

On the Distance of RS Ophiuchi

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Abstract. An unprecedented array of astronomical observatories were brought to bear on the 2006 outburst of RS Ophiuchi. Many calculations and values derived from these measurements are sensitive to the distance. Historically, the distance to RS Oph has fallen in the range 0.5 to >5 kpc with distances in the low end of this range asserted during later epochs. We survey the literature prior to 2006 and review the various approaches taken to determine distances. We report discussion of this issue from the current epoch and make recommendations for further measurements and calculations to bound the distance. Lastly, we report that for the 2006 outburst, the canonical distance is $1.4^{+0.6}_{-0.2}$ kpc.

1. Introduction

During the 2006 outburst of RS Oph, observations were conducted over much of the spectrum, including X-ray (Sokoloski et al. 2006; Bode et al. 2006), visible light, infrared (Monnier et al. 2006; Evans et al. 2006; Das et al. 2006), and radio (Anupama & Kantharia 2006; O'Brien et al. 2006). For the first time, interferometric observations were conducted with the Very Large Telescope Interferometer (Chesneau et al. 2007) and the Keck Interferometer Nuller (Barry et al. 2008). The assumed distance is, of course, a fundamental parameter in the interpretation of all of these.

To assess the true nature of this object, the absolute values of photometric magnitude, emission line and continuum intensity, and plateau luminosity must be determined. In addition, high angular resolution interferometric observations are particularly sensitive to distance (cf. Monnier et al. 2006;

Connelley & Sandage 1958). How does the rate of decline of intensity post-outburst relate to absolute magnitude? What is the density of absorbing circumstellar and interstellar material? Where is dust created? What is the density of the ejecta and the rate of mass transfer from the red giant (RG)? Is mass transfer via Roche lobe overflow or stellar wind capture? Without a reliable knowledge of the distance, our answers to such questions may be inaccurate and could have a significant effect on our understanding of the physics of the source.

In the first section, we survey the literature prior to 2006 and show which techniques remain effective and which need to be modified or re-calibrated. In the second section, we report discussion of this issue for the current epoch. In the third section we discuss outstanding issues and give our distance estimate. In the last section we recommend further measurements and calculations to put bounds on the distance.

2. The Historical Record

As described by Wallerstein in these proceedings, RS Ophiuchi has undergone six recorded nova outbursts at irregular interval in 1898, 1933, 1958, 1967, 1985 and now 2006. The earliest distance estimate was made by Payne-Gaposchkin (1957) following the discovery by Arp (1956) of a relationship between the maximum absolute magnitude and rate of decline (MMRD) of novae. Using RS Oph's fast speed class ($t_3 = 10$ d) and an extinction determined by Joy (1939) from a calibration using Galactic Cepheid variables she derived a distance of 1.7 kpc.

One year later, Connelly & Sandage (1958) derived a peak outburst absolute magnitude for RS Oph of -8.7 , again using the Arp MMRD relationship but, surprisingly, did not estimate a distance. Fully a decade later Pottasch (1967) used a new method (McLaughlin 1960) to check Arp's MMRD relation. A t_3 time of 16 days from the light curve of Eskioglu (1963) resulted in a peak absolute magnitude of $M_v(abs) = -8.5$ in good agreement with Connelley & Sandage. Combining these two estimates they obtained a distance of 5.8 kpc (although this should have been 5.6 kpc using the values they reported). Note Pottasch (1967) did not make a correction for reddening and so the t_3 time is overestimated, resulting in the largest distance estimate recorded.

Following the 1985 outburst and using new calibration of the MMRD relation by Cohen (1985), Cassatella (1985) obtained distances of 2.08 and 2.4 kpc from data on the 1933 and 1958 outbursts respectively (using t_2 times of 3 d and 7 d respectively). Cassatella et al. also introduced a new method of fitting a spectral type to the quiescent optical and NIR spectral energy distribution and noting the TiO bands identify the RG as an M0 III star. Estimates of the appropriate V-band absolute (Mikami & Heck 1982, -0.7) and apparent (Wallerstein 1963, 12.1) magnitudes led to a distance of 1.3 kpc. Cassatella et al. also note that if RS Oph were greater than 2.0 kpc away, the observations would show an interstellar absorption spectrum shifted by 20 km s^{-1} due to cool gas in the Carina spiral arm. Hence, as this was not detected, the MMRD distance is an upper limit.

