Magellanic Cloud Eclipsing Binaries : Distances and Dimensions

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Abstract. This contribution reviews the current state of research aimed at the accurate determination of the distances to and dimensions of Magellanic Cloud eclipsing binary stars and their individual components.

Distances accurate to a few percent should be possible thereby placing tight constraints on the first rung of the cosmic distance ladder. Dimensions, primarily masses and radii, accurate to 1-2 % should be also possible. These measurements provide the first high-accuracy information about stars with metalicities differing significantly from that of the solar neighbourhood.

1. Introduction

[Slide 1]: Good afternoon. My name is John Pritchard. I'm from the University of Canterbury in Christchurch, New Zealand and my talk today is on the measurement of distances to and dimensions of Magellanic Cloud Eclipsing Binaries.

[Slide 2]: There's the abstract which I'm sure you've all read, and which of course bears little, perhaps even no resemblance to the content of the talk I am about to give.

[Slide 3]: So what I *am* going to do today is take a closer look at the handful of Magellanic Cloud Eclipsing Binary systems for which distances and dimensions have been published. I'll begin with a quick recap of the observational requirements for the determination of distances and dimensions. Then I'll discuss four systems which are interesting in their own right but for which, at least one vital component of the available data is of inferior quality and for which further study is, at least for the time being, of lesser importance. Next I will present a system which like the previous four, needs better quality data in at least one respect but is otherwise well observed and which should provide excellent results in the near future provided appropriate telescope time can be secured. After that I'll present the case of HV 2274, which is currently the best example in this field. Finally I will quickly mention the excellent prospects for the future.

2. Observational Requirements

[Slide 4]: A photometric light curve and the two radial velocity curves, one for each component of the system, allows you, at least in theory, to determine, amongst other things, the mass and the radius of each component in the system.

There are of course a number of techniques to determine the stellar temperatures, e.g. spectral classification, calibrated standard photometric relationships, but the method I currently prefer is flux fitting, particularly when ultraviolet spectrophotometry is available, e.g. from *HST*/FOS. Once one has the effective temperatures and the component radii, determination of the luminosity and distance of the system is 'trivial'.

The distance to the LMC is of course of great importance to the cosmic distance scale, since more or less all distance measurements to more distant objects are made relative to the LMC.

Accurate masses, radii and luminosities are needed in order to rigourously test theoretical models for stellar structure and evolution, and to be able to descriminate between models which differ in the details of Helium abundance, opacity, mixing length and/or the overshooting parameter.

Before going on, I should point out that all six systems I will discuss today are composed of massive, early type stars, at least they were when the systems were ZAMS. I should also point out that they are close systems with short periods. The shorted period is 1.9 days, and the longest 5.3 days.

So with all this in mind, on to the results...

3. Harvard Variables LMC-HV 5936, LMC-HV 2241, SMC-HV 2226 & SMC-HV 1620

[Slide 5]: These four systems are amongst the brightest EB systems in the Clouds and no doubt were chosen as the first targets for study mainly for this reason. Despite this fact the available spectroscopy for radial velocity curves is, for several reasons, not of especially high quality and as a result the distances and dimensions are not of particular value.

[Slide 6]: All four systems turn out to be in semi-detached configurations, that is one of the components has evolved to the point where it fills its Roche lobe, as is clearly evident in these representations of the physical configurations of the systems. All four models are shown at orbital phase 0.25 with the same false colour map and at the same scale. The small circle here, here, here and here has a radius of one solar radius. Infact, in all four systems the Roche lobe filling component is the less massive component and yet apparently the more evolved, indicating that these systems have undergone signigicant mass transfer and/or mass loss. This means that interpretation of the the evolutionary states of the components of these systems in terms of single star models is impossible. Mainly for this reason further study of these systems is of rather low priority, in favour of stars like the next two I will discuss.

4. Harvard-Variable LMC-HV 982

[Slide 7]: HV 982 is a great system. It offers everything. Bright, well-detached, deep eclipses, an eliptical orbit... Who could ask for anything more. Well actually it could be in a less crowded field but you can't win them all.

4.1. Light Curves – MJUO $uvbyVI$ CCD photometry – & Radial Velocity Curves – CTIO 45 Å/mm RV curves

It's light curves clearly show the effects of it's eccentric orbit: firstly the time between the two eclipses is different and secondly the duration of the two eclipses is different which both indicate variable speed during the orbit, i.e. a non-circular orbit. Because the orbit has not yet been circularized by tidal interations we can expect that the system is relatively young, certainly still main sequence. Furthermore, since the two eclipses are of nearly equal depth and therefore the surface temperatures of the two components must be nearly equal, the two components must have nearly equal masses. This is borne out by the analysis of the radial velocity curve which is unfortunately not of sufficient quality to say much more than this. Better quality radial velocity data are required to resolve this unfortunate situation.

4.2. Temperature and Distance determination

[Slide 8]: HV 982 also has IUE/SWP and HST/FOS spectrophotometry which are shown here in blue and red respectively. Also plotted, the heavy black line, is the reddened model binary flux distribution derived from Kurucz model atmospheres (Kurucz, 1993) that we published last year. The fit was made before the HST spectrophotometry was available to us and is thus based on the IUE spectrophotometry and low quality Strömgren $uvby$ plus V and I photometry only.

