Astrometry with \textit{Hubble Space Telescope} Fine Guidance Sensor 3:  
The Parallax of the Cataclysmic Variable  
RW Triangulum  

B. E. McArthur and G. F. Benedict  
\textit{McDonald Observatory, University of Texas, Austin, Texas 78712}  

J. Lee, C. -L. Lu \textsuperscript{1}, W. F. van Altena, C. P. Deliyannis \textsuperscript{2}, and T. Girard  
\textit{Department of Astronomy, Yale University, New Haven, Connecticut 05620}  

L. W. Fredrick  
\textit{Department of Astronomy, University of Virginia, Charlottesville, Virginia 22903}  

E. Nelan  
\textit{Space Telescope Science Institute, Baltimore, MD 21218}  

R. L. Duncombe, P. D. Hemenway \textsuperscript{3}, W. H. Jefferys and P. J. Shelus  
\textit{Department of Astronomy, University of Texas, Austin, Texas 78712}  

O. G. Franz and L. H. Wasserman  
\textit{Lowell Observatory, Flagstaff, Arizona 86001}  

\textbf{ABSTRACT}  

RW Triangulum (RW Tri) is a 13th magnitude Nova-like Cataclysmic Variable star  
with an orbital period of 0.2319 days (5.56 hours). Infrared observations of RW Tri  
indicate that its secondary is most likely a late K-dwarf (Dhillon 1998). Past analyses  
predicted a distance of 270 parsec, derived from a black-body fit to spectrum of the  
central part of the disk (Rutten et. al, 1992). Recently completed Hubble Space Tele-
scope Fine Guidance Sensor interferometric observations allow us to determine the first  
trigonometric parallax to RW Tri. This determination puts the distance of RW Tri at  
$341^{+38}_{-31}$, one of the most distant objects with a direct parallax measurement.  
We compare our result with methods previously employed to estimate distances to  
CV’s.  

\textit{Subject headings:} astrometry, stars: distances, stars: novae, cataclysmic variables  

\textsuperscript{1}Now at Purple Mountain Observatory, Nanjing, China  
\textsuperscript{2}Now at Department of Astronomy, Indiana University, Bloomington, Indiana  
\textsuperscript{3}Now at Department of Oceanography, University of Rhode Island
1. Introduction

Cataclysmic Variables (CVs) provide a rich library from which astronomers can study physical phenomena. Magnetic and plasma interactions, winds, nonequilibrium thermo-nuclear reactions, radiative emissions and accretion can all be found in the laboratory of these white dwarfs and their donor companions. All CVs are short-period binary systems that transfer matter via Roche-lobe overflow from a red dwarf companion to the white dwarf. The Nova-Like (NL) CVs have accretion disks which remain bright at all times making it difficult to estimate their distances, since the secondary is very difficult to observe. The mass transfer rate of NLs is high enough to suppress the disc instability mechanism that causes Dwarf Nova type outbursts. RW Tri is an eclipsing NL star. A precise parallax would increase our understanding of this class of object. Estimates of the rates of mass transfer are required for quantitative modeling of the emergent spectrum and evolution of these systems. Only if the distance is known can accurate estimates of the rates of mass transfer be made.

Berriman (1987) reviewed the four types of measurements used to determine distances to CVs: (1) parallaxes and proper motions, (2) interstellar reddening, (3) properties of the accretion disks and (4) the detection of the red dwarf companions. Detection of the red dwarf companion of RW Tri has been detected spectroscopically by skew mapping (Smith et al. 1997) and K-band spectroscopy (Dhillon 1998). A fifth model-independent method using linear polarimetry has recently been proposed (Barrett, 1996). The different methods give widely varying distances, and some measurements should be regarded as lower limits (e.g. when using the K-band magnitude of the secondary star in conjunction with Bailey’s relation - see Section 4), or upper limits (e.g. from blackbody disc models fitted to spectra or photometry). Only recently has there been instrumentation to improve the astrometric database. HIPPARCOS was scheduled to observe 5 CVs (V603 Aql, RR Pic, RW Sex, SS Cyg and AE Aqr), but only AE Aqr yielded a meaningful parallax of 9.8±2.84 mas (Friedjung, 1997). To date a total of four sub-milliarcsecond precision astrometric parallaxes of CVs have been delivered by the Fine Guidance Sensors (FGS) on HST, three dwarf novae SS Cyg, U Gem and SS Aur (Harrison et al., 1999), and the NL RW Tri, which is the subject of this paper.