One year later, Hjellming et al. (1986) reported radio observations including HI absorption measurements using the Very Large Array towards RS Oph and a neighbouring object. The density of neutral hydrogen along each line of sight

was estimated from a relation due to Dickey et al. (1983), yielding a distance of 1.7 kpc in agreement with the lower range of Cassatella et al. Importantly, Hjellming et al. did not see the Carina arm absorption in RS Oph whilst they did in the neighboring object, again confirming the result of Cassatella et al.

Livio et al. (1986) estimate a distance of 3.1 kpc modelling the binary system as two giant stars of type M2 and M0 (masses $3M_{\odot}$ and $2M_{\odot}$ respectively) with an orbital period of 230 days and a separation of $112 R_{\odot}$, a configuration which we now know to be inaccurate. However their assumption has some similarities to the Hachisu & Kato (2001) model, described below, in which the WD is essentially ‘reborn’ as an RG for a short period after outburst.

Identifying the object spectroscopically as an M0III, Evans (1987) inferred an intrinsic infrared brightness. IUE observations of RS Oph and a nearby Cepheid Y Oph allowed Evans to estimate that the reddening $E(B - V) = 0.73$ was largely interstellar which, when combined with the standard extinction law of Savage & Mathis (1979), led to a distance of 1.3 kpc.

Snijders (1987a) also confirmed the Cassatella et al. upper limit to the object of 2.0 kpc, from non-detections of line shifts in IUE observations of the 1985 outburst. Snijders (1987b) then used measurements of a bolometric luminosity plateau between days 8 and 35, as predicted by Starrfield (1985), to estimate a distance of 1.37 kpc assuming that this level was 99% of the Eddington luminosity for a $1.38 M_{\odot}$ WD. Using standard extinction laws (Seaton 1978; Seaton 1979) and a reddening of $E(B - V) = 0.73 \pm 0.1$ Snijders (1987b) obtains a distance of 1.6 kpc (a value particularly sensitive to the assumed reddening).

Sekiguchi et al. (1990) found a distance of 1.0 kpc from the K-band distance modulus assuming RS Oph contains a reddened Bulge-like M1 giant with quiescent $K_{mag} = 6.4$, $E(B - V) = 0.73$ (Frogel & Whitford 1987, Feast & Glass, private communication). However, Harrison (1993) could not reconcile the measured colors in a new quiescent K-band spectrum with those of spectral types M0III – M2III using reddening alone. They suggested missing CO absorption features were being filled in by CO emission and, assuming all K-band luminosity is from an M0III star, they obtained a distance of 1.29 kpc. Note Scott et al. (1994) later found the depth of the $2 \mu\text{m}$ CO bands changed significantly with time, which may affect this distance determination.

More recently, very low distance estimates were made by Hachisu & Kato (2000, 2001) in the context of a reborn RG model for the WD following the TNR. Hachisu & Kato (2000) assumed the UV flux from RS Oph arose in an accretion disk which, when dereddened, yielded a distance of 0.6 kpc. They also argue in favour of a small distance from several other lines of reasoning: the scale of the VLBI observations 77 days after the 1985 outburst (Taylor et al. 1989); the drop-off in soft X-ray emission perhaps caused by “shock break-out” from the RG wind (Mason et al. 1987; Itoh & Hachisu 1990) leading to a distance of 0.65 kpc; interpreting the soft X-ray emission 251 days after outburst as accretion luminosity onto a WD of mass $1.377 M_{\odot}$ and radius $R_{\odot}$ with a blackbody temperature 3.5×10^5 K, gives 0.4 kpc; comparison of predicted H_{β} emission from a $0.003 R_{\odot}$ WD suggests a distance of 0.6 kpc. Hachisu & Kato (2001) developed the disk model, calculating absorptions for a range of distances, and found that 0.57 kpc was consistent with the assumed $E(B - V) = 0.73$ (Snijders 1987b).

