THE ASTROPHYSICAL JOURNAL, 184:873–880, 1973 September 15

THE PERIOD AND SPECTRAL RANGE OF IK TAURI

ROBERT F. WING
Perkins Observatory, The Ohio State and Ohio Wesleyan Universities
AND
G. W. LOCKWOOD
Kitt Peak National Observatory,* Tucson, Arizona
Received 1973 February 23

ABSTRACT

The mean period of IK Tauri, a very cool Mira variable, has been found to be 470 ± 5 days on the basis of 8 years of photometric observations in the 1-μ region. Its mean amplitude of 2.7 mag in $I(104)$ is the largest known among Miras. The spectral type consistently reaches M10 at minimum light and has not been observed earlier than M8.1 at maximum.

It is pointed out that, in the case of a Mira variable observed in only two consecutive cycles, a better estimate of the mean period can be obtained from the interval between successive maxima than from the interval between recurrences of the same magnitude.

Subject headings: infrared sources — long-period variables — spectral classification — stars, individual

I. INTRODUCTION

The infrared star in Taurus discovered by Neugebauer, Martz, and Leighton (1965), frequently referred to as "NML Tau," is listed as IK Tau in the *General Catalogue of Variable Stars* (*GCVS*; Kukarkin *et al.* 1969) and as IRC+10050 in the *Two-Micron Sky Survey* (Neugebauer and Leighton 1969). Observations made in 1965 (Wing, Spinrad, and Kuhi 1966, 1967) showed it to be an M-type Mira variable with a long period and an extraordinarily red color. Multicolor wideband photometry has been published by Mendoza (1965, 1967) and by Hyland *et al.* (1972), who also studied its spectrum in the 2-μ region.

The observations of Wing *et al.* (1967) spanned an interval of 532 days, but they included only one maximum; two possibilities were suggested for the period: $P > 532^d$, and $P \simeq 490^d$. The compilers of the *GCVS* appropriately listed the period as 500 ± days. The light variations of IK Tau were independently noted by Cannon (1966) who, after observing the declining branches of two successive cycles photovisually, reported a much shorter period, 390^d (Cannon 1967).

Sufficient data are now available for a redetermination of the period of IK Tau. Since the first photometry in the 1-μ region was obtained in 1964, the star has passed through maximum six times, and 41 measurements of the $I(104)$ magnitude have been made. The available visual observations are also discussed here, as are the star's remarkable spectral variations. Finally, IK Tau is compared to other Mira variables for which comparable data have been obtained.

II. PHOTOMETRIC RESULTS

The observations of $I(104)$, measured in a clear spectral region near 1.04 μ, and the concurrent photometric determinations of spectral type were made with a variety

* Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

TABLE 1

I(104) OBSERVATIONS OF IK TAURI

JD	Cycle	Phase	I(104)	Spectrum	Observer*
2400000 +					
38678.0	−2	0.38	4.41	M9.2	K
38786.8	−2	.61	4.58	M10.0	K
38990.0	−1	.04	2.09	M8.1	W
39005.0	−1	.07	2.15	M8.2	W
39018.0	−1	.10	2.16	M8.2	W
39033.0	−1	.13	2.20	M8.3	W
39042.0	−1	.15	2.34	M8.4	W
39051.0	−1	.17	2.31	M8.5	W
39059.0	−1	.19	2.39	M8.5	W
39061.9	−1	.20	2.43	M8.5	W
39070.9	−1	.21	2.47	M8.5	W
39097.9	−1	.27	2.62	M8.7	W
39109.9	−1	.30	2.70	M8.9	W
39165.7	−1	.42	3.28	M9.6	W
39201.7	−1	.49	3.78	M10.0	W
39329.0	−1	.76	4.21	--	W
39361.0	−1	.83	3.72	M10.0	W
39372.0	−1	.86	3.27	M10.6	W
39423.0	−1	.96	2.05	M9.7	W
39425.9	−1	.97	2.03	M9.6	W
39552.7	0	.24	2.44	M9.8	W
39726.0	0	.61	4.94	M11.2	W
40104.0	+1	.41	3.04	M10.5	W
40481.9	+2	.22	2.13	M9.4	L
40528.8	+2	.32	2.51	M9.7	LM
40531.9	+2	.32	2.46	M9.7	WBW
40585.6	+2	.44	3.27	M10.3	WBW
40600.7	+2	.47	3.21	M10.3	LM
40853.9	+3	.01	1.48	M9.0	LM
40892.9	+3	.09	1.46	M8.8	WBW
40902.0	+3	.11	1.48	M8.9	WBW
40955.7	+3	.23	1.90	M8.9	L
41027.6	+3	.38	2.58	M9.6	L
41222.0	+3	.79	2.99	M10.3	L
41247.9	+3	.84	2.41	M9.8	L
41278.8	+3	.91	1.84	M9.5	L
41283.9	+3	.92	1.78	M9.3	WBW
41361.7	+4	.09	1.69	M9.3	WBW
41367.7	+4	.10	1.82	M9.4	L
41380.7	+4	.13	1.85	M9.4	WBW
41590.8	+4	0.58	3.70	M10.5	L

