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MML 53: a new low-mass, pre-main sequence eclipsing binary in the Upper Centaurus-Lupus region discovered by SuperWASP

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ABSTRACT

We announce the discovery of a new low-mass, pre-main sequence eclipsing binary, MML 53. Previous observations of MML 53 found it to be a pre-main sequence spectroscopic multiple associated with the 15–22 Myr Upper Centaurus-Lupus cluster. We identify the object as an eclipsing binary for the first time through the analysis of multiple seasons of time series photometry from the SuperWASP transiting planet survey. Re-analysis of a single archive spectrum shows MML 53 to be a spatially unresolved triple system of young stars which all exhibit significant lithium absorption. Two of the components comprise an eclipsing binary with period, $P = 2.097891(6) \pm 0.000005$ and mass ratio, $q \sim 0.8$. Here, we present the analysis of the discovery data.

Key words. binaries: eclipsing – stars: pre-main sequence – stars: fundamental parameters

1. Introduction

Eclipsing binaries are systems in which the masses, radii, temperatures, and absolute luminosities can be measured for two stars with the same age and metallicity (Andersen 1991; Young et al. 2001). In addition, apsidal motion measurements, if available, can further constrain interior stellar physics (Young & Arnett 2005; Schwarzschild 1957). Therefore, these objects are effective tools used extensively for calibrating and testing theoretical stellar evolution models.

Pre-main sequence (PMS) eclipsing binaries are particularly important. Young stars are changing rapidly as they contract onto the main sequence and heat up, so an individual solar-type star covers a large range of temperatures and radii in its first 50 Myr. Furthermore, young stars often have star spots, coronal activity, and/or circumstellar dust which complicates the physics of their formation and early evolution. Thus, empirical measurements of fundamental properties of young stars with a range of masses and ages are needed to fully constrain the pre-main sequence evolution and understand how the properties of young stars are affected by other parameters (e.g. magnetic fields, dust, metallicity, planets, multiplicity).

Pre-main sequence eclipsing binaries are the only objects which can provide precise measurements of the most fundamental physical properties of young stars, however these objects are extremely rare. There are only six known low-mass pre-main sequence eclipsing binaries with $M < 1.5\ M_{\odot}$: RXJ 0529.4+0041A (Covino et al. 2000, 2004), V1174 Ori (Stassun et al. 2004), 2MASS J05352184-20130546085 (Stassun et al. 2006, 2007), JW 380 (Irwin et al. 2007), Par 1802 (Cargile et al. 2008; Stassun et al. 2008), and ASAS J052821+0338.5 (Stempels et al. 2008). In addition, EK Cep (Popper 1987), TY CrA (Casey et al. 1998), and RS Cha (Alecian et al. 2005, 2007) are known to be higher mass eclipsing systems with at least one PMS component.

In this paper, we announce the discovery of a new low-mass PMS eclipsing binary, and the first such object discovered outside of the Orion star forming region. We describe the observations that were used to identify the object as a PMS eclipsing binary (Sect. 2). Using the discovery data, we determine initial orbital parameters for the system and approximate physical properties of its component stars (Sect. 3). Finally, we discuss future observations needed to fully analyse this important system (Sect. 4).

2. Observations

TYC 7310-503-1 (α =14:58:37.7, δ = −35:40:30.4), MML 53, is a late-type star spatially located in the region of the Scorpius Centarus OB association complex. It was identifed as an X-ray source by ROSAT (RXJ1458.6-3541) which lead to further spectroscopic study by several groups with the aim of identifying young stars and mapping the overall star forming region (Wichmann et al. 1997a,b; Mamajek et al. 2002; Torres et al. 2006; White et al. 2007). The object was first identified as a

Table 1. Properties of MML 53 obtained from the literature.

