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# The most massive eclipsing binary with apsidal motion

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**Abstract:** The fundamental properties of a detached and eccentric eclipsing binary (EB) with apsidal motion are presented (M31V J00442326+4127082). The system is composed by two very massive stars (with masses over 40 $M_\odot$). An additional third light is observed that could be the responsible of the discrepancy between the observed apsidal motion (of $2.4 \pm 1.0$ deg yr$^{-1}$) and the value predicted by stellar interior models ($5.4 \pm 0.8$ deg yr$^{-1}$). However, the observed apsidal motion could be more easily explained if the stellar cores were larger than currently predicted. Therefore, additional observations of the EB presented here could be used to test the internal structure of very massive stars.

## 1 Introduction

Eclipsing binaries (EBs) are powerful tools to determine the fundamental properties of massive stars (masses, radii, temperatures, etc). Specially valuable are those systems displaying apsidal motion, since they can be used to test general relativity and the internal distribution of matter. During the course of a project aimed at finding suitable EBs for a distance determination to M31 (Ribas et al. 2005, Vilardell, Ribas & Jordi 2006, Vilardell et al. 2010), a very massive (with masses over 40 $M_\odot$), detached and eccentric EB showing evidence of apsidal motion (M31V J00442326+4127082) was discovered. The fundamental properties of M31V J00442326+4127082 are presented here.

## 2 Masses and radii

The combination of light and radial velocity curves in EBs provides the masses and the radii of the components. In our case, Johnson $B$ and $V$ time series photometry was obtained from Vilardell et al.

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(2006) and from the DIRECT $V$ band photometry (Macri 2004, and references therein). Radial velocities were derived by applying a three dimensional cross-correlation algorithm (TRIMOR, Mazeh et al. 2009) to a set of spectra obtained with GMOS at the Gemini North telescope. The analysis of light and radial velocity curves with the 2003 version of the Wilson & Devinney (1971) algorithm (Fig. 1) revealed a detached EB system composed by two very massive stars ($49 \pm 6$ M$_\odot$ for the primary component and $46 \pm 5$ M$_\odot$ for the secondary) and an important tertiary light source (Table 1). The derived properties (see Vilardell 2009, for further details[1]) place M31V J00442326+4127082 among the few known EBs with very massive components (Bonanos 2009).

