

An Astrometric Study of the Mira Variable R Leonis and the Occultation Binary 19 Leonis

GEORGE GATEWOOD

University of Pittsburgh, Allegheny Observatory, Observatory Station, Pittsburgh, Pennsylvania 15214
 Electronic mail: gdgatewood@nasamail.nasa.gov

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ABSTRACT. The Multichannel Astrometric Photometer (MAP) has been used to determine parallaxes of stars in the region centered on the Mira variable R Leonis. R Leonis, with a parallax of 8.3 ± 1.0 mas (120 ± 15 pc), is significantly closer than most recent estimates. At visual wavelengths, its mean physical diameter is 612 ± 96 times that of the Sun. The photocentric motion of R Leonis is not suggestive of either optical or orbital companions, excluding possible secondary components over a wide range of magnitudes as well as orbital periods of up to approximately one decade. Nineteen Leonis, an occultation-speckle binary with a well-determined orbit and a reference star in the R Leonis field, has a distance of 92.6 ± 12 pc. The 15.2 yr period binary exhibits a slight perturbation during the 4 yr of MAP observations. The similar primary and secondary of this A7 Vn system are 2.41 ± 0.96 and 2.31 ± 0.92 solar masses, respectively.

1. INTRODUCTION

There are no examples of red giant variable stars within the effective range of photographic astrometry. Thus efforts to calibrate the distances of these objects has been hampered by the lack of statistically significant direct trigonometric measurement. Upgren (1975) found the mean spectroscopic parallax of 23 luminous red stars to be 2.3 mas (thousandths of an arcsec). The 47 photographic parallaxes of these stars exhibited a dispersion of 13.9 mas. Upgren concluded that this was about the size to be expected if all of the dispersion was due to the errors of the trigonometric estimations. The importance attached to the task is illustrated by the fact that there have been so many efforts in the face of such difficulty. While modern photographic programs are several times more accurate than the ones included in Upgren's study (e.g., Upgren et al. 1991), still higher precision is indicated. Thus a portion of the Allegheny Observatory (AO) Multichannel Astrometric Photometer (MAP) (Gatewood 1987) parallax program, which has an illustrated 1 mas precision (e.g., Gatewood et al. 1990), has been allocated to the determination of the parallaxes of giant stars.

Mira variables are of particular interest. Their extended size, probable mass, and apparent high luminosity suggest that they dissipate considerable mass (Smak 1966). In an extensive statistical parallax analysis, Osvalds and Risley (1961) found indications of a possible period luminosity relationship. Unfortunately, the few other estimates of the parallaxes of Miras indicate a considerable scattering about the suggested relationship (Smak 1966). Nevertheless, in the first MAP-based study of a Mira variable, Stein (1991) found the absolute magnitude of χ Cyg to agree closely with that predicted by the Osvalds and Risley study.

2. THE CATALOG AND THE ADJUSTMENT TO ABSOLUTE PARALLAX

This region, which includes an interesting secondary target in the binary 19 Leonis, was the target of 52 MAP observations obtained over a 4.0 yr period. Stars observed are designated AO 935–944 and AO 1000¹ (see Table 1). These stars are confined to a somewhat smaller area of the sky than most fields, and they include an unusual number

of main sequence reference stars. The latter leads to a larger than usual adjustment to absolute.

Table 1 is a continuation of a series of parallaxes now under observation with the Thaw refractor and reduced via the central overlap technique (e.g., Gatewood et al. 1990). In that series each reference star is subject to the same analysis as the target object. This approach has the double advantage of finding previously unsuspected nearby stars and providing the information necessary for the reduction (and future improvement in that reduction) of the relative parallaxes to absolute distances. The positions and motions resulting from the current study are listed, over their standard errors, in the last four columns of Table 1. The system of the positions and motions is that of the PPM (Röser and Bastian 1991), ostensibly that of the FK5. The errors are given in the units of the last digit of the parameter to which they pertain and are strictly internal at J2000. It should be noted that they do not include allowance for the zero-point, orientational, or proper motion uncertainties of the reference system.

