Progress Report for ADP Award
"The Development of a Data Archive and Analysis Tools for WIRE"
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Year 1

1. Introduction

Over the past few decades, our understanding of the interior of the Sun – its thermodynamic structure, and its internal rotation and dynamics – has been revolutionized by the technique of helioseismology, the study of the frequencies and amplitudes of seismic waves that penetrate deeply into the solar interior (e.g., Duvall et al 1988, Leibacher et al 1985). The large number ($\sim 10^7$) of modes visible in the Sun permits this detailed modeling. Those modes with long horizontal wavelengths penetrate deeply into the solar interior, and thus provide information on conditions as far down as the core, while short wavelength modes sample the interior of the Sun just below the photosphere.

The lack of spatial resolution in stellar observations limits the number of observable modes to but a few. However, accurate measurements of even those few modes can yield two parameters, $\Delta\nu_0$ and $\delta\nu$, the large and small separations, which are related to the sound speed integral across the stellar radius (and thus to the mean density of the star; Cox 1980) and the sound speed gradient inside the stellar core (e.g., Christensen-Dalsgaard 1984, 1988), respectively. In conjunction with information about the star from other, more traditional sources, these parameters can be used to determine (or set limits on) the stellar distance, mass, age, composition, and convective mixing length (e.g., Ulrich 1986; Gough 1987, 1990; Brown et al 1994).

Techniques for detecting and measuring stellar oscillations fall basically into two groups: those based on spectroscopy, and those based on photometry. Spectroscopic methods have either focused on trying to measure periodic Doppler shifts in spectral features (e.g., Brown et al. 1997), or on detecting the small surface temperature changes associated with oscillations through their effects on line equivalent widths (e.g., Kjeldsen et al. 1995, 1998). Unfortunately, neither approach has been successful to date on solar-like stars. The difficulty they face can best be appreciated by realizing that the expected radial velocity shifts are typically less than 1 m s^{-1} – about an order of magnitude smaller than those associated with recent extrasolar planet searches. In addition, of course, stellar oscillations have periods of minutes (compared to planetary orbital periods of days or years), and thus the luxury of long integration times is not available.

Ground-based photometric approaches, usually based on differential CCD photometry, have not been successful on solar-like targets either, though attempts have been made (Gilliland et al 1993). Solar oscillations have a luminosity amplitude of approximately 4.4 μmag (Schrijver et al. 1991, Kjeldsen & Bedding 1995), or about three orders of magnitude less than the terrestrial atmospheric scintillation noise (typically the largest noise source for a ground-based observation) for a single 1-s observation with a 1-meter telescope. A semi-permanent network of at least 4 4-meter class telescopes would be required in order to achieve the required precision (Gilliland & Brown 1992).

Although a number of missions to perform asteroseismology from orbit are planned, such as the French COROT (currently scheduled for launch in 2004), the Canadian MOST (2002), and the Danish MONS (2003), none has yet been successfully flown. However, from May 1999 through September 2000, the PI of this proposal initiated a program using the star camera on board the WIRE spacecraft to perform high-precision photometry of solar-like and giant stars. This program relied on the on-board star camera, which consists of a 50mm f/1.75 telescope feeding a 512^2 SITe CCD, which can be read out at rates as high as 10 Hz (Smith & Deters 1999). The high cadence of observations available with this star camera is made possible by software that locates the 5 brightest stars in the field and reads only an 8x8 pixel box around one selected image. An additional mode of operation, available since November 1999, makes count rate data available on all five stellar images, with a consequent loss of read rate (to 2 Hz for 5 stars). Stellar images are defocused (to allow for more accurate image centroiding), but the entire stellar image lies within the 64-pixel box. we note that in many ways, this instrument is similar to the French instrument EVRIS, which was intended to perform asteroseismology with a 90 mm telescope, but which unfortunately flew as part of the failed Russian MARS 96 spacecraft.

Although at first a 50 mm objective may appear unreasonably small for a serious scientific instrument, the location of the telescope above the atmosphere more than compensates for its small size. From the ground, the primary contributor to noise is not photon statistics (Poisson noise), but rather scintillation noise due to the Earth's atmosphere. In practice, for bright targets ($m_V \leq 3$), WIRE typically achieves noise levels only 20—25 % greater than the Poisson noise level. Because in asteroseismology we are interested in the detection of periodic signals, a time series consisting of n observations improves our detection limit by approximately $\sqrt{n}$. Thus, in the best case to date, WIRE observations of the bright solar-like star α Cen showed noise levels of approximately 900 μmag per observation; analysis of the complete time series of 10^7 observations gave a 99% detection limit of $\approx 2.6 \mu mag$. A comparison of the capabilities for asteroseismology of WIRE and a large ground-based telescope is shown in Table 1.

