

ROSS 614AB: A REDETERMINATION OF THE MASSES ONE ORBIT LATER¹DIANA S. COPPENBARGER,² TODD J. HENRY,³ AND DONALD W. MCCARTHY, JR.

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ABSTRACT

Accurate masses are reported for the components of the nearby binary Ross 614 AB by supplementing visual and photographic measurements with 1D and 2D infrared speckle data taken during the last seven years. The new data presented here, in conjunction with all available previous resolved observations of the system, yield larger masses for the components, 0.179 ± 0.047 and $0.083 \pm 0.023 M_{\odot}$, than previously reported. Both components are among the handful of systems with masses determined to be $\leq 0.2 M_{\odot}$, and provide important calibration points for the lower main sequence.

1. INTRODUCTION

At a distance of only 4.1 pc, the red dwarf Ross 614 (GJ 234 AB, $6^{\text{h}}26^{\text{m}}51^{\text{s}}$, $-2^{\circ}46'12''$, 1950) was first recognized to be a binary by Reuyl (1936) because of variable proper motion. It is, in fact, the first astrometric binary to be discovered photographically. The system was initially resolved by Baade in 1955, and in the same year Lippincott (1955) published the first masses for the components, 0.14 and $0.08 M_{\odot}$. At the same time, she used 309 Sproul plates (1938–1950) and 51 McCormick plates (1926–1937) to determine the astrometric orbit, and with the single photographic resolution by Baade, was able to find the semimajor axis of the relative orbit, and hence, the masses. Lippincott & Hershey (1972) next presented an updated astrometric study of the system including 868 Sproul plates taken during the interval 1938 to 1972. When combined with the four available resolved observations, their “definitive” photocentric orbit yielded smaller masses for the components, 0.114 and $0.062 M_{\odot}$, primarily due to a smaller semimajor axis. In 1977, Probst measured 285 McCormick photographic plates taken between 1928 and 1976 (spanning nearly three complete orbits) and derived a photocentric orbit using a weighted mean of the McCormick and Sproul data, the orbit being dominated by the Sproul data due to its small formal error. Utilizing five resolved measurements of the pair and the refined astrometric orbit from the combined data, he found masses of 0.13 ± 0.04 and $0.07 \pm 0.02 M_{\odot}$, thereby confirming the very low mass of the secondary. The binary has now completed a full orbit since the last study, and technological advances now allow us to resolve the pair easily. It is therefore appropriate to revisit the system and revise the mass determinations for this important pair.

Ross 614B is especially interesting because it lies close to

the stellar/substellar dividing line at $\sim 0.08 M_{\odot}$ and provides a rare calibration point for the transition region between stars and brown dwarfs. An extensive review of the current research on brown dwarfs is given in Burrows & Liebert (1993). Briefly, these objects have masses below the theoretical lower mass limit for stable hydrogen-burning, main-sequence stars, 0.07 to $0.09 M_{\odot}$ depending on the adopted opacity sources, mixing length, and helium fraction (D’Antona & Mazzitelli 1985; Burrows *et al.* 1989, 1993). Although intrinsically of very low luminosity, they should be detectable in the near-infrared ($1\text{--}5 \mu\text{m}$) because they release gravitational and thermal energy as they cool, and may provide one possible source of the “missing mass” in the solar neighborhood. In this paper, we present 13 new infrared speckle measurements of the angular separation and relative magnitude differences of the components in the Ross 614 system, and derive masses based upon resolved measurements from 1955 to 1992 and the photocentric orbit of Probst (1977).

2. OBSERVATIONS AND DATA REDUCTION

Over the past 7 years, the angular separation and relative magnitudes of Ross 614AB have been measured using infrared speckle imaging. Observations were obtained on the Steward Observatory 2.3 m and Kitt Peak 3.8 m telescopes from 1985 to 1989 using one-dimensional (1D) speckle interferometry (McCarthy 1986), scanning in north–south (NS) and east–west (EW) position angles. Observations in 1991 and 1992 utilized a two-dimensional (2D) speckle camera (McCarthy *et al.* 1990) on the 2.3 m telescope and one 1.8 m mirror of the Multiple Mirror Telescope (MMT). All observations were carried out at wavelengths of $1.25 (J)$, $1.65 (H)$, and $2.2 \mu\text{m} (K)$.