In the light of the much greater spectral range of the HST/FOS spectrophotometry certain deficiencies in the fit are plain. In particular it would appear that the strength of the so called 2200 Åbump has been significantly overestimated. This calls into question the entire extinction curve, the light black curve shown here, used to redden the models in order to compare them with the observations and implies the temperature derived from the IUE plus visual fit is probably seriously in error.

Analysis of the HST spectrum in conjunction with good quality Strömgren photometry should yield an accurate temperature. This result should be forthcoming just as soon as I reduce the Strömgren observations just obtained during January and February at La Silla.

Accuarte determination of the distance will have to wait till precise radial velocity curves are available.

5. Harvard-Variable LMC-HV 2274

5.1. Light Curves – MJUO BVI CCD photometry – Radial Velocity Curves – HST/GHRS RV curves

[Slide 9]: Finally we come to HV 2274. Like HV 982 it is a bright, well-detached, eccentric system with deep eclipes. Furthermore it is in a relatively uncrowded field. This system really does have it all, which probably explains why so much effort has been put it to its investigation.

For this star, the light curves are infact one of the weaker points. The coverage is only just barely adequate but could certainly be improved upon which would no doubt lead to higher precision results.

Similarly, more radial velocities would not go amiss and in fact as Jen Viggo mentioned, his group are currently working very hard to reduce their NTT radial velocity data. It will indeed be interesting to see how the NTT radial velocities compare with the HST/GHRS radial velocities shown here.

5.2. Temperature and Distance determination – HST/FOS

[Slide 10]: Here we have the observed and dereddened HST/FOS spectraphotometry plus visual B and V fluxes. Also plotted, but difficult to see because the model fits the data so well, is the fitted Kurucz spectral flux. The fitting procedure optimises the $T_{\rm eff}$s, metalicity and microturbulance velocity of the model fluxes along with $E(B-V)$ and the normalized extinction curve. The excellent quality of the fit is clearly evident in the close up view of the Balmer jump region. Based on the fit the distance to HV 2274 and hense the LMC itself is determined with the rather impresiive accuracy of ± 0.07 mag. Notice that this result supports the 'short' distance scale which has recently gained support from a number of results, including the so-called Red Clump method.

5.3. Evolutionary status

[Slide 11]: Equally impressive is the agreement between the measured dimensions and $T_{\rm eff}$s of the two components and appropriate single star evolutionary models shown here. Also shown is an 18 Myr isochrone. Within the uncertainties both components have the same age. This is an important constraint since most models for the creation of close binaries require coeval components.

6. Future propects

6.1. EROS, MACHO & OGLE

[Slide 12]: These three Microlensing projects have between them very kindy increased by an order of magnitude the number of known eclipsing binaries in the Large and Small Magellanic Clouds. They also provide excellent 'discovery' light curves, although they are generally not of sufficient quality for the accuracy desired here.

The main benefit is that we can thus target much more precisely systems which are of specific utility to the goals of the project rather than semi-detached or, even worse, contact systems which are not at this stage useful to observe, at least not in the Magellanic Clouds.

7. Summary

[Slide 13]: So to quickly sumarise. We are now on the verge of achieving the accuracy need to place very strict constraints on structure and evolution models for a wider range of metalicity conditions than has ever been possible before. We can also determine the distance to the LMC with unprecedented precision.

Great gains will be made very quickly for the price of relatively little VLT time. Here indeed is a good area for VLT/UVES spectroscopy.

8. The Slides

Magellanic Cloud Eclipsing Binaries : Distances and Dimensions

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Abstract. This contribution reviews the current state of research aimed at the accurate determination of the distances to and dimensions of Magellanic Cloud eclipsing binary stars and their individual components.

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Introduction

- Observation requirements
- Harvard Variables LMC-HV 2226, SMC-HV 5936, LMC-HV 2241 & SMC-HV 1620
- Harvard Variable LMC-HV 982
- Harvard Variable LMC-HV 2274
- New targets :: EROS, MACHO, OGLE.

Observational Requirements

For determination of the component *masses* and *radii* require:

- Photometric Light curves
- Spectroscopic Radial Velocity Curves

For determination of the component *Luminosities/Temperatures* require:

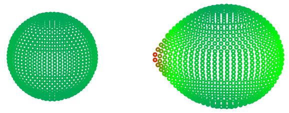
- Spectrophotometry – Visual $\rightarrow$ far-UV, e.g. HST/FOS spectrophotometry + Strömgren calibrated photometry (reddening).

Then the system *Distance* is determined 'trivially' from the *radii* (i.e. Surface Area) and the *Effective Temperatures*.

Accurate masses, radii and luminosities, i.e. with uncertainties of the order of 1–2 %, are needed to provide rigourous tests of theoretical models for stellar structure and evolution.