Parameter	Value	Reference
RA(J2000)	14:58:37.70	
Dec(J2000)	–35:40:30.4	
VT	10.88 mag	1
I	9.85 ± 0.04 mag	2
J	8.639 ± 0.024 mag	3
H	8.062 ± 0.055 mag	3
K	7.870 ± 0.026 mag	3
μ_{RA}	−22.3 ± 1.1 mas yr^{-1}	4
μ_{Dec}	−25.0 ± 1.1 mas yr^{-1}	4
SpT	K2IVe	5
π	7.36 ± 0.77 mas	5
γ	2.0 ± 3.1 km s^{-1}	6
$v \sin i$	30.8 ± 3.1 km s^{-1}	6

References. (1) TYCHO (Høg et al. 2000); (2) DENIS (The Denis Consortium 2005); (3) 2MASS (Skrutskie et al. 2006); (4) NOMAD (Zacharias et al. 2004); (5) (Mamajek et al. 2002); (6) SACY (Torres et al. 2006).

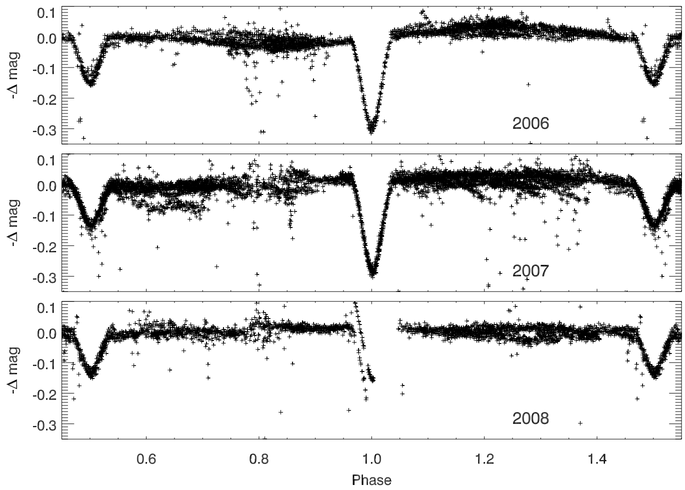

Fig. 1. WASP-South photometry of MML 53 from 2006–2008 obtained in a broad V+R-band filter. The data are phase-folded with the ephemeris derived from the eclipse model, HJD = 2 454 301.3252(7) ± 0.002 + 2.097891(6) ± 0.000005.

T Tauri star (K3-type) through the detection of Li I λ6708 absorption by Wichmann et al. (1997b). Hα emission and significant lithium absorption were detected in all subsequent spectroscopic observations, therefore MML 53 is confirmed to be a young, pre-main sequence (PMS) object.

Mamajek et al. (2002) also kinematically and spatially defined MML 53 as a member of the 15–22 Myr old Upper Centaurus Lupus (UCL) sub-association with a 93% probability. The authors classified the object as a K2IVe star based on several spectroscopic indices and determined a kinematic parallax of 7.36 ± 0.77 mas (136^{+16}_{-13} pc). These values and the high probability of membership in UCL are confirmed in more recent work by these authors (Mamajek, priv. comm.). Torres et al. (2006) made a rotation measurement of $v \sin i$ = 30.8 ± 3.1 km s^{-1} and were the first to identify the target as a possible spectroscopic triple system with a systemic radial velocity, γ = 2.0 km s^{-1}. White et al. (2007) detected a double-lined nature for the object with a single observation and measured the equivalent width of lithium in the individual primary and secondary components (122 and 222 mÅ). White et al. (2007) do not explicitely state which binary component is associated with the reported Li I *EW* values since they are unable to derive an orbit from their spectrum. The approximate values we derive for Li *EW* in Sect. 3.3 are consistent with these measurements if we assume the primary star has the larger *EW* (222 mÅ).

As a known PMS object, MML 53 has also been included in the Spitzer Legacy project investigating the formation and evolution of planetary systems (FEPS) Meyer et al. (2006). Spitzer observations of the object were obtained in all IRAC and MIPS bands from 3.6–70 μm (Carpenter et al. 2008), but no primordial or a debris disk was detected (Silverstone et al. 2006; Carpenter et al. 2009). In Table 1, we list the known properties of the star obtained from the literature.

2.1. SuperWASP photometry

In addition to the targeted surveys of young stars mentioned above, MML 53 was observed in the field-of-view of the SuperWASP transiting planet survey (Pollacco et al. 2006). SuperWASP is a wide-field photometric variability survey designed to detect transiting gas-giant planets around bright main sequence stars. The survey cameras repeatedly (∼8 min sampling) observe bright stars (V ∼ 9−13) at high precision (1%) using a broad V+R-band filter.