3. Epoch 2006

Following the 2006 outburst, Sokoloski et al. (2006) used a rough comparison between the expected physical size of the blast wave, based on the velocity evolution inferred from the post-shock gas temperature, and the size of the observed radio image to derive a distance of approximately 1.6 kpc. Rupen et al. (2008) later used a comparison between their more precise determination of the angular size of the expanding nova remnant seen in VLBI radio imaging and velocities from the broad bases of infrared emission lines, to obtain a distance estimate of 2.45 ± 0.4 kpc. Their use of the IR line widths at zero intensity (rather than, say, the line widths at half maximum, the velocities from optical spectra, or the X-ray velocities) however, was strongly motivated by the suggestion of Tatischeff & Hernanz (2007) that a substantial amount of energy could have gone into the acceleration of cosmic rays, so that the simple strong-shock relation between post-shock temperature and shock velocity might not be correct for RS Oph. In the event that the blast wave actually lost very little energy to cosmic-ray acceleration, so that the X-ray velocities accurately represent the motion of the blast wave, the estimate of Rupen et al. (2008) would become 1.4 ± 0.2 kpc. Systematic uncertainties relating to the inclination of the radio shell and the correspondence of the infrared emission with different parts of this shell were included.

A new determination of the cool red giant wind velocity of -36 km s^{-1} (Iijima, these proceedings) modifies the findings in Hachisu & Kato (2001). Using a shock breakout time of 90-100 days leads to a mean shock velocity of 3000 km s^{-1} along the line of sight and effectively doubles the distance estimate of Hachisu & Kato (2001) to about 1.2 kpc.

Lynch et al. (2006) gave a distance of 5.3 ± 0.5 kpc for V1187 Sco with an extinction of $A_V = 4.3$ magnitudes. Barry et al. (2007) note that if RS Oph had the same absolute V-band magnitude at peak brightness as V1187 Sco and is located at 1.6 kpc it should have a peak apparent magnitude in the range 4.6 to 5, comparable to that observed and hence confirming this distance.

Assuming a peak V-band magnitude of 4.5 on JD 2453779.329 (Narumi et al. 2006) and with $t_3 = 10.19$ days from AAVSO data, Barry et al. (2007) use a recalibrated MMRD (Downes & Duerbeck 2000) to obtain a peak absolute magnitude of $M_{V_{t3}} = -9.43 \pm 0.91$. Using $E(B - V) = 0.73 \pm 0.06$ (Snijders 1987a), $R_v = 3.1$ (Cardelli et al. 1989) they obtain an extinction $A_v = 2.263 \pm 0.186$ and hence estimate a distance of 2.44 ± 1.14 kpc. However, applying an upper limit of approximately 2.0 kpc from the lack of absorption from the Carina arm (see above), the distance range is then 1.65 ± 0.35 kpc. We note that there is some theoretical evidence that the use of the MMRD expression as derived for CN may not be directly applicable to RNe; however, historical values found using this method, while sensitive to calibration, do give distances that are within reason.

All historical and current distance estimates are recorded in Table 1. Distances are given together with the date of determination, the method used, and a reference. A comparison of the distance determinations grouped according to method is given graphically in Figure 1. Note that the extreme estimate by Potasch (1967) of 5.8 kpc has been removed as no dereddening was used.

Table 1. Distance determinations (D) for RS Ophiuchi

D (kpc)	Date	Method	Reference
1.7	1957	MMRD ^a	Payne-Gaposchkin (1957)
5.8	1967	MMRD	Pottasch (1967)
2.08 ^b	1985	MMRD	Cassatella et al.(1985)
2.4 ^b	1985	MMRD	Cassatella et al.(1985)
1.3	1985	QED, M0 III ^c	Cassatella et al.(1985)
≤ 2.0 ^d	1985	AGS ^e	Cassatella et al.(1985)
1.7	1986	HI ^f	Hjellming et al. (1986)
3.1	1986	RLO ^g QED, M0III + M2 III	Livio et al.
1.3	1987	QED, M0 III	Evans (1987)
≤ 2.0	1987	AGS	Snijders (1987a)
1.6	1987	EED, 1.39M _☉ ^h	Snijders (1987a)
1.44	1987	EED, 1.39M _☉	Snijders (1987b)
1.0	1990	QED, Bulge – M1 III	Sekiguchi et al. (1990)
1.29	1993	QED, M0 III	Harrison et al. (1993)
0.6	2000	Model UV ALED ⁱ	Hachisu & Kato (2000)
0.45	2000	UV ALED	Hachisu & Kato (2000)
0.57	2001	Model UV ALED	Hachisu & Kato (2001)
0.65	2001	SBT ^j	Hachisu & Kato (2001)
0.4	2001	Model SS X-ray ALED	Hachisu & Kato (2001)
0.6	2001	$H\beta$ absorption	Hachisu & Kato (2001)
1.6	2006	PDD ^k	Sokoloski et al. (2006)
2.45 ± 0.4	2007	PDD	Rupen et al. (2007)
1.2	2007	SBT	Hachisu
1.65 ± 0.35	2008	MMRD + AGS	Barry et al. (2007)
3.1 ± 0.5	2008	RLO QED, M0 III	Barry et al., these proceedings
$1.4^{+0.6}_{-0.2}$	2008	Aggregate 2006 distance	Barry et al., these proceedings