*K - Kuhi, scanner (Wing et al. 1967).
L - Lockwood, unpublished five-color filter photometry.
LM - Lockwood and McMillan (1971), five-color filter photometry.
W - Wing (1967 and unpublished), scanner. Preliminary reductions of most of these observations were reported in Wing et al. (1967).
WBW - Wing, Baumert, and White, unpublished eight-color filter photometry.

of instruments on several different telescopes and are compiled in table 1. The observations are coded according to observer and instrumentation, and the magnitudes are on a scale defined by $I(104) = 0.00$ for α Lyr. Some of the $I(104)$ magnitudes were previously reported (Wing 1967; Lockwood and McMillan 1971) but are included for completeness. The observations prior to JD 2440400 were made by Wing using the Lick Observatory prime-focus scanner with a 30-Å passband at 27 wavelengths, except for the first two observations which were taken from continuous scans by L. V. Kuhi. The data after JD 2440400 were obtained from filter photometry by Wing and his colleagues and by Lockwood using, respectively, eight and five narrow-band interference filters in the wavelength region 0.7–1.1 μ to measure some of the same features as had been studied previously with the scanner. The eight-color observations were made at Lowell Observatory, Perkins Observatory, Cerro Tololo Inter-American Observatory, and Kitt Peak National Observatory (KPNO), and the five-color observations were made at KPNO. Careful intercomparison of the three photometric

TABLE 2

V OBSERVATIONS OF IK TAURI

JD	Cycle	Phase	V	Observer*
2400000 +				
38993.0	-1	0.05	11.94	WSK
39004.9	-1	.07	11.97	M
39008.0	-1	.08	12.37	WSK
39014.0	-1	.09	12.56	WSK
39019.0	-1	.10	12.60	WSK
39024.0	-1	.11	12.74	WSK
39032.8	-1	.13	12.75	M
39033.9	-1	.14	12.75	M
39034.8	-1	.14	12.77	M
39035.8	-1	.14	12.81	M
39037.9	-1	.14	12.86	M
39040.0	-1	.15	13.17	WSK
39053.9	-1	.18	13.34	WSK
39059.9	-1	.19	13.40	WSK
39062.9	-1	.20	13.43	WSK
39095.9	-1	.27	13.90	WSK
39421.9	-1	.96	13.42	W
39445.8	0	.01	13.38	M
39447.7	0	.02	13.45	M
39448.8	0	.02	13.34	M
39448.9	0	.02	13.63	W
39508.7	0	.15	13.91	W
40853.9	+3	.01	11.93	L
40955.7	+3	.23	12.52	L
41027.6	+3	.38	13.58	L
41222.0	+3	.79	14.46	L
41247.9	+3	.85	13.47	L
41278.8	+3	.91	12.36	L
41367.7	+4	.10	12.25	L
41382.6	+4	.13	13.06	W

*L - Lockwood, unpublished.
M - Mendoza (1967).
W - Wing, unpublished.
WSK - Wing, Spinrad, and Kuhi (1967).

systems (Lockwood and Wing 1971) assures that the individual $I(104)$ scales agree within ± 0.03 mag for all spectral types.

All photoelectric measurements of the visual magnitude of IK Tau known to us are collected in table 2. The values are nominally on the standard Johnson V system, but appreciable errors in transformation may occur for such a red star. In the few cases of concurrent observations by different observers, however, the agreement is satisfactory.

Using the $I(104)$ observations, we find the best-fitting period to be 470^d. Since the fit is noticeably less good for 465^d and 475^d, we give the period as $470^d \pm 5^d$. This result is consistent with, but more accurate than, the preliminary value $P = 465^d \pm 10^d$ which we announced recently (Lockwood and Wing 1972). The accuracy of the new determination is limited by the irregularities in the light variations; a significant improvement in the mean period will not be possible until many more cycles have elapsed.