Table 1 summarizes the resolved observations of Ross 614AB over nearly four decades, including photographic, visual, and visual speckle observations, as well as the 1D and 2D infrared speckle data. The first five observations have been taken from Table 5 of Probst (1977), the one visible speckle point is from McAlister & Hartkopf (1988), and the last 13 observations have been made by this group at infrared

¹Observations reported here were obtained at the Multiple Mirror Telescope Observatory, a facility operated jointly by the Smithsonian Institution and the University of Arizona.

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TABLE 1. Observations of Ross 614AB

Date	Method	λ (μm)	Δm (mag)	p ($''$)	$\theta^{\text{a}}_{\text{observed}}$ ($^{\circ}$)	ρ ($''$)	$\theta^{\text{a}}_{\text{predicted}}$ ($^{\circ}$)	scale p/ρ
1955 Mar 23	photograph	vis	3.5	1.19	36.0	0.391	36.9	3.043
1956 Mar 13	visual	vis	3.5	1.16	43.2	0.396	44.1	2.930
1957 Apr 14	visual	vis	—	1.22	51.9	0.382	52.2	3.192
1965 Feb 05	visual	vis	3.0	0.50	201.0	0.210	204.9	2.380 ^j
1974 Jan 16	photoelec	0.9	2.1-2.5	1.27	—	0.379	—	3.354
1982 Oct 04	speckle	0.55	—	0.50	214.6	0.168	235.5	2.973
1985 Oct 30 ^b	1D NS ^f	1.65	1.64	1.04	—	0.272	—	3.831
1985 Oct 30 ^b	1D NS ^f	2.2	1.51	—	—	—	—	—
1986 Dec 14 ^c	1D NS ^f	2.2	1.53	1.11 ⁱ	22.6 ^j	0.346	24.8	3.218
1986 Dec 14 ^c	1D EW ^f	2.2	1.50	—	—	—	—	—
1987 Nov 08	1D NS ^f	1.65	1.70	1.12	—	0.320	—	3.502
1988 Feb 07	1D EW ^g	1.25	1.79	0.98	—	0.218	—	4.489 ^j
1989 Feb 19	1D EW ^g	1.25	1.49	0.81	—	0.266	—	3.045
1991 Nov 23 ^d	2D SSA ^h	2.2	1.44	1.19	66	0.340	64.4	3.496
1991 Nov 24 ^d	2D SSA ^h	1.65	1.48	—	—	—	—	—
1991 Nov 24 ^d	2D SSA ^h	2.2	1.34	—	—	—	—	—
1992 Feb 21 ^e	2D 1X ^g	1.65	1.71	1.10	66.3	0.331	67.0	3.323
1992 Feb 22 ^e	2D 1X ^g	1.25	2.08	—	—	—	—	—
1992 Feb 23 ^e	2D 2X ^g	2.2	1.65	—	—	—	—	—

Notes to TABLE 1

- ^a position angles not listed for 1D scans in only one direction
^{b c d e} same observing run — combined data for separation and position angle
^f Kitt Peak 3.8m
^g Steward Observatory 2.3m
^h 1.8m mirror C of Multiple Mirror Telescope
ⁱ orthogonal 1D measurements combined
^j high and low scale values not used in final semimajor axis determination

wavelengths. For the 2D speckle measurements, SSA indicates simple shift-and-add data, 1X is for speckle data taken using an 8'' field, and 2X for speckle data taken in a 4'' field. The measured magnitude differences are given in column 4, and the observed separations and position angles in columns 5 and 6. In addition, the predicted photocentric perturbation as defined by the astrometric orbit of Probst (1977) is given in column 7, and the predicted position angle of the secondary in column 8. The final column lists the scale factor, discussed in Sec. 3.1.

The image reduction and Fourier analysis techniques used to reduce the data have been described by McCarthy (1986) for 1D, and by Christou (1991) and Henry *et al.* (1992b) for 2D. Once calculated, the Fourier amplitudes and phases were fit with a binary model using the least-squares algorithm described in Freeman *et al.* (1992).

The observations from the MMT in 1991 November were handled differently than usual. Because of excellent seeing during data acquisition, a shift-and-add method was sufficient to resolve the components. A fraction of the frames was coadded by centroiding to produce a single image like that shown in Fig. 1 (Plate 111). This image includes 99 of the 1500 original frames taken with an exposure time of 250 milliseconds at 2.2 μm on 1991 Nov 23. The Fourier analysis techniques typically used to reduce the speckle data require a standard star for deconvolution of the binary components. However, when the shift-and-add images were taken no such comparison star was observed. To obtain a comparison, the primary component from a single source frame was separated from the combined image and used as a comparison. The original image was deconvolved using this "reference" frame to produce the Fourier modulus and phase, and then the usual reduction techniques could be utilized.