MML 53 was observed with the WASP-South telescope and instrumentation (Pollacco et al. 2006; Wilson et al. 2008) in the spring observing season from 2006 to 2008. 3492 photometric data points were obtained between 4 May–30 July 2006; 5602 measurements were made between 16 Feb. 2007–19 July 2007; and 2886 observations were taken from 18 Feb. 2008–17 Apr. 2008. All data sets were processed independently with the standard SuperWASP data reduction and photometry pipeline (Collier Cameron et al. 2006). The light curves, which were detrended along with other stars in the field using the SysRem algorithm (Tamuz et al. 2005), were then run through our implementation of the box least squares (BLS) algorithm (Kovács et al. 2002; Collier Cameron et al. 2006). The BLS algorithm is designed specifically to detect square shaped dips in brightness in an otherwise flat light curve. It is very effective at detecting transits by extrasolar planets (Tingley 2003) and eclipsing binary systems (Hartman et al. 2009).

Using the BLS algorithm, we identified MML 53 as having an eclipsing binary light curve with a period of ∼2.1 days. Figure 1 shows the phase-folded SuperWASP data. The target is isolated, and the field-of-view shows no other nearby stars that could have contaminated the large photometry aperture (∼48″) causing the resulting light curve.

The primary and secondary eclipses are apparent in the light curve as well as sinusoidal out-of-eclipse variability which is particularly evident in the 2006 data. Brightness variations due to photospheric star spots are often present on young and/or active stars and can be used to measure stellar rotation periods. Thus, we investigated the presence of rotational variability on MML 53 to determine if the system is tidally synchronized. We measured the period of the out-of-eclipse variability by applying the Lomb-Scargle algorithm (Scargle et al. 1982; Horne & Baliunas 1986) to each season's light curve independently after removing all the in-eclipse data. We searched periods between 0.2–30 days. In the 2006 data, there is a highly signficant sinusoidal signal with a period, P = 2.09 days (see Fig. 2). Aliased peaks due to the window function are also present at a reduced

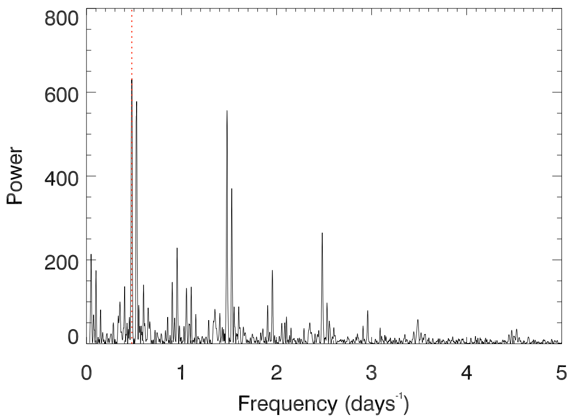

Fig. 2. Lomb-Scargle periodogram results from the 2006 SuperWASP photometry with the in-eclipse data removed. Periods between 0.2–30 days were searched. A periodic signal was detected at $P \sim 2.09$ days in all 3 seasons of data, but the signal is strongest in the 2006 data shown here. The dotted line denotes the orbital period of the binary, $P = 2.097891(6) \pm 0.000005$.

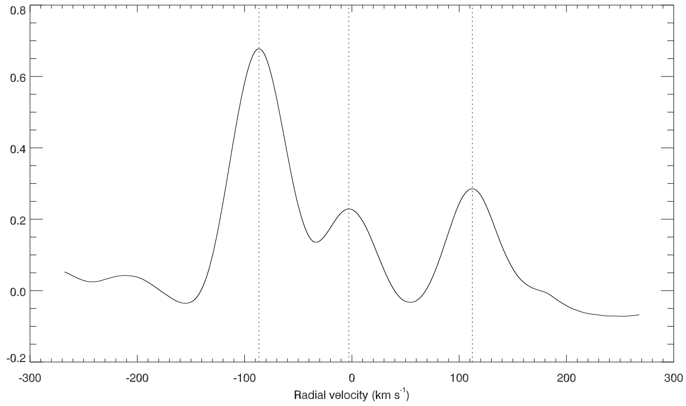

Fig. 3. Cross correlation function of the FEROS spectrum of MML 53 obtained on 2006 June 23 compared to the template. The analysis shows three different spatially unresolved components in the system with radial velocities of −85.8, 111.1 and −3.5 km s^{-1} for the primary, secondary, and tertiary components, respectively.