The visual magnitudes are important for establishing the epoch of zero phase, which by definition refers to visual maximum. We find no reason to alter the epoch JD 2439440 given in the *GCVS*, which evidently is based upon Cannon's (1967) observations of 1966.

The phases and cycle numbers given in tables 1 and 2 have thus been obtained from the following elements:

$$JD = 2439440 + 470E,$$

and the resulting $I(104)$ and V light curves are shown in figure 1. The V curve includes the measurements made photographically by Cannon (1967), from which we have subtracted a constant, 0.5 mag, to bring them into agreement with several concurrent photoelectric values. This large systematic effect must be a result of the very red and irregular energy distribution of the variable, coupled with a somewhat different instrumental response function.

Although the time of visual maximum has been well observed in only one cycle, the distribution of points from other cycles about the phase-zero line in figure 1 confirms the correctness of the epoch used, with an uncertainty of perhaps $\pm 15^d$. Further confirmation of the adopted elements is given by the fact that they cause the observed

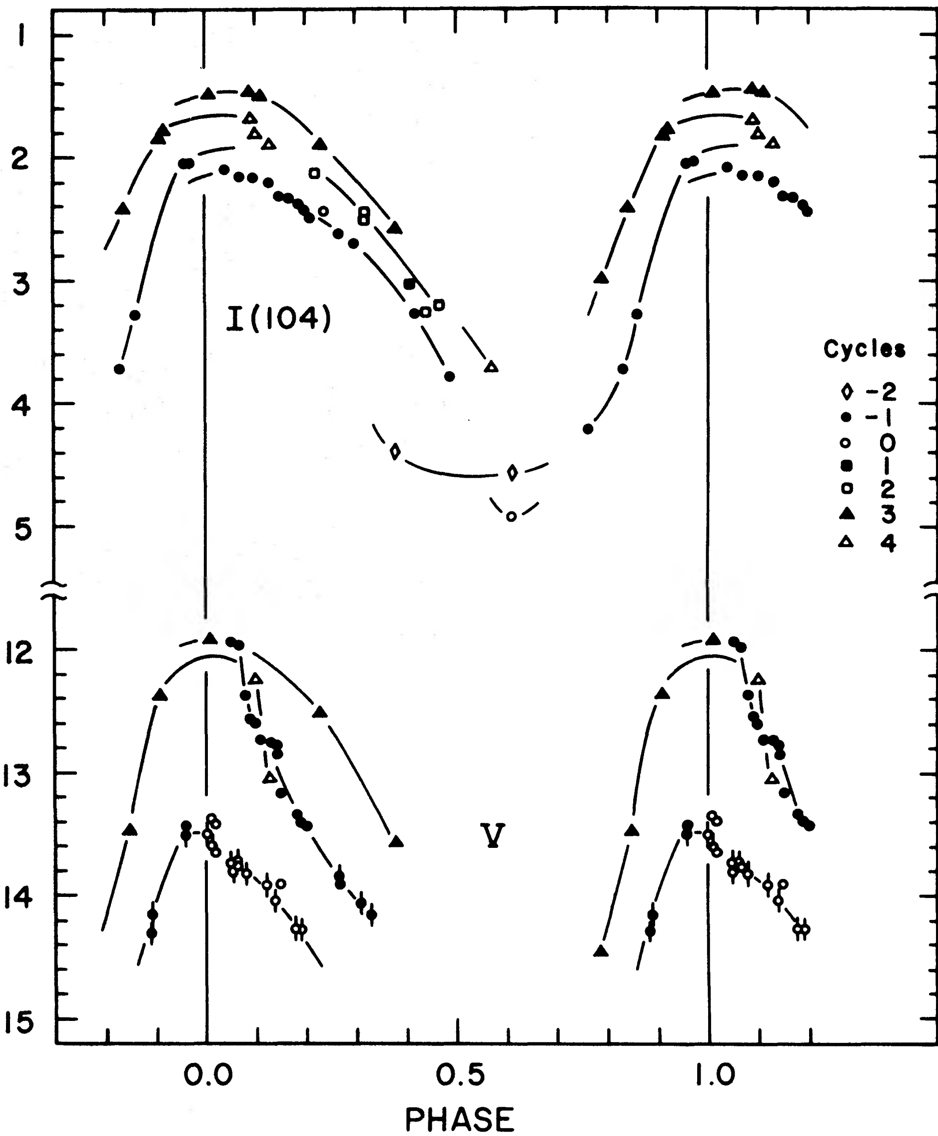

FIG. 1.—Light curves for IK Tau in $I(104)$ (*above*) and V (*below*), based on a mean period of 470^d. Data from tables 1 and 2. Different symbols denote different cycles, according to the legend at the right of the figure. Points with vertical bars have been transformed from Cannon's (1967) photovisual magnitudes.

