A new level of photometric precision: 
WIRE observations of eclipsing binary stars

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Abstract. The WIRE satellite was launched in March 1999 and was the first space mission to do asteroseismology from space on a large number of stars. WIRE has produced very high-precision photometry of a few hundred bright stars (\(V < 6\)) with temporal coverage of several weeks, including K giants, solar-like stars, \(\delta\) Scuti stars, and \(\beta\) Cepheids. In the current work we will describe the status of science done on seven detached eclipsing binary systems. Our results emphasize some of the challenges and exciting results expected from coming satellite missions like COROT and Kepler. Unfortunately, on 23 October 2006, communication with WIRE failed after almost eight years in space. Because of this sad news we will give a brief history of WIRE at the end of this paper.

1. Observing bright stars with the WIRE star tracker
The failure of the main mission of the WIRE satellite shifted focus to the star tracker, which has a small aperture of 52 mm and is equipped with a 512×512 pixel SITe CCD. During observations the main target is positioned near the middle of the CCD and the four brightest stars in the 8×8 degree field of view are also monitored. These four secondary stars are chosen automatically by the on-board software. Each observation comprises a time stamp and an 8×8 pixel window centred on the target. Two images per second are collected for each star, resulting in typically one million CCD windows in three weeks. Due to pointing restrictions two fields are observed during each WIRE orbit. The duty cycle for one star per orbit is optimally 40\%, but can be as low as 20\%. The orbital period has decreased from 96 to 93 minutes over the course of the mission. The filter response of the star tracker is not well defined but Johnson \(V + R\) has been suggested \cite{1}. For more details about WIRE see Sect. 4.

2. Eclipsing binary stars observed with WIRE
The location of the 100 WIRE targets with the best photometry are shown in Fig. 1. The seven detached eclipsing binaries (dEBs) observed by WIRE are marked, and basic information for these objects is given in Table 1. For each of these systems the WIRE light curve is hugely better than existing observations, allowing definitive analyses of even the difficult objects.

2.1. The seven eclipsing binaries observed with WIRE
Four of the dEBs (\(\beta\) Aur, AR Cas, \(\delta\) Cap and \(\lambda\) Sco) were observed as primary targets by WIRE. \(\mu\) Eri was a secondary target but is known to be a remarkable object which shows slowly
pulsating B-type (spB) star variation and eclipses [2]. The sixth system, π Sco, is probably an ellipsoidal variable. Finally, ψ Cen was discovered to be a dEB from its WIRE light curve. The fact that we are still discovering eclipses in stars visible to the naked eye illustrates just how much science remains to be done with the brightest and closest stars to Earth.

We are in the process of modelling the light curves of the dEBs observed by WIRE in order to measure their properties. When combined with radial velocity analyses we will measure the masses and radii of the component stars with an accuracy better than 1%, which is generally needed to apply detailed constraints to the properties of theoretical stellar evolutionary models [3].

To analyse the light curves we are using the JKTEBOP modelling code\(^1\) [4], which is based on the EBOP code written by Etzel [5]. The major advance of JKTEBOP is the implementation of a Monte Carlo error estimation algorithm [6–8], which is a vital source of reliable parameter uncertainties when only one light curve is available for a dEB. For our work on the WIRE light curves we have added several new features, including non-linear limb darkening laws [9; 10] and the direct incorporation of spectroscopic light ratios and times of minimum light [9].

\(^{1}\) JKTEBOP is written in FORTRAN77 and the source code is available at http://www.astro.keele.ac.uk/~jkt/

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**Figure 1.** Hertzsprung-Russell diagram of around 100 stars observed with WIRE. The locations of the seven dEBs and the Sun are marked.
2.2. Further observations of the newly discovered eclipsing binary ψ Cen

In [13] we presented the discovery and photometric analysis of a new bright \( V = 4.1 \) well-detached EB, ψ Cen, previously known to have a variable radial velocity [14]. The phased WIRE light curve in Fig. 2 shows two deep flat-bottomed eclipses. WIRE observed a short additional light curve of a primary eclipse of ψ Cen in 2006 July, allowing us to refine the orbital period to \( P = 38.811929 \pm 0.000012 \) d.