2. Observations and Reductions

The observations of RW Tri (J2000: 02 25 36.20, +28 05 50.5) were made with Fine Guidance Sensor 3 (FGS3) on the HST. Astrometry with the HST Fine Guidance Sensors has been previously described (Benedict et al., 1994, Benedict et al., 1993), as has the FGS instrument (Bradley et al., 1991). Ten observations (one orbit each) of RW Tri at maximum parallax factor were made between 1995 and 1998 with FGS3 in POS (fringe tracking) mode. HST FGS parallax observing strategies and reduction and analysis techniques have been described by Benedict et. al. (1999), Harrison et al. (1999) and van Altena et. al. 1997).

As seen in Table 1, the standard errors resulting from the solutions for relative parallax and proper motion are sub-milliarcsecond. Figure 1 shows histograms of the residuals of the target and reference frame stars obtained from our astrometric modeling. The proper motions and parallaxes determined with HST are relative to the reference frame stars. To determine the correction to absolute parallax, spectrophotometric parallaxes were derived for the reference frame stars r from spectra obtained at the WIYN telescope4, multiobject spectrograph (MOS/Hydra) and classified by spectral type and luminosity class. The final correction, 0.34±0.16 milliseconds of arc (mas) is based upon $A_v = 0.2$. This $A_v$ is an upper limit derived from Burstein and Heiles (1984), using the galactic latitude of RW Tri.

3. Trigonometric Parallax and Absolute Magnitude of RW Tri

The modeling of the observations gives an HST relative parallax for RW Tri of 2.59±0.29 mas. The correction to absolute parallax adds 0.34 mas, giving an absolute parallax of 2.93±0.33 mas, and a distance of 341±31 parsecs (Table 3). This distance lies in the range of distances predicted from many other non-astrometric methods (Table 3).

The distance modulus for RW Tri is 7.67. Using Bruch and Engel’s (1994) visual magnitude of 13.2 for the apparent magnitude we obtain an absolute magnitude ($M_V$) of 5.53±0.22. When using trigonometric parallaxes to estimate the absolute magnitude

4The WIYN Observatory is a joint facility of the University of Wisconsin-Madison, Indiana University, Yale University, and the National Optical Astronomy Observatories.
of a star, a correction should be made for the Lutz-Kelker (LK) bias. Because of the galactic latitude and distance of RW Tri, and the scale height of the stellar population of which it is a member, we do not use a uniform density in space for calculating the LK bias, but derive a density law that falls off as the -0.5 power of the distance at the distance of RW Tri. This translates into \( n = -3.5 \) as the power in the parallax distribution. This \( n \) is then used in an LK algorithm modified by Hanson (H)(1979) to include the power law of the parent population. A correction of \(-0.12 \pm 0.05\) mag is derived for the LKH bias, which makes the absolute magnitude 5.41 +0.23/−0.21.

Although RW Tri (Galactic coordinates: \( l = 147.03, b = -30.33 \)) is well below the plane of the galaxy, our proper motion determination gives it a velocity of only 15 km s\(^{-1}\) relative to the reference stars. This is consistent with the 14 NLs with known radial velocities all being less than 40 km s\(^{-1}\) (Shara 1999). This indicates that RW Tri is a member of the disk population of our galaxy.

4. The Bailey Relation

In 1981, Bailey presented a formula for surface brightness which has been used to estimate the distances of CVs.

\[
\log(d) = \left( \frac{K}{5} \right) + 1 - \left( \frac{S_K}{5} \right) + \log \left( \frac{R_2}{R_\odot} \right) \tag{1}
\]

where \( d \) is the distance in parsecs, \( K \) is the observed K magnitude, \( S_K \) is the surface intensity in the K-band, and \( R_2 \) is the radius of the secondary. In 1994, Ramseyer examined additional data and showed that \( S_K \) was not constant over a large range of \( V - K \) as previously thought. Using a \( V - K \) of 3.08 (average of \( V \) at minimum of Smak (1995), Longmore et. al. (1981) and Walker (1963) minus the \( K \) from Longmore et. al. (1981)), and

\[
S_K = 4.35 + 0.022 * (V - K) \tag{2}
\]

from Ramseyer (1994) Table 1 (Class V, \( V - K \) 3.0-5.0), we get a \( S_K \) of 4.42. Using the mass-radius relation from Warner (1995)

\[
R_2 = M_2^{(13/15)} \tag{3}
\]

with Smak’s (1995) secondary mass of 0.63, we get \( R_2 = 0.67 \). Using these numbers in Equation 3 we derive a distance of 238 parsecs. If the period-radius relations of Warner (1995) or Patterson (1984) or the mass-radius relation of Smith and Dhillon (1998) are used the distance estimate drops further to 217 parsecs.

