

THE SPECTRAL TYPE AND INFRARED BRIGHTNESS OF R DORADUS

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The southern semiregular variable R Doradus has been classified M8.0 on the basis of narrow-band photoelectric measurements in the near infrared. It is one of the brightest stars in the infrared and the brightest star visually to have such a late spectral type.

Key words: spectral type — infrared photometry — late-type star

As part of a program of narrow-band infrared photometry of bright stars, the semiregular variable R Doradus (= HD 29712 = BS 1492; $\alpha = 4^h35^m36^s$, $\delta = -62^\circ16'$ (1900)) has been observed from the Cerro Tololo Inter-American Observatory and has been found to have a remarkably late spectral type, in view of its bright visual magnitude and small light amplitude. Gaposchkin (1946) has published a photographic light curve for this star and found a mean period of about 338 days. The space velocity vectors of R Dor (Eggen 1962) suggest that it may belong to the γ Leonis moving group of high-velocity stars. Wide-band photometry on the *BVRI* system has been reported by Mendoza (1967*a*, 1969), and measurements at longer wavelengths to 10 microns are given in the following paper by Neugebauer et al. (1971). R Dor is one of the brightest objects in the infrared sky.

The narrow-band observations were made with a set of eight interference filters ranging in wavelength from 7120 Å to 10.970 Å and averaging ~ 55 Å in width. The filters serve to measure band strengths of the TiO, VO, and CN molecules, as well as the continuous energy distribution. This photometric system has recently been described in greater detail elsewhere (Wing 1971).

The results for R Dor are summarized in Table I. $I(104)$ is the magnitude at 1.04μ (= 10,400 Å) on the system defined by Wing (1967*a*), on which Vega provides the zero point; the

spectral types in the last column are based on measurements of TiO at 7120 Å and VO at 10.540 Å. R Dor was first observed at the CTIO 36-inch telescope, where it was uncomfortably bright for the equipment and a large correction for photocell fatigue had to be applied. A confirmatory observation was therefore made eleven days later at a 16-inch telescope, where R Dor was compared directly to several of the brightest stars at 1.04μ . Finally, another 16-inch observation was made after an interval of six months. The results of the three observations are very similar: there was no detectable change in spectral type, and the range of 0^m.05 in brightness is hardly greater than the uncertainty of measuring a star which is considerably brighter than any nearby standard star.

The classifications for R Dor are based upon comparisons with eight-color observations of several small-range variables of types M7 and M8 (HD 207076, BK Virginis, RT Virginis, RX Bootis, and W Hydrae) which had previously been classified repeatedly with 27-color scanner measurements (Wing 1967*b*). Of these stars, RX Boo (M8.0) is the most valuable as a standard by virtue of the remarkably small range in magnitude and spectral type that it has shown in recent years. (The notation M8.0, rather than simply M8, is used when the type is definitely later than M7.5 and definitely earlier than M8.2.) The photometric indices of spectral type have been calibrated by means of the MK standard stars classified by Keenan (1963), who first suggested using RX Boo to define type M8.

The photometric type for R Dor, M8.0, agrees well with an independent result by Keenan (unpublished), who obtained M8 on the basis of

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TABLE I
RESULTS FOR R DORADUS

Date	JD	$I(104)$	Type
1969 Dec. 26	2440581.753	-1^m87	M8.0
1970 Jan. 6	2440592.615	-1.83	M8.0
1970 Jul. 12	2440779.954	-1^m88	M8.0

