

## Asteroseismology with the WIRE satellite

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### Abstract

I give a summary of results from the WIRE satellite, which has been used to observe bright stars from 1999–2000 and 2003–2006. The WIRE targets are monitored for up to five weeks with a duty cycle of 30–40%. The aim has been to characterize the flux variation of stars across the Hertzsprung-Russell diagram. I present an overview of the results for solar-like stars,  $\delta$  Scuti stars, giant stars, and eclipsing binaries.

### Introduction

The Wide-field Infra-Red Explorer (WIRE) satellite was launched on 4 March 1999 with the aim to study star-burst galaxies (Hacking et al. 1999). The mission was declared a failure only a few days after launch when it was realized that the hydrogen coolant for the main camera had leaked. Since May 1999 the star tracker on board WIRE has been used to measure the variability of bright stars (Buzasi et al. 2000). Previous reviews of the performance and science done with WIRE were given by Buzasi (2001, 2002, 2004), Laher et al. (2000), and Buzasi & Bruntt (2005).

### Observing with WIRE

WIRE is in a Sun-synchronous orbit with a period that has decreased from 96 to 93 minutes from 1999 to 2006. Constraints from the pointing of the solar panels limits pointing in two roughly  $\pm 30^\circ$  strips located perpendicular to the Sun-Earth line (Buzasi et al. 2000). In order to limit scattered light from the illuminated face of the Earth the satellite switches between two targets during each orbit. Each target has a duty cycle of typically 30–40%.

The star tracker has a 52-mm aperture and a  $512^2$  pixel SITE CCD. Windows of  $8 \times 8$  pixels centred on the star are read out from the CCD at a cadence of 10 Hz. An example is shown in the left panel of Fig. 1. During the first few months of operation only the primary target was read out in the 10 Hz high cadence mode, but after refining the on-board software up to five targets were read out (each target read out at 2 Hz). In the right panel of Fig. 1 I show the distribution of  $x, y$  positions for 56 000 windows centred on the main target ( $\alpha$  Cir). The FWHM of the distribution is just one hundredth of a pixel. One pixel on the CCD corresponds to about one arc minute. For details on the photometric pipeline and a discussion of scattered light see Bruntt et al. (2005).

In the early WIRE runs from 2000–1 the field was slowly rotating which meant that the secondary targets moved across the CCD at timescales of one pixel every few days (depending on the distance from the main target which is centred on the CCD). These data are thus only of limited use since it is not possible to take flat fields. Due to lack of funding WIRE was put into sleep mode for about two years from September 2001 – November 2003. For the past three years WIRE has observed in a new mode where the secondary stars stay fixed on the same position on the CCD. As a consequence, the number of stars observed with high photometric precision has increased from a few dozen to more than two hundred.

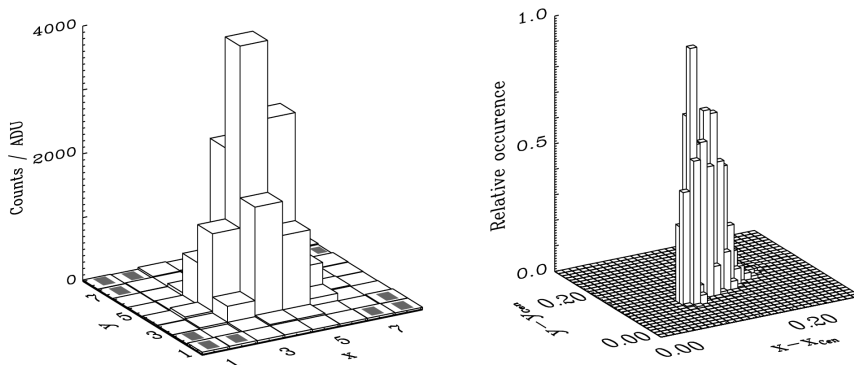


Figure 1: The left panel shows a CCD window from WIRE. The grey boxes mark the pixels used for determination of the sky background. The right panel shows the distribution of the  $x$ ,  $y$  position of the central target from 56 000 CCD windows.

## An overview of stars observed with WIRE

In Table 1 I list the brightest stars observed with WIRE from March 1999 to June 2006. There are 45 main sequence stars (luminosity class IV-V) on the left part of the table and 45 evolved stars on the right. I give the common name of each star (usually the Bayer designation), the Henry Draper number,  $V$  magnitude, and spectral class. This information was extracted from the SIMBAD database. I have also marked the stars for which the analysis has been published (marked with a  $\checkmark$ ) and the stars that are currently being analysed (marked with a  $\circ$ ).