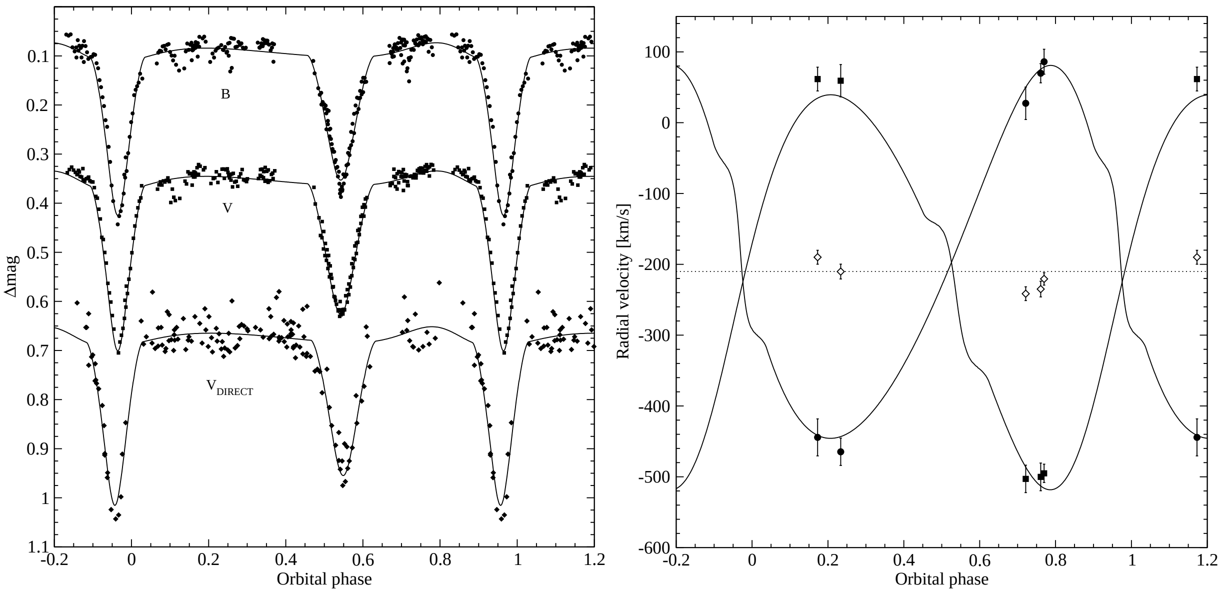


Figure 1: Observations for M31V J00442326+4127082 with the corresponding fits. Left: $B$, $V$, and DIRECT $V$ light curves with arbitrary offsets for clarity. Right: Radial velocity curves

# 3 Radiative properties

The detached nature of M31V J00442326+4127082 allowed the comparison of the derived masses and radii with the Geneva stellar evolutionary models of Lejeune & Schaerer (2001). As a first step, the mass-radius diagram was used to infer suitable evolutionary tracks (Fig. 2, left). The resulting most likely models were used to determine the temperature and luminosity of both components (Fig. 2, right). The derived properties are fully compatible with a coeval system having an age of $2.2 \pm 0.5$ Myr (Table 2). In addition, by assuming that the tertiary light source is a single coeval component (either belonging to the same stellar association or forming a triple system), its physical properties could also be determined. The derived properties (with a mass of $36 \pm 6$ M$_\odot$ and a radius of $10.8 \pm 1.7$ R$_\odot$) reveal that the tertiary component could also be massive.

Once the intrinsic properties of the three components were derived, their combined absolute magnitudes in $B$ and $V$, together with the distance to M 31 (Vilardell et al. 2010) and the observed photometry, could be used to derive a line-of-sight absorption and a color excess. The assumption of a tertiary coeval component is useful to illustrate that, even with a hot tertiary component, the total-to-selective extinction ratio is far from the mean value of $\mathcal{R}_V = 3.1$ usually adopted ($\mathcal{R}_V = 4.2 \pm 0.6$). GALEX photometry (Thilker et al. 2005) confirms that the extinction law is non-standard, but additional observations in the infrared are required to confirm the value of $\mathcal{R}_V$.

[1]Accessible online at: http://www.tdx.cat/TDX-0526109-091957

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Table 1: Properties of M31V J00442326+4127082 derived from the analysis with the Wilson & Devinney code.

| System properties | | | | |
|---|---|---|---|---|
| $B$ magnitude at maximum light[a] | 19.284±0.017 | mag | | |
| $V$ magnitude at maximum light[a] | 19.195±0.014 | mag | | |
| Period | 5.75268±0.00005 | days | | |
| Time of minimum | 2 452 546.586±0.008 | HJD | | |
| Eccentricity | 0.17±0.02 | | | |
| Argument of periastron | 45±7 | deg | | |
| Apsidal motion | 2.4±1.0 | deg yr$^{-1}$ | | |
| Inclination | 81.3±1.9 | deg | | |
| Systemic velocity | -210±11 | km s$^{-1}$ | | |
| Semi-major axis | 62±2 | $R_\odot$ | | |
| Third light contribution in $B$ | 0.21±0.08 | | | |
| Third light contribution in $V$ | 0.20±0.09 | | | |
| Component properties | Primary | | Secondary | |
| Mass | 49±6 | $M_\odot$ | 46±5 | $M_\odot$ |
| Radius | 15.3±1.3 | $R_\odot$ | 14.7±1.3 | $R_\odot$ |

[a] Out of eclipse average: $\Delta\phi = [0.04 - 0.45, 0.63 - 0.88]$

# 4 Apsidal motion

The combination of the DIRECT $V$ band photometry (Macri 2004, and references therein) with our obtained data provides a time baseline of ∼7 years (1996-2003) and allowed the detection of an apsidal motion of $2.4 \pm 1.0$ deg yr$^{-1}$. M31V J00442326+4127082 is, therefore, the most massive EB system with measured apsidal motion ever reported. The deformation of the components (dependent