To further constrain the parameters of the ψ Cen system, we have obtained radial velocity data from FEROS at the ESO 2.2 m telescope on La Silla. We have spectra from 33 epochs covering the full orbit and the data are currently being processed. Also, we have obtained Johnson \( B,V \) photometry in order to measure the colour difference in the eclipses, which will in turn allow us to constrain the ratio of the \( T_{\text{eff}} \)s of the two stars.

![Figure 2. Phased light curve of ψ Cen from WIRE. We show the original time series from 2004 along with the new data from 2006 in red colour.](image)

2.3. WIRE observations of β Aur, the first known double-lined eclipsing binary

β Aur was the first known double-lined spectroscopic binary, discovered in the course of the Henry Draper Catalogue project by [15]. It was subsequently found to be eclipsing [16], making it also the first known double-lined eclipsing binary. It is very bright \( V = 1.9 \), has an orbital period close to four days \( P = 3.9600 \) d, and shallow eclipses which are less than 10% deep.

| Star | Spectral types | Period [d] | Notes |
|------|----------------|------------|-------|
| δ Cap | Am F | 1.02 | Active component, see [11] |
| π Sco | B1V B2 | 1.57 | β Cep components |
| β Aur | A1 m A1 m | 3.96 | Published [9] |
| λ Sco | B1.5 IV B2 V | 5.95 | Triple system [12] |
| AR Cas | B4 V A6 V | 6.06 | spB component |
| μ Eri | B5 IV ? | 7.38 | spB component, see [2] |
| ψ Cen | B9 V A2 V | 38.81 | Published [13] |
These characteristics have made it a remarkably difficult object to study, particularly in the current era of rapidly increasing telescope aperture size. Conversely, the similarity and low rotational rates of the two stars mean it is very easy to study spectroscopically. As a result, the best study of $\beta$ Aur [17] was based on light curves from the 1960s [18] and a photographic radial velocity analysis from the 1940s [19]. $\beta$ Aur also has a high-precision parallax from HIPPARCOS [20] and an orbital parallax from the Mark III Optical Interferometer [21].

We obtained a WIRE light curve (Fig. 3) covering 21 days in 2006 April and consisting of 30,015 observations with a point-to-point scatter of only 0.3 mmag. The characteristics of the light curve required us to modify the JKTEBOP code to include spectroscopic light ratios and times of minimum light directly in the solution. We also took the opportunity to measure the coefficients of non-linear limb darkening laws for the first time for an EB system. The best-fitting model is an excellent match to the data (Fig. 3) and yields the fractional radii of the two stars to 0.5%. Using the radial velocity analysis of [19] we find masses of $M_A = 2.38 \pm 0.03 M_\odot$ and $M_B = 2.29 \pm 0.03 M_\odot$, and radii of $R_A = 2.76 \pm 0.02 R_\odot$, $R_B = 2.57 \pm 0.02 R_\odot$ for the two stars [9]. The surface brightness method [22] gives a distance to $\beta$ Aur of $25.0 \pm 0.4$ pc, in very nice agreement with the HIPPARCOS distance of $25.2 \pm 0.5$ pc.

![Figure 3. Top panel: phased light curve of $\beta$ Aur obtained using WIRE. Bottom panel: residuals of the best JKTEBOP fit.](image)

2.4. A new system: $\mu$ Eri

$\mu$ Eri was found to be an spB star by [23] and subsequently discovered to be eclipsing [2]. It was observed by WIRE as a secondary target for eight days in 2004 February and 24 days in 2005 August. The light curves are shown in the top panels in Fig. 4: both show variation at timescales of 1.5–2.5 days with beating of several modes. These periods are consistent with spB variations also seen by [2] and in agreement with the spectral type of B5IV. In addition, eclipses occur every $\approx 7.4$ days (marked by triangles in Fig. 4). In the middle panels we show the amplitude spectra of the light curves (excluding data taken during the eclipses). Note that the variation at low frequencies leak into frequencies near the orbital frequency of WIRE at $\approx 15.4$ cycles/day. In the bottom panels we shown the two time series with the oscillations removed and phased with the orbital period of 7.381 d.
We have fitted the detrended light curve with JKTEBOP and have confirmed that there is a chance of measuring the radii of the two stars to within a few per cent. However, this brute-force approach will need refining to obtain trustworthy results: at present it can be seen that the eclipse depth is apparently variable in the detrended data (Fig. 4). We will need to obtain new radial velocities, and then study these simultaneously with the oscillations and eclipses. This work is in progress.