In Fig. 2 I show the location in the Hertzsprung-Russell diagram of 200 stars observed with WIRE. In the following I will briefly discuss the main results for different classes of stars.

### Solar-like stars

The first solar-like star observed with WIRE was  $\alpha$  Cen (Rigel Kentaurus; G2V). Preliminary results based on the 50-d light curve observed in high-cadence mode were reported by Schou & Buzasi (2001), who could claim the first clear detection of the characteristic comb pattern of  $p$  modes in the star. This was confirmed in radial velocity by Bouchy & Carrier (2001, 2002). Bedding et al. (2004) identified 40 modes from a multisite radial velocity study, and Kjeldsen et al. (2005) constrained the lifetime of the modes to  $\tau = 2.3^{+1.0}_{-0.6}$  days. The main limitation on the uncertainty of the lifetime is the limited time baseline. Fletcher et al. (2006) recognized this, made a refined analysis of the WIRE data set and measured a mode lifetime of  $\tau = 3.9 \pm 1.4$  days which is in agreement with the result from the radial velocity survey.

Karoff et al. (2007) applied the same method to the WIRE data of the evolved solar-like star  $\beta$  Hydri (G2IV). They found clear evidence of solar-like oscillations and measured a mode lifetime very similar to  $\alpha$  Cen ( $\tau = 4.2^{+2.0}_{-1.4}$  d).

Like  $\beta$  Hydri,  $\alpha$  CMi (Procyon; F5IV-V) is slightly more massive and more evolved than the Sun. Bruntt et al. (2005) found excess power in the power spectrum which they interpreted as a combination of granulation and solar-like oscillations. This was in disagreement with the null result by Matthews et al. (2004) based on 32 days of continuous photometry from the MOST satellite. As discussed by Bruntt et al. (2005), the noise level per data point in the MOST data was more than three times higher than in the WIRE data. This is likely due to high scattered light levels in the MOST data (see also Bedding et al. 2005).

Table 1: The brightest main sequence (left) and evolved stars (right) observed with WIRE. The name, HD number,  $V$  magnitude, and spectral type are given. Stars whose observations have been published are marked by  $\checkmark$ , while stars currently being analysed are marked by  $\circ$ .