Table 1: Comparison of WIRE and Keck for Asteroseismology

Parameter	WIRE	Keck
t_{exp} (s)	0.1	0.1
$\sigma_{Poisson}$ (μmag)	660	2.1[1]
ε (μmag)[2]	640	3400
σ_{total} (μmag)	920	3400
N[3]	8.7×10^5	1.2×10^7
Duty Cycle[4]	0.42	0.5
Time Required (days)	2.4	55.6

1. In practice, this level is difficult to achieve because of the large number of counts ($\approx 2\times10^{11}$) that it represents, which requires defocusing the stellar image on the CCD to a diameter of more than 10^3 pixels. At this level of defocus, read noise resulting from the required 10 MHz read rate is likely to become a problem. The table assumes an ideal detector.

2. Number of data points required to detect 4.4 μmag oscillations with a signal-to-noise ratio of 5, derived using an expression due to Scargle (1982) for sensitivity to coherent oscillations: $a = 2\sigma[SNR/N]^{0.5}$, where a is the oscillation amplitude, σ is the noise level of a typical data point, N is the number of data points in the time series, and SNR is the required signal-to-noise ratio.

3. The duty cycle estimate for WIRE is based on the assumption of 12 minutes on target per 90 minute orbit, while for Keck I've assumed 12 usable hours per night, on average.

The sun-synchronous orbit of WIRE would be ideal for asteroseismology were it not for the additional constraint imposed by the fixed solar panel orientation, which does not allow viewing down (or even near) the Earth's shadow cone. The result is that the time series are not continuous, but instead are interrupted once per 96-minute orbit. Since the maximum time per orbit on a particular target is limited to at best ~42 minutes, our duty cycle is only ~40% and thus data analysis is somewhat complicated by aliasing in the power spectrum.

The observing log for the WIRE asteroseismology program targets is shown in Table 2. Most objects were observed twice at intervals separated by approximately 6 months. In addition to the targets shown, 10 fields were observed as part of engineering programs and/or a high-precision photometry testbed program carried out by the KEPLER team.

Table 2: WIRE Asteroseismology Observing Log, sorted by spectral type

Name [Common Name]	Spectral Type	Number of Segments[1]	Data Analysis Status Flag
β Cru	B0 IV	214	Partial [publication expected 2001]
κ Sco	B2 III-IV	544	no
κ Vel	B2 IV	134	no
α Pav	B3 IV	294	no
σ Sgr	B3 V	350	no
α Leo [Regulus]	B7V	377	Partial [comp star for α UMa]
ε UMa	A0p	1203	Partial [publication expected 2001]
α PsA [Fomalhaut]	A3 V	311	no
β Leo	A3 V	415	no
α Oph	A5 III	333	no
θ^2 Tau	A7 III	466	no
α Aql [Altair]	A7 V	520	partial [data provided to MOST]
γ Equ	F0 IIIp	80	Partial [publication expected 2001]
α Cir	F0 V	769	partial [publication expected 2001]
α CMi (Procyon)	F5 IV-V	505	partial [publication expected 2001]
β Cas	F5 V	34	partial [publication expected 2001]
HD 209458	F8 V	507	no
η Cas	F9 V	189	no
α Cen (Rigel Kentaurus)	G2 V	1040	Partial [published 2001]
HD 113226	G8 III	365	no
α Boo [Arcturus]	K0 III	328	no
α UMa (Dubhe)	K0 III	880	Partial [published 2000]
ε Cyg	K0 III	502	no
ε Peg	K2 Ib	243	no
ε Eri	K2 V	224	no
HD 56855	K3 Ib	89	no
ε Car	K3 III	113	no
β Umi	K4 III	910	no
β Peg	M2 II-III	692	no

[1] The number of orbital segments for which each object was a target. Typically, an orbital segment corresponds to ~40 minutes.