TABLE 3

SUMMARY OF RESULTS FOR IK TAURI

	Extreme Values	Normal Cycle
I(104) magnitude......	1.46–4.94	1.8–4.5
I(104) amplitude......	3.48	2.7
Spectral range........	M8.1–M11.2	M9.0–M10.5

I(104) maxima to occur in the phase interval 0.0–0.2, as is the case with virtually all other Miras.

In table 3 we list the brightest and faintest *I*(104) magnitudes observed for IK Tau, which show the very large extreme range of 3.48 mag. The corresponding quantities for a normal cycle, as judged from figure 1, are also given; the mean amplitude, 2.7 mag, is the largest we have observed in a Mira variable and is further discussed in § IV.

Little can be said about the visual amplitude, since all actual measurements of V are confined to the brighter half of the cycle. The visual maxima show a wide range in brightness, with a mean value near $V \simeq 12.5$.

Observations of the K magnitude by Hyland *et al.* (1972) are consistent with the period found here, and they show that the light amplitude near 2 μ is significantly smaller than that near 1 μ. The extreme range in K appears to be about 2.4 mag, while the amplitude of a typical cycle is about 0.9 mag.

III. THE SPECTRAL VARIATIONS

All but one of the observations of *I*(104) listed in table 1 were accompanied by measurements at other wavelengths in the 0.7–1.1 μ region so that indices of the band strengths of TiO and VO could be obtained. To derive spectral types from the photometry it has been our practice to use a combination of the TiO and VO indices for all types later than about M6, where VO absorption first becomes appreciable; details of the procedures have been given elsewhere for the 27-color system (Wing 1967), the eight-color system (Wing 1971), and the five-color system (Lockwood 1972).

Simultaneous observations of late M stars have recently been made on all three systems, specifically for the purpose of checking the compatibility of the three systems of spectral types. The results showed poor correlation among the various indices of TiO strength for types later than M8, as a result of deterioration of the continuum shortward of 1.0 μ. On the other hand, the measurements of VO absorption near 1.05 μ on the three systems were found to correlate closely with each other, differing only by scale factors. In our opinion the best spectral types that can be obtained from our photometry of stars later than M8 are those based upon the VO strength alone. The VO types are therefore used exclusively in this paper.

Our calibration of VO spectral types is based upon the adoption of type M8.0 for RX Boo and type M10.0 for R Cas at a typical minimum. Several stars are known to attain later types than R Cas at minimum, but rather than change these convenient and widely adopted definitions, we introduce types later than M10.0 by linear extrapolation in the VO index. Types based upon VO are given to 0.1 subclass since they are reproducible to that accuracy; the uncertainties in transforming from one photometric system to another do not exceed 0.05 subclass.

The results for IK Tau are extraordinary. A spectral type of M10.0 or later has been recorded in all seven cycles that have elapsed since the first spectroscopic observations. The latest type observed is M11.2, and the mean type at minimum is about M10.5, decidedly later than that of R Cas.

The earliest type attained at maximum differs greatly in different cycles, ranging from M8.1 to M9.6 and averaging about M9.0. There appears to be no correlation between the type at maximum and the $I(104)$ magnitude at maximum, but the visually fainter maxima are associated with later spectral types as a direct result of the band absorption in the V filter. It should be noted that the observation reported as M7 by Wing *et al.* (1967) was changed to M8.0 after formal reduction of the photometry (Wing 1967) and is now given as M8.1 on the basis of VO alone. This is the earliest type we have observed in IK Tau. The *GCVS* gives its range as M6e–M10e, but we have not found the source of the type M6e and we suspect a misprint. The last line of table 3 summarizes the spectral variations observed in IK Tau.