	Name	HD	$V$	Type		Name	HD	$V$	Type
$\checkmark$	$\alpha$ Cen	128620	0.0	G2V	$\checkmark$	$\alpha$ Boo	124897	0.0	K1.5III
$\checkmark$	$\alpha$ CMi	61421	0.3	F5IV-V		$\alpha$ Ori	39801	0.6	M2Iab
$\checkmark$	$\alpha$ Aql	187642	0.8	A7V	$\checkmark$	$\alpha$ UMa	95689	1.8	K0Iab
	$\alpha$ Vir	116658	1.0	B1III-IV		$\epsilon$ Car	71129	2.0	K3IIIva
$\checkmark$	$\beta$ Cru	111123	1.3	B0.5IV		$\beta$ CMa	44743	2.0	B1I/III
	$\alpha$ Leo	87901	1.4	B7V	$\circ$	$\alpha$ UMi	8890	2.0	F7 Ib-II
$\circ$	$\lambda$ Sco	158926	1.6	B2IV+		$\beta$ UMi	131873	2.1	K4III
$\checkmark$	$\epsilon$ UMa	112185	1.8	A0p		$\gamma$ Dra	164058	2.2	K5III
$\circ$	$\beta$ Aur	40183	1.9	A2IV+		$\alpha$ Lup	129056	2.3	B1.5III
	$\alpha$ Pav	193924	1.9	B2IV	$\checkmark$	$\kappa$ Sco	160578	2.4	B1.5III
	$\delta$ Vel	74956	2.0	A1V		$\epsilon$ Peg	206778	2.4	K2Ib
	$\gamma$ Leo	—	2.0	K0		$\beta$ Peg	217906	2.4	M2.5I-I
	$\sigma$ Sgr	175191	2.1	B2V		$\alpha$ Peg	218045	2.5	B9III
	$\beta$ Leo	102647	2.1	A3V		$\epsilon$ Cyg	197989	2.5	K0III
	$\beta$ Cas	432	2.3	F2IV		$\gamma$ Aql	186791	2.7	K3II
	$\delta$ Sco	143275	2.3	B0.2IVe		$\epsilon$ Vir	113226	2.8	G8III
	$\eta$ Cen	127972	2.3	B1.5Vne		$\eta$ Peg	215182	2.9	G2II-III
	$\kappa$ Vel	81188	2.5	B2IV-V		$\iota^1$ Sco	161471	3.0	F2Iae
	$\zeta$ Oph	149757	2.6	O9V		$\alpha$ Ind	196171	3.1	K0IIICNv
	$\alpha$ Col	37795	2.6	B7IVe		$\beta$ Col	39425	3.1	K2III
	$\eta$ Boo	121370	2.7	G0IV		$\phi$ Sgr	173300	3.2	B8III
	$\nu$ Sco	158408	2.7	B2IV		G Sco	161892	3.2	K2III
$\checkmark$	$\beta$ Hyi	2151	2.8	G2IV		$\kappa$ Oph	153210	3.2	K2III
	$\alpha$ Ara	158427	2.8	B2Vne		$\beta$ Cep	205021	3.2	B2IIIeva
	$\pi$ Sco	143018	2.9	B1V+		$\tau$ Sgr	177716	3.3	K1IIIB
	$\zeta$ Tau	37202	3.0	B2IV		$\epsilon$ Cas	11415	3.3	B3III
$\circ$	$\alpha$ Cir	128898	3.2	A5V		$\zeta$ Cep	210745	3.4	K1.5Iab
	$\delta$ UMa	106591	3.3	A3V	$\checkmark$	$\theta^2$ Tau	28319	3.4	A7III
	$\delta$ Eri	23249	3.5	K0IV		$\xi$ Hya	100407	3.5	G7III
	$o$ Vel	74195	3.6	B3IV		$\gamma$ Tau	27371	3.7	K0III
	$\beta$ Aql	188512	3.7	G8IV		$\beta$ Ind	198700	3.7	K1II
	$\epsilon$ Eri	22049	3.7	K2V		$\xi$ Dra	163588	3.7	K2III
	$\rho$ Sco	142669	3.9	B2IV-V		$\nu$ Eri	29248	3.9	B2III
	$\pi$ Lup	133242	3.9	B5V		$\nu^2$ CMa	47205	4.0	K1III+
$\checkmark$	$\psi$ Cen	125473	4.0	A0IV		$\nu$ Boo	120477	4.1	K5.5III
	$\mu$ Eri	30211	4.0	B5V		$\delta$ Cep	213306	4.1	F5Iab
	$\rho$ Lup	128345	4.0	B5V		—	5848	4.2	K2II-III
	$\mu$ Ori	40932	4.1	A2V		Q Sco	159433	4.3	K0IIIB
$\checkmark$	$\epsilon$ Cep	211336	4.2	F0IV		$\pi$ Aur	40239	4.3	M3II
	90 Tau	29388	4.3	A6V		CE Tau	36389	4.4	M2Iab
	$o$ Lup	130807	4.3	B5IV		V761 Cen	125823	4.4	B7IIIPva
	$\delta$ UMi	166205	4.3	A1Vn		$\sigma$ Lup	127381	4.4	B2III
	$\gamma$ Col	40494	4.3	B2.5IV		$\nu^3$ CMa	47442	4.4	K0II/III
	$\tau^2$ Lup	126354	4.4	F7		$\rho$ Cas	224014	4.5	G2IaOe
	$\iota$ Oph	152614	4.4	B8V		11 Cep	206952	4.5	K1III

