New observations and analysis of the bright semidetached eclipsing binary $\mu^{1}$ Sco

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ABSTRACT

Using new and published photometric observations of $\mu^{1}$ Sco (HR 6247), spanning 70 years, a period of 1.446 2700(5) days was determined. It was found that the epoch of primary minimum suggested by Shobbrook at HJD 244 9534.178 requires an adjustment to HJD 244 9534.177 00(9) to align all the available photometric data sets. Using the resulting combined data light curve, radial velocities derived from International Ultraviolet Explorer data and the modelling software PHOEBE, a new system solution for this binary was obtained. It appears that the secondary is close to, or just filling, its Roche lobe.

Key words: binaries: eclipsing.

1 INTRODUCTION

$\mu^{1}$ Sco (HR 6247; HD 151890; HIP 82514) was only the third spectroscopic binary to be discovered and is listed in the General Catalogue of Variable Stars (GCVS) (Samus et al. 2004) as an eclipsing binary variable. Over the intervening years, there have been a number of detailed measurements and several significant studies. It is now classified as a semidetached (sd) binary as one component is believed to fill its Roche lobe. Cester et al. (1977) considered $\mu^{1}$ Sco, to be unusual owing to:

(i) their determination of an apparently high mass ratio;
(ii) indications that the secondary component has a larger radius than the primary and overflows its Roche lobe;
(iii) both components appear to lie on the main sequence and
(iv) it being a member of the Scorpius–Centaurus cluster thus indicating an age of no more than 10$^7$ years hence the possibility this system has just arrived on the main sequence.

A comprehensive analysis of $\mu^{1}$ Sco was undertaken to determine the best estimate of period from all available photometric data, establish a suitable epoch and calculate the key parameters defining the system.

The photometric data used included published measurements from:

(i) Rudnick & Elvey (1938),
(ii) van Gent (1939),
(iii) Stibbs (1948),
(iv) Tycho collected between 1990 and 1993 (European Space Agency 1997; Ochsenbein et al. 2000),
and new measurements taken in 2006, 2007 and 2008 by one of the authors (Moon).

The photometric data were then combined with radial velocities obtained by Stickland, Sahade & Henrichs (1996) from International Ultraviolet Explorer (IUE) spectral data (International Ultraviolet Explorer Data 2009) and the resulting data set analysed using the software program PHOEBE (Prša 2003; Prša & Zwitter 2005; Prša et al. 2008) based on the established Wilson & Devinney (1971) theoretical construct (Kallrath & Milone 1999).

2 PUBLISHED DATA

The star $\mu^{1}$ Sco was first reported to be a spectroscopic binary by Bailey (1896). Maury (1920) undertook an extensive study of this star using 184 spectra collected over the period 1892–1918 and obtained a radial velocity curve of one component with respect to the other. From these data, she determined a period of 1.446 27 d and selected an epoch for the zero-point of the recession of the brighter component of the binary at HJD 241 2374.434. The total light variation was between 0.3 and 0.4 of a magnitude and the combined mass of the system was estimated by her to have a minimum of 16.5 $M_{\odot}$.

Rudnick & Elvey (1938) made 128 photoelectric measurements of $\mu^{1}$ Sco using a photometer based on a Kunz potassium hydride (KH) photocell as described by Stebbins (1931). This cell had peak sensitivity near 460 nm and was typically used in conjunction with blue and yellow filters to define band passes with effective wavelengths around 400 and 500 nm. Rudnick and Elvey do not, however, indicate the band pass for their measurements or whether filters were used. Using their photometric measurements with the
spectroscopic elements given by Maury (1920), they determined the mass of the system to be 24.0 M☉, consistent with the minimum value of 16.5 M☉ determined earlier by Maury. Additionally, they estimated the effective temperatures of the components to be 17,000 and 13,000 K.

Around the same time, the light variations of μ¹ Sco were also measured by van Gent (1939) using photographic techniques. His 86 m/pg measurements showed variations for the primary and secondary eclipses of 0.30 and 0.19 mag, respectively – similar to that obtained by Rudnick and Elvey and consistent with the original estimate made by Maury. There was, however, a systematic difference in the magnitudes made on the two different systems with van Gent’s being 0.02 mag brighter than those of Rudnick and Elvey (although both sets of measurements used μ² Sco as the comparison star). This difference was attributed to the significantly different effective wavelengths at which the two sets of measurements were made as there is only a very small difference between the colour indices of the variable and comparison star.

