

# Measuring Radial Velocities of Low Mass Eclipsing Binaries

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Due to the complex nature of the spectra of low-mass M type stars, it is difficult to determine their metallicities and temperatures directly. By studying eclipsing binary pairs comprising one F, G, or K type star with an M type star, we are able to use what we know about the primary star to learn more about the secondary star. For example, measuring the orbital reflex motion of the primary star, together with the eclipse light curve of the M star as it transits the primary star, allows us to determine the mass, radius, temperature, and metallicity of the M star.

We studied 23 low mass eclipsing binaries (EBLMs) previously discovered by SuperWASP photometry. We obtained spectra using the Cerro Tololo Inter-American Observatory (CTIO) SMARTS 1.5-meter echelle spectrograph between June 2009 and January 2011. Each EBLM target was typically observed about 8 times over this time period. The spectra were processed using standard astronomical software, and a cross-correlation method was used to measure the radial velocity of the target star at each observed epoch.

Radial velocities were successfully determined for 21 of the 23 EBLM target objects. Orbital periods, radial velocity amplitudes, and eccentricities for these EBLMs were determined from these radial velocities together with the preexisting light curves. Using these values and by assuming a mass for the primary star, we will be able to calculate the masses of the secondary M type star in each EBLM system.

## Introduction

The main goals of this research were to determine radial velocities of F/G/K + M eclipsing binary stellar systems in order to study the orbits of the systems. M type stars are the most common class of star (with masses of  $0.1 - 0.4 M_{\text{Solar}}$ ), but these stars are also the most difficult for which to obtain accurate measurements. As a result, the mass-radius relationship currently used for M stars is not very accurate, which leads to discrepancies in stellar evolution models. By studying F/G/K + M eclipsing binaries, also called low mass eclipsing binaries or EBLMs, we can obtain a more accurate mass-radius relationship for M stars in these systems, which can then be applied to M stars in general, leading to more accurate stellar evolution models (Hebb et al 2007) (Stassun et al 2006).

The cooler temperature of M type stars allows for the presence of molecules on the stars, which make their spectra very complex. This makes the metallicity and temperature of this class of star very difficult to measure directly. However, the simpler spectra of F, G, and K type stars make their metallicities and temperatures possible to accurately determine directly. Therefore, studying pairs of an M star with an F, G, or K type star is beneficial because it allows us to determine properties like metallicity for the M star, because we can assume that the stars have the same metallicity by assuming they were formed from the same material, so we get the metallicity for the M star from studying the primary star.

Eclipsing binaries are classical two-body systems where two stars orbit each other around a

mutual center of mass. The orientation of the orbit is such that the stars repeatedly eclipse one another at periodic intervals through their orbit. Thus, the masses and radii of the two stars in the binary can be derived by modeling the line-of-sight (radial) velocity curves of the binary components combined with the photometric brightness variations of the system (due to the eclipses) throughout an orbit. Combining radial velocity curves with photometric light curves of eclipsing binaries can lead to important properties of the stars, such as masses, radii, the period, eccentricity, and inclination of the orbit, and the temperature ratio of the two stars. Eclipsing binaries are extremely useful because they allow the calculation of these properties using very accurate direct measurements (Stassun et al 2004) (Hebb et al 2010).

The study sample contains 23 F/G/K + M eclipsing binaries discovered by SuperWASP, a program that uses photometry to detect transiting extrasolar planets (Pollaceo et al 2006). Because these EBLMs were discovered by SuperWASP, good light curves for each EBLM already exist. Radial velocity measurements from spectra are needed to use in combination with the photometry to determine orbital parameters and masses for these objects. The specific goals of this research project were to reduce the raw spectra into usable spectra and to calculate radial velocities for EBLMs 1-23 using the reduced data.

## Data and Methods

### Data

Research was conducted using spectra taken at the Cerro Tololo Inter-American Observatory (CTIO) SMARTS 1.5 meter echelle spectrograph between June 2009 and January 2010. The instrument has a fixed cross-disperser with 266 lines per millimeter. We used a slit size of 130  $\mu$  for our observations, with a spectral resolving power of 30,000. At this resolving power we expect to obtain radial velocity precision of  $\sim 0.5$  km/s (Hebb et al 2010). The range of wavelengths observable by the instrument is 4020-7300 Angstroms, with each order including 150 Angstroms.

Each night that an object was to be observed, a Thorium-Argon comparison spectrum was taken before the science exposures. The ThAr calibration files are used to determine wavelength calibration, mapping each pixel position into a wavelength. Ideally, three science exposures were taken for each object each night it was observed. Each EBLM target was observed at five to nine different epochs.