The infrared spectroscopic parallax, when compared to the HST parallax, shows that excess luminosity is present in the K-band of these objects. This causes problems with the Bailey method of distance determination. The distance may be underestimated in Equation 3 due to the assumption that the disc is not contributing to the K-band luminosity.

5. Summary

Trigonometric parallaxes can provide distances which are independent of the assumptions (such as the intrinsic absolute luminosity or shape of the spectral energy distribution of the accretion disk) that have been used in the previous methods of determining the distances for CVs. Our trigonometric parallax places RW Tri at a greater distance than previously thought. The more precise distance reported here will improve knowledge of the physical processes associated with this interesting object, placing it on an absolute scale.
| Star     | $\xi$ (asec) $^a$ | $\eta$ (asec) $^a$ | $\sigma_\xi$ (mas) | $\sigma_\eta$ (mas) | V magnitude | Spectral Type |
|---------|------------------|------------------|------------------|------------------|-------------|--------------|
| Ref 1   | 9.320            | -41.837          | 0.30             | 0.42             | 14.2        | G1 III       |
| Ref 2   | -271.562         | 43.123           | 0.54             | 0.72             | 14.1        | G0 II        |
| RW Tri  | 30.600           | -88.424          | 0.45             | 0.72             | 13.2        | Novalike     |
| Ref 4   | 109.025          | -55.341          | 0.32             | 0.38             | 11.2        | A6 III       |
| Ref 5   | -73.128          | 66.071           | 0.50             | 0.76             | 13.8        | F5 Ib-II     |
| Ref 6   | 262.725          | -8.728           | 0.55             | 0.56             | 12.8        | G9 III       |

$^a$\(\xi\) and $\eta$ are relative positions
Table 2
Parallax and Proper Motion of RW Tri

| Relative $\mu_\alpha$ (mas/yr$^{-1}$) | Relative $\mu_\delta$ (mas/yr$^{-1}$) | Relative Parallax (mas) | Observed Ref. Parallax $^a$ (mas) | Parallax (mas) | Distance (parsec) |
|--------------------------------------|--------------------------------------|-------------------------|-----------------------------------|----------------|-------------------|
| 7.1 ±0.4 | 0.03 ±0.7 | 2.59±0.29 | 0.34±0.16 | 2.93±0.33 | 341$^{+31}_{-38}$ |

$^a$Correction to absolute parallax is derived from WIYN spectra
| Reference                        | Distance in parsecs | Method                                                                 |
|---------------------------------|---------------------|------------------------------------------------------------------------|
| Young & Schneider (1981)        | > 107               | Non-detection of M1 dwarf - flux deficit in TiO Band                   |
| Young & Schneider (1981)        | > 161               | Non-detection of M4 dwarf - flux deficit in TiO Band                   |
| Frank & King (1981)             | 180 ± 70            | Best fit to the light curves in a quiescent state                    |
| Borne (1977)                    | 200                 | Spectroscopic Parallax                                                |
| Young & Schneider (1981)        | > 224               | Non-detection of M3 dwarf - flux deficit in TiO Band                   |
| Warner (1987)                   | 224                 | K-band magnitude                                                     |
| Bailey (1981)                   | 247                 | V - K Surface Brightness Calibration                                  |
| Smak (1995)                     | 270 ± 40            | Light Curve fitting                                                   |
| Rutten et. al (1992)            | 270                 | Black body fit to spectrum of central part of disk                    |
| Rutten et. al (1992)            | 330                 | Derived from fractional contribution of Secondary Star                |
| HST (1998)                      | 341 ± 38            | Trigonometric parallax, this paper                                    |
| Young & Schneider (1981)        | > 347               | Non-detection of M1 dwarf - flux deficit in TiO Band                   |
| Longmore et. al (1981)          | 400                 | Light curves at near IR wavelengths                                   |
| Horne & Steining (1985)         | 500                 | Modeling of Disk Properties from eclipse maps                         |
REFERENCES