- **LMC-HV 5936** (Bell et al., 1993)
  - Danish BVI CCD photometric light curves ($\sigma_V = 0.014$ mag)
  - AAT/RGOS $33\,\text{Å}\,\mathrm{mm}^{-1}$ radial velocity curves ($\sigma_1 = 39\,\mathrm{km\,s^{-1}}$, $\sigma_2 = 50\,\mathrm{km\,s^{-1}}$)
  - Temperature clssification from spectra + $uvby$ photometry ($\sigma_{T_{\mathrm{eff},1}} = 3\,500\,\mathrm{K} = {\sim}10\%$)
- **LMC-HV 2241** (Pritchard et al., 1998)
  - MJUO $uvbyVI$ CCD photometric light curves ($\sigma_I = 0.017$ mag)
  - CTIO $45\,\text{Å}\,\mathrm{mm}^{-1}$ radial velocity curves ($\sigma_1 = 29\,\mathrm{km\,s^{-1}}$, $\sigma_2 = 32\,\mathrm{km\,s^{-1}}$)
  - Temperature clssification from IUE/SWP spectrophotometry + $uvbyVI$ photometry ($\sigma_{T_{\mathrm{eff},1}} = 3\,000\,\mathrm{K} = {\sim}10\%$)
- **SMC-HV 2226** (Bell et al., 1991)
  - Danish BVI CCD photometric light curves ($\sigma_V = 0.015$ mag)
  - AAT/RGOS $33\,\text{Å}\,\mathrm{mm}^{-1}$ radial velocity curves ($\sigma_1 = 21\,\mathrm{km\,s^{-1}}$, $\sigma_2 = 34\,\mathrm{km\,s^{-1}}$)
  - Temperature clssification from spectra + $uvby$ photometry ($\sigma_{T_{\mathrm{eff},1}} = 2\,000\,\mathrm{K} = {\sim}7\%$)
- **SMC-HV 1620** (Pritchard et al., 1998)
  - MJUO $uvbyVI$ CCD photometric light curves ($\sigma_V = 0.012$ mag)
  - CTIO $45\,\text{Å}\,\mathrm{mm}^{-1}$ radial velocity curves ($\sigma_1 = 51\,\mathrm{km\,s^{-1}}$, $\sigma_2 = 39\,\mathrm{km\,s^{-1}}$)
  - Temperature clssification from IUE/SWP spectrophotometry + $uvbyVI$ photometry ($\sigma_{T_{\mathrm{eff},1}} = 4\,500\,\mathrm{K} = {\sim}14\%$)

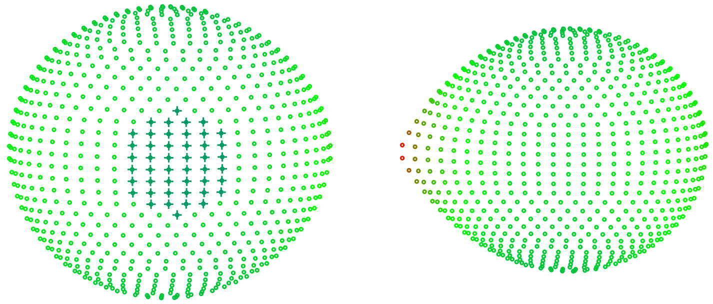
LMC-HV 5936



○

$$\mathcal{M}_1 = 7.2 \pm 0.9\mathcal{M}_\odot : \mathcal{M}_2 = 3.3 \pm 0.5\mathcal{M}_\odot$$
$$\mathcal{R}_1 = 4.6 \pm 0.3\mathcal{R}_\odot : \mathcal{R}_2 = 5.7 \pm 0.3\mathcal{R}_\odot$$
$$(m - M)_0 = 18.1 \pm 0.3$$

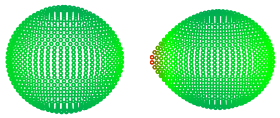
LMC-HV 2241



○

$$\mathcal{M}_1 = 35 \pm 14\mathcal{M}_\odot : \mathcal{M}_2 = 20 \pm 8\mathcal{M}_\odot$$
$$\mathcal{R}_1 = 16 \pm 2\mathcal{R}_\odot : \mathcal{R}_2 = 14 \pm 2\mathcal{R}_\odot$$
$$(m - M)_0 = 18.5 \pm 0.5$$

SMC-HV 2226



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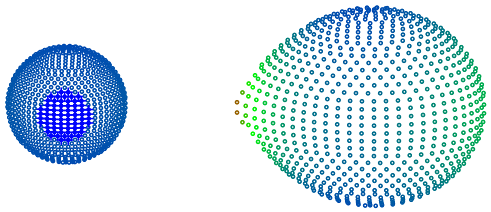
$$\mathcal{M}_1 = 9.3 \pm 0.7\mathcal{M}_\odot : \mathcal{M}_2 = 5.6 \pm 0.5\mathcal{M}_\odot$$
$$\mathcal{R}_1 = 5.6 \pm 0.2\mathcal{R}_\odot : \mathcal{R}_2 = 5.3 \pm 0.2\mathcal{R}_\odot$$
$$(m - M)_0 = 18.6 \pm 0.3$$

