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JHKL PHOTOMETRY OF LMC STARS

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SUMMARY

JHKL photometry of 13 members of the Large Magellanic Cloud is presented. Long-wavelength excesses are found to be present in the energy distributions of at least two of the late-type super-supergiants and in R108, one of the ' pec ' stars of Feast, Thackeray & Wesselink. Two ' pec ' stars in the programme have the infrared colours of K5 supergiants and may be of VV Cephei type.

1. INTRODUCTION

JHKL photometry of several members of the Large Magellanic Cloud was carried out during 1973 September and October. The photometer described by Glass (1973) was used at the Cassegrain focus of the Radcliffe 74-in. (1·88-m) telescope except for two measures of S Dor which were made with the 40-in. (1·0 m) at Sutherland. The measurements were usually standardized by observation of HR 2015 ($J = 3{\cdot}85$, $H = 3{\cdot}75$, $K = 3{\cdot}71$, $L = 3{\cdot}69$), but other stars from Glass (1974) were used at first.

Stars were selected from the list of Feast, Thackeray & Wesselink (1960, FTW) and are referred to by their Radcliffe numbers. They include the five red super-supergiants, some objects with [Fe II] in their spectra, HV 883 (Cepheid), W Men (R CrB type) and S Dor. The results of the photometry are given in Table I. The errors quoted in the table are composed of statistical parts and estimated systematic parts; for stars with well-determined magnitudes the estimated errors are mostly due to the latter. Table II gives the average values of the photometry with colours and spectral types.

Table III gives the de-reddened *JHKL* data. The E_{B-V} values for some stars are taken from FTW and for others an A_V of 0·3 is assumed.

2. THE RED SUPER-SUPERGIANTS

Known stars with bolometric luminosities such as these have are rare in the galaxy and the five examples in the LMC are therefore of great interest. They exhibit, in some cases, variations and are thought to be unstable. Two of those in the LMC, R59 (Humphreys, Strecker & Ney 1971) and R150 (Ney 1972), are already known to possess infrared excesses.

R59. This star was considered to be G5Ia by FTW; while Ardeberg *et al.* (1972, AMBP) comment that it appeared to them nearer G8. However, Morgan & Keenan (1973) make R59 their definition of G7O. FTW comment that V and B show brightenings of $0^m{\cdot}22$ and $0^m{\cdot}16$ respectively over a period of 4 yr. Andrews (private communication) has been monitoring this star since 1967 and has observed variations in V of amplitude between $0^m{\cdot}2$ and $0^m{\cdot}4$. In the infrared this star is the

TABLE I

JHKL photometry of stars in the Large Magellanic Cloud

Star	*J*	*H*	*K*	*L*	JD244000+
R59	8·07±0·07	7·61±0·06	7·44±0·05	7·12±0·14	1927
	8·05±0·07	7·60±0·06	7·43±0·06	7·28±0·11	1959
R67	8·80±0·08	8·02±0·06	7·73±0·06	7·70±0·21	1927
	8·77±0·08	8·00±0·06	7·74±0·05	7·65±0·15	1960
R69	10·55±0·09	10·06±0·10	9·66±0·09	—	1959
R71	9·20±0·12	9·08±0·08	9·01±0·12	—	1927
R76	8·63±0·07	8·42±0·07	8·38±0·06	8·95±0·65	1928
R88 (S Dor)	—	—	8·29±0·13	—	1648
	8·58±0·07	8·34±0·07	8·22±0·10	—	1707
	8·62±0·07	8·39±0·07	8·25±0·05	7·94±0·10	1740
	8·53±0·07	8·40±0·08	8·12±0·08	7·88±0·13	1959
R94	7·53±0·07	6·89±0·06	6·69±0·05	6·51±0·11	1929
R102	—	—	11·81±0·35	—	1929
R108	9·12±0·09	8·39±0·06	8·12±0·05	7·50±0·20	1927
	9·23±0·07	8·39±0·07	8·18±0·06	7·54±0·17	1960
R117	8·18±0·08	7·77±0·07	7·55±0·08	8·14±0·41	1742
	8·14±0·07	7·73±0·06	7·60±0·07	7·35±0·08	1961
R143	9·60±0·09	9·35±0·13	9·10±0·09	8·83±0·49	1960
R150	8·46±0·07	8·18±0·07	7·91±0·07	7·11±0·15	1927
	8·44±0·07	8·13±0·07	7·85±0·06	7·18±0·10	1959
R92	8·57±0·07	8·42±0·07	8·32±0·07	7·81±0·14	1929
	8·50±0·07	8·39±0·07	8·32±0·08	7·99±0·11	1960