The dominant error in separations given for the 1D obser-

vations is a systematic error in the calibration of the detector's spatial scale, estimated to be 10%. For the 2D observations, errors in the separation include a 4% systematic error in scale determination due to uncertainties in the orbits used for detector scale determination, and errors in individual datasets. The position angles are accurate to 2°, and have been measured by observations of the calibration binaries, and by trailing star images across the detector in right ascension and declination. More details about these errors can be found in Henry *et al.* (1992b).

Figure 2 illustrates all the resolved observations and the astrometric orbit of Probst enlarged by the scale factor found here (see Sec. 3.1). The observed position angles match those predicted by the astrometric orbit well, differing by more than a few degrees only in the visible speckle point. This point is one of only two available near a periastron passage. The second, Worley's visual point of 1965, matches the predicted position angle well, but falls well inside the orbit. However, the only other Worley point also falls inside the orbit where several other points indicate a larger separation. The McAlister and Hartkopf visual speckle point also falls inside the orbit but the measured position angle is 21° from that predicted, a much larger difference than any other point. We note that both measurements have been made by competent researchers, and though a possible revision to the orbit may be necessary, it is premature at present to attempt such a revision without more data near periastron. Fortunately, the situation should be clearer after the next periastron passage in 1999. At present, we adopt the orbital elements as given by Probst and only the scale between the astrometric and relative orbits remains to be found in order to calculate the masses of the components.

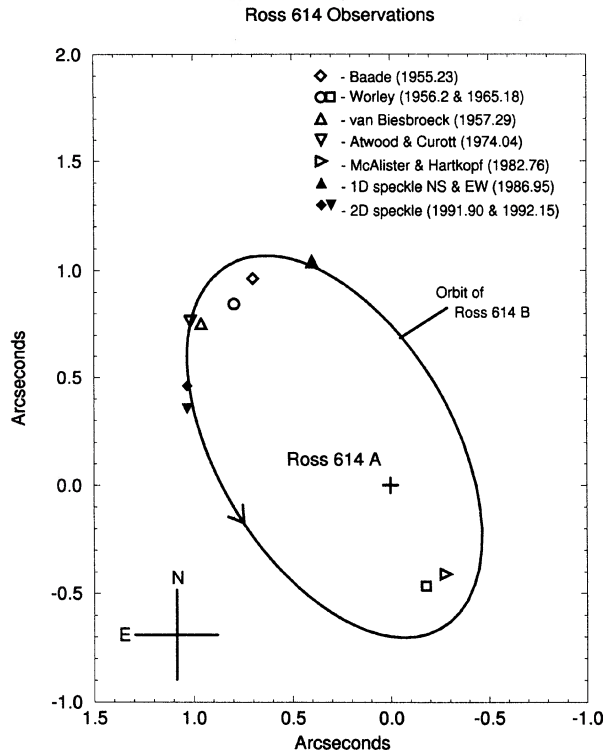


FIG. 2. A plot of all observations of Ross 614AB listed in Table 1 with the exception of the 1D measurements, which could not be plotted due to lack of position angle. The three 1991 November observations have been averaged into one point, as were the three observations from 1992 February.

3. DISCUSSION

3.1 Masses Determined Dynamically

To derive the masses of the components dynamically, we use the method discussed in detail in Henry & McCarthy (1993, hereafter referred to as HM93). Throughout the following discussion, formal standard errors are quoted.

The scale factor of the relative to astrometric orbit, p/p (where p is the observed separation and p is the predicted photocentric perturbation at the epoch of observation), is found to be 3.264 ± 0.273 from eleven independent determinations listed in Table 1—the high and low observations have been discarded, as they are poor observations more than 3σ from the mean. From this scale factor and the semimajor axis of the photocentric orbit $[(0.309 \pm 0.007)''$, Probst 1977], the semimajor axis of the relative orbit is found to be $(1.009 \pm 0.087)''$, or 4.2 AU.