2. Current Status

2.1 Computer Hardware Status

In the plan of work attached to the original proposal, we expected to purchase the necessary computer hardware, transfer all WIRE data to USAFA, and construct some software tools during the first year. Progress has been slightly delayed due to the events of 11 September 2001 and the ensuing increase in security at DOD facilities. For example, we have had to generate a security plan for the WIRE computer facility; the plan is included in this report as a separate document. However, we have successfully accomplished many of our goals:

A. Essentially all of the necessary computer hardware has been purchased and installed, including two multiprocessor Linux systems with more than 120 GB of disk space, DLT and DAT tape drives, and CD-RW capability. Both systems have been successfully incorporated in the USAFA network, and have access through the USAFA firewall to the outside world.

B. Approximately half of the WIRE data has been transferred to USAFA. This portion includes the earliest WIRE observations and is intended to be the first data to be delivered to NSSDC later this calendar year. We expect to have the remainder of the data in-house by the end of summer 2002.

C. Software tools for data reduction have been written, so that users wishing to rereduce the data using different parameters than those we have established as "standard" will be able to do so. However, we are still completing user-friendly user interfaces for these tools. Data reduced using the "standard" parameters have been supplied to research groups in the US, Denmark, Belgium, and Australia for testing.

D. The instrument has been characterized as well as is possible for us, including wavelength response, sensistivity, pointing characteristics and subpixel CCD structure.

2.2 A Standardized Approach to WIRE Data Reduction

Below we describe in some detail the standard data reduction package we have developed. As noted above, however, tools for performing the data reduction will be made generally available for those users wishing to rereduce the data in a different fashion. In addition, in a few specialized cases (such as for α Cen) we have diverged somewhat from the standard routine, though in those cases we plan to supply NSSDC with data reduced both according to the standard scheme and the approach we have determined to be optimal.

In the 5-star mode, which became the standard mode of operation after November 1999, the WIRE star camera defines 5 8x8 pixel "slots" or boxes on the CCD. Pixel data from each slot was telemetered to NASA/GSFC, and then delivered to IPAC. At IPAC, a software pipeline performs rudimentary filtering of poor data and generates a series of time-tagged 8x8 images. We then perform aperture photometry on the images, along with rudimentary background subtraction. The primary complication in handling WIRE images stems from their small size, which is only ~3 times wider than the FWHM of the stellar image. We make a first estimate of the background using a "four corners" algorithm, which uses the fluxes at the corners of the 8x8 image.

At this point, the data typically look something like those in Figure 2 below, which shows a small portion (26 segments, or about 125,000 observations) of an observation of the δ Scuti star θ^2 Tauri. As noted above, WIRE's sun-synchronous orbit, combined with limitations on pointing deriving from the solar panel orientation, means that under perfect circumstances a target can only be observed for ~42 minutes during each ~96 minute orbit, and the consequent sampling is obvious in the Figure. The most obvious flaw in this particular data is that the wrong star was observed for three orbital segments! Usually when this occurs, the reason is that the on-board software mislabeled the "slot" where the target star was located. In this particular case, the low-lying points come from the considerably fainter star located in slot 2. Repairing this problem involves examining each slot for each observation (in this case, a total of approximately 6 million observations) to confirm or correct the software identification of the star.

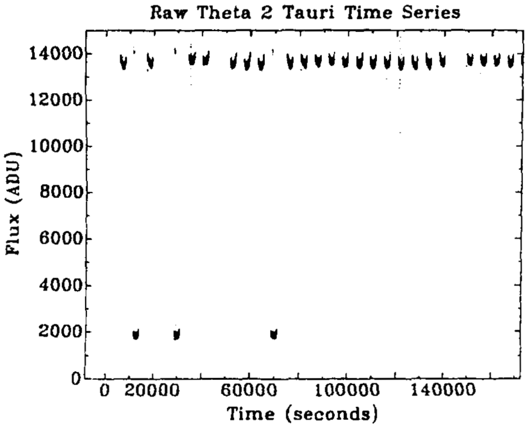


Figure 1: A portion of the WIRE time series for θ^2 Tauri, after on-board processing and first-stage pipeline reduction. Approximately 125,000 observations are shown. The periodic interruption of the signal is due to observation constraints imposed by the satellite orbit and solar panel orientation. The most obvious flaw at this point is the fact that the wrong star is identified as θ^2 Tauri for 3 orbital segments!

At the same time, we perform a number of 5σ clips on the data, in order to remove obviously low-quality data. The most significant clip is based on flux, but we also examine the position of the star on the CCD and discard points more than 5σ from the mean position. Typically the clips affect less than 1% of the data, though for particularly low signal-to-noise ratio or high background data the effect can be more significant. The result is shown in Figure 2.