## Methods

### Data Reduction

The first step was to take the raw images from the telescope and reduce them into a format from which radial velocities could be calculated. An example of the raw target spectra can be seen in Figure 1.

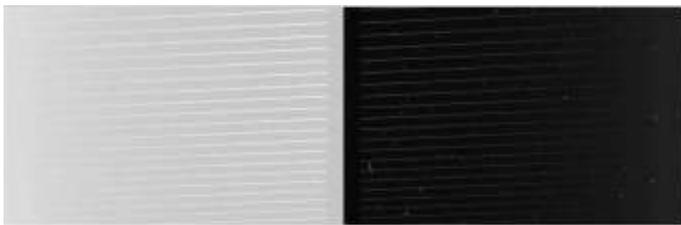


Figure 1. Raw target spectra before data reduction process. The horizontal white lines are the separate orders of the spectrum.

Some data was initially reduced by hand using the standard astronomical software IRAF in order to gain an understanding of the data reduction process, and then all data was reduced using an automated pipeline in IDL (F. Walter, private communication). This process took the raw spectra as seen in Figure 1 and produced a collection of spectra, one for each order. An example of one of these orders can be seen in Figure 2.

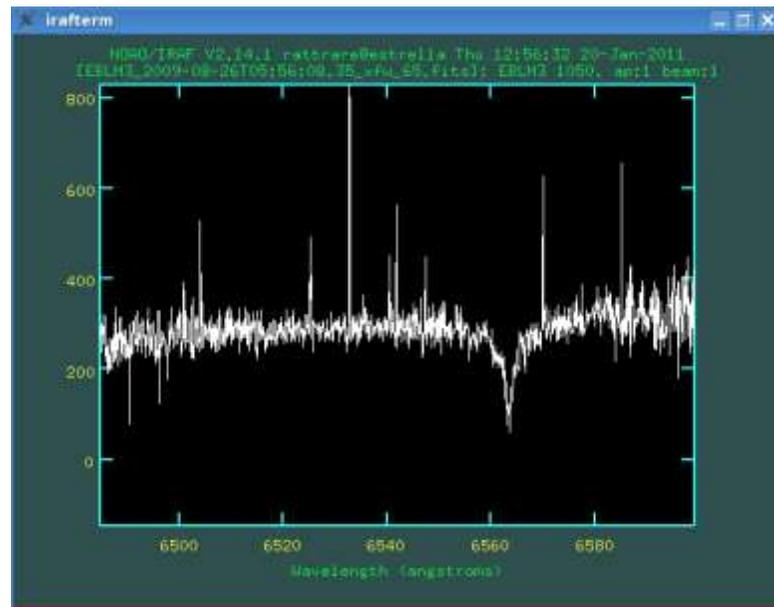


Figure 2. One order of a reduced spectrum, showing the hydrogen-alpha feature.

### Radial Velocity Measurements

Radial velocity measurements were made with the fxcor command in IRAF. Fxcor is a cross-correlation program that compares target spectra with template spectra (the template object is an object for which the radial velocity is already well known) and calculates the pixel shift between each pair of spectra. It then converts the pixel shift to a wavelength shift, and uses the Doppler formula,  $\lambda = \lambda_0(1+v/c)$ , to calculate the radial velocity of the target object. The template object used for these measurements was HD1461. An example of the cross-correlation function produced by fxcor for one of the objects, showing the pixel shift and final radial velocity measurement, is provided in Figure 3.

