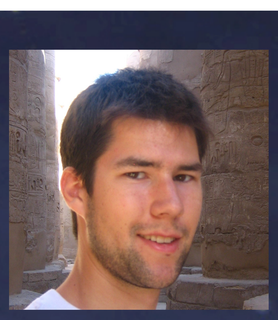

A new, low-mass, pre-main sequence eclipsing binary with evidence of a circumbinary disk

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Abstract

We present the discovery of a double-lined, detached eclipsing binary (EB), comprising two pre-main sequence M-dwarfs, in the 3 Myr old NGC 2264 star-forming region. Eclipses were detected in this system, during a continuous 23-day observation of NGC 2264 by the CoRoT space mission in 2008. Multi-epoch optical and near-IR follow-up spectroscopy with VLT/FLAMES and WHT/ISIS yielded a full orbital solution.

We derive fundamental stellar parameters by modelling the light curve and radial velocity data, finding that the two stars travel on essentially circular orbits with a period of 3.8745745 ± 0.0000014 days and have masses of 0.67 ± 0.01 and 0.495 ± 0.007 $M_\odot$ with corresponding radii of 1.30 ± 0.04 and 1.11 ± 0.05 $R_\odot$

The CoRoT light curve also contains large-amplitude, rapidly evolving out-of-eclipse variations, which are difficult to explain with star spots alone. SED modelling of the system's broadband optical and infrared magnitudes reveals a mid-IR excess, which we model as emission from a small amount of dust located within the inner cavity of a circumbinary disk. In turn, this opens up the possibility that the out-of-eclipse variability could be due to occultations of the central stars by material located at the inner edge or in the central cavity of the circumbinary disk.

1. CoRoT Lightcurve

The CoRoT space satellite takes time series photometry in a broad 300-1000nm bandpass with a time sampling of 512 seconds. The CoRoT lightcurve from the 2008 observations (Fig. 1a) shows out-of-eclipse variations in addition to the stellar eclipses.

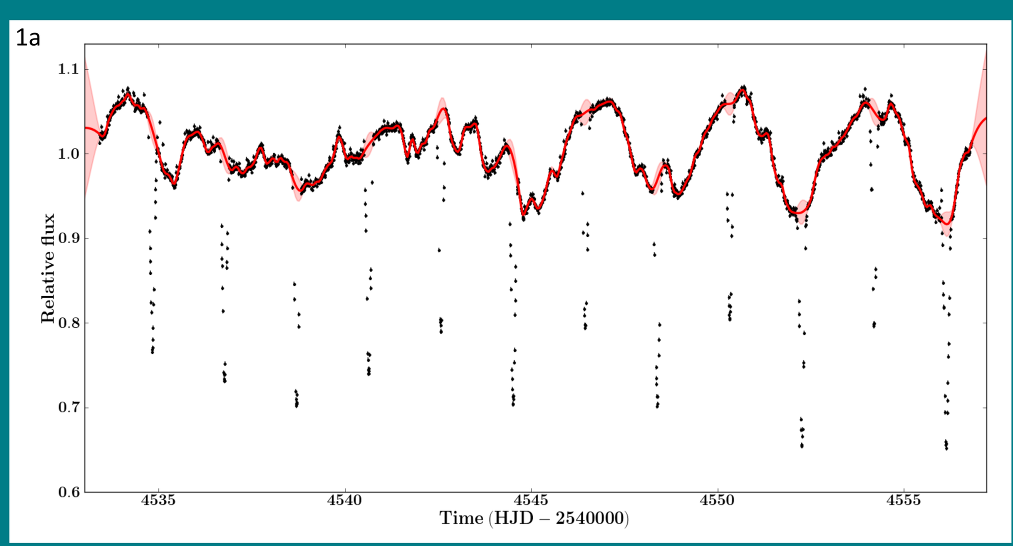
The amplitude and evolutionary timescale of these variations make it extremely difficult to reproduce with stellar activity models alone.

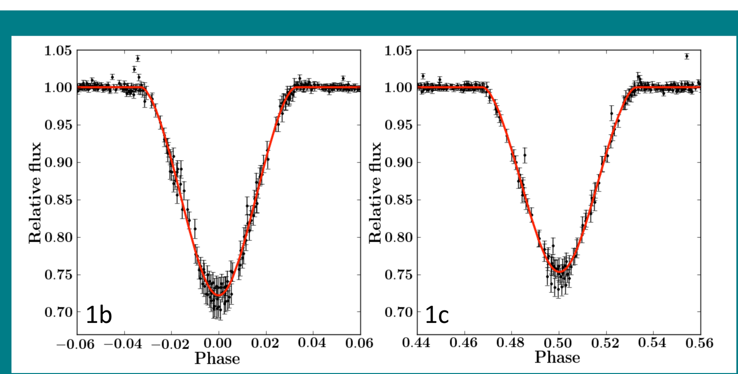
We are looking into alternative possibilities, such as a combination of occultations by circumbinary material and accretion-related variability.