For the magnitude versus phase plot of van Gent, there also appears to be a small shift in phase when it is compared to all the other photometric data sets. This shift corresponds to approximately 0.02 of the phase for the secondary minimum which equates to 40 min. It is not clear whether this is a real feature or a measurement error. When comparing the various photometric data sets (see Fig. 1), his is the only data set displaying this discrepancy. An adjustment was thus made to all van Gent measurements along similar lines to that discussed in Moon & van Antwerpen (2009).

In his analysis, van Gent (1939) noted the primary and secondary minima appeared to be symmetrically and equally spaced. By calculating the difference between the observed secondary minimum and the halfway point between consecutive primary minima, he showed the values for the eccentricity and longitude of periastron given by Maury were inconsistent with the observed light curve. Consequently, he suggested the eccentricity is close to zero and considered a circular orbit for his subsequent analysis. This was confirmed through new spectroscopic observations (see Stibbs 1948). Using the observed light curve, along with a radii ratio adopted from Maury’s estimate of line intensity ratios, van Gent determined the mass of the system to be 25.5 M☉ and the effective temperatures of the components to be 20,000 and 12,500 K.

Stibbs (1948) results were derived from 358 photoelectric observations made with a gas-filled sodium cell operating in a broad spectral passband from 325 to 570 nm with an effective wavelength of 397 nm. Using these data, along with the ratio of luminosities of the two components determined by Struve & Elvey (1942), he calculated orbital elements for the μ¹ Sco binary system and compared his results with those of Rudnick & Elvey (1938) and van Gent (1939) showing that there was general agreement between them. Stibbs determined the mass of the system to be 23.2 M☉; μ¹ Sco was thus considered to comprise a primary component around 13–14 solar masses with a secondary around 9 solar masses in a relative orbit with a radius of a little over 10⁶ km. The secondary was considered to be filling its Roche lobe and larger than the

![Figure 1](https://academic.oup.com/mnras/article-abstract/401/3/2059/1098628)
primary by about 10 per cent. The data tabulated were determined by assuming the measurements made were symmetrical about the epoch of the minimum under consideration, and then combined into normals containing 10 observations, the normals being formed progressively at intervals of five observations. This is in effect making the assumption that the orbit is circular. Stibbs then reduced his 358 observations to 72 values covering half a period. Only the 72 measurements are available from the literature.

Cester et al. (1977) analysed data for 12 systems classified as being sd-binaries which presented what was, at that time, regarded as an evolutionary paradox because the less massive secondary component appeared to be in a more advanced stage of evolution than the primary. For their analysis of $\mu^1$ Sco, they used Stibbs (1948) data and determined masses and radii consistent with earlier works. In their discussion of this star, Cester et al. (1977) remarked that the radius of the secondary, which appeared to be overflowing its Roche lobe, coupled with the high mass ratio was unusual for sd-binaries. Additionally, they regarded its position in Hertzsprung–Russell diagram to be unusual as both components appeared to be lying on the main sequence. Noting that $\mu^1$ Sco was a member of the Scorpius–Centaurus cluster whose age is at most 10$^7$ years, Cester et al. (1977) suggested that this star may have just arrived on the main sequence.

Schneider, Darland & Leung (1979) also studied $\mu^1$ Sco using Stibbs data and determined masses and radii generally consistent with earlier works. They evaluated the effective temperatures of the primary and secondary components to be 21 500 and 16 200 K but, in contrast to earlier works, found the primary component to be about 5 per cent larger than the secondary.

Shobbrook (2004) undertook a program of fresh observations of those bright eclipsing binaries which had not been observed for many years with a view to establishing more recent eclipses and more accurately determining their periods. Observations were made in the Strömgren $y$ band and transformed to $V$ magnitudes. Shobbrook determined a period of 1.446 270(1) d for $\mu^1$ Sco and established a new epoch for its primary minimum of HJD 244 9534.178 using his 112 new measurements, Hipparcos measurements and those taken by Stibbs 17 533 days earlier.