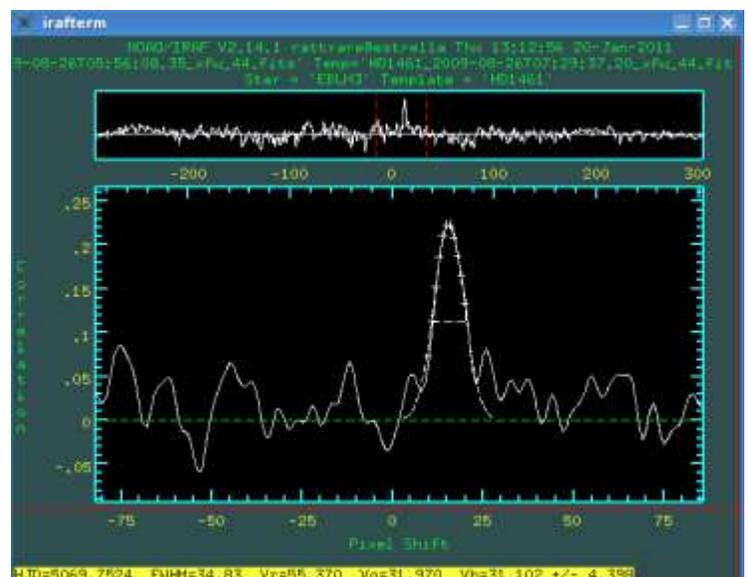


Figure 3. Example of fxcor process, showing final radial velocity measurement

Once the fxcor process was completed, weighted radial velocity means were calculated for each object for each observation date by averaging over the multiple spectral orders in each spectrum. This was done for each object for each observation date showing the radial velocity measurements and errors for each individual order. An example can be seen in Figure 4.

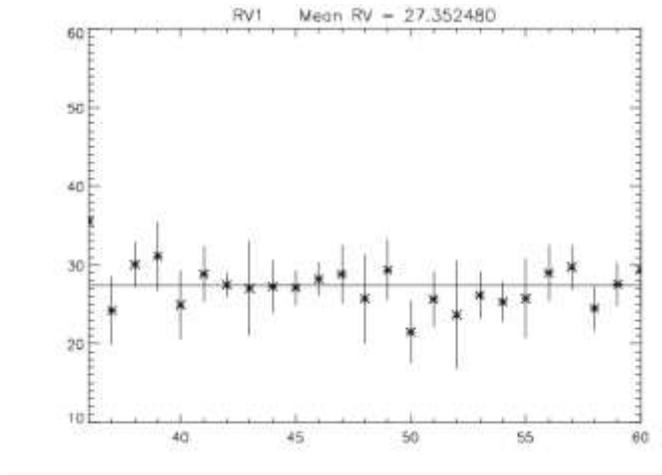


Figure 4. Example of radial velocity measurements for one object for one observation date. Each data point corresponds to the radial velocity measurement for one order. The x-axis represents order number and the y-axis represents radial velocity in units of km/s. The horizontal line through the data points represents the mean radial velocity for this observation date. The mean radial velocity is also written at the top of the graph.

## Results

Radial velocities were calculated for all target objects except EBLM12 and EBLM14, because these objects had too much noise to be able to correctly measure radial velocities. Mean radial velocities and errors for five sample objects on each observation date can be found in the following table.

	0						
EBL M10	5409.80299 0	-46.419	0.301	EBLM 11	5409.8449 40	-52.358	0.554
	5429.71617 0	-62.88	0.335		5429.7837 30	-50.112	0.395
	5436.71874 0	-59.406	0.313		5445.6044 90	-52.926	0.324
	5446.55868 0	-39.091	0.744		5454.7293 00	-8.105	25.48 1
	5454.62401 0	-63.459	0.25		5468.6200 20	-48.716	0.337
	5468.50606 0	-39.34	0.334		5477.6064 30	-49.04	0.511
EBL M16	5446.78749 0	20.04	0.565				
	5477.86850 0	22.496	0.524				
	5490.76744 0	29.244	0.281				
	5519.62810 0	0.569	0.254				
	5538.62523 0	30.524	0.325				
	5540.61528 0	21.456	0.228				
	5548.60903 0	23.505	0.176				

## Discussion and Conclusions

Once radial velocities had been measured for 21 target objects, these could be used in combination with preexisting photometry for these objects to determine the orbital period of the objects. Examples of figures showing both the discovery and follow-up photometry and figures showing the phase-folded radial velocity plots for each of the five sample objects selected above are included below.

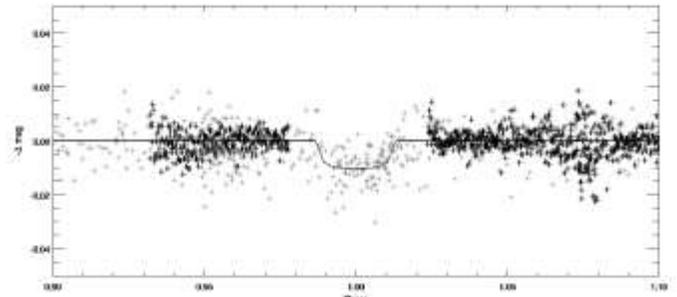


Figure 5. Photometry for EBLM1. The points show the light curve of the object, line of best fit for the data, and the dip in the light curve shows the eclipse.