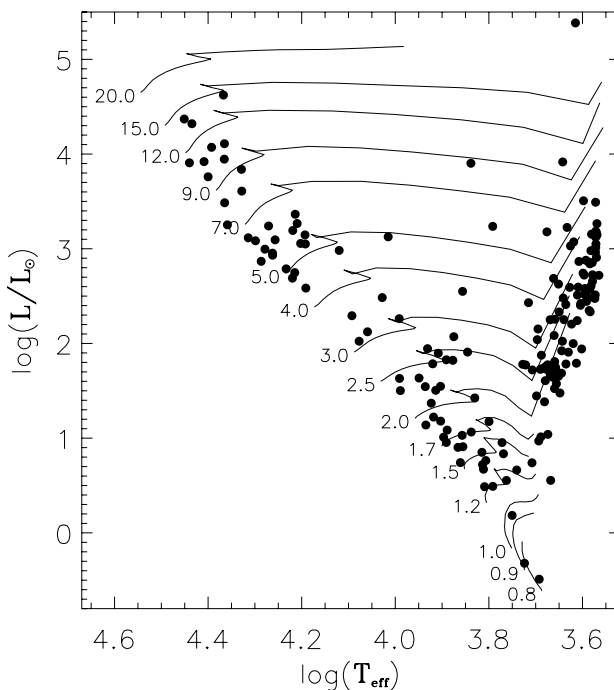


Figure 2: Hertzsprung-Russell diagram of about 200 stars observed with WIRE.

### Delta Scuti Stars

Several  $\delta$  Scuti stars have been monitored with WIRE. Poretti et al. (2002) made an analysis of the binary  $\delta$  Scuti star  $\theta^2$  Tau (the primary is A7III) and found 12 frequencies which were in agreement with results by Breger et al. (2002) from a ground-based multisite campaign. The detection of a peak at high frequency seen in both the WIRE and ground-based data led Breger et al. (2002) to argue that this mode is real (i.e. not an alias or combination frequency) and likely due to oscillations of the secondary star in the  $\theta^2$  Tau binary system.

Poretti et al. (2002) were the first to point out that WIRE is capable of doing time-series of the often neglected brightest stars in the sky, which are simply too bright for typical 0.5–1.0-m telescopes normally used for multisite campaigns on  $\delta$  Scuti stars (e.g. the DSN and STEPHI networks). Indeed, Buzasi et al. (2005) found seven low-amplitude (0.1–0.5 mmag) modes in  $\alpha$  Aql (Altair; A7V), which is now the brightest  $\delta$  Scuti star at  $V = 0.8$ .

Bruntt et al. (2007a) combined WIRE photometry and Strömgren  $uvby$  ground-based observations in an attempt to identify the modes of the  $\delta$  Scuti star  $\epsilon$  Cep (F0IV). The space-based data provided a superior spectral window and low noise level. Using the extracted frequencies from WIRE Bruntt et al. (2007a) measured the amplitudes and phases in the  $uvby$  filters from ground-based photometry. However, the limited amount of ground-based data made the accuracy of the amplitudes and phases too poor to be able to identify the

modes from phase differences and amplitude ratios (e.g. Garrido, Garcia-Lobo & Rodriguez 1990). Bruntt et al. (2007a) estimated that it would require more than 100 nights of data to obtain the accuracy on the phases and amplitudes to be able to identify the modes.

### B-type stars

More than 35  $\beta$  Cep and SPB stars have been observed with WIRE. Cuypers et al. (2002) confirmed the variability known from spectroscopy of  $\beta$  Cru (Mimosa; B0.5IV) and in addition found new low-amplitude modes ( $A \simeq 0.2-0.3$  mmag). Cuypers et al. (2004) analysed WIRE data of the known multi-periodic  $\beta$  Cep star  $\kappa$  Sco (part of Girtab; B1.5III) and also detected low-amplitude modes not observed previously.

Bruntt & Buzasi (2006a) gave preliminary results for  $\lambda$  Sco (Shaula; B2IV) which is a known triple system (Uytterhoeven et al. 2004). From spectroscopy it is known that  $\lambda$  Sco comprises two B type stars in a wide orbit ( $P \simeq 1083$  d); one of these components has a low mass companion ( $P \simeq 5.95$  d). After subtracting the  $\beta$  Cep pulsation Bruntt & Buzasi (2006a) could clearly see the primary and secondary eclipses in the close system. From their preliminary light curve analysis they constrained the masses and radii of the component stars.

### Giant stars

The giant stars comprise around half of the targets observed with WIRE (cf. Fig. 2). This is because only the main target is chosen, while four additional secondary targets are selected automatically by the on-board computer based on the apparent brightness of stars in the field of view (about  $8^\circ$  square).