amplitude. In the 2007 and 2008 data sets, the signal is weaker, but still present. This period is matched to the orbital period of the binary suggesting the out-of-eclipse variability is due to starspots on the surface of one or both of the binary components and that the component stars are rotating synchronously with the orbit. The sinusoidal variability is changing phase and amplitude on the timescale of months which manifests as visible scatter in the light curve (see Fig. 1) indicating a slow drift in the starspot pattern, but the measured rotation period is consistent in all the seasons of data. For a short period binary like MML 53, we expect the components to be rotating synchronously despite their young age (Zahn & Bouchet 1989; Mathieu 1994, and references therein).

2.2. Archive FEROS spectrum

After determining the system was an eclipsing binary, we searched for existing archival spectroscopic data on the object and found one high resolution ($R \sim 50\,000$) spectrum located in the European Southern Observatory (ESO) archive. The spectrum was obtained at heliocentric Julian date, HJD = 2 453 909.622300 with the FEROS spectrograph on the 2.2m ESO telescope at La Silla (observing program 077.C-0138(A), which forms the basis of the SACY survey, see Torres et al. 2006). We reduced this spectrum with the echelle data reduction package REDUCE (Piskunov & Valenti 2002), using calibration data obtained on the same night. We also downloaded and reduced the spectrum of a radial velocity standard, HD 10700. Our final reduced spectrum covers the wavelength range of 3765–8862 Å and has a signal-to-noise of ~30 per pixel at 6000 Å.

When the spectrum was examined by eye, multiple stellar components were clearly present as previously reported (Torres et al. 2006; White et al. 2007) and as expected for an eclipsing binary where both the primary and secondary eclipses are visible. However, White et al. (2007) report the system as a double-lined spectroscopic binary (SB2) while Torres et al. (2006) suggest the possibility of a third component (SB3). To determine whether the system contains a third star and to measure the radial velocities of the components, we perform a standard cross-correlation (Fig. 3) and also apply our implementation of the least-squares deconvolution (LSD) algorithm to the MML 53 spectrum. Least-squares deconvolution allows for deriving a very high signal-to-noise average absorption line profile of the system by properly combining the many individual lines throughout the entire spectrum (Donati et al. 1997). This technique can be used in spectroscopic binary work to identify faint unresolved companions. Both the cross-correlation function (CCF) and the result of the LSD analysis clearly show three stellar components present in the spectrum. We measure their radial velocities to be −85.8, 111.1 and −3.5 km s^{-1}, for the primary, secondary and tertiary, respectively.

3. Analysis

3.1. Light curve modelling

In order to derive an ephemeris for the system and initial parameters for the individual eclipsing binary components, we first generated a single rectified light curve from the discovery data by removing the out-of-eclipse variability on each night and combining all three seasons of SuperWASP photometry. We fit a second order polynomial to the out-of-eclipse photometry on each night and applied the polynomial fit to all the data obtained that night. We excluded from the rectified light curve any data taken on nights in which there was no out-of-eclipse photometry. The fitting functions are not physical, and we made no attempt to model the starspot variability because the existing data are only in a single band and therefore any physical model would be too full of degeneracies to provide a useful result. The data include 17 near complete primary or secondary eclipses which show the eclipse minimum and out-of-eclipse photometry before and/or after the eclipse. The final rectified light curve contains 11 808 photometric measurements.