Hipparcos $H_p$ and Tycho $V_T$ magnitudes for $\mu^1$ Sco were taken from the Hipparcos and Tycho catalogues (European Space Agency 1997) made available through the vizier data base (Ochsenbein et al. 2000). The Hipparcos data cover the period from 1990 January 27 to 1993 February 22, and the Tycho data from 1990 February 10 to 1993 February 22. In the analysis undertaken, only data where the value of the quality flag was less than or equal to 2 were used.

Stickland et al. (1996) noted the paucity of radial velocity data available for $\mu^1$ Sco and undertook an analysis of spectroscopic data available from the IUE satellite (International Ultraviolet Explorer Data 2009), resulting in 19 measurements for each component. They noted the signal of the secondary to be less than one-third of that of the primary, making measurements of radial velocity for both components difficult. Based on their analysis, they concluded that the orbit may have a small eccentricity of 0.019 ± 0.017. Additionally, there could be effects arising from tidal influences, gas streams or gravity darkening. Stickland et al. (1996) determined the system to be at an inclination of approximately 62°, with a primary component of 8.6 M$_\odot$ and a secondary of 5.6 M$_\odot$, just filling its Roche lobe.

Arias et al. (2005) examined $\mu^1$ Sco spectra for discrete UV features and, in the process, obtained radial velocity estimates from the 18 spectra they collected during 1990 July. While stating their radial velocity estimates to be in very good agreement with those of Stickland et al. (1996), they only provide a combined spectral plot, the resolution of which is insufficient for a satisfactory estimate of velocity values to be made. Their results do, however, confirm those of Stickland et al. (1996).

Fig. 2 displays the radial velocity data and resulting theoretical fit using PHOEBE.

### 3 UNPUBLISHED DATA

Photoelectric measurements of $\mu^1$ Sco were made by one of the authors (Moon) from 2006 July 3 to 2008 October 8 using an Optec SSP-5A photometer attached to a permanently mounted 10-cm telescope that is housed in an observatory with a roll-off roof. For each measurement, the integration time is 10 s with each observation being the mean of five consecutive measurements. As the observatory is situated in an outer suburb of a major (Australian) city, the background sky was measured for each observation. When measuring through both $B$ and $V$ filters, the sequence was $V_{\text{star}}$, $B_{\text{star}}$, $B_{\text{sky}}$, $V_{\text{sky}}$ (Otero & Moon 2006). The resulting 133 new measurements of $V$ magnitude and 68 of $B - V$ were determined relative to $\mu^2$ Sco as function of phase using an epoch of HJD 244 9534.1770 and a period of 1.446 270 d.

### 4 ANALYSIS

#### 4.1 Correction of photometric measurements to Johnson $V$ magnitudes

The $\mu^1$ Sco photometric data assembled by the authors comprises measurements made with different photometric systems and is thus a heterogeneous data set; the particulars of the various photometric systems are given in Table 2. Corrections were applied to the individual data set to adjust them to the Johnson $V$ band. Owing to its line-of-sight alignment with $\mu^1$ Sco, and similarity in both magnitude and spectral type, $\mu^2$ Sco is an ideal comparison star and has been used as such by all observers listed here with most
\[ \mu^4 \text{ Sco} \text{ measurements given simply as a magnitude difference relative to } \mu^2 \text{ Sco}. \text{ In measurements made by Shobbrook (2004), and those by Moon, } \mu^2 \text{ Sco was used as the primary comparison star with HR 6214 used as a check star. The consistent use of } \mu^2 \text{ Sco as the comparison star makes the adjustment of the various data sets to the Johnson V band easier.} \]

The General Catalogue of Photometric Data (GCPD) (Mermilliod, Hauck & Mermilliod 1997) value of \( V \).
4.2 Determining effective temperature from photometric indices or spectral types

While separate spectra for the components of μ¹ Sco can be discerned, their spectral types remain somewhat uncertain. Maury (1920) first assigned a spectral type of B3 to both components but noted a difference in their line intensities which is discussed in detail by Struve & Elvey (1942). The GCVS classifies the components of μ¹ Sco as B1.5V + B6.5V although Stickland et al. (1996) discuss the possibility of the secondary being of a type earlier than B6.

As the measured colour indices for μ¹ Sco are for the combined light of the two components, tables of effective temperature and absolute magnitude as a function of spectral type or colour index cannot be readily used. It is, however, useful to examine if suitable values for the temperatures of the two components can be estimated from the combined light colour index so as to assist with the initial choice of these parameters for subsequent modelling.