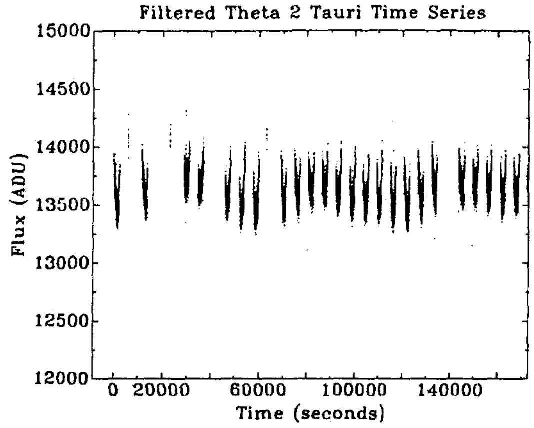


Figure 2: The data misidentified as due to θ^2 Tauri have been removed, and the correct (but misplaced by the flight software) data inserted in its place. In addition, observations which vary more than 5σ from the mean flux or position have been removed.

The pointing characteristics of WIRE have proven to be excellent – Figure 3 shows the pointing behavior for a 48 day time series (~10^7 observations) for the G2 V star α Cen. For a single orbital segment, the rms pointing jitter is ~0.6 arc seconds, while for the entire time series it is ~1.9 arc seconds (extremely impressive, considering that the entire time series contains over 420 separate pointings!). Good pointing is crucial for this instrument due to the lack of a good flat field, which makes correction for image drift extremely difficult.

The next stage of data reduction involves removal of the scattered light background. The scattered light signal is primarily due to the bright limb of the Earth, but there are clearly contributions from scattered sunlight present as well. Raw background levels are typically 30-100 ADU/pixel/second. A first-order effort at removal was already made with the "four corners" algorithm, but – particularly in cases where scattered light levels are high – this approach is clearly insufficient. Our first approach to removing the background is to determine if correlations are present between the "four corners" background level and the signal nominally due to the star. We then fit the background as a function of the total signal and remove it; results for θ^2 Tauri are shown in Figure 4.

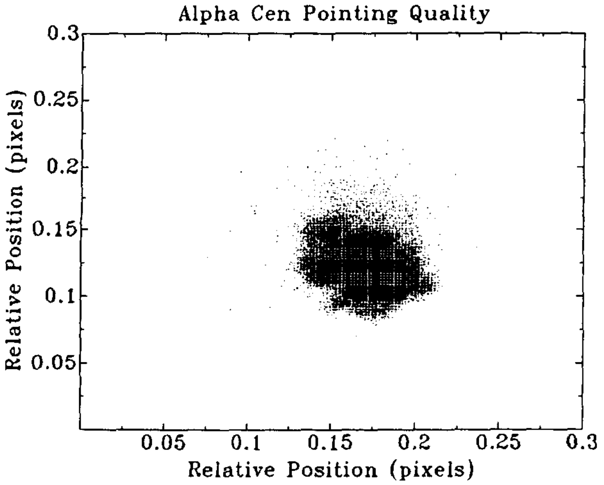
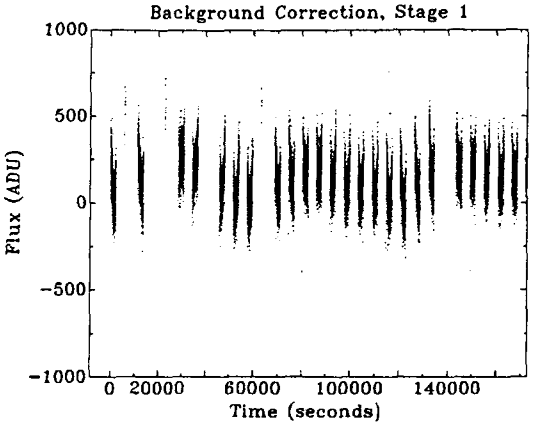


Figure 3: The pointing quality for WIRE observations is typically excellent. The figure shows results from 48 days' worth of observations of α Cen (only every 100th observation is shown). The image scale is approximately 60 arc seconds per pixel.

Figure 4: The-time series after stage 1 of the background correction, which removes an estimated background by decorrelation of the background signal with the stellar signal.