We fit the rectified light curve using the JKT eclipsing binary orbit program (EBOP) (Popper & Etzel 1981; Southworth 2007). The program determines the optimal model light curve that matches the observed photometry and reports the binary parameters for the model. The algorithm on which it is based is only valid when analysing well-detached eclipsing binaries in which the tidal distortion is small (i.e. nearly spherical stars with oblateness <0.04). This is the case for MML 53. The derived light curve parameters include the period, P, time of minimum light, T_0, surface brightness ratio in the SuperWASP filter, J_{V+R}, relative sum of the radii, $(R_1 + R_2)/a$, inclination angle, i, eccentricity, e, and angle of periastron, ω. The routine takes into

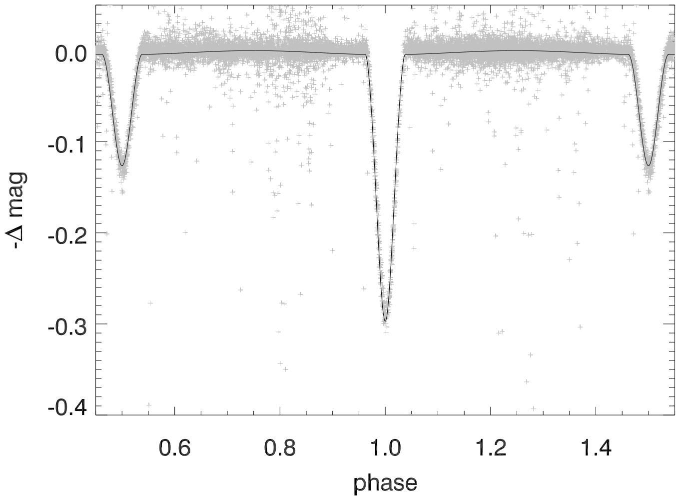

Fig. 4. Rectified SuperWASP light curve phase-folded with ephemeris, HJD = 2 454 301.3252(7) ± 0.002 + 2.097891(6) ± 0.000005. The EBOP model fit is overplotted (solid black line).

account the effects of limb darkening, gravity brightening, and reflection effects and can account for the presence of light from a third component.

We adopted the quadratic limb darkening coefficients from Claret (2000) using the temperatures for the eclipsing components that are defined below in Sect. 3.3, $T_{\rm eff,1}$ = 4886 K and $T_{\rm eff,2}$ = 4309 K. We initially ran the fitting program allowing the eccentricity to be a free parameter, however the resulting value was within 3σ of zero, and there is no further evidence in the light curve for a non-circular orbit.

Thus, in the final run of the light curve modelling program, we fixed the eccentricity and angle of periastron to zero. The result is shown in Fig. 4 with the best fitting model overplotted on the final rectified light curve. The fit provides a precise system ephemeris of:

$$\begin{aligned}\mathrm{Min(HJD)} &= 2\,454\,301.3252(7) \pm 0.002\\ &\quad +2.097891(6) \pm 0.000005\,E.\end{aligned}$$

As an additional check, we determined the ephemeris from each individual season of data, and found the periods agree to within 5×10^{-6} days. However, the epoch of mininum light varies by ~0.001 in phase (~3 min) between the 2006 and 2007–2008 seasons. This offset could be caused by effects from the third component (e.g. direct gravitational influence, light travel time variations), if ultimately confirmed with current epoch eclipse data. Based on the variations from season to season, we adopt an uncertainty on the time of minimum light of 0.002 days and an uncertainty on the period of 0.000005 days.

The model fit also gives a measurement for the relative sum of the radii, $(R_1 + R_2)/a$ = 0.260, the inclination angle, i = 83.1°, and the surface brightness ratio in the SuperWASP filter, J_{V+R} = 0.461. These values depend on the flux contribution of the third component which we estimate to be 15% of the total luminosity based on our self consistent analysis of the light curve and the FEROS spectrum described in Sect. 3.3. However, we stress that the fitted parameters will change when definitive temperatures for all three components and accurate luminosity ratios can be derived through spectral disentangling of multiple high resolution, high signal-to-noise spectra of MML 53. Furthermore, star spots which we know are present are likely to have an affect on these parameters, and multi-band photometry is necessary to derive a comprehensive solution that models both the spots and the eclipses.