SMC-HV 1620



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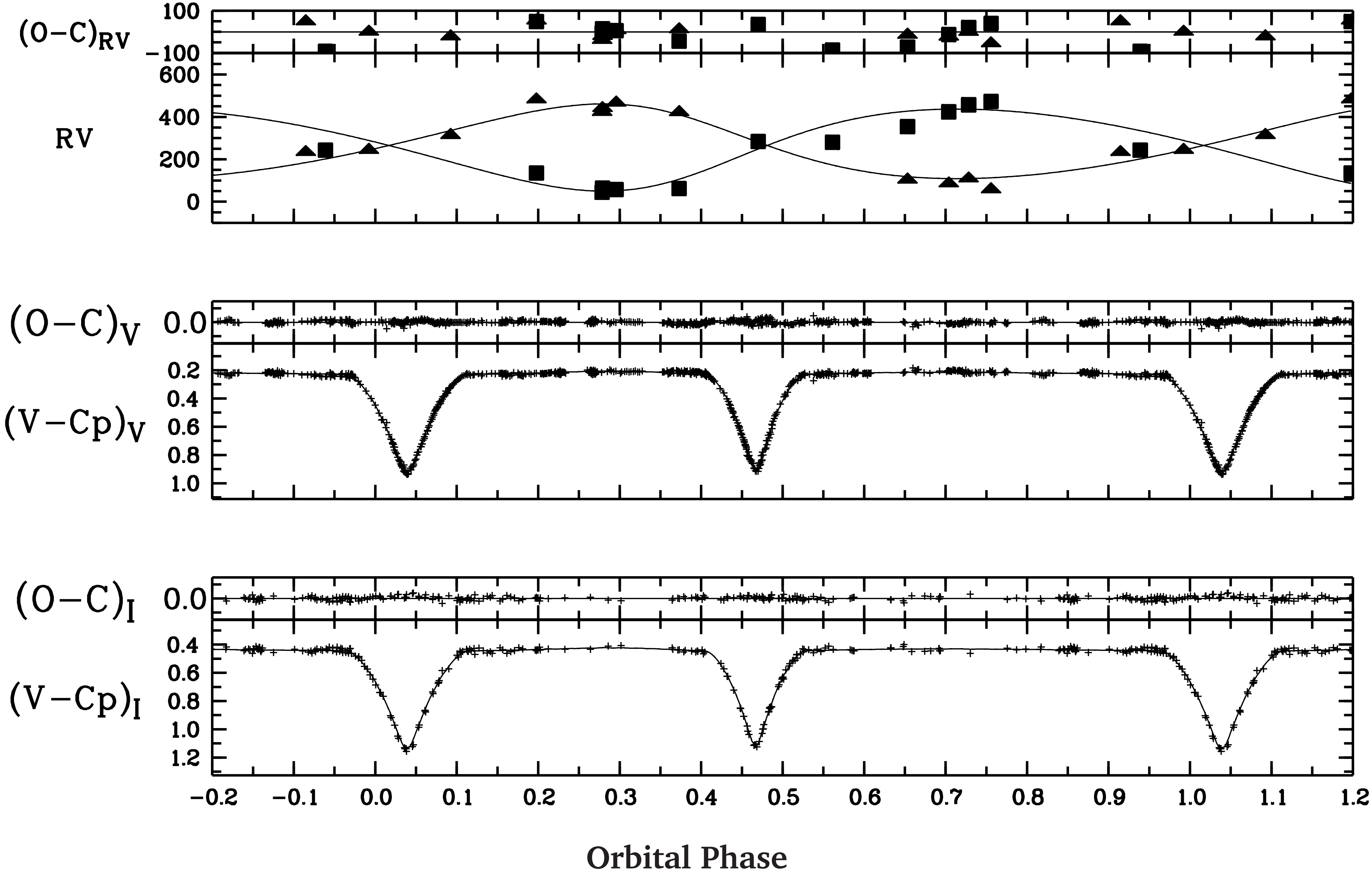
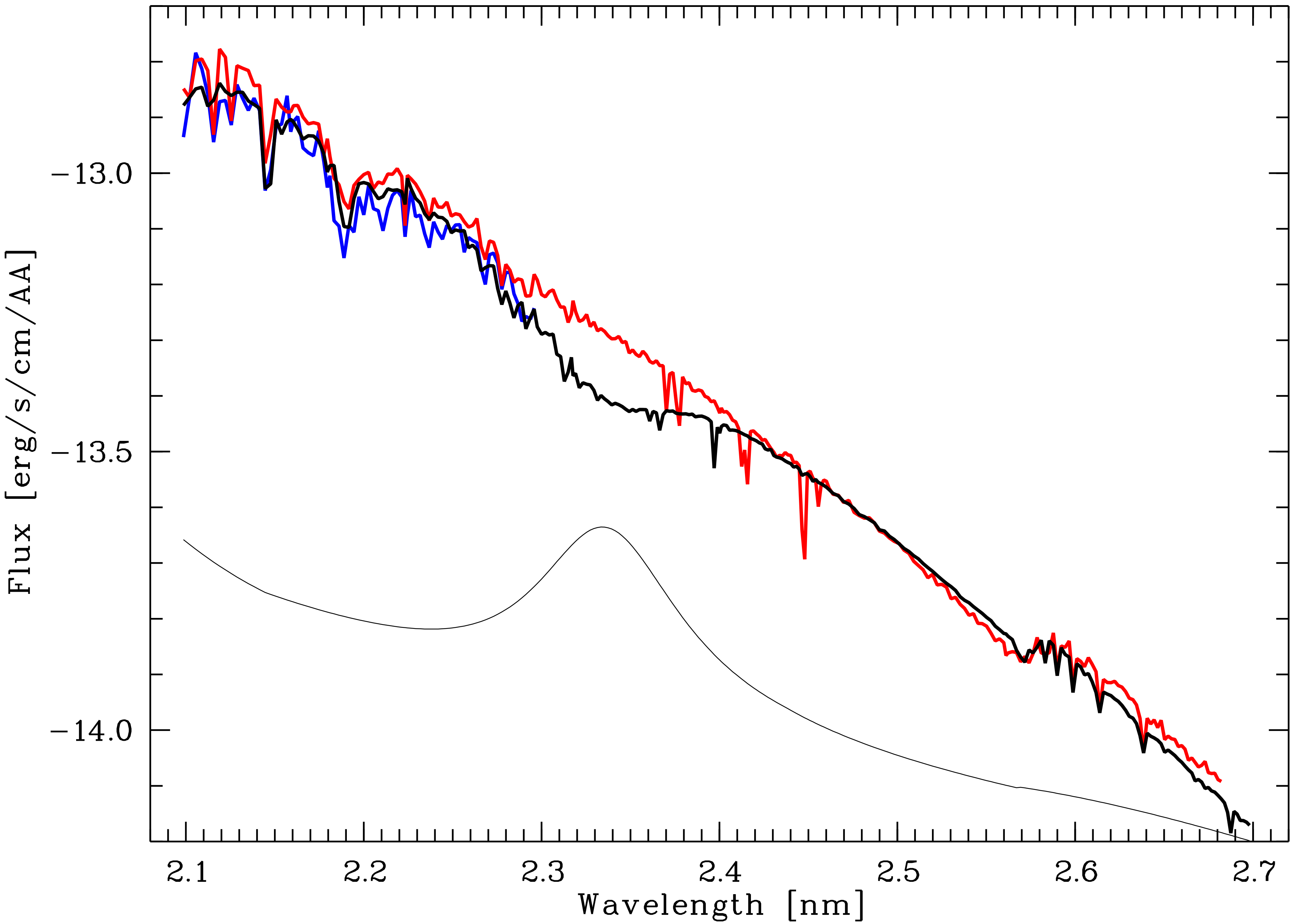
$$\mathcal{M}_1 = 20 \pm 8\mathcal{M}_\odot : \mathcal{M}_2 = 15 \pm 6\mathcal{M}_\odot$$
$$\mathcal{R}_1 = 6.0 \pm 0.9\mathcal{R}_\odot : \mathcal{R}_2 = 11 \pm 2\mathcal{R}_\odot$$
$$(m - M)_0 = 18.6 \pm 0.5$$