	Julian Date	Mean RV (km/s)	Error (km/s)		Julian Date	Mean RV (km/s)	Error (km/s)
EBL M1	5112.87712 0	24.11	0.412	EBLM 3	5069.7523 70	27.352	0.574
	5118.85769 0	181.884	5.297		5075.7262 50	42.253	0.699
	5125.85514 0	24.4	0.753		5089.6788 50	44.013	0.695
	5166.78162 0	48.027	0.333		5093.6953 90	49.218	1.229
	5207.66031 0	57.051	0.391		5103.6137 50	22.295	0.963
	5213.72359 0	55.149	0.716		5125.5655 00	35.211	0.821
	5226.73204	22.739	1.702				

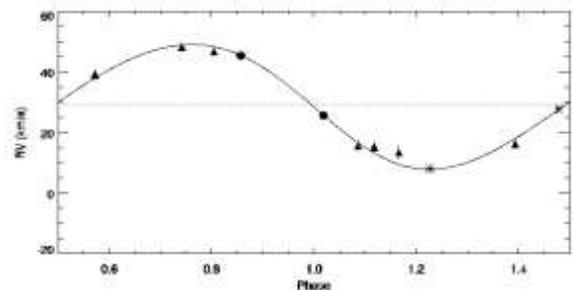


Figure 6. Phase-folded radial velocity plot for EBLM1. The triangles are data points from this research project, the circles and asterisks are preexisting radial velocity measurements.

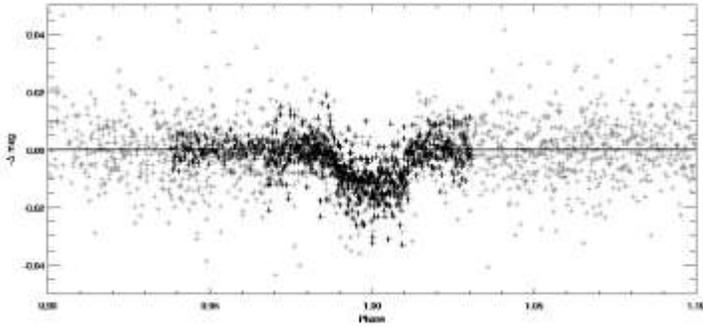


Figure 7. EBLM3

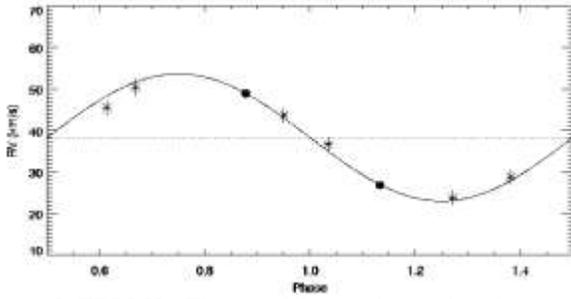


Figure 8. EBLM3. The asterisks are data points from this research project, the circles are preexisting radial velocity measurements.