Since no trace of ZrO bands has been found, IK Tau appears to be a pure M star. It has, however, been suggested on the basis of the band strengths of TiO and VO that IK Tau has an oxygen-to-carbon (O/C) abundance ratio in the range of the S stars, i.e., lower than in normal M stars (Wing *et al.* 1967). Support for this idea was found in measurements of the H_2O bands by Mertz and Coleman (1966) and McCammon, Münch, and Neugebauer (1967), as well as in the broad-band photometry of Mendoza (1967). However, with the exception of a few of Mendoza's color measurements, all of the observations which seemed to indicate a low O/C ratio were made in the autumn of 1965, when evidently all of the oxide bands were abnormally weak for the temperature. Since the band weakness did not recur in the following cycle (Spinrad and Wing 1969), there is no evidence that the chemical composition of IK Tau differs from that of normal M-type Miras. Rather, the spectroscopic peculiarities exhibited in 1965 represent an extreme example of a stratification effect that is often evident in the spectra of Mira variables.

The spectrum of IK Tau in the 2-μ region illustrated by Hyland *et al.* (1972) shows strong H_2O absorption; according to our elements, this spectrum was recorded at phase 0.48 of cycle +1 (1968) when the spectral type was close to M10.5. Frogel (1971) shows 2-μ spectra at phases 0.24 and 0.42 in cycle +2 (1969) when the types, from interpolation in table 1, were M9.5 and M10.2, respectively.

IV. DISCUSSION

a) Remarks on Period Determinations for Mira Variables

The mean period found for IK Tau, 470^d, differs by 20 percent from the value 390^d obtained by fitting the declining branches of the 1965 and 1966 cycles (Cannon 1967), and it is of some importance to understand the reason for this large discrepancy.

The authors have recently published $I(104)$ light curves for several Mira variables, with observations from different cycles combined by means of well-established mean periods (Lockwood and Wing 1971). Although variations in the phase of maximum light are often evident, the individual cycle lengths seldom differ from the mean period by more than 5 percent. On the other hand, Miras show large cycle-to-cycle differences in the magnitudes reached at a given phase, particularly in the heavily blanketed V magnitude, but also in the infrared continuum. Consequently, spurious periods will often result if one uses the time interval separating occurrences of a given magnitude. In the case of IK Tau, the second cycle observed by Cannon was much fainter visually than the first, so that the same magnitude on the declining branch recurred after less than one complete cycle.

b) Comparison of IK Tauri with Other Mira Variables

The star IK Tauri may be compared with other Mira variables by means of a catalog of the $I(104)$ magnitudes, amplitudes, and photometric spectral types of ~ 300 Miras now being prepared for publication (Lockwood and Wing 1973). It is evident that IK Tau has several properties which are extreme even among Miras.

TABLE 4

LARGE AMPLITUDE MIRAS

Star	Spectral Type	Period (days)	$I(104)$ at Mean Maximum	Mean $I(104)$ Amplitude
R And.........	S3,5–S7,5*	408.97	+1.95:	2.45
W Aql.........	S3,9–S6,9*	490.16	+2.52	2.18
TX Cam.......	M8.7–M10.4†	557.4	+2.44	2.11
S Cas..........	S3,4e–S5,8e‡	611.44	+4.02	2.13
χ Cyg..........	S7,2e–S9,5e‡	406.84	−0.15	2.00:
IK Tau........	M8.1–M11.2§	470.	+1.80:	2.70:

* Wing 1972. † Lockwood and Wing 1973. ‡ Keenan 1966. § This paper.

With an average $I(104)$ magnitude of 1.8 at maximum light, IK Tau is among the two dozen brightest Miras at 1.04 μ. Its mean amplitude in $I(104)$, 2.7 mag, is the largest we have observed in a Mira variable. The 25 Miras studied by Lockwood and Wing (1971) have mean $I(104)$ amplitudes averaging only 1.0 mag.

In table 4 we list all the Miras from Lockwood and Wing (1973) having mean $I(104)$ amplitudes greater than 2.0 mag. Colons in the table indicate an observed cycle-to-cycle variation of more than 0.25 mag, either in $I(104)$ at maximum light or in the amplitude of individual cycles. It is noteworthy that all of the stars listed in table 4 have periods greater than 400^d and that all except TX Cam and IK Tau are S stars, which at a given period tend to have significantly larger amplitudes at $I(104)$ than M stars. The stars TX Cam and IK Tau are thus members of a very exclusive class.