Buzasi et al. (2000) claimed the detection of a comb-like pattern below  $25 \mu\text{Hz}$  ( $P > 0.5$  d) associated with solar-like oscillations in  $\alpha$  UMa (Dubhe; K0III). In addition, two significant peaks were found above the acoustic cut-off frequency (see Dziembowski et al. 2001; Guenther et al. 2000). Retter et al. (2003) also found a series of peaks around  $4.1 \mu\text{Hz}$  ( $P \simeq 2.8$  d) in WIRE data of  $\alpha$  Boo (Arcturus; K1.5III). However, their simulations of a pure noise source showed similar spacings as found in both  $\alpha$  UMa and  $\alpha$  Boo. The spacings reported in the two stars are  $\Delta\nu = 2.9 \pm 0.3 \mu\text{Hz}$  and  $\Delta\nu = 0.83 \pm 0.05 \mu\text{Hz}$ . This is uncomfortably close to the frequency resolution at  $1/T_{\text{obs}} = 1.1 \mu\text{Hz}$  and  $0.6 \mu\text{Hz}$  for the data sets of  $\alpha$  UMa and  $\alpha$  Boo, respectively.

To conclude, the WIRE photometry of K giant stars shows clear evidence of excess power at low frequencies. In order to investigate whether this is due to solar-like oscillations and to find further evidence of a comb-like pattern, a larger sample of bright K giant stars is currently being analysed.

### Eclipsing binary stars

Bruntt et al. (2006b) discovered that  $\psi$  Cen (A0IV) is a bright detached eclipsing binary (dEB), based on photometry from WIRE and the Solar-Mass Ejection Imager (Howard et al. 2006) on the Coriolis spacecraft. The  $\psi$  Cen system comprises a B9 and an A2 type star in an eccentric orbit ( $e = 0.55$ ) with a long period ( $P = 38.8$  d). Bruntt et al. (2006b) determined the fractional radii of the stars to just 0.1%. In addition they found evidence of  $g$ -mode oscillations in the primary star, despite the star being somewhat cooler than the predicted SPB instability strip. I am currently analysing spectra of  $\psi$  Cen to determine absolute radii and masses with accuracies better than 0.5%.

Realizing the unique potential of WIRE to measure masses and radii of detached dEBs with unprecedented accuracy, a program has been started to monitor about a dozen known bright eclipsing binaries. Bruntt & Southworth (2007) presented preliminary light curves of the known Algol-type systems AR Cas (B4IV) and  $\beta$  Aur (Menkalinan; A2IV).

## Discussion

I have given an overview of the different classes of stars observed with the WIRE satellite. It is interesting that a star tracker never designed for the purpose has in fact resulted in important discoveries. One important lesson learnt from WIRE is that accurate pointing (attitude control) is important when flat fields are not available. Also, it is of tremendous value to have the “raw data” in the form of individual CCD windows. With this in hand one can correct for instrumental effects like scattered light, sub-pixel drift etc.

In the near future the dedicated photometry missions COROT and Kepler will provide high precision photometry with much longer time baselines (150 d for COROT; up to six years for Kepler) and nearly 100% duty cycle. This will be particularly interesting for long-period variables and may potentially solve the ambiguous results from WIRE for the K giants as was discussed here. However, less costly small satellites are also being planned (e.g., Weiss 2007) and will likely result in interesting science of bright stars.

The WIRE results for  $\delta$  Scuti stars and B-type stars point to the important fact that detailed comparison with theoretical models is not possible due to the lack of mode identifications. This must be considered carefully when planning ground-based support for the upcoming missions.

**Acknowledgments.** It was Derek L. Buzasi (US Air Force Academy) who had the bright idea to use the failed WIRE satellite to do asteroseismology from space. I started working with DLB in 2003 and spent five months with his group at USAFA during 2004. Our collaboration has been very fruitful as we continue to monitor bright stars with WIRE. I received support from the Danish Research Agency (Forskningsrådet for Natur og Univers), the Instrument center for Danish Astrophysics (IDA), and the Australian Research Council.

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## DISCUSSION

*Kaye:* Using WIRE to help understand 9 Aurigae would be useful. Many of us would find these additional data helpful, despite the fact that we still have single-site multicolour photometry of 9 Aurigae. Since nobody can figure out what it's doing, it might be useful to put WIRE at it; it's 5th magnitude and there are two frequencies at 0.8 and 0.3 c/d.

*Hatzes:* you said WIRE has only a year left. Is this just because of lack of funding?

*Bruntt:* It's getting closer down to the Earth's atmosphere. We don't know exactly how long it has left.

*Matthews:* For the eclipsing binary with the g mode, do you have evidence that it is tidally excited?

*Bruntt:* No.