Modelling the light curve

To extract useful information on the binary components, we first need to model and remove the out-of-eclipse variability, which we do using Gaussian Processes[1] (GPs; see Fig 1a).

We subtract the GP fit and model the residuals using JKTEBOP[2], specifying a quadratic limb darkening description with coefficients set according to surface temperature and log *g* estimates from stellar atmospheric models[3]. Figs 1b and c shows the best-fit JKTEBOP model through the primary and secondary eclipses





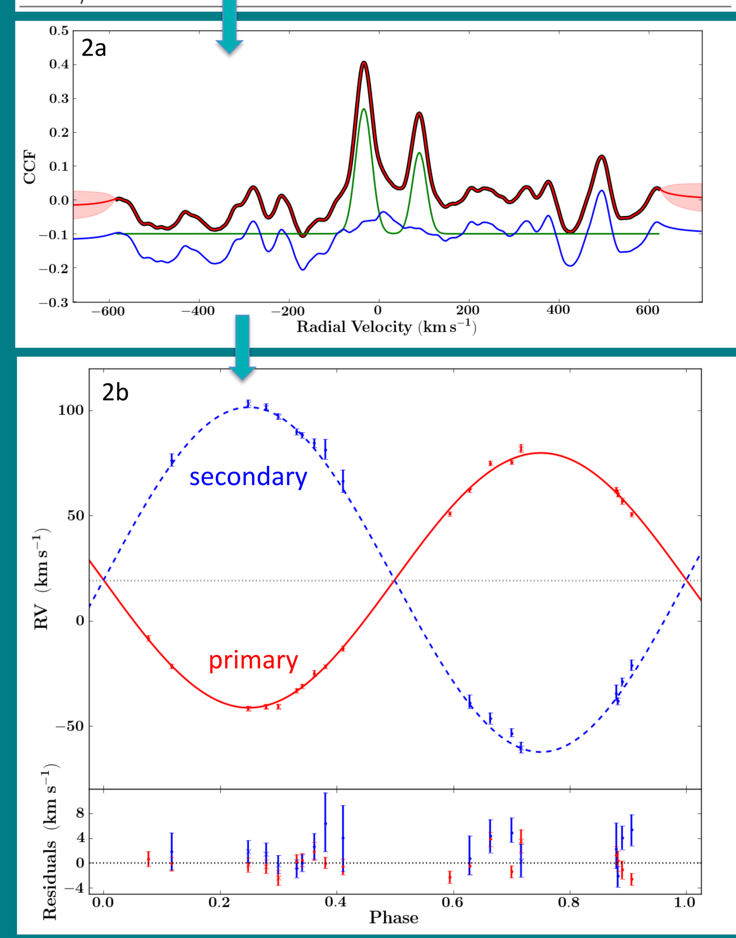
2. Spectra

We performed both low and medium resolution spectroscopy to infer the combined spectral type of M2 and extract radial velocities (RVs) respectively (see Table 2 and Fig 2).

We determine RVs by cross-correlating with MARCS theoretical model spectra[4]. In Fig 2a we model the cross correlation function (CCF, black) as the sum of 2 Gaussians (green) plus a stochastic noise term, which is described by a GP (blue, both offset for clarity), and indicate the combined model (red) and 1σ confidence interval (pink shaded region). Our RV orbital solution is shown in Fig 2b. FLAMES and ISIS spectra are indicated by dots and crosses, respectively. The horizontal grey dotted line depicts the systemic velocity, which is in agreement with the cluster's recessional velocity to within 1σ.

