [OI] lines at 6300 Å and 6363 Å are weak and blended and therefore could not be used. We have used the OI line in the 6150 Å region, synthesized the 6152Å–6163Å region and compared with the observed spectrum (see Fig. 2). C and O are of approximately solar abundance. No convincing identification of NI could be made. Two possible candidates yield an upper limit [N/H] > 1.5, which exceeds the expected abundance of a supergiant.

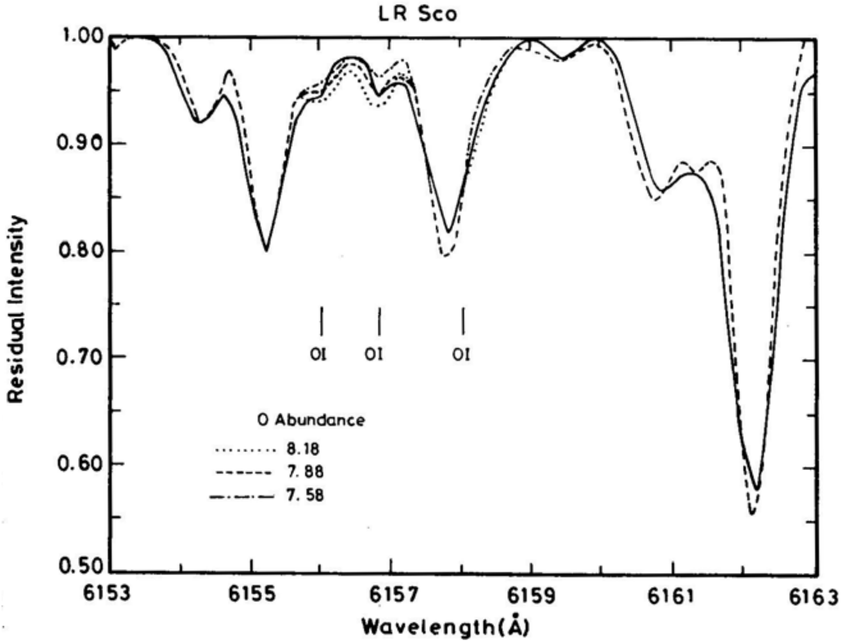

Figure 2. The agreement between the observed spectrum (continuous line) and the synthesized spectrum (dashed line) in 6153–6163 Å region that contains OI lines. The calculations are made for O abundance of 7.58, shown by dash dot line, 7.88 shown by dashed line and 8.18 shown by dotted line.

4.2 *Na–Ca Abundances*

Three NaI lines used in present analysis are of weak to moderate strength (NaI D lines were excluded), and the derived abundances are consistent (see Fig. 2 for comparison with synthetic spectrum).

The available Mg I lines were quite strong ($W_\lambda \cong$ 140–300 mÅ). Silicon is well represented by 13 neutral and 2 singly ionised lines. Although SiII lines are strong, they give an abundance value that is consistent with that estimated from the SiI lines. Sulphur is represented by 5 neutral lines of moderate strength and the scatter in the derived abundance is very small. We could measure 17 CaI lines and this element appears to be deficient compared to other elements (use of $T_{\rm eff}$ = 6000 K would result in a solar abundance for CaI but this is inconsistent with FeI, FeII). Na, Mg and AI indicate mild deficiencies, whereas Si and S show a mild excess.

4.3 *Fe-peak Elements*

Scandium and Vanadium were represented by just a few lines of one ionisation state. We could measure a few TiI and TiII lines, but the TiII lines were very strong and the TiI lines weak and susceptible to blending effects. We had good coverage for CrI and CrII lines and the derived abundances are quite consistent. We could measure a large number of FeI and a reasonably good number of FeII lines and hence the derived abundance are of better accuracy. A reasonably good number of neutral Mn and Ni lines were available and scatter in derived abundances is very small. All these Fe-peak elements show mild deficiency (by a factor of almost 2 relative to the Sun).

4.4 *s-process Elements*

We could estimate the abundances for Y and Ba. The YII and BaII lines show an underabundance of the same magnitude as shown by Fe-peak elements.