Figure 4. Top panels: light curves of $\mu$ Eri from February 2004 (in red) and August 2005. Middle panels: amplitude spectra of the light curves (eclipses removed). Excess power below 1 c/day is seen to leak to frequencies around the orbital frequency of WIRE. Bottom panels: the phased time series after oscillations have been subtracted.

2.5. Preliminary results for AR Cas
AR Cassiopeiae is a bright ($V = 4.9$) dEB composed of a B4 V primary star and a much less massive A6 V secondary component. [24] were the first group to find the secondary star in the spectrum, as this component only contributes a few per cent of the light of the system. AR Cas has an orbital period of 6.06 days, an eccentric orbit, and exhibits apsidal motion, probably with a long apsidal period [24]. Our WIRE light curves of AR Cas show that the system undergoes shallow total eclipses. We have fitted the data with JKTEBOP and the phased light curve and fit (solid line) are compared in Fig. 5. The light curve fit is good for the eclipses but is less good outside eclipse as the primary component of AR Cas is intrinsically variable. A periodogram of the residuals of the best fit shows significant power at several frequencies and suggests that the primary of AR Cas may be an spB star.

We are in the process of studying AR Cas both photometrically and spectroscopically. At this point we have obtained over 100 grating spectra using the Isaac Newton Telescope and IDS spectrograph and 27 high-resolution échelle spectra with the recently-installed FIES instrument.
at the Nordic Optical Telescope, and will be obtaining further data in 2007 October. The light curve will need a similar approach to $\mu$ Eri – simultaneous inclusion of both pulsational and eclipse effects – and an implementation of this into JKTEBOP is in progress.

\image{light_curve.png}{Figure 5. The phased light curve of AR Cas (points) is compared to the best JKTEBOP fit (solid line). The pulsations have not been subtracted from the light curve.}

2.6. Preliminary results for $\delta$ Cap

The last dataset to be obtained from the WIRE satellite was a twelve-day light curve of the active star $\delta$ Cap ($V = 2.9$). The phased light curve shown in Fig. 6 shows shallow eclipses with a “nasty” orbital period of 1.02 days, making it nearly impossible to observe from the ground. The primary component is a metallic-lined A-star and the much fainter secondary is probably an F-star. The system is a known X-ray source and was detected by ROSAT [25]. Again, the analysis of this light curve presents serious challenges: the total light contribution from the secondary star is comparable to the amplitude of the brightness changes of the primary star.

\image{wire_light_curve.png}{Figure 6. Top panel: the phased WIRE light curve of $\delta$ Cap shows clear primary eclipses, very shallow secondary eclipses, and significant intrinsic variation arising from the much brighter primary star. Bottom panel: a periodogram of the residuals of the fit displays a rich power spectrum characteristic of an active star.}
3. Conclusion

We have presented on-going work on the observations and modelling of several eclipsing binary systems observed with the WIRE satellite. The week-long temporal coverage of the targets has made it possible to study dEB systems that are notoriously difficult to observe from the ground, due to their periods being close to an integer number of days. The high precision of the photometry from WIRE is a huge improvement compared to even the best photometric observations from the ground. The two important advantages of space based photometry are:

- No atmospheric scintillation noise
- High stability of the WIRE star tracker over periods of several weeks.

These data have made it possible to push the limits on the constraints we can put on the theoretical models of these stars, covering the HR diagram from early B to late F type main sequence stars. However, at this level of precision the oscillations of the component stars, although amplitudes are small, need to be taken into account as part of the light curve analysis.