While parallax was included in each iteration after the initial reference catalog pass (which used a weight of 1 for all measurements), no constraints were placed on their weighted mean. Thus the system of equations converged on the relative, not the absolute, parallaxes. The most reliable way to determine the difference between the relative and the absolute parallaxes is to determine the spectroscopic parallax of as many reference stars as possible and to average the difference. This adjustment is then applied to all of the relative parallaxes. Of course this requires a photometric and spectroscopic calibration of the individual reference stars and is the origin of the photometric efforts of Castelaz and Persinger (e.g., Persinger and Castelaz 1990), and of the spectroscopic calibrations of AO program stars by Stephenson (e.g., Gatewood et al. 1990).

Astrometric, photometric, and spectroscopic observations combine to give us eight reference stars with reasonably dependable astrometric and spectroscopic parallaxes

¹The Allegheny Observatory (AO) numbering system is sequential in the approximate order of publication, photometric data usually preceding the astrometric study.

TABLE 1
Astrometric Parameters of Stars in the Region of R Leonis^a

AO No.	<i>d</i>	<i>V</i> (mag)	<i>B-V</i>	abs. π (mas)	R.A. (2000)			PM (R.A.) (s)	Dec. (2000)			PM (Dec.) (s)
					h	m	s		°	'	"	
935	2	11.33	0.58	5.7	9	46	30.18326	-0.000810	11	18	49.3558	-0.02759
				2.3			0.00102	0.000084			0.0151	0.00125
936	2	11.96	1.33	18.8	9	46	53.96020	-0.005340	11	32	7.0887	-0.06389
				2.3			0.00091	0.000074			0.0133	0.00110
937	2	11.91	1.01	8.4	9	46	58.64952	-0.001728	11	9	56.2069	0.00435
				2.8			0.00114	0.000096			0.0164	0.00138
938	2	12.11	0.53	1.7	9	47	10.28389	-0.000811	11	33	42.2925	0.00071
				7.5			0.00628	0.000583			0.0856	0.00811
939	2	9.19	1.17	-1.0	9	47	15.62888	-0.002840	11	25	41.3294	-0.01447
				0.5			0.00052	0.000042			0.0076	0.00063
940	2	6.60	0.30	10.9	9	47	25.96312	-0.003140	11	34	5.4809	0.00260
				1.3			0.00067	0.000055			0.0099	0.00082
1000	2	10.80	1.80	8.3	9	47	33.47641	-0.000310	11	25	43.7121	-0.03904
				1.0			0.00040	0.000032			0.0058	0.00047
941	2	10.84	1.17	7.0	9	47	48.37133	-0.001557	11	7	51.3062	-0.01417
				1.3			0.00055	0.000046			0.0079	0.00066
942	1	12.39	0.85		9	48	5.10613	-0.000719	11	19	33.8489	-0.01886
							0.05001	0.001246			0.6364	0.01595
943	2	11.50	0.68	1.7	9	48	11.09193	-0.000160	11	28	20.5013	-0.04988
				1.3			0.00074	0.000061			0.0111	0.00091
944	2	10.00	0.68	13.5	9	48	21.05816	0.000960	11	18	12.6136	-0.01317
				1.0			0.00049	0.000040			0.0073	0.00060

^aThe absolute parallaxes were obtained by adding an adjustment to absolute of 6.3 mas. Column *d* denotes the device used to gather the astrometric data. A 2 indicates that the data was obtained with the MAP, a 1 indicates that the data is from plates measured on the AO Theiss machine. All standard errors, for example, those of the positions, are strictly internal and do not allow for any of the zero-point errors of the reference system. The latter are often on the order of tenths of an arcsec while those in proper motion are on the order of several mas per year.

(Table 2). Persinger and Castelar (1990) report *U*, *B*, *V*, *R*, *I*, C4548, C4245, C4142, and C3841 for 10 of the 11 stars in this region. For the two hottest stars, they also report *b-y*, *m1*, *c1*, and *H β* photometry. The spectroscopic parallaxes listed in Table 2 and used for the calibration of the adjustment to absolute differ slightly from those of Persinger and Castelar mostly in that the adjustment detected little or no interstellar absorption in the direction of this region. Reduced absorption and interstellar reddening led to the adoption of slightly cooler spectral types for AO 943 and 944, both G5 V instead of the G4 V classifications of Persinger and Castelar. The DDO photometry for AO 941 lies between luminosity classes III and V in the c4245/c4142 and c4245/c4548 relations given by Claria

and Osborn (1976) and is similar to the values found for luminosity class-IV stars by McClure and Forrester (1982).