5. Sodium D lines

The strong sodium D lines show somewhat asymmetric profiles with long wavelength side being steeper indicating clearly the presence of blue-shifted components (Fig. 3). We have separated out these components by reflecting the longer wavelength part of each profile to the shortward side. The symmetrical profile generated this way was subtracted from the original line profile (point-by-point subtraction). We have plotted the separated D1, D2 components and the original D1 and D2 line in Fig. 3. We are interested in ascertaining the origin of these line components.

The central wavelengths for these components are found to be 5888.79 Å and 5894.72 Å indicating a radial velocity shift of – 47 kms^{-1} and – 50 kms^{-1} respectively with respect to the stellar lines. The corresponding equivalent widths are 177mÅ and

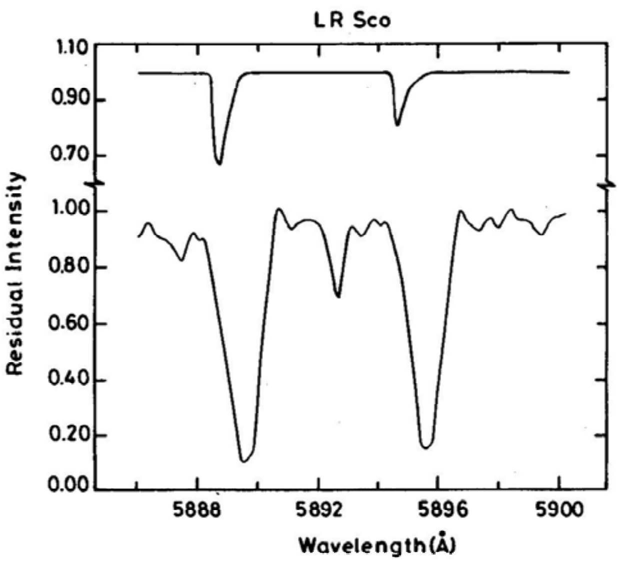

Figure 3. The lower portion of the figure shows observed profiles of NaI D1, D2 lines. The upper portion shows the circumstellar components extracted from the observed line profiles.

75mÅ for D1 and D2 respectively. The equivalent widths ratio is effectively 2:1 corresponding to the ratio of their gf values, and implies that the lines are optically thin. The column densities can then be estimated using the gf-value of 0.327 for D2- N(NaI) = $7.4 \times 10^{11} cm^{-2}$.

The question arises whether the observed line components are interstellar or of circumstellar origin. We believe they are of circumstellar origin for the following reasons. The radial velocity of the star $V_{LSR} = -17.4 kms^{-1}$ indicates a distance of around 2 kpc if it follows the galactic rotation (Pottasch 1984). If the cloud producing the NaI components is interstellar and also follows the galactic rotation then the cloud distance turns out to be about 6 kpc, hence the identification of the components as interstellar matter is unlikely. Further evidence comes from the fact that published 21 cm HI spectra taken closest to the location of LR Sco (1 = 345°, b = – 3°; Sinha 1980) do not reveal any gas at the velocity of the NaI components. There might be interstellar components in the velocity range 10 to – 10 kms^{-1} which blend with the strong stellar line itself. Finally, there is a strong absorption component in the hydrogen alpha line profile which is blue shifted and corresponds to a velocity of – 60 kms^{-1} (see Fig. 1 where the component is indicated by an arrow). The – 60 kms^{-1} component is probably the deep absorption part of a P-Cygni profile. We, therefore, consider that the NaI absorption components are most likely of circumstellar origin.