At all phases, the spectral type of IK Tau is unusually late. No other well-observed Mira so consistently reaches M10 at minimum. In the group of $\sim$300 Miras that we have observed, fewer than 10 percent reach a type as late as M9.5 at minimum, and only eight of these have been observed at M10.0 or later. While IK Tau is not the brightest of these, it is likely to be the only one which reaches M10 in every cycle. It also has the latest type at normal minimum (M10.5) and the latest extreme type (M11.2) of any star in this group. A few of the IRC stars now being identified and classified by Lockwood have also been observed at type M10.0 or later, but to date little is known about their periodicity.

c) *Ephemeris for IK Tauri*

To encourage further observations, we list the calculated dates of visual maximum (phase 0.0) and minimum (phase 0.6) in table 5 for the years 1973 through 1980. Infrared maxima occur approximately 30^d after visual maxima. Observers wishing to calibrate their systems of photometry or spectral classification with an M10 spectrum

TABLE 5

EPHEMERIS FOR IK TAURI

Cycle	Maximum (phase 0.0)	Minimum (phase 0.6)
5...........	1973 April 17	1974 January 24
6...........	1974 July 31	1975 May 9
7...........	1975 November 13	1976 August 21
8...........	1977 February 25	1977 December 4
9...........	1978 July 10	1979 March 19
10...........	1979 September 23	1980 July 1

should observe IK Tau within six weeks of a predicted date of minimum. We particularly encourage spectroscopic observations at minimum to look for molecular bands that may appear only at the latest types.

We thank the various observatories involved in this study for their hospitality. Support to R. F. Wing in the form of a Lick Fellowship and subsequent National Science Foundation grants is gratefully acknowledged.

REFERENCES

Cannon, R. D. 1966, *Observatory*, **86**, 150.
———. 1967, *ibid.*, **87**, 231.
Frogel, J. A. 1971, Doctoral dissertation, California Institute of Technology.
Hyland, A. R., Becklin, E. E., Frogel, J. A., and Neugebauer, G. 1972, *Astr. and Ap.*, **16**, 204.
Keenan, P. C. 1966, *Ap. J. Suppl.*, **13**, 333 (No. 118).
Kukarkin, B. V., Kholopov, P. N., Efremov, Yu. N., Kukarkina, N. P., Kurochkin, N. E., Medvedeva, G. I., Perova, N. B., Fedorovich, V. P., and Frolov, M. S. 1969, *General Catalogue of Variable Stars* (3d ed.; Moscow: U.S.S.R. Academy of Sciences).
Lockwood, G. W. 1972, *Ap. J. Suppl.*, **24**, 375 (No. 209).
Lockwood, G. W., and McMillan, R. S. 1971, in *Proceedings of the Conference on Late-Type Stars*, ed. G. W. Lockwood and H. M. Dyck (Tucson: Kitt Peak National Observatory Contribution No. 554), p. 171.
Lockwood, G. W., and Wing, R. F. 1971, *Ap. J.*, **169**, 63.
———. 1972, *Bull. A.A.S.*, **4**, 322.
———. 1973, in preparation.
McCammon, D., Münch, G., and Neugebauer, G. 1967, *Ap. J.*, **147**, 575.
Mendoza, E. E. 1965, *Bol. Obs. Tonantzintla y Tacubaya*, **4**, 51.
———. 1967, *ibid.*, **4**, 114.
Mertz, L., and Coleman, I. 1966, *Ap. J.*, **143**, 1000.
Neugebauer, G., and Leighton, R. B. 1969, *Two-Micron Sky Survey—A Preliminary Catalog*, NASA SP-3047.
Neugebauer, G., Martz, D. E., and Leighton, R. B. 1965, *Ap. J.*, **142**, 399.
Spinrad, H., and Wing, R. F. 1969, *Ann. Rev. Astr. and Ap.*, **7**, 249.
Wing, R. F. 1967, Doctoral dissertation, University of California, Berkeley.
———. 1971, in *Proceedings of the Conference on Late-Type Stars*, ed. G. W. Lockwood and H. M. Dyck (Tucson: Kitt Peak National Observatory Contribution No. 554), p. 145.
———. 1972, 17th Liège Colloquium (*Mém. 8° Soc. Roy. Sci. Liège*, 6th ser., **3**), p. 123.
Wing, R. F., Spinrad, H., and Kuhi, L. V. 1966, *A.J.*, **71**, 187.
———. 1967, *Ap. J.*, **147**, 117.