The DDO photometry for AO 937 suggests a luminosity class of III or IV while the relative parallax suggests a luminosity class V. Because of this unusual uncertainty, the star was left out of the initial calculation of the adjustment to absolute. The parallax derived, however, left little doubt about its luminosity class and it was included as a class V in the final calculation. Its inclusion does not change the value of the parallax derived for R Leonis but reduces that of 19 Leonis by 0.1 mas. The two faintest reference stars, for which few astrometric observations

TABLE 2
Adjustment to Absolute in the Region of R Leonis

AO No.	Adopted Spec.	Spec. Para.	Est. Error	Relative Para.	Calc. Error	Adjust to Abs.	Weight	Observed Para.	Spec.-Observed
935	G0 V	4.10	1.32	-0.56	2.33	4.66	0.37	5.70	-1.60
936	K7 V	15.40	4.25	12.50	2.25	2.90	0.21	18.76	-3.36
937	K3 V	9.10	4.19	2.17	2.80	6.93	0.20	8.43	0.67
939	K2 III	1.60	1.10	-7.24	0.52	8.84	0.82	-0.98	2.58
940	A7 Vn	10.67	1.47	4.67	1.29	6.00	0.51	10.93	-0.26
941	K3 IV	3.00	2.21	0.78	1.29	2.22	0.39	7.04	-4.04
943	G5 V	5.20	1.91	-4.56	1.34	9.76	0.43	1.70	3.50
944	G5 V	10.50	3.86	7.19	0.94	3.31	0.25	13.45	-2.95

Weighted mean adjustment to absolute=6.26 mas
Standard error of weighted mean adjustment=0.65 mas

were available, and R Leonis were not used in these calibrations.

Listed in Table 2 are the adopted spectral classification and luminosity type of each of the eight reference stars mentioned above. This is followed by the spectroscopic parallax, estimated from the Persinger and Castelar photometry, and an estimate of the error of the spectroscopic parallax based on the certainty of its absolute magnitude (e.g., Stein 1991). The next column lists the observed relative parallax followed by its calculated error, and the adjustment found by comparing the spectroscopic and relative parallaxes. The statistical weight of this value is derived from the two preceding error estimates. Listed in the last two columns are the calculated absolute parallax and the residuals to this adjustment.

The weighted mean adjustment found from columns 7 and 8, and listed at the bottom of Table 2, is 6.3 ± 0.7 mas. The adjustment was added to the observed relative parallaxes of stars in this region and the sum listed in Table 1. Applying it to the derived relative parallax of R Leonis, we find an annual parallax of 8.3 ± 1.0 mas. The standard error of a single comparison (column 10), which includes the errors due to photometry, spectral classification, and the trigonometric parallax, was 1.8 mas. This is slightly smaller than, but acceptably close to, that which might be expected from the formal estimations of the errors of the quantities involved.

3. R LEONIS

In his study of luminous red stars, Uggren notes the Mount Wilson study of R Leonis, which found a parallax of 2 ± 19 mas, and reports a new Van Vleck value of 27 ± 17 . The relative weight of these studies, combined with the fact that their mean is not significantly different than that found here, leads to a rather unusual result. The weighted mean and estimated error, of all three studies, agrees to within the round-off with the parallax and standard error found with the MAP alone. Thus we adopt 8.3 ± 1.0 mas for the parallax of R Leonis, a distance of 120 ± 15 pc. Ignoring interstellar absorption, which seems minimal in this region, the measured parallax corresponds to a distance modulus of 5.41 ± 0.26 mag. Since R Leonis varies from approximately fifth to tenth apparent magnitude, its absolute magnitude must be calibrated at a mean. Clayton and Feast (1969) list the mean visual maximum apparent magnitude and the mean visual light intensity at 5.8 and 7.4, respectively. Thus the absolute magnitudes of R Leonis at these two points on the light curve are 0.4 and 2.0, respectively.

The angular diameter of R Leonis has been measured in a wide range of wavelengths by speckle interferometry and during lunar occultation (Nather and Wild 1973). While the measured diameters do not show an obvious correlation with phase, Labeyrie et al. (1977) have pointed out a variation of the diameter with wavelength. The mean of seven of the eight measurements, with a mean phase of 0.3, is 47.3 ± 4.8 mas, or 612 ± 96 solar diameters. Most outstanding of the variations from the mean are a pair at 5400 and 7400 Å yielding a diameter of 401 ± 67 solar diameters and one at 11 μm, not included in the mean, yielding a diameter of 36 astronomical units.