3.2. Initial estimates of the masses and radii of the MML 53 eclipsing components

Using the radial velocity measurements of the primary and secondary star from the single archive spectrum, the precise ephemeris and inclination angle estimate from the photometry, and the systemtic radial velocity from the literature, we derive approximate masses for the individual eclipsing components of MML 53. The FEROS observation was obtained very near to quadrature at an orbital phase of 0.287. With the phase of the observation fixed, the radial velocity measurements for the primary and secondary (−85.8, +111.1 km s^{-1}) constrain the amplitudes of the sinusoidal (circular orbit) radial velocity curves for the two components, K_1 and K_2. Adopting 2.0 km s^{-1} (Torres et al. 2006) for the systemic RV, we find K_1 = 90 and K_2 = 112 km s^{-1} (assuming no uncertainty in the RV measurements). This gives a mass ratio for the system, M_2/M_1 = 0.8. Taking the period and inclination angle derived from the SuperWASP eclipse photometry, we find individual masses of $M_1 \sim 1.0\ M_\odot$, $M_2 \sim 0.8\ M_\odot$, and an orbital separation, $a \sim 8.4\ R_\odot$.

The derived mass estimates are consistent with the pre-main sequence status of MML 53 determined from the observed youth indicators previously discussed. Young stars should be comparatively large in radius, since they are still contracting onto the main sequence. For MML 53, the sum of the radii measured from the light curve ($R_1 + R_2$ = 2.2 $R_\odot$) is ~30% larger than what is expected for two main sequence stars (age of 300 Myr) with masses of 1.0 and 0.8 $M_\odot$ according to theoretical stellar evolution models (Baraffe et al. 1998).

Finally, we note the properties of MML 53 derived here are only approximations, and a complete radial velocity curve will be required to determine accurate masses for the stellar components of MML 53. Furthermore, the third component, which cannot be studied in detail with the existing data could also affect the radial velocity measurements if it is found to be gravitationally bound to the system, which is still unknown.

3.3. Composite model spectrum: temperatures and lithium abundances

Despite the lack of time-series spectra, we perform a joint analysis of the single observed FEROS spectrum and the SuperWASP light curve in order to approximate the effective temperatures, radii and relative luminosities of the three stellar components of MML 53. To do this, we derive a three-component model spectrum (based on synthetic Kurucz 1993, model atmospheres) that is a reasonable fit to the observed spectrum and is also consistent with the constraints from the light curve. The model for each component is defined by its effective temperature and its luminosity relative to the total system luminosity at ~6700 Å (R-band). These properties are interdependent, so we iterate until they provide a self consistent solution.

After several iterations, we find temperatures of 4886 K, 4309 K, and 4130 K for the primary, secondary and tertiary, respectively. In addition, the fractional R-band luminosities we use to scale the model spectra are 0.64:0.21:0.15 for the three components. These values provide a self consistent solution in which the third light input value for the light curve model is reproduced by the final temperature and radius of the tertiary. In addition, the properties of the eclipsing components are consistent with

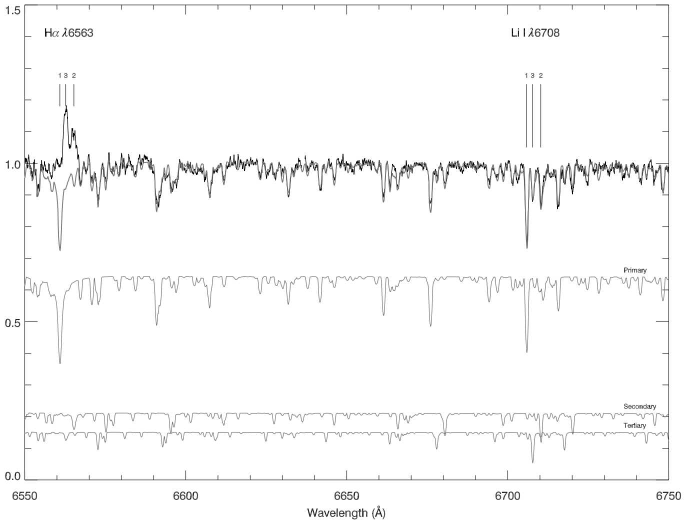

Fig. 5. FEROS spectrum of the order containing Hα and the Li I doublet at 6708 Å. The solid black line is the observed spectrum. Overplotted is the three-component model spectrum (grey line). The model is a good match to the observed spectrum except near Hα where MML 53 shows emission and the model shows significant absorption. Plotted below are the three individual synthetic spectra with temperatures of 4886 K, 4309 K, and 4130 K for the primary, secondary and tertiary. They are scaled according to the derived *R*-band luminosity ratios of 0.64:0.21:0.15 and shifted by the velocity offsets found in the CCF analysis.