HV 982 :: Radial Velocity and CCD Light Curves

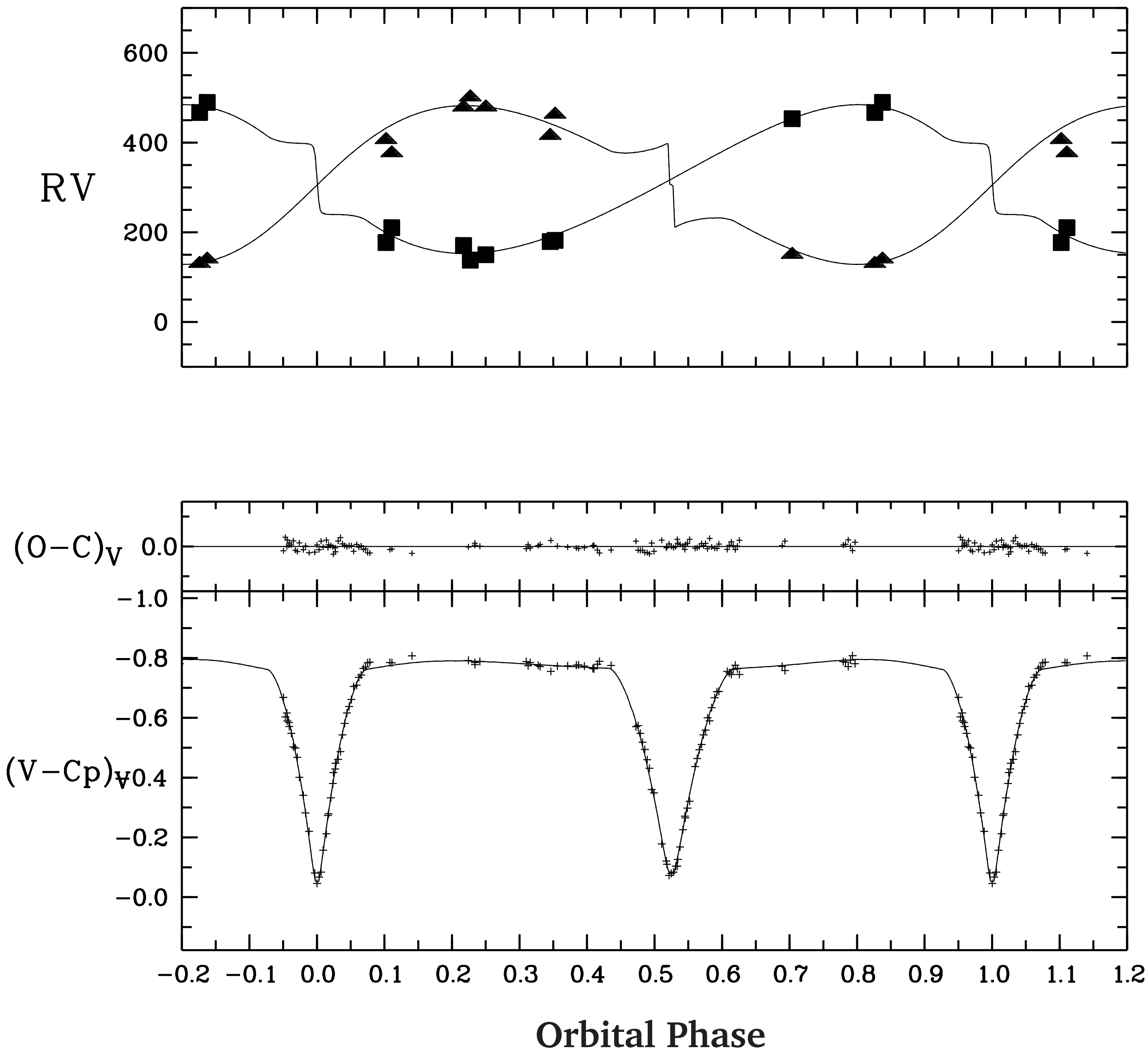


HV 982 :: IUE/SWP, HST/FOS and Kurucz Model

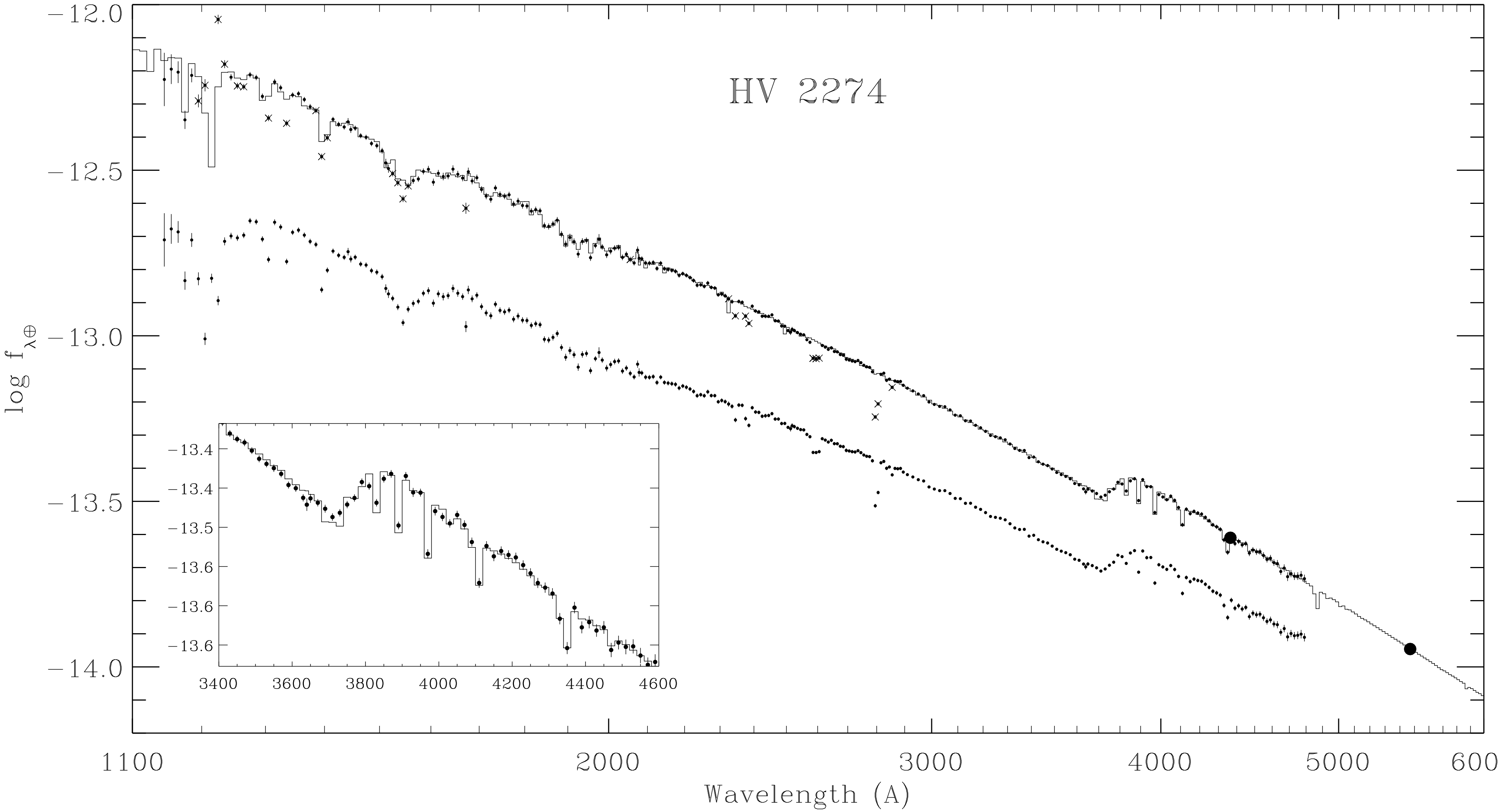


IUE/SWP :: HST/FOS :: **Kurucz Model** :: Extinction