The second stage of background correction proceeds similarly to the first, only this time we model the background with the goal of removing correlations between background level and the position of the stellar image on the CCD. Figure 5 shows the resulting time series for θ^2 Tauri after this algorithm has been applied; the change from Stage 1 background correction is negligible in this particular case. For those stars where extremely high signal-to-noise is available (to date, only α Cen and Procyon) , we also fit the background as a function of the spacecraft orientation with respect to the limb of the Earth.

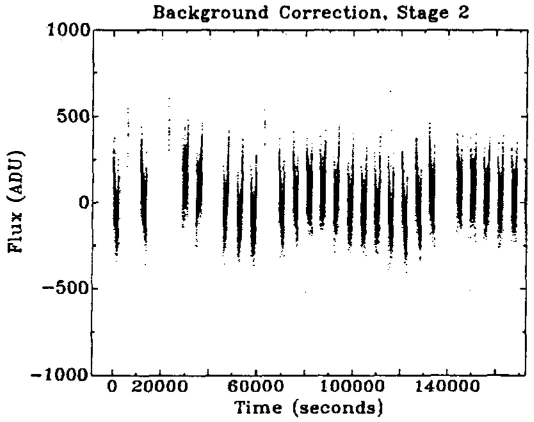
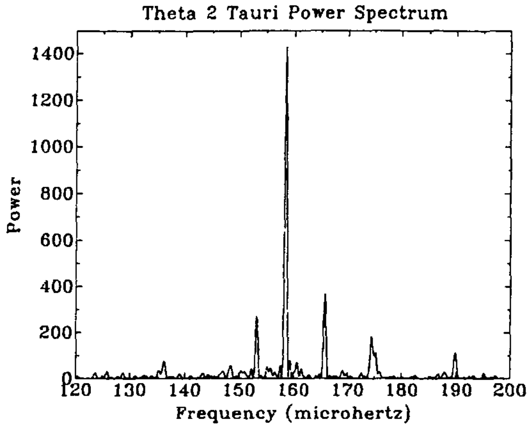


Figure 5: The time series resulting after the second stage of the background correction algorithm is applied. This stage decorrelates the stellar flux with the image centroid location on the CCD. In this particular case, second-stage background correction has a negligible impact on the time series.

Finally we have a time series which can be analyzed. In the case of θ^2 Tauri, simple inspection shows that there are clearly periodic signals present at the 10 mmag level. For comparison, the rms noise per data point in this time series is approximately 2.7 mmag. A number of tools can be used for more precise analysis; below (Figure 6) we show results from an unwindowed Lomb-Scargle periodogram, which clearly shows the presence of multiple oscillation frequencies with the largest amplitude peak at ~158 μHz; a more detailed analysis has found 12 separate peaks with SNR > 4.

Figure 6: A portion of the Lomb-Scargle periodogram of the time series in Figure 5. A number of significant peaks are easily visible – the largest has amplitude ~10 mmag. The three largest peaks represent modes already identified from ground-based observations.



Finally we show the reduced time series phased at the ~158 μHz frequency; the light curve has an amplitude of ~10 mmag and is clearly sinusoidal.

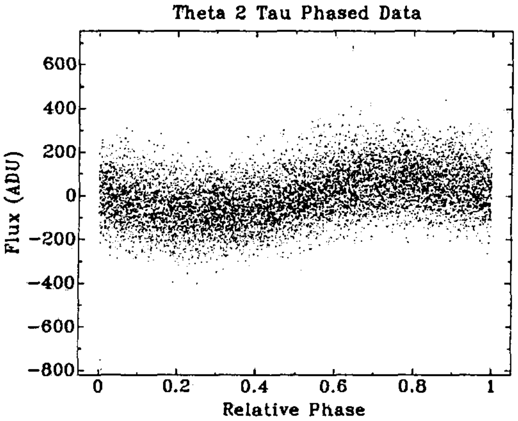


Figure 7: The time series from Figure 5, phased according to the period corresponding to the largest peak in Figure 6. The sinusoidal nature of the light curve of this oscillation mode is readily apparent.