The fractional mass of the secondary, B , is found using $(B - \beta)^{-1} = p/p$, in which β is the secondary's fractional luminosity at visual wavelengths where the astrometric data were taken. To find β , we use the observed infrared magnitude differences between Ross 614A and B from the speckle work: $\Delta J = 1.79 \pm 0.30$, $\Delta H = 1.63 \pm 0.11$, $\Delta K = 1.50 \pm 0.10$. These values, combined with the system infrared photometry from Leggett (1992) $[(J, H, K) = (6.38, 5.78, 5.49) \pm 0.03]$ and the parallax from Gliese

TABLE 2. Comparison of elements and masses determined dynamically.^a

	Lippincott (1955)	Lippincott & Hershey (1972)	Probst (1977)	this paper (1994)
P (yr)	16.5	16.60	16.60 ± 0.03	16.60 ± 0.03^b
a (")	0.98	0.904	0.932 ± 0.081	1.009 ± 0.087
f	0.35	0.351	0.338 ± 0.028	0.317 ± 0.026
π (")	0.251 ± 0.005	0.248 ± 0.005	0.2432 ± 0.0020	0.2421 ± 0.0017^c
M_A ($M_\odot$)	0.14	0.114	0.135 ± 0.036	0.179 ± 0.047
M_B ($M_\odot$)	0.08	0.062	0.069 ± 0.019	0.083 ± 0.023

Notes to TABLE 2

^astandard errors given

^bfrom Probst (1977)

^cfrom Gliese and Jahreiss (1991)

& Jahreiss (1991) $[0.2421 \pm 0.0017]$ yield the absolute magnitudes for the components:

$$\begin{aligned} A: M_J &= 8.49 \pm 0.06, & B: M_J &= 10.28 \pm 0.25, \\ M_H &= 7.92 \pm 0.04, & M_H &= 9.55 \pm 0.10, \\ M_K &= 7.65 \pm 0.04, & M_K &= 9.15 \pm 0.09. \end{aligned}$$

Lippincott & Hershey (1972) give a $\Delta m_I = 2.1$ and M_I of the components of $(M_I)_A = 10.2$ and $(M_I)_B = 12.3$, as do Currott & Atwood (1975). Using the $I-J$, H , K from Leggett (1992), these translate to comparable values at J , H , and K , showing the consistency of these measurements.

With these absolute magnitudes in hand, we use the new absolute infrared magnitude–color relations of HM93 that include single, nearby stars to determine the magnitude difference at V , $\Delta V = 3.33 \pm 0.26$, and the absolute magnitudes at V for $A[12.78 \pm 0.04]$ and $B[16.11 \pm 0.29]$. This is similar to the $\Delta V = 3.5$ value estimated by Baade in the original resolution of the pair. From Feerman (1971), this ΔV corresponds to $\beta = 0.009 \pm 0.006$, and we then find the fractional mass, $B = 0.317 \pm 0.026$. Finally, through Kepler's Third Law, the combination of the period from Probst (1977) $[P = 16.60 \pm 0.03 \text{ yr}]$, the semimajor axis, the parallax and the fractional mass yields the component masses: $\mathcal{M}_A = 0.179 \pm 0.047 \mathcal{M}_\odot$ and $\mathcal{M}_B = 0.083 \pm 0.023 \mathcal{M}_\odot$.

A comparison of the earlier mass determinations and the data presented here is given in Table 2. The larger semimajor axis results in a total mass for the system greater than that reported previously, although a larger fraction of that mass now appears to lie in the primary. The fundamental limitation of the earlier mass calculations was the difficulty in resolving the close binary, resulting in poor determinations of the semimajor axis and fractional mass from only a few resolved observations. With the many observations reported here these quantities are better determined, and as can be seen in Fig. 3 of HM93, the higher mass for the primary places it in better agreement with theoretical models for low mass stars of young disk age. In this figure it can be seen that the 1σ error-bars in the Ross 614B mass overlap ages of a few Gyr, a likely age for the system, as discussed in the next section.

Infrared speckle observations of another nearby low mass binary, Wolf 424AB, indicate that the secondary is not following the predicted orbit, and that the very low masses reported by Heintz (1989) may be in error (Henry *et al.* 1992a). Photometric mass estimates for Wolf 424A and B

TABLE 3. Age indicators for the Ross 614 system.