TABLE II

JHKL photometry of stars in the Large Magellanic Cloud (averaged)

Star	*J*	*H*	*K*	*L*	Spectrum
R59	8·06	7·61	7·44	7·20	G5Ia
R67	8·79	8·01	7·74	7·68	Pec
R69 (=HV883)	10·55±0·09	10·06±0·10	9·66±0·09	—	G2I: Cepheid
R71	9·20±0·12	9·08±0·08	9·01±0·12	—	B2·5Iep
R76	8·63	8·42	8·38	—	A3Ia-O(e)
R88 (=S Dor)	8·53	8·40	8·12	7·88	Aeq
R92	8·54	8·41	8·32	7·90	F8Ia
R94	7·53	6·89	6·69	6·51±0·11	B comp
R102 (=W Men)	—	—	11·8±0·4	—	F8: Ip
R108	9·18	8·39	8·15	7·52±0·14	Pec
R117	8·18	7·75	7·63	7·46	GoIa
R143	9·60±0·09	9·35±0·13	9·10	8·8±0·5	F7Ia
R150	8·45	8·16	7·88	7·15	GoIa

Notes

1. Errors in $JHK \leqslant 0{\cdot}07$; in $L \leqslant 0{\cdot}10$ unless otherwise mentioned.
2. Spectra from Feast *et al.* (1960).

TABLE III

Unreddened JHKL colours of stars in the LMC

(a) Stars unreddened by FTW data

Star	K	$J-K$	$H-K$	$K-L$
R59	7·38	0·52	0·14	0·21
R92	8·30	0·19	0·08	0·41
R117	7·59	0·48	0·10	0·15
R150	7·83	0·48	0·26	0·71

(b) Stars unreddened by $A_V = 0{\cdot}3$

Star	K	$J-K$	$H-K$	$K-L$
R67	7·71	1·00	0·26	0·05
R69	9·63	0·84	0·39	—
R71	8·98	0·14	0·06	—
R76	8·35	0·20	0·03	—
R88	8·09	0·36	0·27	0·23
R94	6·66	0·79	0·19	0·17
R108	8·12	0·98	0·23	0·62
R143	9·07	0·45	0·24	0·3

Note

De-reddening has been executed according to the relations

$$A_V : A_J : A_H : A_K : A_L = 1 : 0{\cdot}25 : 0{\cdot}13 : 0{\cdot}09 : 0{\cdot}05$$

TABLE IV

Comparison of R59 with HR5171A

	R59	HR5171A
Spectral type	(G5–G8)Ia	G8Ia$^+$
Assumed value of A_V	0·63	3·18
De-reddened V	9·62	3·47
$B-V$	1·32	1·24
$V-K$	2·24	2·25
$J-K$	0·52	0·53
$H-K$	0·14	0·25
$K-L$	0·21	0·40

brightest of those measured (except for R94 whose membership of the LMC is doubtful) at K. It does not appear to have more than a mild excess in $K-L$. Measurements by Humphreys *et al.* (1971) disagree with this conclusion. They found 2·3 μ and 3·6 μ magnitudes of 7·56 and 6·72 respectively, giving a $(K-L)_{\text{HSN}}$ of 0·84 as compared to 0·24 (this paper). It seems unlikely that the difference between these two results can be explained by the small changes in effective wavelengths of the bands. Intercomparison of their data with mine for α CMa, α Car and HR5171A show that there are important systematic differences in the photometry.