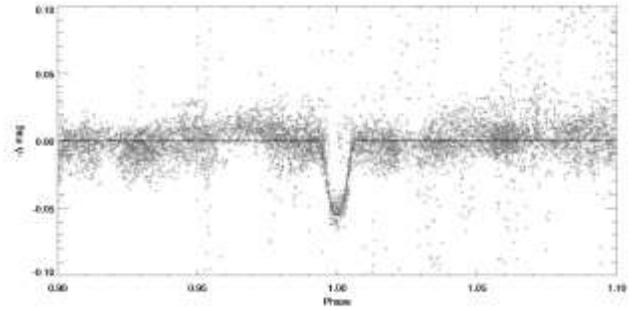


Figure 11. EBLM11

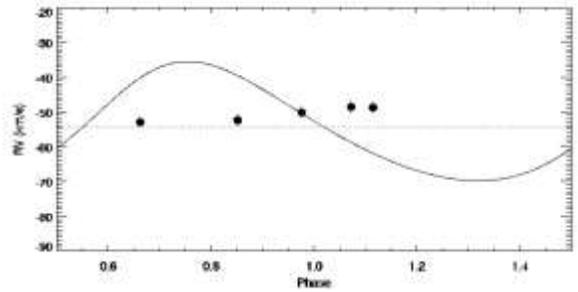


Figure 12. EBLM11

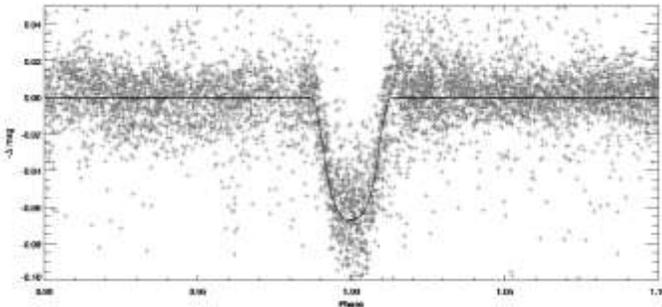


Figure 9. EBLM10

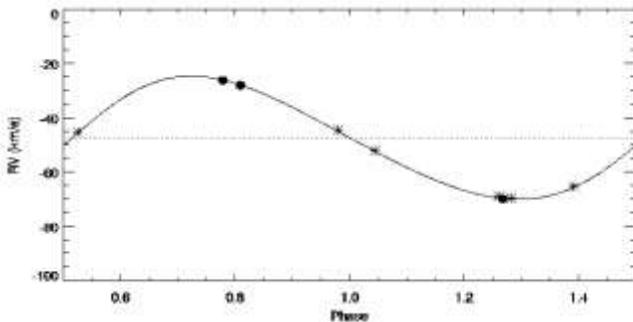


Figure 10. EBLM10. The asterisks are data points from this research project, the circles are preexisting radial velocity measurements.

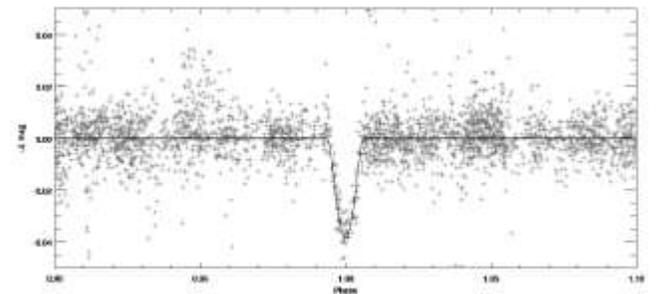


Figure 13. EBLM16

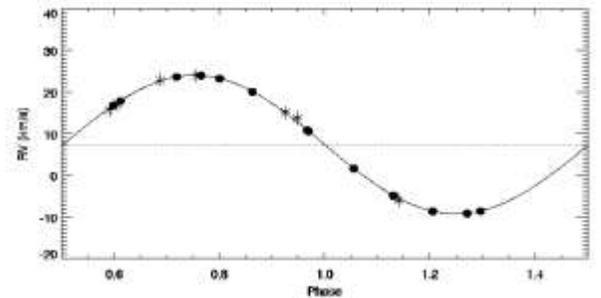


Figure 14. EBLM16. The circles are data points from this research project, the asterisks are preexisting radial velocity measurements.

For most target objects, the radial velocity measurements phase very well with the photometry. We expect the zero-velocity crossing to coincide with the eclipse, since the radial velocity of zero must occur during the eclipse of each system, and this was observed in almost every case. Notable exceptions include EBLM11 and EBLM19, whose radial velocities did not vary over time. It remains unclear why, but we can speculate that these were perhaps

false eclipsing binary detections, or that maybe the M star is actually a low mass companion, such as a brown dwarf, which would cause the radial velocity variation of the primary star to be very slight.

These radial velocity measurements provide more accurate knowledge of the orbital periods, radial velocity amplitude ( $K_1$ ), and eccentricity for these 21 EBLM objects. This information can be used to determine the masses of the M-type stars in these systems once we assume a mass for the primary star. The equation for determining the mass of the secondary star is

$$\frac{M_2^3}{(M_1 + M_2)^2} \sin^3(i) = (1.036 \times 10^{-7}) \times K_1^3 \times P \times (1 - e^2)^{3/2}$$

where P is the orbital period in days,  $K_1$  is the radial velocity amplitude in km/s,  $M_1$  and  $M_2$  are the mass of the primary and secondary stars in solar masses,  $e$  is the eccentricity, and  $i$  is the angle of inclination.  $M_1$  can be estimated from the temperature or color of the star, and  $M_2$  can then be calculated based on what has previously been measured. For example, for EBLM 16, we have  $P = 11.76119 + 2.08260E-05 - 1.63776E-05$  days,  $K_1 = 16.63670 + 0.00578 - 0.00556$  km/s,  $M_1 = 1.16277 + 0.11257 - 0.11267 M_{\text{solar}}$ ,  $e = 0.00564 \pm 0.00031$ ,  $i = 87.56693 + 0.29132 - 0.24700$  degrees, from which we calculate  $M_2 = 0.222082 \pm 0.00009 M_{\text{solar}}$ . Future work will involve deriving  $M_2$  in this manner for the rest of the sample.

### Acknowledgements:

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