HV 2274 :: Radial Velocity and CCD Light Curves

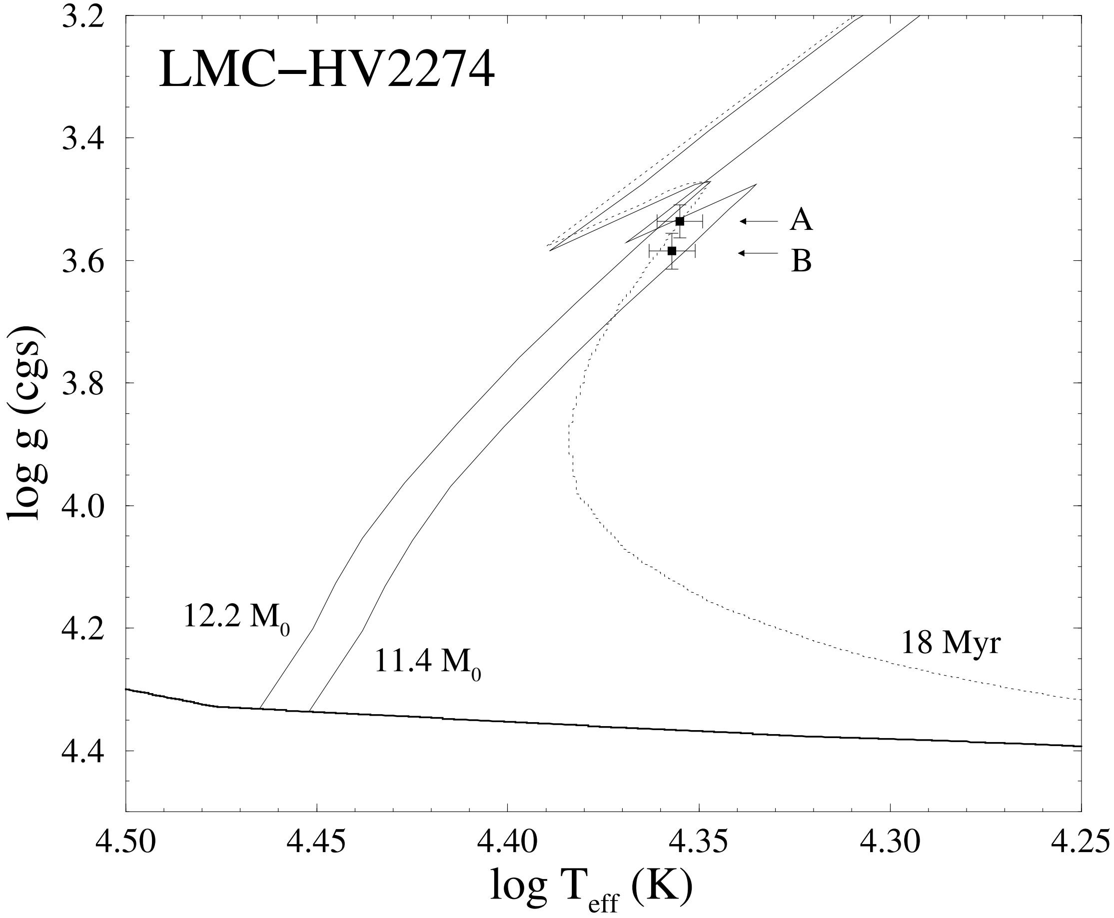


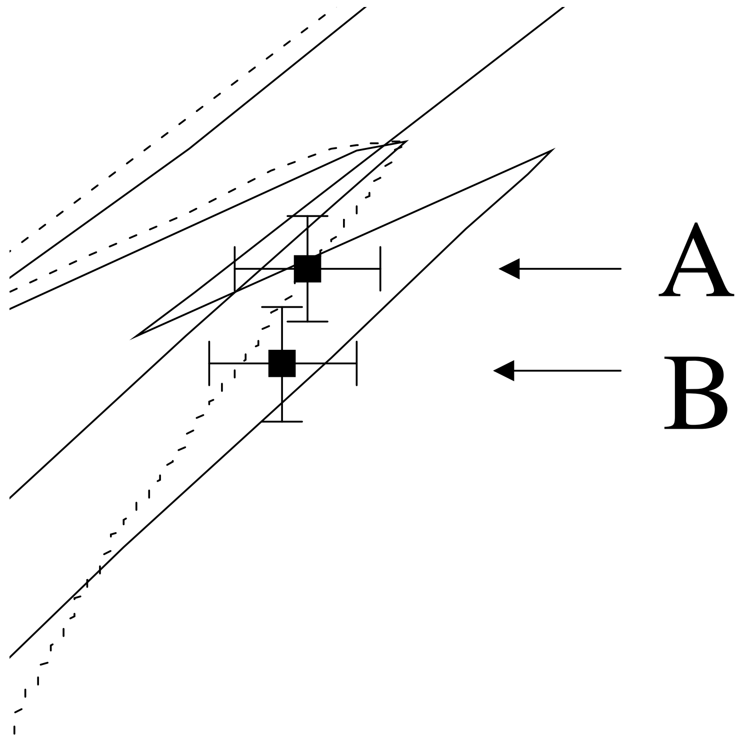
HV 2274 :: HST/Fos and Kurucz Model



$$(m - M)_{0,\mathrm{HV\,2274}} = 18.35 \pm 0.07 \Rightarrow (m - M)_{0,\mathrm{LMC}} = 18.30 \pm 0.07$$