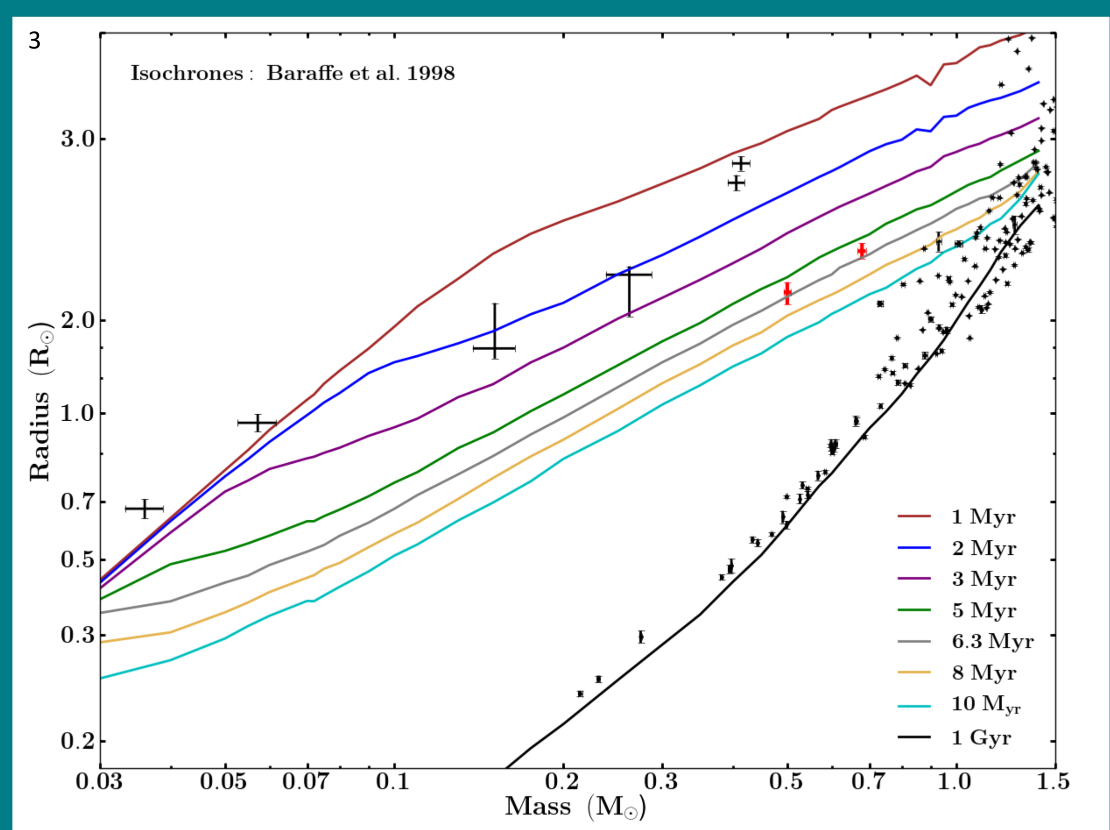
Table 2

Instrument	Resolution	λ range (Å)	No. of spectra
Spectral Type			
Calar Alto 2.2m / Cafos	~ 7 Å	~4600 – 7700	1
RVs			
VLT / FLAMES	$R \sim 17000$	~6440 – 6820	15
WHT / ISIS	$R \sim 12000$	~7850 – 8900	7
INT / IDS	$R \sim 9300$	~7650 – 9300	3



3. Fundamental Parameters

Masses and radii for young, detached, double-lined EBs, such as this, can be determined model independently (see Table 1) and are extremely valuable in testing pre-main sequence (PMS) stellar evolutionary models. On the PMS, evolution is rapid, the models are still sensitive to their initial conditions and we currently have very few constraints. The figure shows the Mass-Radius relation for low mass, detached-EBs with Baraffe et al.[5] model isochrones (coloured lines). Black points depict known EBs[6] and this system is shown in red. We note that this system lies in a very sparsely populated region of the diagram, highlighting its value and also that both components lie on the same isochrones (~5-7Myr), in agreement with model predictions.