Age indicator	Data	Age estimate	Reference
Flaring activity	$L_f(U) = 9.2 \times 10^{26} \text{ erg s}^{-1}$ $L_f(U) = 1.87 \times 10^{27} \text{ erg s}^{-1}$	young? young?	Kunkel (1973) Pettersen & Sundland (1991)
H α	eq. width = +3.56 Å	young?	Stauffer & Hartmann (1986)
Metallicity	photometry	young disk	Leggett (1992)
Kinematics	$(U, V, W) = (+3, -24, +4)$	young/old disk	Leggett (1992)

yield higher masses and a better agreement with theoretical models, as is the case for the new dynamical mass reported here for Ross 614A. Other speckle imaging observations (Perrier *et al.* 1991) show evidence that the period of Wolf 424AB may be about half of what it was believed to be, placing this pair significantly above the brown dwarf cutoff of $0.08 M_{\odot}$ and making the dynamical masses agree more closely with the photometric masses listed in Henry *et al.* (1992a).

3.2 Age of the Ross 614 System

It is possible to estimate the masses of the components using the M_J , M_H , and M_K values given above and the mass–luminosity relations in HM93. However, below $0.2 M_{\odot}$ luminosity is a strong function of age so care must be taken when estimating the masses photometrically. In order to utilize the relations correctly for Ross 614A and B, the system must first be shown to be of similar age to the stars used to determine the mass–luminosity relations (middle disk age, a few Gyr).

While assigning a precise age to an individual star or stellar system is difficult at best, it is instructive to use a combination of observational attributes to evaluate the age of the Ross 614 system (see Table 3). Four indicators, flaring activity, H α equivalent width, a metallicity classification, and kinematic information can be used to estimate ages for red dwarfs.

The level of chromospheric activity in low mass stars, flaring in particular, is one indicator of youth. Ross 614AB was first observed as exhibiting flare activity by Kunkel (1967) in the U band. Further observations in 1969 February by Kunkel (1973) resulted in the determination of the average flare luminosity, $L_f(U) = 9.2 \times 10^{26} \text{ erg s}^{-1}$. These findings were later improved upon by Pettersen & Sundland (1991), who observed more than twice the amount of flare activity, $L_f(U) = 1.87 \times 10^{27} \text{ erg s}^{-1}$, or approximately 1% of the total U luminosity. The system has very strong H α emission (Stauffer & Hartmann 1986), also indicating an active chromosphere and youth. However, most stars with spectral types this late (M4.5, Kirkpatrick *et al.* 1991) are in emission, so it is difficult to make any quantitative statement about the age from this data alone, although it is unlikely that the system is a member of the halo population. Leggett (1992) places the system among young disk stars using a photometric/metallicity indicator, and in the young/old disk population based upon kinematics. Taken together, all of the age information makes plausible the idea that the proper grouping for this system is the young disk, and the aforementioned mass–luminosity relations should be applicable to the

Ross 614 system. We emphasize that the photometric mass estimates are for illustrative purposes only, and that the dynamical masses are to be preferred.

3.3 Masses Estimated Photometrically

As reported in HM93, the mass–luminosity relations used to estimate photometric masses for Ross 614A and B include the two objects as points. These points must be removed from the calibration in order to estimate the masses independently. Fits to the remaining eight points at K and H , and seven at J (those in the low mass regime outlined in HM93) lead to mass estimates of $0.184 M_{\odot}$ at all three wavelengths for A, and 0.097 to $0.105 M_{\odot}$ for B. Inclusion of the two Ross 614 points leads to mass estimates of 0.183 to $0.185 M_{\odot}$ for A and 0.096 to 0.103 for B. These are nearly identical to those determined without the points, and indicate that the components of the Ross 614 system fall along the mean mass–luminosity relation for objects with $M < 0.18 M_{\odot}$. The photometric mass of the primary matches the mass determined dynamically very well, whereas the secondary's values overlap at the 1σ level.

4. SUMMARY

Ross 614AB has been observed using speckle imaging techniques at near-infrared wavelengths. Analysis yields absolute magnitudes for the primary and secondary at V , J , H , and K , and when combined with photometric and visual measurements and the astrometric orbit of Probst (1977), we derive dynamical masses of $0.179 \pm 0.047 M_{\odot}$ and $0.083 \pm 0.023 M_{\odot}$. Available age indicators show that the system is probably of young disk age and that photometric mass estimates are consistent with the dynamical masses. As can be seen in Fig. 3 of HM93, both components are among the ten lowest luminosity objects known with masses determined dynamically, and provide important points for the calibration of the red end of the main sequence. Ross 614B is especially interesting, because it falls near the transition region between true stars and brown dwarfs. To improve the mass determinations and to evaluate better the nature of Ross 614B, continuing infrared speckle observations are planned.

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