the light curve model. Finally, these values result in a composite model spectrum which is a good match to the absorption line depths of all three components in the observed spectrum in the region between Hα and Li I. In Fig. 5, we show this region of the observed spectrum (black solid line) overplotted with the composite model defined by our best fitting stellar properties. The model assumes a solar metallicity for all three components, and we adopt rotational velocities for the stars of $v \sin i = 29.0$, 23.2, and 20.0 km s^{-1}. Note that the $v \sin i$ values for the primary and the secondary are determined from the assumption of corotation and are reasonably consistent with the value of 30.8 km s^{-1} measured by Torres et al. (2006).

As can be seen in Fig. 5, MML 53 shows significant Li I absorption in all three components and Hα in emission for the secondary and tertiary. We measure the equivalent width (*EW*) for each Li line in the combined spectrum to be 236, 75, and 82 ± 10 mÅ for the primary, secondary and tertiary, respectively. We then correct each of these values for the increased contiuum due to the other components to derive corrected equivalent widths of $EW(\text{Li}) = 369 \pm 15$, 356 ± 47, 550 ± 67 mÅ which we translate into lithium abundances of $\log n$ (Li) = 3.2, 2.3, and 3.0.

The uncertainties on the lithium *EW*s quoted above do not include the systematic error in the relative luminosity ratios which are difficult to estimate. The lithium abundance of the tertiary is unexpectedly larger than that of the secondary which suggests some inaccuracies in our derived temperatures and luminosities. However, with additional observations of time series spectra, we will be able to apply spectral disentangling which will allow for deriving accurate temperatures for the individual components and measuring Li equivalent widths to greater precision.

4. Summary

We report on the discovery of a new pre-main sequence ecipsing binary, MML 53, located in the Lupus star forming region. There are very few such objects known, but they are extremely important for informing and calibrating stellar evolution models at young ages where stars are changing rapidly as they contract onto the main sequence. This is only the seventh low-mass PMS eclipsing binary to be discovered.

Previous studies found the object to be a young spectroscopic multiple system associated with the 15–22 Myr Upper Centaurus Lupus cluster. Through our analysis of SuperWASP photomery and a single archive spectrum, we determine MML 53 to be a triple system of young stars where two of the components are eclipsing. All three components show significant lithium absorption, and Hα emission is seen in the secondary and tertiary.

We determine the orbital period of the eclipsing pair to be $P = 2.097891(6) \pm 0.000005$ using many primary and secondary eclipses observed with the SuperWASP instrument over several years. The light curve also shows out-of-eclipse variability consistent with star spots on the surface of at least one of the eclipsing components which is rotating synchronously with the orbit.

Analysis of the existing data suggests the eclipsing component stars have masses of $M_1 \sim 1.0\ M_\odot$ and $M_2 \sim 0.8\ M_\odot$. Therefore, MML 53 is a slightly older analogue of the V1174 Ori PMS eclipsing binary found in the ∼10 Myr Orion OB1c sub association ($M_1 = 1.0\ M_\odot$ and $M_2 = 0.73\ M_\odot$). When MML 53 is fully analysed, relative comparison of the two objects will allow for constraining the PMS evolution of a solar-type star to very high accuracy. In addition, because MML 53 has an expected age older than any of the other known low-mass PMS eclipsing binaries, it will be valuable for exploring a slightly later stage of PMS evolution.

However, additional data is required to derive precise fundamental properties for the components of MML 53 before comparing to stellar evolution models and other PMS eclipsing binaries. Time-series spectroscopic data are needed to define a complete radial velocity curve which will allow for determining masses of the primary and secondary components. Additional high resolution, high signal-to-noise spectra will allow for determining precise temperatures and relative luminosities of the three components stars. Multi-band photometry will ultimately provide a complete solution for the system with individual masses, radii, temperatures and luminosities for two young, pre-main sequence stars.

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