Plots of the residuals of R Leonis are not suggestive of a significant perturbation on either axis, nor does a power spectrum analysis show any significant periodicities at any

frequency between a week and 6 months (an observing season) or at any significantly longer periods. Indeed, such periods would not seem to be likely. Foy et al. (1975) compute mean masses from the mass/period relationship of Langer (1971) for the Osvalds and Risley groups. R Leonis falls within the group with masses, depending upon the overtone mode of the pulsations, of either 1.0 or 1.5 solar masses. Thus, adopting the mean mass of the group, a secondary mass equal to one-half of that of the primary, and the diameter derived above, a minimal extra-atmospheric period is 3.9 or 3.2 yr, respectively.

4. A TEST FOR ASTROMETRIC VARIABILITY

The position of the photocenter of an image, composed of two or more sources, will vary in synchronization with the photometric variations of either source. Where A and B are the brighter and fainter signal sources, I_A and I_B are their respective intensities and I_T the measured total intensity, ρ is the separation of A and B, and is approximately constant during the observation, and β is the distance of the photocenter from the brighter source, in this instance the variable, we have

$$I_A \beta = I_B (\rho - \beta). \quad (1)$$

From which

$$I_T \beta = I_B \rho, \quad (2)$$

where $I_B \rho$ may be assumed to be approximately constant over short intervals. Thus β will vary inversely with the total light of the system and, over intervals that are short with respect to significant change in the direction or magnitude of ρ , relative photocentric displacements may be compared with total intensity. Where numerical subscripts denote sequence:

$$\beta_2 / \beta_1 = I_1 / I_2. \quad (3)$$

The absolute value of the photocentric shift may be found from two or more observations by iteration:

$$\Delta \beta = (\beta_2 + \Delta \beta) I_2 / I_1 - \beta_1, \quad (4)$$

where the converged value of $\Delta \beta$ must be added to the observed values to derive estimates of the true values of β_2 and β_1 , the distances of the primary from the photocenter at the epochs of observations 1 and 2.

The problem becomes more complicated in the presence of a significant rate of change in ρ , such as that caused by a short-period astrometric orbit. With the exception that it varies with I_T , β is equivalent to that illustrated on p. 169 of *Principles of Astrometry* (van de Kamp 1967). Thus the position of the primary star is the observed displacement of the photocenter from the barycenter "B-β" (in van de Kamp's notation) plus β , as derived above. But to derive β , the offsets β_2 and β_1 must be compared to the same point. Thus, only if the photometric period is short compared to the gravitational orbit is the problem tractable. As we will see, this would probably be the situation for R Leonis. A prize that awaits the unraveling of a data set comprised of both forms of variations is the ratio of the barycentric to the photocentric displacements. This ratio compares the mass and luminosity of the unseen secondary to that of the more evident primary.

The wide variations in the luminosity of R Leonis, and the MAP's freedom from magnitude-associated errors, are ideal for this test. If R Leonis was accompanied by an

TABLE 3
Photocentric Positions as a Function of Magnitude and Epoch

Mean Epoch	mv	No.	SE	X	Y
1987.1	8.0	8	1.4	+0.1	-1.1
	9.5	19	0.9	-0.8	+0.4
1989.1	6.5	4	2.0	-2.0	+3.1
	9.5	3	2.3	-0.8	+1.3
1987.8	6.5	7	1.5	-1.3	+1.6
	8.0	20	0.9	+1.3	-0.8
	9.5	24	0.8	-0.7	+0.3

extra-atmospheric companion, the separation between the two stars would be at least 2.9 AU or 24 mas. If the apparent magnitude of the companion was approximately 10, the photocenter of the pair would shift from less than 0.33 mas from the center of R Leonis at mean maxima to approximately 12 mas from the primary near mean minima. At 60 AU this hypothetical companion would still be within 0.5 arcsec of R Leonis, and thus be unresolved by most techniques, but it would produce an astrometric signal as large as 250 mas.