Table 3 lists the GCPD (Mermilliod et al. 1997) mean photometric values in the UBV and uvby systems for μ¹ Sco (accessed online, 2008 December 18). Being at a distance of about 150 pc, interstellar reddening would be expected to be small for μ¹ Sco. Using the Q value calculated from the UBV photometry, assuming a standard reddening law can be applied to the combined light of the components, and using the relationships given by Budding & Demircan (1973) gave an E(1) = 0.02. Additionally, from the uvby data, an E(b − y) = 0.014 was calculated which is consistent with the calculated E(B − V) value. A value of B − V = −0.232 is thus adopted for the combined B − V colour index of μ¹ Sco.

With the data in Table 4 (assembled from various sources), the B − V colour arising from combination of various spectral types was then explored using a spreadsheet. Within the stated error of the listed B − V, the modelling indicated that the primary could not be earlier than B1.5V or later than B2V. For a primary of B1.5V, the colour index varied only slightly as the secondary was varied in type from B3V to B8V. Within the listed error for the colour index, the spectral type of the secondary thus remains indeterminate. Best estimates for the effective temperatures of the components of μ¹ Sco using the combined B − V colour index, the spreadsheet modelling and the values given in Table 4 are thus 22 800 K for the primary and between 12 000 and 17 000 K for the secondary.

The error in T_eff may be estimated from the errors in log(T_eff) for the stars used by Flower (1996) to determine his B − V, T_eff relationship. For the 26 stars listed with −0.30 < B − V < −0.15, a mean error in log(T_eff) of 0.02 was calculated. This translates to an error of approximately ±1000 K for an early B star.

Using the parallax of 6.51 ± 0.91 mas for μ¹ Sco given by van Leeuwen (2007), along with a V ≈ 3.0 for the combined light of the components, an M_V ≈ −2.9 ± 0.3 was calculated. This is consistent with a spectral type for the primary of B1.5V–B2V and in the range B3V–B8V for the secondary.

4.3 Choice of epoch

The earliest published photoelectric measurements with an accompanying epoch are those by Rudnick & Elvey (1938) where they applied a correction of −0.006 day to Maury’s published epoch. van Gent (1939), Stibbs (1948), Stickland et al. (1996), Danielkiewicz-Krosniak & Kurpinska-Winiarska (2002) and Shobbrook (2004) also supply epochs based on the primary minimum. Table 5 summarizes the various epochs listed. Shobbrook’s epoch was selected as a starting point as not only was it the most recent, but a small adjustment of the order of −0.001 day (within Shobbrook’s stated error of ±0.002 day) resulted in a good alignment of the available data sets. By trying different values around that given by Shobbrook, an epoch for the primary minimum of HJD 244 9534.177 00(9) was selected as the value where there was the best alignment of the available photometric data sets. This was confirmed using the fitting routine within the PHOEBE software.

4.4 Determination of the period

The period listed in the GCVS is based on that given by Stibbs (1948). More recent values are, however, available from Shobbrook (2004), or Arias et al. (2005). Table 5 details the various periods given in the literature with quoted errors where available.

Starting with Shobbrook’s period estimate, small adjustments were made until the data sets aligned. It was found that a period of 1.446 2700(5) d best represents the 512 measurements

| Sp. Type | B − V | M_V | T_eff | b − y | M_V(b − y) |
|----------|-------|-----|-------|-------|------------|
| B0       | −0.30 | −4.00 | 33620  | −0.120 | −3.75      |
| B1       | −0.26 | −0.30 | 34338  | −0.115 | −3.31      |
| B2       | −0.24 | −2.45 | 21261  | −0.102 | −2.08      |
| B3       | −0.20 | −0.80 | 16958  | −0.080 | −1.33      |
| B5       | −0.16 | −1.20 | 14203  | −0.068 | −0.97      |
| B6       | −0.14 | −1.12 | 13197  | −0.059 | −0.74      |
| B7       | −0.12 |       | 12368  |       |            |
| B9       | −0.09 | −0.25 | 11376  | −0.045 | −0.32      |
|         | −0.06 |       | 10612  | −0.037 | 0.22       |

Note. B − V indices are from Zombeck (1990), M_V from Cox (2000), T_eff from Flower (1996) and b − y and M_V(b − y) are from Moon (1985).
collected over the period of the available measurements which is about 70 years. Fig. 1 shows that there is an excellent alignment between the various data sets using this refined value of the period along with the chosen epoch. The fitting routine within PHOEBE confirmed this result.