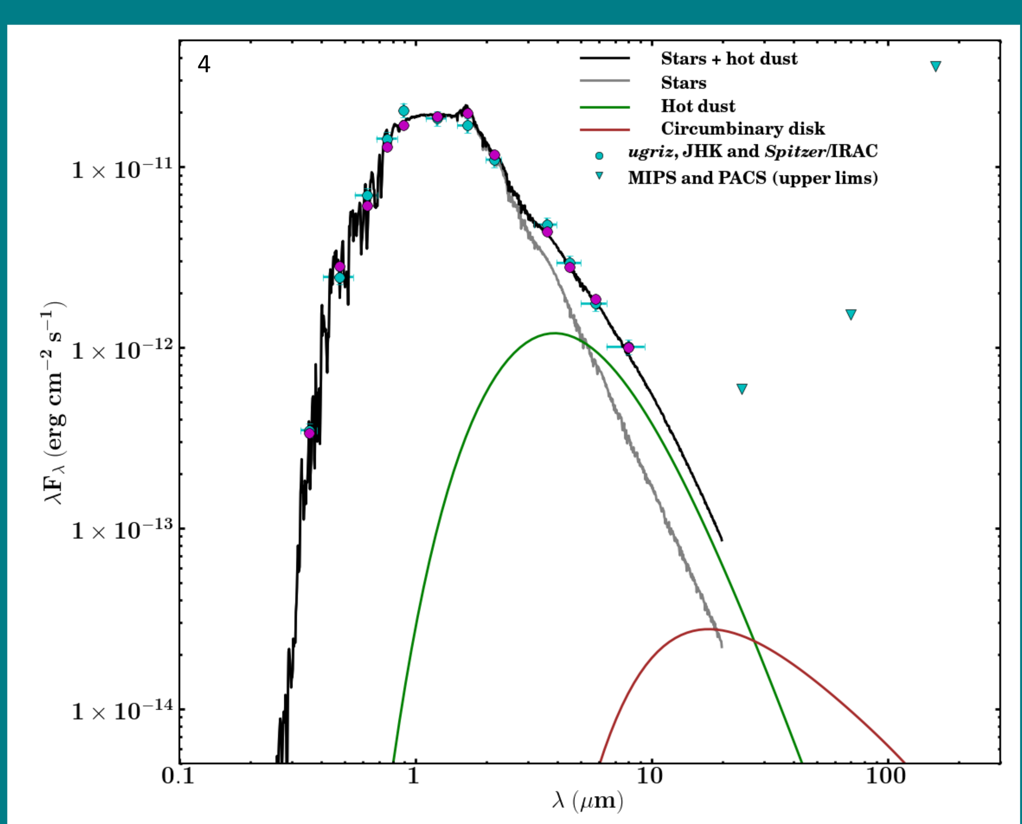


5. Future Work

CoRoT re-observed NGC 2264 in Dec 11 / Jan 12 as part of a co-ordinated program including Spitzer, CFHT and VLT/FLAMES.

Simultaneous CoRoT and Spitzer photometry (spanning 38, 23 and 28 days respectively for CoRoT and Spitzer [3.6] and [4.5]) show that the out-of-eclipse variability is still present with both similarities and differences seen in the separated bandpasses. These will be analysed jointly with the time-dependent Hα emission seen in the FLAMES spectra (Table 2), and with CFHT light curves obtained the following month, to refine the parameters of the central binary components and to investigate the source of the out-of-eclipse variability in more detail.

4. Spectral Energy Distribution (SED)



We modelled the SED to look for evidence of dust emission in the environment of the two stars, and there is definitely an IR excess compared to the SED expected from the two stars alone.

In a PMS close-binary system one can expect a) circumstellar disks around each star extending up to ~1/3 of the binary separation[7,8] and b) a circumbinary disk around both stars with an inner cavity of radius ~ twice the binary separation[9], but neither would explain the SED: the circumstellar disks would be too hot for dust to survive, and the circumbinary disk too cool to have much effect on the SED at *Spitzer*/IRAC wavelengths.

We therefore model the IR excess as coming from a small amount of dust (~$5\times10^{-13} M_\odot$) in the inner cavity of the circumbinary disk, as seen in some other (non eclipsing) PMS binaries[10], and this fits the SED well. This could be a sign that low-level accretion through the cavity is ongoing.

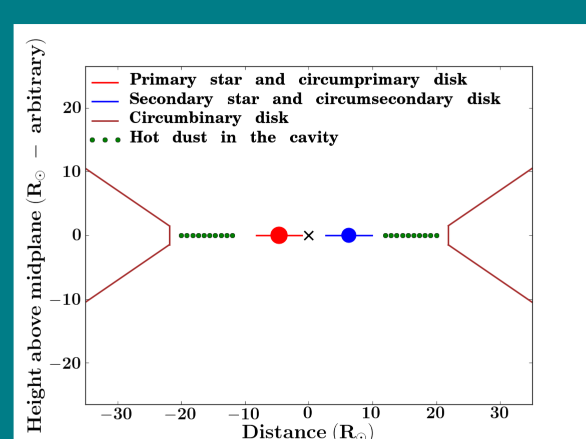


Fig 5: Schematic representation of the proposed system geometry. The size and separation of the stars are to scale.

Table 1: System parameters

Parameter	Primary	Secondary
Derived Parameters		
Mass $(M_\odot)$	0.668 ± 0.011	0.4952 ± 0.0071
Radius $(R_\odot)$	$1.295\,^{+0.040}_{-0.036}$	$1.107\,^{+0.043}_{-0.051}$
Semi-major axis $(R_\odot)$	$10.92\,^{+0.053}_{-0.056}$	
Fitted parameters from LC and RV analysis		
K $(\mathrm{km\,s^{-1}})$	60.49 ± 0.39	81.55 ± 0.62
V_{sys} $(\mathrm{km\,s^{-1}})$	19.43 ± 0.27	
P (days)	3.8745745 ± 0.0000014	
i (°)	$85.09\,^{+0.16}_{-0.11}$	
$e\cos\omega$	0.00049 ± 0.00027	
$e\sin\omega$	-0.0033 ± 0.0040	
e	$0.0037\,^{+0.0036}_{-0.0025}$	
J	0.871 ± 0.036	
L_{sec}/L_{pri}	0.642 ± 0.092	

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