To allow tests for astrometric variability, the photometric phase was computed at the time of each astrometric observation and the data divided into sequential groups. These were delineated as the brightness of the star varied through three visual magnitude ranges: (1) less than 7.0; (2) between 7 and 9; (3) greater than 9. Since the photometric period of the star is a little less than 1 yr, an observing season (approximately 6 months) may include observations in all of these categories. Furthermore, since the minimum orbital period for a companion is approximately 4 yr, and in this case would have to have a low eccentricity, ρ will be roughly constant throughout an observing season.

Table 3 lists data at two magnitudes for two observing seasons and, as a more precise test for long orbital periods or an optical double, the entire population of observations was divided into the three magnitude ranges and listed at the end of the table. Column 1 lists the approximate median visual magnitude of the set, column 2 lists the number of observations within the set followed by the error that would normally be expected for that number of MAP observations (Gatewood 1987), and the last two columns give the mean displacements (orthogonal components of β) of that set of data in X and Y (in the directions of increasing right ascension and declination, respectively).

Table 4 lists the computed photocentric displacement components of β during the three intervals listed in Table 3. The last set, produced from the total observational population, yields six solutions, two for each intensity set. In the absence of significant results, the intensities (column 2) of the different sets were not computed rigorously, but for purposes of propagation of the errors (column 3) are treated as exact (if warranted the MAP data could have been used to derive accurate photometry). Columns 4 and 5 list the photocenters as computed above. Only six displacements are as large or larger than their formal errors and none are twice as large. With three of these positive and three negative, the distribution appears approximately normal and probably results entirely from accidental error.

The astrometric behavior of R Leonis shows no significant variation from that of a single star. If the mass pre-

TABLE 4
Reduced Photocentric Positions of R Leonis

Mean Epoch	I	SE	X	Y
1987.1	4	2.0	-0.2	+0.5
	1	1.7	-1.7	+2.0
1989.1	16	2.8	+0.1	+0.1
	1	3.1	+1.3	-1.7
1987.8	16	2.1	+0.9	-0.2
	4	1.8	+3.5	-2.6
1987.8	16	2.1	0.0	0.0
	1	1.7	+0.6	-1.3
1987.8	4	1.3	-0.2	+0.4
	1	1.2	-2.2	+1.5

dictions of Foy et al. are correct, a late K dwarf companion orbiting just above the atmosphere, would cause a perturbation of at least 5 mas, more than two standard deviations above any reasonable interpretation of the observations. Nor is there any evidence of the astrometric variability that would be associated with an early K dwarf. While the sensitivity of this study to a gravitational perturbation is limited, by the duration of the observations, to orbits of a decade or less, the sensitivity of the test for astrometric variability increases for longer period orbits. From the first of the two shorter-duration data sets, ignoring any brightness feature that might result from the proximity,² a one-standard-error positional shift would result from a 13th-magnitude contact companion. The sensitivity of the second data set is less, a one-standard-error photocentric shift representing the effect of a 12th-magnitude contact companion. The importance of the second set is that it greatly reduces the chance that such an object was missed because it was in eclipse. Allowing for the distance modulus found above, the sensitivity of these two tests is one standard error at $M_v = 7.7$ and 6.7, respectively. Stars 0.6 mag brighter are excluded with a certainty of approximately 90%.

The standard error of the faintest group in part 3 of Table 3, where the presence of a second light source would be most obvious, is 0.8 mas, $\pm 1/30$ th the radius of the star. These data are most sensitive to more distant companions. For example, a 16.5 mag object ($M_v = 11.1$) at 0.5 arcsec, 60 AU, where ρ would be virtually constant throughout the duration of the MAP observations, would produce a one-standard-error deflection in this observation. Here again a star 0.6 mag brighter would be excluded at the 90% level. Thus, barring a very unlikely nearly end-on alignment during all three sets of the observations, it is unlikely that an object as massive and as bright as an early K dwarf orbits R Leonis.

It is also worth noting that the behavior of this data set further illustrates the validity of the MAP at precisions of one mas as well as its freedom from systematic errors associated with the apparent magnitude of the observed stars.

²A set of models of the photocentric motions of various mass contact binaries would be constructive in these estimates.