TABLE II
THE BRIGHTEST STARS AT 1.04μ

Rank	Star	Sp. Type	$I(104)$	n
1	α Ori	M2 <i>Iab</i>	-2^m72 to -2^m64	8
2	α Sco	M1 <i>Ib</i>	-2.30 to -2.19	8
3	R Dor	M8.0	-1.86	3
4	α Boo	K2 IIIp	-1.84	5
5	α Her	M5 II	-1.75 to -1.68	9
6	γ Cru	M3 II	-1.61	2
7	β Gru	M3 II	-1.58	3
8	α Tau	K5 III	-1.47	7
9	W Hya	M8.2-M8.8	-1.46 to -0.32	6
10	α CMa	A1 V	-1.39	4
11	$\circ$ Cet	M5.5-M9.2	-1^m37 to -0^m15	36

blue spectrograms taken at Cerro Tololo on 16 January 1970. Spectral types in the literature are consistently somewhat earlier—various catalogues give M7, gM7, or M7 III—but these may all be based upon the same early Harvard result (Townley, Cannon, and Campbell 1928). No emission lines were visible on the Harvard plates, but Keenan notes weak hydrogen emission, as in RX Boo.

In Table II the eleven brightest stars at 1.04μ are listed in order of decreasing brightness. Variable stars are ranked according to their brightest observed $I(104)$ magnitude, and their maximum and minimum values are both given. The red supergiants Betelgeuse (α Orionis) and Antares (α Scorpii) occupy the first and second positions, while Sirius (α Canis Majoris), the brightest star visually, is in tenth place at this wavelength, just ahead of the variable Mira ($\circ$ Ceti) at its infrared maximum. The mean $I(104)$ magnitude of R Dor, -1.86 , used here for lack of definite evidence of variability at 1.04μ , places it third on the list, just above Arcturus (α Boo); at 1.10μ , however, R Dor exceeds α Boo by 0^m30 . The coolest star on this list, and the only one not contained in the *Catalogue of Bright Stars* (BS; Hoffleit 1964), is W Hya, which

is sometimes called a small-amplitude Mira variable and sometimes a large-amplitude semi-regular variable. Keenan (1966) considers it a Mira variable on the basis of its spectral changes, and its relatively large infrared amplitude supports this conclusion.

The last column of Table II gives the number of nights on which each star has been observed since the first $I(104)$ magnitudes were measured in 1965. The data for $\circ$ Cet are from Lockwood and Wing (1971); the other magnitudes are from Wing (1967*b*) and from more recent unpublished material. The spectral types have been taken from the *Catalogue of Bright Stars* except for the three stars of latest type, for which my photometric types are given. Table II is believed to be complete: future observations may increase the ranges of the variables but should not add new stars to the list or upset the order given here.

As their spectral types indicate, R Dor, W Hya, and $\circ$ Cet are redder than the other stars in Table II and accordingly will rank higher on lists compiled at longer wavelengths. In fact I have predicted, on the basis of the near-infrared narrow-band data, that R Dor should be the brightest star in the sky at wavelengths near

3μ (Wing 1971). When it was observed in November 1970 by Neugebauer et al. (1971) it was about 0^m25 fainter than α Ori in K (2.2μ) and about 0^m1 fainter in L (3.5μ). However, Neugebauer et al. also report an earlier and brighter (by 0^m34) measurement of the K magnitude. Apparently R Dor and α Ori alternate as the brightest in both K and L . In the M (4.8μ) filter, however, R Dor is surpassed by the much cooler carbon star IRC +10216 (Becklin et al. 1969).

An attempt to list all stars equal to or brighter than $K = -3^m00$ has resulted in the nine stars of Table III. For the small-range variables α Ori,

TABLE III
THE BRIGHTEST STARS AT 2.2μ

Rank	Star	K
1	α Ori	-4^m12
2	R Dor	-4.03^*
3	α Sco	-3.85
4	W Hya (max)	-3.6 (est.)
5	α Her	-3.51
6	β Gru	-3.3 (est.)
7	γ Cru	-3.2 (est.)†
8	$\circ$ Cet (max)	-3.07
9	α Boo	-3^m00

*R Dor: evidently sometimes brighter than α Ori, but only two observations exist (see Neugebauer et al. 1971).