4.5 The system’s orbital characteristics

PHOEBE was developed by Prša and Zwitter (Prša 2003; Prša & Zwitter 2005; Prša et al. 2008) and, while it is based on the Wilson–Devinney model (Wilson & Devinney 1971), it includes many recent theoretical developments (Kallrath & Milone 1999). Version 0.31a of the model (c. 2008) was used in this analysis. This software package requires separate radial velocity data for each component; hence, the extensive data of Maury (1920), which give a radial velocity for the components combined, were not used.

Using estimated spectral types for the components of μ¹ Sco, some parameters can be fixed in advance of modelling of the system’s orbital characteristics. Owing to the radiative nature of B-type stars, the albedos of both the primary and secondary components were set to one as were the values for gravity darkening. The synchronicity parameter for each star was also set to one. The option of an atmospheric model for the stars was enabled as was the option of a reflection effect (set to four reflections). Factors such as third light, opacity, extinction and starspots were not considered. The limb-darkening model adopted is based on a logarithmic law and van Hamme’s tables (van Hamme 1993).

μ¹ Sco is a member of the Scorpius–Centaurus OB association (Preibisch & Mamajek 2008), the nearest such association to the Sun. D’Orazi et al. (2009) have analysed the metallicity distribution of open clusters within 500 pc of the Sun and note that the majority of the clusters with close-to-solar metallicity are part of the local association which includes the Scorpius–Centaurus association. The metallicity for the μ¹ Sco components was thus set to the solar value.

The type of eclipsing binary to be modelled by PHOEBE is selected from a range of options. Initial attempts to fit the photometric data using some of the various options for the system failed to adequately represent features present within the data. It was found that the sd option, with the secondary filling its Roche Lobe, appeared to provide a solution that best represents all the photometric data. The analysis thus concentrated on this option although a detached option was also investigated as it was able to represent many of the key features as the size of the secondary approached its Roche limit.

4.5.1 Mass ratio, masses, semimajor axis and inclination

Using the radial velocity data of Stickland et al. (1996), based on IUE data (International Ultraviolet Explorer Data 2009), along with the PHOEBE software, radial velocity curves were obtained and the mass ratio, semimajor axis and inclination determined. These values (slightly different to those found by Stickland et al. 1996) are given in Table 6. Fig. 3 displays the radial velocity data from Stickland et al. (1996) and resulting theoretical fit.

While the values derived here are consistent with those of Stickland et al. (1996) to within the measurement errors, they are

Table 5. Published epochs of primary minimum and periods. Arias et al. (2005) values based on Danielkiewicz-Krosniak & Karpinska-Winiarska (2002).

| Reference                  | Epoch of minimum (HJD) | Period (d) |
|----------------------------|------------------------|------------|
| Maury (1920)               | 241 2374.434           | 1.446 27   |
| Rudnick & Elvey (1938)     | 242 8281.250           | 1.446 27   |
| van Gent (1939)            | 242 8414.2978          | 1.446 2683 ± 0.000 0004 |
| Stibbs (1948)              | 243 2001.0451          | 1.446 27 ± 0.000 001 |
| Stickland et al. (1996)    | 244 8102.521           | 1.446 271 ± 0.000 0044 |
| Shobbrook (2004)           | 244 9534.178           | 1.446 270 ± 0.000 001 |
| Arias et al. (2005)        | 243 2001.0475          | 1.446 26876 |
| Proposed in this paper     | 244 9534.17700        | 1.446 2700 ± 0.000 0005 |

Table 6. μ¹ Sco system properties determined from modelling and analysis.