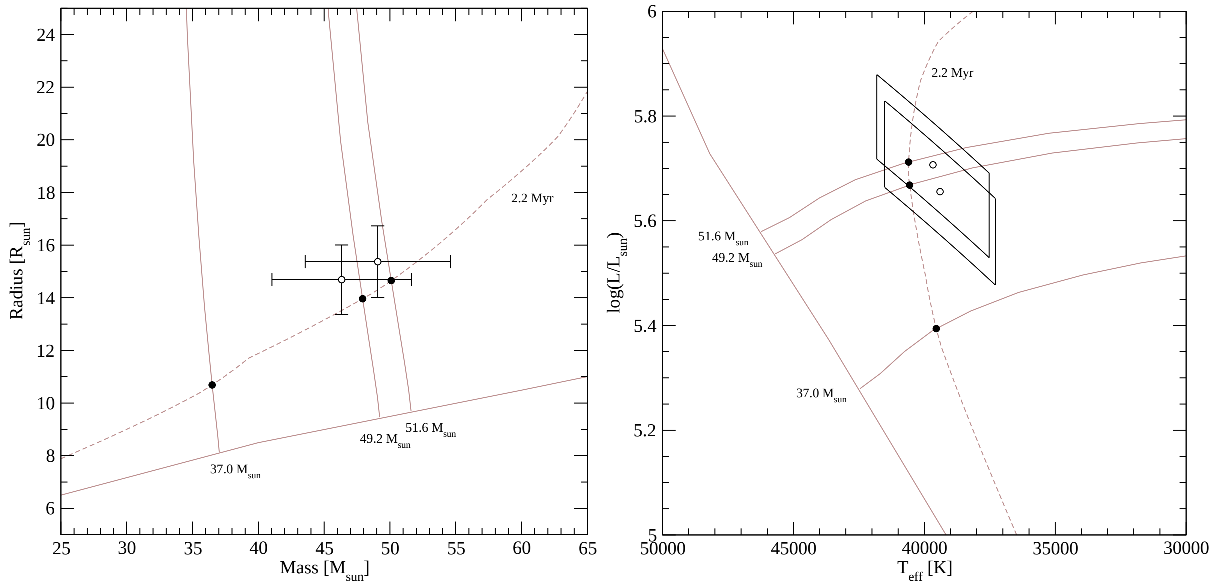


Figure 2: Best fitting stellar evolutionary tracks (solid lines) and isochrone (dashed line) to the observed properties of M31V J00442326+4127082. Left: Mass-radius diagram. Right: Hertzsprung-Russel diagram.

Table 2: Properties of M31V J00442326+4127082 derived from comparison with stellar evolutionary models and assuming that the three components are coeval.

| System properties | | | | | | |
|---|---|---|---|---|---|---|
| Age | | | | | 2.2±0.5 | Myr |
| Absolute $V$ magnitude | | | | | -6.86±0.19 | mag |
| Color excess in $B-V$ | | | | | 0.40±0.02 | mag |
| Line-of-sight absorption in $V^a$ | | | | | 1.7±0.2 | mag |
| Total-to-selective extinction ratio | | | | | 4.2±0.6 | mag |
| Component properties | Primary | | Secondary | | Tertiary | |
| Mass | 50±5 | $M_\odot$ | 48±5 | $M_\odot$ | 36±6 | $M_\odot$ |
| Radius | 14.8±1.4 | $R_\odot$ | 14.1±1.4 | $R_\odot$ | 10.8±1.7 | $R_\odot$ |
| Effective temperature | 40 000±2 000 | K | 40 000±2 000 | K | 39 000±2 000 | K |
| Intrinsic luminosity in $\log L/L_\odot$ | 5.71±0.08 | mag | 5.67±0.08 | mag | 5.37±0.20 | |

$^a$ Adopting a distance modulus of $24.36 \pm 0.08$ mag (Vilardell et al. 2010)

on the internal structure of the stars) seems to be the most likely explanation. However, the observed apsidal motion rate is discrepant (at the $1.5\sigma$ level, the predicted value is $5.4 \pm 0.8$ deg yr$^{-1}$) with current stellar interior models (Claret 2004). Although similar results have also been obtained for other B-type EBs (e.g., V380 Cyg), where stellar interior models for massive stars predict cores that are too small when compared with observations, the possible presence of a tertiary massive companion could also be affecting the observed apsidal motion. Therefore, additional observations of the EB presented here are required to determine the possible effect of the tertiary component on the observed apsidal motion and to test whether current stellar interior models correctly predict the internal structure of very massive stars.

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