2.3 Observations and Results to Date

Asteroseismology observations began on 30 April 1999 and were terminated on 30 September 2000 due to lack of funding for continued satellite operations. During that time, 28 objects were observed primarily as asteroseismology targets and an additional 10 were observed for other projects. The asteroseismology target list was designed as a survey and thus spans all spectral types from B through M and all luminosity classes from Ib through V (see Table 2). The large variety of targets has made single-handed analysis essentially impossible, and we have set up a number of collaborations. Some early results from WIRE have been reported in Buzasi et al. (2000) and Schou & Buzasi (2001), and below we summarize selected results.

a. α Cen: Analysis of the data from this star is ongoing, in collaboration with Jesper Schou (Stanford). Sample data from α Cen were shown above, in Figure 3, and the power spectrum. Excess power is present in the power spectrum at the expected frequency range of 1-2 mHz (Guenther & Demarque 2000) and Figure 8 shows that we have resolved the large and small separations. The large separation agrees with theoretical predictions, but the small separation is toward the high end of the expected range, which may indicate that α Cen is a bit younger than thought. Results have been published in Schou & Buzasi (2000) and Schou & Buzasi (2001).

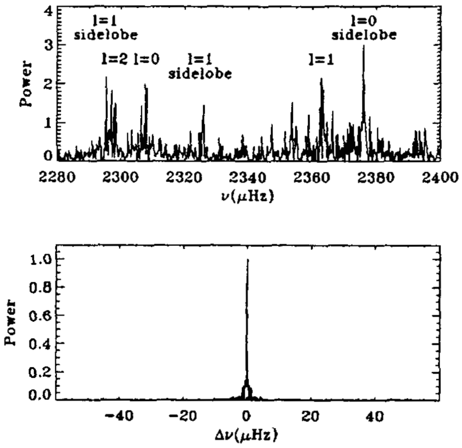


Figure 8: A small portion of the α Cen power spectrum – in this case a discrete Fourier transform – is shown (above) together with the window function (below). Modes and sidelobes are identified; the amplitude of the largest peaks corresponds to approximately 5 μmag.

Separately, we are working with a Spanish group (Teo Roca and collaborators) on applying a new comb filter technique that they've developed for GONG to the Alpha Cen data set (Roca et al. 2000).

b. α Cir: Together with Schou (Stanford) and Kreidl (Northern Arizona University), we have verified the known dominant mode at 2442 microhertz. There have been several detections of other frequencies reported in the literature (mostly by Kurtz et al 1994); our noise level is at least an order of magnitude better than the best ground-based data, and we generally don't confirm these frequencies. We do see a few new frequencies at levels that would be undetectable from the ground. Also, we can detect the rotational period of the star directly (in addition to seeing frequency splitting), and thus unambiguously – the result is curious in that our photometric period of ~2.24 days is only half the period of 4.47 days implied by the frequency splitting of the 2442 μHz mode. This appears to imply either that the dominant mode is highly non-normal, or that there are equatorial spot distributions present. Analysis is continuing with input from Don Kurtz (U. Central Lancashire).

c. γ Equ: This was a very short and very early observation for WIRE, so the data quality is not as good as some of the later observations, though the new background removal algorithms have helped tremendously. Working with Kreidl (NAU) we have verified the 4 known frequencies, and detect two new ones never detected from the ground. A paper is in preparation.

d. θ^2 Tauri: See above for data samples. Working with Ennio Poretti (Osservatorio Astronomico di Brera) we have found 12 frequencies in the power spectrum of this δ Scuti star, 7 of which have never been seen before. The smallest amplitude mode is ~500 μmag, and we have also confirmed the previously suspected presence of modal amplitude variability. We have presented a paper at IAU Colloquium 185 (Leuven, Belgium; July 2001), and recently submitted a paper to Astronomy & Astrophysics.

e. β Crucis: In collaboration with Aerts (Institute of Astronomy, Leuven, Belgium) and Cuypers (Royal Observatory of Belgium), we observed the 16 solar mass β Cephei-type variable β Cru, which has proven monoperiodic based on ground-based photometry. To date, we have found 6 frequencies in this star. Three of these frequencies confirm three frequencies found spectroscopically (but never confirmed photometrically), while three appear to be entirely new. These results were presented at IAU Colloquium 185 (July 2001) and at the Eddington workshop in Spain in June 2001. A paper is in preparation for submission to Astronomy & Astrophysics.