| Property                      | sd model                  |
|-------------------------------|---------------------------|
| Primary star’s spectral type  | B1.5V (22, 800 ± 1000 K)  |
| Primary star’s mass           | 8.49 ± 0.05 M☉            |
| Primary star’s radius         | 4.07 ± 0.05 R☉            |
| Primary star’s T eff (PHOEBE) | 23, 725 ± 500 K           |
| Primary star’s potential      | 3.85 ± 0.01               |
| Secondary star’s spectral type| B8 – B3 (12, 000–17, 000 K)|
| Secondary star’s mass         | 5.33 ± 0.05 M☉            |
| Secondary star’s radius       | 4.38 ± 0.05 R☉            |
| Secondary star’s T eff (PHOEBE)| 16, 850 ± 500 K           |
| Secondary star’s potential    | 3.07 ± 0.01               |
| Orbital inclination           | 65.4 ± 1°                 |
| Semimajor axis                | 12.90 ± 0.04 R☉           |
| Eccentricity                  | 0.0                       |
| Orbital period                | 1.4462700(5) d            |
| Centre of mass velocity       | −6.26 ± 0.04 km s⁻¹       |
| Mass Ratio                    | 0.627 ± 0.004             |

Figure 3. PHOEBE’s theoretical fit to all of the measured magnitudes of μ¹ Sco as function of phase using an epoch of HJD 244 9534.1770 and a period of 1.446 2700 d.
4.5.2 Eccentricity, argument of periastron and surface potentials

Using the available data, noting the phase difference between the primary and the secondary minimums and the durations of the primary and secondary eclipses, it is possible to determine the eccentricity. After normalizing the photometric data sets, a best-fitting analysis using PHOEBE derived an eccentricity of zero thus indicating the orbit is circular. Consequently, the argument of periastron was set to zero along with the first time derivative of periastron. The circular orbit is consistent with previous analyses of $\mu$ Sco and that tidal interactions in close binaries tend to circularize the orbit over time (Hut 1981; Kallrath & Milone 1999). The surface potentials were estimated using the mass ratio, radii and semimajor axis values established from fitting the radial velocity curves.

4.5.3 System properties

The $\mu$ Sco system was modelled iteratively starting with the recent data acquired by Moon (presented in this paper) and that of Shobbrook (2004) as they have the smallest photometric errors and together comprise half of the photometric measurements taken to date. Using initial estimates provided by this first phase, all available data were then used in the modelling of the $\mu$ Sco binary system; the system properties thus determined are given in Table 6. These values differ markedly from those determined by Maury, van Gent, Rudnick and Elvey and Stibbs. In particular, the masses calculated are significantly less.

Similarly, the effective temperatures determined by PHOEBE were somewhat different to those determined in earlier studies but were found to be consistent with those estimated from the combined colour index. The theoretically derived fit, using the parameters in Table 6 and all available photometric measurements, is plotted in Fig. 3. A geometric configuration for the stars at phase 0.25 is presented in Fig. 4.

From the revised parallax for this star of 6.51 ± 0.91 mas (van Leeuwen 2007), the semimajor axis of the orbit is calculated to be 0.39 mas. This star may thus be a suitable target for the Sydney University Stellar Interferometer (SUSI).

5 CONCLUSIONS

The light variations of $\mu$ Sco appear to be stable over the 70 years for which photometric data exists. Using the comprehensive data set of more than 500 photoelectric measurements assembled here, the period was determined to be $1.4462700(5)$ d. A suitable epoch based on the primary minimum is suggested to be HJD 244 9534.177 00(9).

Using all readily available data, and the PHOEBE software package, the data for $\mu$ Sco could be best represented by considering the system to be an sd binary in which the size of the secondary is close to, or fills, its Roche Lobe. The system properties determined from comprehensive, iterative modelling using PHOEBE indicate that the masses of the components may be somewhat less than previously thought. With the secondary appearing to fill its Roche lobe, it may be possible to obtain spectroscopic evidence of gaseous streams in the $\mu$ Sco system noting that Doppler tomography has produced indirect images of gas flows in interacting binaries (Richards 2006). However, for Algol-type binaries the gaseous streams are faint relative to the main-sequence primary star and their detection challenges current techniques. Improvements to techniques would likely be required to detect such gas flows in $\mu$ Sco.

There are currently only limited radial velocity data available for the $\mu$ Sco. Given that the radial velocity data provide initial values for parameters such as the semimajor axis, masses and radii, further data could be useful in improving the modelling of this binary system. Additionally, photometric measurements near phases 0.1, 0.4, 0.6 and 0.9 could aid refinement of the current theoretical model through better defining some apparent features.

With the semimajor axis of the orbit subtending 0.39 mas, this star may be a suitable target for the SUSI.

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Figure 4. A geometric configuration for $\mu$ Sco at phase 0.25 based on the modelling and analysis undertaken, axes in units of semimajor axis.
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