We do not have sufficient information to estimate the degree of ionisation of Na in the circumstellar envelope. We assume that initially the physical situation in LR Sco is similar to that prevailing during the shell episode of ρ Cas studied by Sargent (1961) when the star (a F8Ib supergiant) showed shell lines including NaI D lines with an expansion velocity of about 40 kms^{-1} and emission in the Hα line. We use the parameter $\log(n_e/w)$ which is the ratio of the electron density and the dilution factor estimated for ρ Cas, and proceed to calculate the column density of N(Na) for LR Sco. We obtain N(Na) = $2 \times 10^{17} cm^{-2}$, and for a solar Na abundance derive the column density of hydrogen N(H) = $7 \times 10^{22} cm^{-2}$. Extending the analogy with ρ Cas further and assuming $M_v = -8$ for LR Sco, the stellar radius wiil be around $390 R_\odot$ Sargent (1961) estimated that the shell is situated at $2R$ from the star for ρ Cas. With this estimate we can calculate mass loss rate of the, star as given by $M = 4\pi \mu m_H N_H R_i V$, where μ is the mean molecular weight, m_H is the mass of the hydrogen atom, N_H is the hydrogen column density, R_t is the inner radius of the shell (assumed as $2R_*$) and V is the expansion velocity. We obtain $M = 7 \times 10^{-6} M_\odot yr^{-1}$. On the other hand, if LR Sco is like a Ib supergiant with $M_v = -4.5$ then the corresponding radius would be $81 R_\odot$ and $M = 1 \times 10^{-6} M_\odot yr^{-1}$.

The Hα profile of LR Sco is rather complex. A comparison with another G0 Ia supergiant HD6474 (illustrated in Giridhar *et al.* 1991; see Fig. 1) shows that there is a P-Cygni kind of profile superposed on the normal absorption line. The deepest part of absorption seems to occur at $-60 kms^{-1}$ with respect to the neighbouring FeI lines. The emission is not very pronounced; the comparison star HD6474 may also have weak emission component. A comparison with the predicted Hα line profile (Kurucz 1979) brings out the P Cygni feature quite clearly (see Fig. 1). The absorption wings of Hα profile in LR Sco seem to extend more and are slightly deeper than those in HD6474 indicating a slightly hotter temperature for LR Sco.

6. The observed infrared excess

As mentioned earlier, LR Sco shows an infrared excess extending upto 100μm as illustrated in Fig. 4. The infrared flux shows a peak near 3.5 μm. The observed flux cannot be characterised by a single blackbody. One needs a combination of blackbodies at different temperatures (ranging from 1400 K to 100 K) to explain the observed flux distribution between 1 μm to 100 μm. The observed infrared excess between 1–100μm is 7 × 10^{-9} ergs $cm^{-2}s^{-1}$ and the infrared luminosity is $20d^2L_\odot$ where d is the distance in kpc. The observed (B–V) colour is quite consistent with the model atmosphere and does not indicate a significant reddening for the star. If we assume no reddening, then taking the bolometric correction from Kurucz (1979), the stellar luminosity comes out to be $120d^2L_\odot$ i.e. about 14 percent of stellar flux is radiated in the infrared.

Detailed modelling is necessary to be able to estimate the mass of the circumstellar dust. The photosphere is apparently oxygen–rich and hence the grains are probably silicates. An estimate of the dust mass can be made by assuming that the mean blackbody temperature of the dust is 830 K; this temperature corresponds to an infrared excess peak at 3.5μm. If we assume the dust shell to be optically thin, the dust mass following Barlow (1983) and Hildebrand (1983), is given by

$$M_d = \frac{4a\rho d^2 F_\nu}{3Q_\nu B_\nu(T_d)} \text{gm}$$

where ρ is the grain density (3.4gm cm^{-3} for silicates), F_ν is the observed flux at a given frequency, Q_ν is the absorption efficiency, a is the grain radius, and $B_\nu(T_d)$ is