This star has been compared with the high-luminosity galactic supergiant HR5171A (G8Ia$^+$) by Humphreys *et al.* (1971). Harvey (1972) has shown that HR5171A has both short-term variations and a slow continual decline in light output. The following table V compares the de-reddened colours of the two stars using Harvey's (early 1972) BV measures of HR5171A, Humphreys *et al.*'s value of A_V ($3^{\text{m}}{\cdot}18$, derived from colours of the Bo companion HR5171B), FTWs BV photometry and estimated A_V of R59 and infrared data from this work for both stars. (HR5171A was measured on JD 2441370). It is seen that the colours are fairly similar (within the limits of the de-reddening procedure) except for a slightly

stronger excess in K–L for HR5171A. HR5171A has a long wavelength excess ($N = -3{\cdot}1$, $Q = -4{\cdot}2$, JD 2441499). R59 should be easy to measure at 10 μ if it possesses a similar infrared energy distribution.

R92. This F8Ia star shows a definite excess in K–L even when de-reddened. The visual photometry shows no significant secular changes.

R117 GoIa. Shows no pronounced excess. Within nebulosity Hen N57. AMBP suggest a spectral type later than FTW do, but this difference may arise from the lack of suitable standards for such luminous stars.

R143 (F5–F7)Ia. In 30 Dor region. No photometry available in *UBVRI*. Its apparent J–K colour of 0·50 implies $E_{J-K} = 0{\cdot}20$ or $A_V = 1{\cdot}3$. Possibly reddened by nebulosity.

R150 GoIa. FTWs' visual photometry gives slightly fainter and redder values than AMBP and Mendoza (1970). This may confirm the variability of $0^m{\cdot}14$ in B noted by FTW. However, according to Thackeray (private communication) R150 lies in a bright knot of a curved wisp which is part of NGC 2086, and this may have contaminated the photometry. This object has the most pronounced K–L excess of all the objects measured in the LMC and also shows some excess at H–K. Ney (1972) has remarked that R150 has ' a 10 micron excess almost as extreme as HR5171A '.

3. HIGH-LUMINOSITY BLUE STARS

Interest in these stars has arisen from studies which predict short-period variations to occur in very massive evolved early-type stars. Two stars in this list, R71 and R88 (S Dor) show short-term variations which may be related to this phenomenon. When bright, these objects have larger B–V than when faint and have pronounced P Cyg character. When faint, they show [Fe II] lines (Thackeray 1974).

R71 is classes B2·5Iep. S Dor is A(2–5)eq. S Dor has been followed spectroscopically for a number of years by Thackeray and photometrically by Alexander (see Alexander & Thackeray 1971). It shows small fluctuations on a time scale of days and longer term changes on scales of up to 10 yr or more. Appenzeller (1972) has observed significant fluctuations in the brightness of these stars within one night of observing.

Infrared photometry of S Dor has been obtained over a period of about 1 yr during which time it has brightened to almost its maximum recorded value. If the rise is taken to have been linear in magnitude between JD (244)1285 and 2014 during which time V changed by 0·61 then one might have expected a change of 0·26 in V during the period covered by the infrared observations. A marginal brightening appears to have taken place in the infrared.

The infrared and visual colours of S Dor are peculiar and do not permit meaningful de-reddening by the normal procedure to Johnson's colours for an early-type supergiant star. The visible-region photometry (by Warren) of R71 which is nearest in time to the infrared may be taken with the infrared value of K to give $A_V = 1{\cdot}3$ (or $E_{J-K} = 0{\cdot}21$) by comparing with Johnson's intrinsic colours for supergiants. However, B–V is then predicted to be 0·43 whereas its actual value is 0·33. R71 is thus more nearly ' normal ' than S Dor. The photometric history of R71 is less well known than that of S Dor. However, photometry by Mendoza (1970), Appenzeller (1972) and Warren (private communication) show that it has

brightened up considerably during the last few years, but not as far as $B = 9{\cdot}2$ the value given for it in the HDE.

4. PECULIAR AND COMPOSITE STARS

Certain stars in the list of FTW are called ' pec ' when they have an emission spectrum to which no normal type can be assigned. Two of these were included (R67 and R108).

R67. This spectrum was said by FTW to resemble η Car, on account of its large number of Fe II and [Fe II] lines. Photometry of η Car (JD 2441370) gives $J = 3{\cdot}47$, $H = 2{\cdot}66$, $K = 1{\cdot}16$ and $L = -1{\cdot}63$. Comparison with the values for R67 clearly shows that the long wavelength behaviour of these objects is completely different, even though R67 has the highest value of J–K recorded in this study. The unreddened $VJHKL$ measurements of R67 are consistent with Johnson's (1966) intrinsic colours for about a K5 supergiant. The B–V and U–B colours are those of an earlier type but are almost certainly contaminated by the strong emission lines. The data appear to suggest a composite object of VV Cephei type (see, for example, Swings & Allen 1972).