† γ Cru: the value $K = -3.0 \pm 0.5$, consistent with the above prediction, has been measured with survey equipment by Price (1968).

R Dor, α Sco, and α Herculis, and for the non-variable α Boo, the K magnitudes are the means of the individual published observations (Johnson et al. 1966; Neugebauer et al. 1971), except that I have excluded one discordant observation of α Ori and one of α Sco. For the large-amplitude variables the values at maximum are given: the value for $\circ$ Cet is the brightest of 20 measurements reported by Mendoza (1967b), while the value for W Hya, which has not been observed at maximum, was estimated by assuming that its $I(104) - K$ color at maximum is equal to that of R Dor. Finally, the K magnitudes of the southern stars β Gruis and γ Crucis have been predicted from the relation

$$K = 1.219I(104) - 0.219V - 0.91$$

which has been derived from the observed magnitudes of 50 nonvariable and small-amplitude giants and supergiants of types K5 to M5. This formula expresses the linear relation between the $V - K$ and $V - I(104)$ colors for such stars, the scatter in which is only $\pm 0^m05$. It also shows that the predicted K magnitudes depend much more heavily on $I(104)$ than on V , so that useful predictions can be made even when the only available visual magnitudes are catalogued values of unknown reliability. The visual magnitudes used for β Gru (2.11) and γ Cru (1.63) are from photoelectric observations made at the Cape Royal Observatory, as given in Table 9 of Johnson et al. (1966). One additional star, the cool Mira variable R Leo, may reach $K = -3^m0$ at infrared maximum, although the brightest observation reported for it to date is $K = -2^m63$ (Wiśniewski et al. 1967); otherwise Table III is believed to be complete.

There is some confusion as to the visual magnitude and range of R Dor. The third edition of the *General Catalogue of Variable Stars* (GCVS; Kukarkin et al. 1969) gives the range as 5.9 to 6.9 visually and refers to Gaposchkin (1946), who, however, reported a photographic range of 7.1 to 8.1 and remarked that the visual range had been found by the AAVSO to be 4.5 to 5.8, a range which does not even overlap with the one in the GCVS. Mendoza (1969) has given $V = 5^m50$ as the mean of three photoelectric measurements, tending to confirm the brighter range of the AAVSO. Gaposchkin's (1946) photographic light curve shows that although the full observed range is 1^m0 , the individual cycles have smaller ranges, typically 0^m5 . The visual light curve is probably very similar to the photographic, as in the case of other M-type semiregular variables (Smak 1964). In short, it seems likely that the visual magnitude of R Dor is usually within $\pm 0^m3$ of $V = 5^m5$, with only occasional excursions to brighter or fainter values.

This visual magnitude is substantially brighter than that of any other star of such a late spectral type. In fact, I know of no other true M8 star brighter than $V = 6^m5$, the limit of the *Catalogue of Bright Stars*. Several Mira variables are later than M8 at minimum light and brighter than $V = 6^m5$ at maximum light, but the two condi-

tions are seldom if ever met simultaneously; α Cet and R Hya reach M8.0 at approximately $V = 6^m5$, but the other Mira variables are fainter. BS 8421, listed in the BS as a gM8 star with $V = 6^m12$, is in fact an M4 star. W Hya, whose type is always fully M8, has been observed to range from $V = 6^m62$ to 9^m03 (Wing 1967*b*). RX Boo, whose spectrum closely matches that of R Dor, is fully two magnitudes fainter than R Dor with an observed range from $V = 7^m55$ to 7^m99 in 13 observations. Thus R Dor presents unique opportunities for high-dispersion studies of a very late-type star.

It is very likely that R Dor is the closest giant star later than M6, and it is unfortunate that its trigonometric parallax has not been measured since the luminosities of late M stars are still poorly known. W Hya has been similarly neglected. Finally, it may be remarked that R Dor should have one of the largest angular diameters of any stellar photosphere, comparable to, and perhaps exceeding, those of α Ori.

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