HV 2274 :: Evolutionary Status





$$\mathcal{M}_A = 12.1 \pm 0.4 \mathcal{M}_\odot : \mathcal{M}_B = 11.4 \pm 0.4 \mathcal{M}_\odot$$

$$\mathcal{R}_A = 9.84 \pm 0.24 \mathcal{R}_\odot : \mathcal{R}_B = 9.03 \pm 0.20 \mathcal{R}_\odot$$

$$T_{\mathrm{eff,A}} = 23\,000 \pm 300\,\mathrm{K} : T_{\mathrm{eff,B}} = 23\,110 \pm 180\,\mathrm{K}$$

New Targets :: EROS, MACHO, OGLE

- **EROS**: 79 LMC systems (Grison et al., 1995).
- **MACHO**: 611 LMC systems (Alcock et al., 1997).
- **OGLE**: 1459 SMC systems (Udalski et al., 1998) and $\sim$2600 soon with perhaps another 2000 later (Udalski, A.; private communication)

Summary

It has been shown that with today's ground- and space-based facilities masses, radii and luminosities of well-detached Magellanic Cloud Eclipsing Binaries can be determined with suffucient accuracy and precision to *rigourously* test modern theoretical models for stellar structure and evolution.

Furthermore the distance to these systems can be determined with high accuracy and precision, thereby solidifying an important rung on the Cosmic Distance Scale ladder.

The current primary observational requirement is High Resolution, High Signal-to-Noise spectra requiring big-aperture telescopes – i.e. VLT.

”Here is a good area for VLT/UVES spectroscopy”

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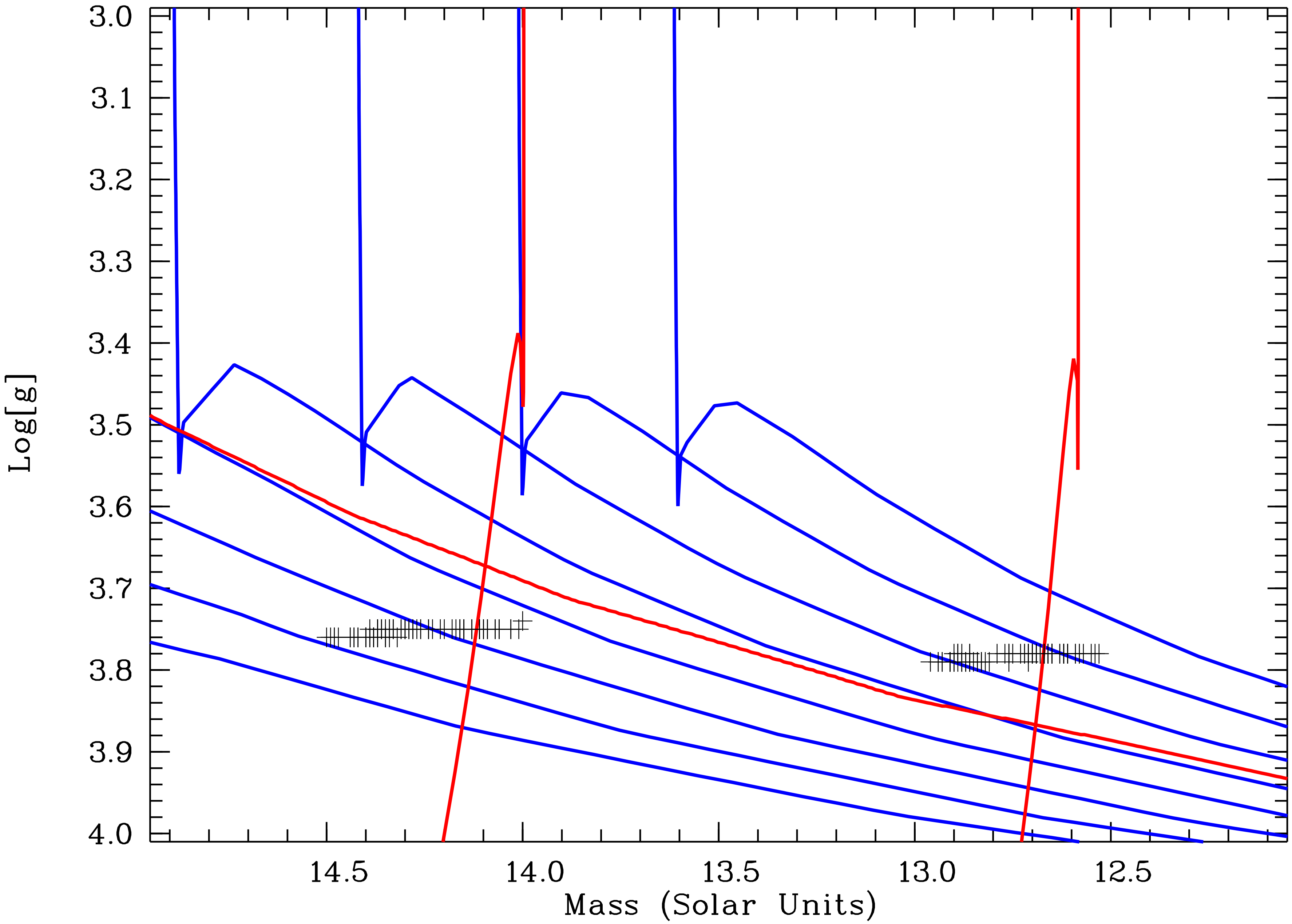
HV 982 :: Evolutionary Model tracks and Isochrones



Geneva (Schaerer et al. 1993) :: Claret (Claret 1995; 1998)