In a broader context, the results presented here give an idea of the potential of secondary science on dEBs that can be done with data from the future satellite photometry missions. Many new systems will be discovered with COROT (see [26]) and Kepler as discussed by [27]. Although the new systems will be much fainter, follow-up spectroscopy and multi-band photometry can still be done from the ground.

4. WIRE epitaph: eight years of high-precision photometry from space

In 1994, WIRE was selected as the fifth NASA satellite mission under the Small Explorer (SMEX) program. WIRE was successfully launched into a sun-synchronous low-Earth orbit on 4 March 1999 [28]. Equipped with a 12” telescope and an infrared camera cooled with hydrogen, it was designed to study faint star burst galaxies [29]. However, the cover for the main camera opened three days too soon and the instrument was exposed to sun light. As a result, the

Figure 7. The WIRE satellite with its successful star tracker on the side of it.
hydrogen coolant was quickly lost, and as a consequence the main mission failed. Derek L. Buzasi, who was working at NASA at the time, realized that the fully functional star tracker could potentially be used to monitor oscillations in bright stars [1]. The planned mission lifetime of WIRE was only four months, but the secondary asteroseismology mission with the star tracker lasted nearly eight years.

WIRE was used for two epochs with slightly different observing modus. In epoch 1 from May 1999 to September 2000 around 25 stars were monitored. The star tracker kept the prime target on the same position within a few hundredths of a pixel over periods of several weeks [30]. In addition four other stars were observed, but due to the slow rotation of the space craft, the four secondary stars drifted across the CCD pixels. It was not possible to acquire a flat field so variations of a few per cent were seen in the data with typical time scales of a day. As a consequence, the secondary targets in epoch 1 were not usable for detailed studies. Highlights of the research from epoch 1 include the detection of \( p \) modes in the solar-like stars \( \alpha \) Cen A [31; 32] and Procyon A [33], and the discovery that Altair is the brightest \( \delta \) Scuti star in the sky [34; 35]. Mainly due to funding problems there was a break for over three years until the observations started again in late 2003.

Epoch 2 lasted from December 2003 until 23 October 2006 at 18.14 UT, when communication with the satellite failed. Reprogramming the modus operandi of the satellite made it possible to keep all five “tracker stars” fixed on the same pixel position, thus avoiding the problem of not having a flat field image. Consequently, a multitude of secondary targets were observed and today 300 light curves of around 200 stars exist in the WIRE database [30]. During the second epoch a pipeline was developed to reduce the data [33]. In the last two years of operation a few campaigns were organised where ground-based support was made. For two \( \delta \) Scuti stars, \( \epsilon \) Cep [36] and 29 Cyg (now being analysed), simultaneous Strömgren \( uvby \) data were collected in an attempt to identify the oscillation modes by measuring amplitude ratios and phase differences between different filters. Furthermore, large ensembles of pulsating stars of different spectral types were observed. Around 20 \( \beta \) Cep and 15 spB-type pulsators have been monitored (see Fig. 1). Also, a systematic change with evolutionary status of the amplitude and frequency in K giants has recently been reported [37].

The idea of observing the oscillation of stars from space came about in the early 1980s [38]. After the unfortunate loss of the EVRIS mission in 1996, another 10 years passed until COROT was launched in December 2006 (see Michel, these proceedings). Before that the WIRE satellite and the Canadian MOST asteroseismology mission were launched in March 1999 and June 2003, respectively. The potential promise of great science from photometry from space was realized somewhat earlier, based on the HIPPARCOS mission and the guide stars used by the Hubble Space Telescope [39].

The future looks bright for asteroseismology from space with more missions being planned. NASA’s Kepler mission is set for launch in February 2009 [40], and will observe 512 asteroseismic targets (at high cadence) for up to four years. A recently proposed ESA mission is Plato (see Catala, these proceedings). On a slightly smaller scale we mention the SMEI instrument now flying on the Coriolis mission [41] and the upcoming BRITE-Constellation of microsatellites [42].

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