Bailey, J. 1981, MNRAS, 197, 31

Barrett, P. 1996, PASP, 108, 412

Benedict, G. F., Nelson, E., McArthur, B., Story, D., van Altena, W. F., Ting-Gao, Y., Jefferys, W. H., Hemenway, P. D., Sholes, P. J., Whipple, A. L., Franz, O. G., Fredrick, L. W., Duncombe, R. L. 1993, PASP, 105, 487

Benedict, G. F., McArthur, B., Nelson, E., Story, D., Whipple, A. L., Jefferys, W. H., Wang, Q., Sholes, P. J., Hemenway, P. D., McCartney, J., van Altena, W. F., Duncombe, R., Franz, O. G., & Fredrick, L. W. 1994, PASP, 106, 327

Benedict, G. F., McArthur, B., Nelson, E., Story, D., Whipple, A. L., Sholes, P. J., Jefferys, W. H., Hemenway, P. D., Franz, O. G., Wasserman, L. H., Duncombe, R. L., van Altena, W. F., & Fredrick, L. W. 1999, AJ, in press

Berriman, G. 1987, A&A, 68, 41

Borne, K. D. 1977, Bull. AAS, 9, 556

Bradley, A., Abramowicz-Reed, L., Story, D., Benedict, G., & Jefferys, W. 1991, PASP, 103, 317

Bruch, A., & Engel, A. 1994, A&A, 104, 79

Burstein, D., & Heiles, C. 1984, ApJS, 54, 33

Dhillon, V. 1998. in Wild Stars in the Old West, ASP Conference Series, Volume 137, eds Howell, S., Kuulkers, E., & Woodward, C. 132

Frank, J., & King, A. R. 1981, MNRAS, 195, 227

Friedjung, M. 1997, New Astronomy 2, 319.

Harrison, T. E., McNamara, B., Szkody, P., McArthur, B., Benedict, G. F.,Klemola, A., & Gilliland, R. L. 1999, ApJ, 515, L93

Hanson, R. B. 1979, MNRAS, 186, 875

Horne, K. D., & Steining, R.F. 1985, MNRAS, 216, 933

Katichuck, R. H., Honeycutt, R. K., & Schlegel, E.M. 1983, ApJ, 267, 239

Longmore, A. J., Lee, T. J., Allen, D. A., & Adams, D. J. 1981, MNRAS, 195, 825

Lutz, T. E., & Kelker, D. H. 1973, PASP, 85, 573.

Ramseyer, T. 1994, ApJ, 425, 243

Patterson, J. 1984, ApJS, 54, 443

Rutten, R.G.M., van Paradijs, J., & Tinbergen, J. 1992, A&A, 260,213

Shara, M. 1999. Personal communication

Smak, J. 1995, AcA, 45, 259

Smith, D. A., & Dhillon, V. S. 1998, MNRAS, 301, 767

Smith R C, Cameron A C, Tucknott D S 1993, in Cataclysmic Variables and Related Physics, eds Regev O, Shaviv G, IoP: Bristol, 70

Standish, E. M., Jr. 1990, A&A, 233, 252

van Altena, W.F., Lu, C.-L., Lee, J.T., Girard, T.M., Guo, X., Dellioumis, C., Platais, I., Kozhurina-Platais, V., McArthur, B., Benedict, G.F., Duncombe, R.L., Hemenway, P.D., Jefferys, W.H., King, J.R., Nelson, E., Sholes, P.S., Story, D., Whipple, A., Franz, O.G., Wasserman, L., Fredrick, L.W., Hanson, R.B., Klemola, A.R., Jones, B.F., Mendez, R., Tsay, W.-S., & Bradley, A. 1997, AJ, 486, L123

van Altena, W.F., Lee, J.T., & Hoffleit, E.D. 1995, New Haven, CT: Yale University Observatory, 4th ed., completely revised and enlarged

Wade, R.A. 1984, MNRAS, 208, 381.

Walker, M. 1963, AJ, 137, 485

Warner, B. 1995. Cataclysmic Variables, Cambridge University Press

Warner, B. 1995, Ap&SS, 232,89

Warner, B. 1987, MNRAS, 227,23

Young, P. J., & Schneider, D. P. 1981, AJ, 247, 960

This 2-column preprint was prepared with the AAS LATEX macros v4.0.
Fig. 1.— Histograms of x and y residuals obtained from modeling RW Tri and its reference frame. Distributions are fit with Gaussians.