R94 B composite. Part of Michigan double 946, sep 0″·65, mags 10·3, 12. According to FTW the red star is the brighter of the two but only the blue component is known to be a cloud member. The infrared photometry is satisfied by a spectral type around K4. This star is the brightest recorded at all four of $JHKL$ and it is therefore of great interest to know if it really belongs to the LMC.

R108 (peculiar). This is on the edge of the cluster NGC 2004 and shows [Fe II] emission. Its J–K and H–K colours make it resemble R67, but at K–L it shows a pronounced infrared excess. These data are also consistent with VV Cephei type.

5. MISCELLANEOUS

R69. Cepheid period 134^{d}. This star is redder in J–K than any of those mentioned in Wizniewski & Johnson (1968). However, it has a much longer period also. The J–K and H–K colours do not agree well with the intrinsic colour of any normal star but this may not be significant when the probable errors of the photometry are taken into account.

R76 A3Ia-O. The brightest known member of either Magellanic Cloud. The spectral typing is somewhat doubtful within ±1 subclass. The colours when unreddened by $A_V = 0^{m}{\cdot}3$ appear to match A5 or F0 better than the given type. No significant changes in magnitude or colour have occurred since the work of FTW.

R102. One of several known RCrB type variables in the LMC, having a range $13^{m}{\cdot}8$–16^{m} pg. According to photoelectric measures by Andrews (private communication), when bright, $V = \sim 13{\cdot}83$ and B–$V \sim 0{\cdot}45$. Its K magnitude of $\sim 11{\cdot}8$ is at the limit of detectability with the given equipment. The V–K colours of galactic R CrB type stars vary from about 1·3 to 4 (combining data of Feast & Glass (1973) with private communications from Andrews), and the V–K for W Men at 2·0 falls within this range. Feast (1972) compares W Men with RY Sgr and R CrB itself. RY Sgr has V–$K \sim 1{\cdot}3$ when bright.

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REFERENCES

Alexander, J. B. & Thackeray, A. D., 1971. *Observatory*, **91**, 25.
Appenzeller, I., 1972. *Publ. astr. Soc. Japan*, **24**, 483.
Ardeberg, A., Maurice, E., Brunet, J. P. & Prévot, L., 1972. *Astr. Astrophys. Suppl. Ser.*, **6**, 249.
Feast, M. W., 1972. *Mon. Not. R. astr. Soc.*, **158**, 11P.
Feast, M. W. & Glass, I. S., 1973. *Mon. Not. R. astr. Soc.*, **161**, 293.
Feast, M. W., Thackeray, A. D. & Wesselink, A. J., 1960. *Mon. Not. R. astr. Soc.*, **121**, 337.
Glass, I. S., 1973. *Mon. Not. R. astr. Soc.*, **164**, 155.
Glass, I. S., 1974. *Mon. Not. R. astr. Soc. Sth Afr.*, **33**, 53.
Harvey, G. M., 1972. *Mon. Not. astr. Soc. Sth Afr.*, **31**, 81.
Humphreys, R. M., Strecker, D. W. & Ney, E. P., 1971. *Astrophys. J. Lett.*, **167**, L35.
Johnson, H. L., 1966. *A. Rev. Astr. Astrophys.*, **4**, 193.
Mendoza, E. E., 1970. *Bol. Obs. Ton. Tac.*, **5**, 269.
Morgan, W. W. & Keenan, P. C., 1973. *A. Rev. Astr. Astrophys.*, **11**, 29.
Ney, E. P., 1972. *Publ. astr. Soc., Pacific*, **84**, 613.
Swings, J. P. & Allen, D. A., 1972. *Publ. astr. Soc. Pacific*, **84**, 523.
Thackeray, A. D., 1974. *Mon. Not. R. astr. Soc.*, **168**, in press.
Wizniewski, W. Z. & Johnson, H. L., 1968. *Comm. Lun. Plan. Lab.*, **7**, 57.