5. 19 LEONIS

19 Leonis (BD +12°2095, WDS 09474+1134, AO 940) was discovered to be binary during the lunar occultation of 1971 June 27 (Eitter and Beavers 1974). Observed at red and blue wavelengths, the observations indicate a magnitude difference of 0.2 mag with the difference between the two bandpasses of only 0.04 magnitudes. The latter suggests that the fainter component is slightly cooler. The observations are both compared to the total light of the system and the error of the mean difference is not immediately apparent. For further calculations we have adopted 0.2 ± 0.1 as the magnitude difference of the A and B components. Cowley and Bidelman (1979) classify the system's combined light as A7 Vn (fast rotation). Hartkopf et al. (1989), from almost one full period of speckle interferometry, finds a period of 15.17 ± 0.09 yr and a semimajor axis of 112.0 ± 0.02 mas.

19 Leonis is the most northerly star in the R Leonis field, slightly farther north than AO 936 and AO 938, but it is near the center of the range in right ascension and well within the maximum possible extent of the field above the target. Its position at the northern edge of the reference frame places it at the point of maximum parameter variance in the coordinate with the largest orbital perturbation. Fortunately the system's parallax is relatively large and the derived parameters are well determined. From the 4 yr of observations the absolute parallax and photocentric semimajor axis are found to be 10.9 ± 1.4 and 3.9 ± 5.4 mas, respectively, the error of the latter value being further exaggerated by the small fraction of the orbit observed. From the above, the total mass of the system is 4.72 ± 1.82 solar masses while those of the A and B components are 2.41 ± 0.96 and 2.31 ± 0.92 solar masses, respectively.

6. DISCUSSION

Both the luminosities and the masses of components of 19 Leonis are within their errors of the generally accepted values for an A7 V star. With a distance modulus of 4.81 ± 0.28 , and a magnitude difference of 0.2 ± 0.1 , the primary star has an absolute magnitude of 2.3 ± 0.3 . At nearly the same temperature and only 0.2 mag fainter, its companion is probably quite similar. The system seems to be composed of two normal late A dwarfs. But, in light of the possible extra feature in the occultation light curve of Eitter and Beavers, and the differences between the orbits of Hartkopf et al. and Tokovinin (1987), it is interesting to note that the system is slightly over massive. The insignificant discrepancy could also be removed by a larger value for the adjustment to absolute parallax. This, however, would result in a yet larger absolute magnitude for R Leonis.

The absolute magnitude of R Leonis is more than 1 mag larger than values derived, for its group, from the proper motion studies of Osvalds and Risley (e.g., Foy et al. 1975). This discrepancy is reduced by 0.3 mag if we adopt the absorption used by Osvalds and Risley for R Leonis. Their data, which has been rereduced several times, is traditionally analyzed in the period related sets used by the original investigators. Smak suggests that the masses of individual Miras may show considerable variation about such period-luminosity relationships. Celis (1980) has suggested spectral type as a third parameter to explain this variation. While this concept cannot be confirmed by a

single trigonometric parallax, the absolute magnitude at mean maximum 0.4 ± 0.26 comes close to the value predicted by this relationship. Adopting $Sp = 16.1$ for R Leonis, an M8 IIIe star in his Eq. (16b) yields an absolute magnitude of 0.0. If we use the absorption mentioned above and used by most other investigators, the Celis formula yields a result within 0.1 mag of that found here.

Van Altena (1991) has derived tables, dependent upon galactic latitude, for the mean parallaxes of stars over a wide range of magnitudes. The mean value found from these tables for stars of the magnitudes of those in this region is 4.2 mas. While this value is not directly comparable to that found in Table 2, it is an interesting reference. If Table 2 was composed of a set of average stars from this region of the sky, and if the weight assigned to the adjustment computed from each star was one, then the mean should be approximately the value given by Van Altena. Because of the large number of main sequence stars found in this region, the value in Table 2 is 2.1 mas greater.

It is interesting to note that a similar condition exists for the MAP region centered on Mira, still under observation. Thus at least two out of the four Mira's selected for the MAP program lie in regions containing a number of dwarfs, and each has a larger than predicted correction to absolute. While the differences result from quasi-random fluctuations in the stellar background, they can result in significant systematic error. Where the number of representative stars of a given class is small, and generally distant, such statistical variations could lead to significant systematic error in our estimations of the luminosity of the whole class. The precision of modern relative parallaxes is now sufficient to warrant considerable care in the estimation of the adjustment to absolute. Determination of the adjustment to absolute now requires a careful study of the characteristics of each of the reference stars.

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