^aMaximum Magnitude Rate of Decline Relationship.^bMMRD applied to data from two outbursts: 1933 & 1958, respectively.^cQuiescent Extinction Distance estimate with identification of secondary.^dImposition of outer distance limit.^eUpper limit from Absence of Galactic Signature from Carina arm.^f $H\beta$ absorption.^gExtinction distance estimate assuming secondary Roche Lobe Overflow.^hEddington Extinction Distance estimate from Chandrasekhar-mass WD at Eddington limit.ⁱAccretion Luminosity Extinction Distance, post-outburst light dominated by disk luminosity.^jShock Breakout Timing^kParallax & Direct Deceleration, see text for how these PDD estimates are subject to discussion of Tatischeff & Hernanz (2007)

4. Outstanding Issues and a Distance Estimate

The first outstanding issue is that the true linear size of the RG, $R_g \sin i = 105 \pm 13 R_\odot$, as inferred from its rotation velocity (Zamanov et al. 2007) and assuming the giant is synchronized, appears quite large, implying the RG may

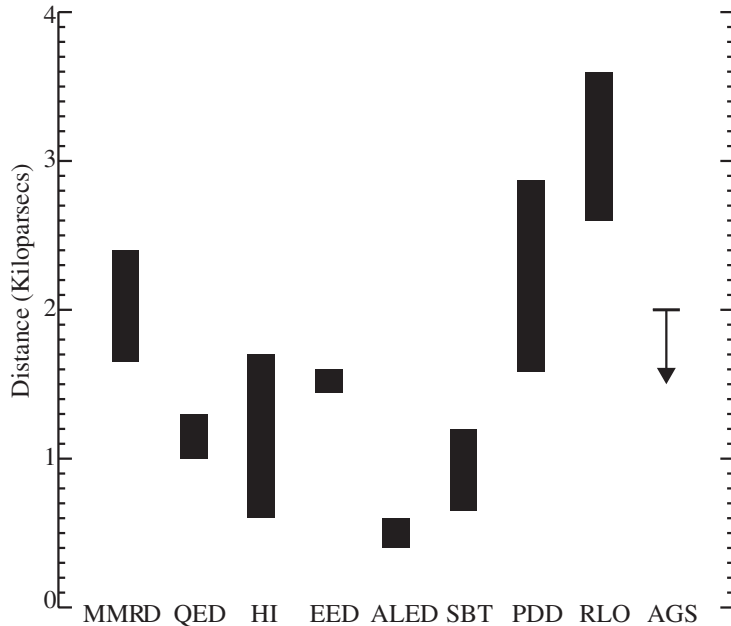


Figure 1. The different distance determinations for RS Ophiuchi grouped according to method as defined in Table 1. Note that the 5.8 kpc MMRD finding by Pottasch (1967) has been omitted, as indicated in the text.

fill its Roche lobe. If this is the case, the distance must be sufficiently large to account for the observed low flux levels in quiescence. Assuming the RL is filled and using binary parameters from Brandi et al. (these proceedings), we estimate $R_g = 106 \pm 15 R_\odot$, implying a distance of 3.1 ± 0.5 kpc. We note that if the RG is at about 1.5 kpc then these measurements imply the RG is a factor of two smaller than the RL, and its measured rotational velocity is at least twice the synchronized value. If the RG does *not* fill its RL and the distance is about 1.5 kpc, we have another outstanding issue: why are the evolutionary status and mass transfer mode of RS Oph so different from those of T CrB? In particular, RS Oph is more active during quiescence and has much shorter time between outbursts than T CrB. While it is possible that RG wind capture is the primary mass transfer mechanism, it is easier to ensure the required high mass transfer/accretion rate if the RG is filling or close to filling its RL.