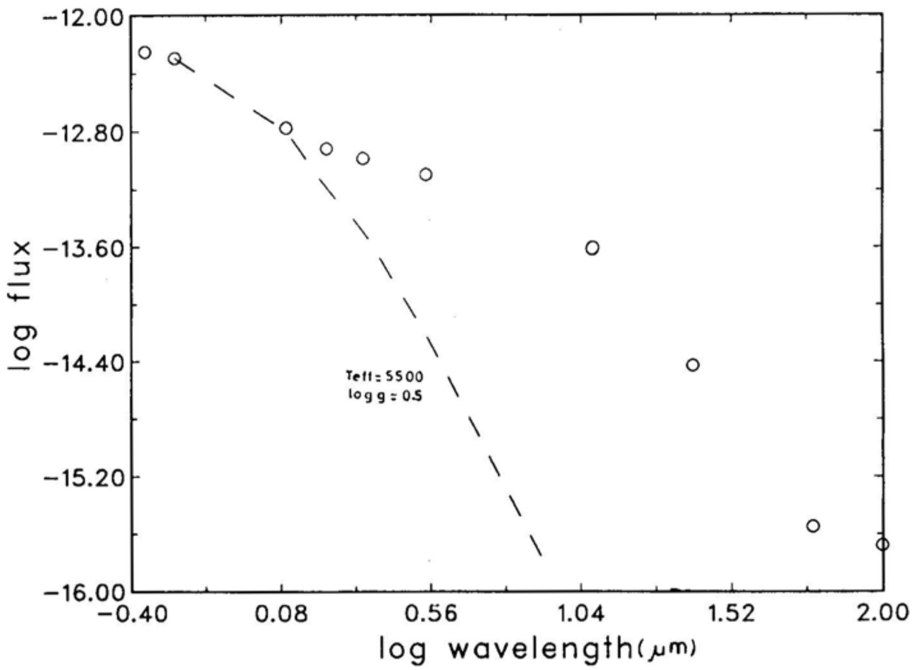

Figure 4. Observed infra red flux is plotted as a function of wavelength. The figure also shows theoretical fluxes for a stellar model atmosphere with T_{eff} =5500K, log g = 0.5 taken from Kurucz (1979).

the Planck Function for the dust temperature. We have taken the Q_v/a value from Draine (1981) for the astronomical silicates. The estimated dust mass is $4\times10^{24}d^2$gm where d is in kpc. If we assume a distance of around 2 kpc, the dust mass is about $7\times10^{-9}M_\odot$

Although the observed (BV) index is consistent with the intrinsic value for a star of this spectral type, it is conceivable that neutral extinction is present possibly caused by an optically thick dust envelope or due to the presence of larger grains in the envelope or both. The presence of neutral extinction is indicated from the following argument: the kinematical distance estimated from the radial velocity of the star is about 2 kpc. If LR Sco is considered as a Ia supergiant with $M_v = -8$, then the neutral extinction A_v turns out to be 6.2 mag. If M_v is assumed to be –4.5 (similar to Ib supergiant), then A_v is around 2.7 mag. Since $\tau_v/\tau_{3\cdot5\mu}$ is proportional to $Q_{absv}/Q_{abs3.5\mu}$, the $\tau_{3\cdot5}$ is ~0.6 (see Draine 1981), and thus, even at 3.5 μ the dust might still be optically thick.

At the IRAS band of 12, 25, 60 and 100μ the dust is optically thin and leads to a more reliable estimate of mass loss (particularly at 60μ). Several methods of estimating the mass loss based on the modelling of circumstellar dust envelopes using IRAS band fluxes have been proposed for oxygen rich AGB stars with silicate dust. Herman *et al.* (1986) and Jura (1987) have obtained relations for mass loss rate based on 60μ IRAS flux densities (see also van der Veen & Olofsson (1990)). If we use the expression of Herman *et al.* (1986)

$$M = 0.66\mu V_{15} d^2 L_4^{-0\cdot47} F_v(60\mu) K_v \quad M_\odot\, yr^{-1}$$

where μ is gas to dust mass ratio, V_{15} is the expansion velocity in terms of 15kms^{-1}, d is the distance in kpc, L_4 is the stellar luminosity in terms of $10^4\, L_\odot$, and $F_v(60)$ is the flux density in Jy. If we assume $\mu = 100$, V_{15} is around 3 (estimated from NaD line components) $d = 2$, and assuming that the $M_v = -4.5$, $L_4 = 0.5$, $F_v(60)$ observed is = 3.4 Jy and $k_v = 240$ cm2/gm leads to a mass loss rate $\sim4\times10^{-6}M_\odot\ yr^{-1}$. If we use a similar expression given by Jura (1987), we obtain mass loss rate of $2\times10^{-6}M_\odot yr^{-1}$.