A second issue is the effect of cosmic ray braking. Charged particles interact to first order, through the mediation of an amplified pre-existing magnetic field (Baring 2004; Lucek & Bell 2000), with the entire shock front, which has a significant mass and is travelling at around 3500 km s^{-1} . Those moving against the blast wave are preferentially boosted in energy, depleting the kinetic and thermal energy of the shock as they escape the region (and perhaps affecting its shape at early times). These interactions may cause a decrease in temperature of the post-shock plasma, a parameter which is used to estimate the shock velocity and obtain a distance from comparison to the radio angular size (cf. Sokoloski et al. 2006). Such a distance would then be an underestimate. Tatischeff &

Hernanz (2007) suggest that cosmic ray acceleration is indeed taking place in RS Oph.

Recently, Brandi et al. (these proceedings) have derived spectroscopic orbits for both stars based on the radial velocities of the M giant absorption lines and the broad emission wings of $H\alpha$. They have also constrained the orbit inclination, $i \geq 49 \pm 3$, using the estimated hot component mass, $M_h \sin^3 i = 0.59 M_\odot$, and assuming that the WD mass cannot exceed the Chandrasekhar limit. (Due to a lack of appropriate UV observations, we cannot establish whether the WD is spinning – and thus be theoretically allowed to exceed the mass limit as theorized by Yoon & Langer 2004). It is not clear, however, exactly how the orbital inclination is related to that of the radio ring observed by O’Brien et al. (2006). If the radio ring is really 2-dimensional, then the obvious explanation is that it is preferentially bright in the orbital plane. But, if this were true, its low inclination requires the orbital inclination to be low, which is excluded by Brandi et al. If, on the other hand, the radio ring is a limb-brightened sphere, as Rupen et al. (2008) suggest, then it should look circular whatever the orbital inclination and Brandi et al. does not constrain the result. In any case, it is evident from Rupen et al. that approaches that rely on geometric parallax will be sensitive to the origin of the radio ring and that this needs to be further measured, modeled and constrained.

Each of the effects outlined above would underestimate the distance. Given this, we suggest that the calculations of Sokoloski et al. (2006) and Rupen et al. (2007) (discounting cosmic ray braking) be taken as a lower limit, with the upper limit set by the absence of the Galactic signature. We note that this upper constraint is somewhat soft as it is unknown how deep within the Carina arm the object would have to be embedded to begin to show a measurable 20 km s^{-1} feature. This would bear further analysis through modeling of the density profile of the Galactic arm. We further note that the calculation in Barry et al. (2008) using the very latest, calibrated MMRD equation gives a number closer to the historical 1.6 kpc. Given these constraints and observations, we assert that a conservative estimate of the distance to RS Oph would then be $1.4_{-0.2}^{+0.6} \text{ kpc}$.

5. Some Possible Observations to Resolve the Distance Issue

One way of improving the distance estimate is through the use of interferometric measurements of the dust environment in the coming decade. Barry et al. (2007) propose a new physical model of RS Oph, in which spiral shock waves associated with the motion of the two stars through the cool wind from the red giant create density enhancements within the plane of their orbital motion. Interferometric measurements of this phenomenon, if the spiral does reform as hypothesized, taken together with new radial velocity measurements by Brandi et al. and the revised spectroscopic orbit calculated therein could be used to resolve the $\cos i$ ambiguity. New radio geometric parallax measurements could also be undertaken in the event that, in quiescence, the ring can still be detected.

We recommend that a renewed effort be made to measure the ellipsoidal variation of the RG using near infrared photometry over several orbital cycles. This will tell us the size of the RG relative to its Roche lobe. At the same time, high resolution spectra should be obtained at several orbital phases. An

independent confirmation of the rotation velocity as measured by Zamanov et al. (2007) would be worthwhile and would provide another estimate of the absolute size of the RG, since it may be co-rotating with the orbit. Similarly, spectroscopic observations should be undertaken similar to those of Hjellming (1986) to check for the absence of the Galactic signature and modeling should be conducted to determine the density profile of the Galactic arm. Finally, we recommend measurements and an analysis of the possible effects of cosmic ray braking in a nova outburst. Such measurements could possibly be undertaken using the recently-launched GLAST spacecraft.

6. Summary & Conclusion

We have reviewed the literature on the topic of the distance to RS Oph. We have also undertaken to identify the unknowns that bear on this calculation and conclude that the historical record speaks of large systematic uncertainties in the techniques used that require their careful calibration. Given this, we recommend that estimates should always be reported with an associated uncertainty interval. Finally, we report that for the 2006 outburst of RS Oph, the canonical distance is $1.4^{+0.6}_{-0.2}$ kpc.

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