Another expression for estimating the mass loss uses the ratio of flux densities at 12 and 25μm IRAS bands (van der Veen & Olofsson 1990). This expression is derived for circumstellar envelopes of oxygen rich AGB stars with continuous mass loss, assuming a radiation pressure driven wind with perfect coupling between the dust and the gas:

$$M = 1.3\times 10^{-5} V_{15}^{-1} L4 (F_v[25\mu m]/F_v[12\mu m])^{2.9}\, M_\odot\ yr^{-1}.$$

For LR Sco with the values mentioned. above the mass loss rate obtained is $1\times10^{-6}M_\odot yr^{-1}$

Thus all these three relations using 12,25 μm and 60 μm flux densities give consistent value for the mass loss rate (i.e. gas + dust $\cong 2\times10^{-6}M_\odot\ yr^{-1}$) for LR Sco from the dust which is in surprisingly good agreement with mass loss derived from the NaI D component lines (i.e. $1\times10^{-6}\, M_\odot$ when we assume $M_v = -4.5$).

7. Discussion

By luminosity and location, LR Sco appears to be a massive star. Luminous massive supergiants are known to be semi-regular variables with periods of the order of 100 days. Identification of LR Sco as a massive young star is not immediately supported by two observations: (i) the infrared excess, and (ii) the nonsolar values of certain elemental abundances ratios X/Fe.

Supergiants of spectral type earlier than about mid-G generally do not show an infrared excess (Stickland 1985; Jura & Kleinman 1990). We have argued that LR Sco is feeding a circumstellar shell that is presumably the site of the infrared emitting grains. Such mass loss and mass ejection is episodic; Jura & Kleinman argue that ρ Cas (spectral type F8 Ia) has recently developed an infrared excess as a result of mass shed during the star's deep minimum in 1946–1947.

The chemical composition of LR Sco is not exactly that of a massive supergiant. In Table 2, we show the expected abundance of a massive supergiant as derived from observations presented by Luck & Bond (1989) and adjusted to [Fe/H] = –0.3 by assuming [X/H] = 0. The most striking difference between LR Sco and the representative supergiant are seen for Ca and Sc which appear underabundant in LR Sco. Other large differences are seen for Si and Mn.

A competing identification of LR Sco would suppose it to be a post-AGB star. A pronounced infrared excess is a characteristic of post-AGB stars. Certainly LR Sco's composition resembles that of 89 Her, a well known high galactic latitude supergiant of (presumably) low mass (see Table 2). Note the similar Ca/Fe and Sc/Fe ratios of

Table 2. Elemental abundances for LR Sco and other supergiants.

	LR Sco			FG-Supergiants*			89 Her†		
Element	[A/H]	S.E.	N	[A/H]	S.E.	N	[A/H]	S.E.	N
CI	−0.05	0.17	5				−0.26	0.04	12
OI	−0.10		1				−0.27		1
NaI	−0.10	0.15	3	0.10	0.20		0.14	0.10	3
MgI	−0.35	0.20	3	−0.4			−0.02	0.43	9
AlI	−0.41		1	−0.1			−0.19		1
SiI	0.11	0.11	13	−0.2			0.01	0.32	16
SiII	0.29	0.29	2	−0.2					
SI	0.19	0.07	5				−0.26	0.03	2
CaI	−0.56	0.18	17	−0.2			−0.44	0.19	18
ScII	−0.94	0.82	4	−0.3			−0.89	0.18	2
TiI	−0.45	0.29	5	−0.1			0.19	0.92	58
TiII	−0.30	0.38	5	−0.2			−0.73	0.21	19
VI	−0.20	0.30	5	−0.1					
VII				−0.1			−0.36	0.06	2
CrI	−0.21	0.29	14	−0.2					
CrII	−0.20	0.23	7	−0.2			−0.03	0.12	12
MnI	−0.02	0.18	11	−0.5			−0.36	0.24	8
FeI	−0.27	0.20	181	−0.3			−0.38	0.28	245
FeII	−0.29	0.17	24	−0.3			−0.44	0.16	22
NiI	−0.23	0.23	37	−0.3			−0.29	0.23	32
ZnI	−0.55	0.05	2				−0.38	0.29	3
YII	−0.15		1	−0.1			−0.43	0.38	12
BaII	−0.19	0.16	3	−0.2			−0.79	0.26	2

*Mean abundances for 65 supergiants from Luck & Bond (1989)

† Abundances taken from Luck, Bond & Lambert (1990).

the two stars. A careful determination of the CNO abundances may provide the evidence to distinguish the competing identifications of LR Sco's evolutionary status.

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