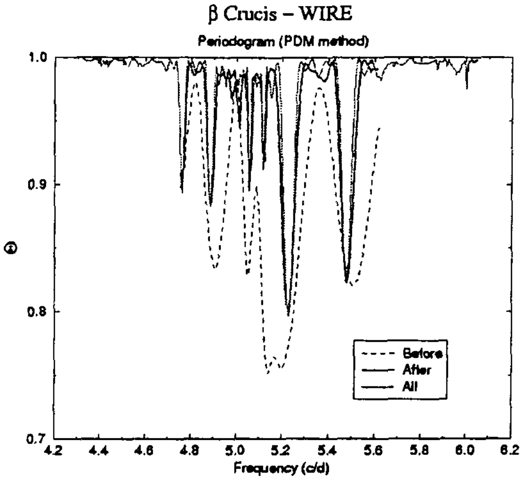


Figure 9: The periodogram for the β Cephei star β Crucis, obtained using the phase dispersion modulation method (Stellingwerf 1978). The "before" and "after" lines label times before and after an instrumental glitch, which appears to have had no meaningful effect on the data. From the ground, β Cru is photometrically monoperiodic, though recently three modes were detected spectroscopically (Aerts et al. 1998). For the first time, we confirm these modes in photometry, and detect at least four more.

f. β Cas: Early work on this δ Scuti star with Aerts (Leuven) and Cuypers (Royal Observatory of Belgium) confirms the one period detected from the ground. Our search for other modes continues, but even if we should find none we will be able to place detection limits on additional oscillations approximately 20 times more stringent than are possible from the ground. This data as well were presented at IAU Colloquium 185 (July 2001) and at the Eddington workshop in Spain in June 2001.

g. Procyon: This solar-like star is proving difficult, albeit in an interesting way. There is a significant drift, at the 100 ppm level, in the data with typical time periods of days, which complicates the analysis. However, the drift itself is interesting since it appears to be "real" – i.e., stellar in origin and not instrumental (it's not correlated with any other instrumental characteristics, or – most telling – any other stars in the field), so we may be seeing starspots. Data analysis will continue through the summer.

Papers published during the first year of this award are listed at the end of this report.

3. Plans for Upcoming Year

As noted above, we are only slightly behind our schedule as originally proposed. During Year 2, we plan to

A. Finish and release Version 1.0 software tools for data reduction
B. Deliver the first year of WIRE data to NSSDC

During the third and final year of the award, we will deliver the remaining WIRE data and update tools as necessary based on input from the user community.

4. Publications Resulting from Year 1 of Award

1. Retter, A., Bedding, T.R., Buzasi, D., & Kjeldsen, H. 2002, "Evidence for Solar-like Oscillations in Arcturus (α Boo)," in proceedings, Asteroseismology Across the HR Diagram, in press.

2. Cuypers, J. Aerts, C., Buzasi, D., Catanzarite, J., Conrow, T., & Laher, R. 2002, "Multiperiodicity in the light variations of the β Cephei star β Crucis," A&A, in press.

3. Poretti, E., Buzasi, D., Laher, R., Catanzarite, J., & Conrow, T. 2002, "Asteroseismology from space: The δ Scuti star θ^2 Tauri monitored by the WIRE satellite," A&A 382, 157.

4. Buzasi, D. 2002, "Asteroseismic Results from WIRE," in proceedings IAU Colloquium 185: Radial and Nonradial Pulsations as Probes of Stellar Physics, p. 616.

5. Cuypers, J., Aerts, C., Buzasi, D., Catanzarite, J., Conrow, T., & Laher, R. 2002, "A Flower on a WIRE: Asteroseismology of a Massive Star," in proceedings IAU Colloquium 185: Radial and Nonradial Pulsations as Probes of Stellar Physics, p. 620.

6. Poretti, E., Buzasi, D., Laher, R., Catanzarite, J. Conrow, T., & Laher, R. 2002, "Asteroseismology from Space: WIRE Monitoring of the δ Scuti star θ^2 Tauri," in proceedings IAU Colloquium 185: Radial and Nonradial Pulsations as Probes of Stellar Physics, p. 624.

7. Buzasi, D. L., Kreidl, T. J., Schou, J., Preston, H. L., Laher, R., Catanzarite, J., & Conrow, T. 2001, "Asteroseismology of the roAp Star α Cir Using the WIRE Star Camera," BAAS 33.11.

8. Kreidl, T. J., Buzasi, D. L., Preston, H. L., Laher, R., Catanzarite, J., & Conrow, T. 2001, "Space-Based Asteroseismology of the roAp star γ Equ," BAAS 33.12.

9. Schou, J. & Buzasi, D. L. 2001, "Observations of p-modes in α Cen," in Proceedings of the SOHO 10/GONG 2000 Workshop: Helio- and asteroseismology at the dawn of the millennium, ed. A. Wilson,

10. Cuypers, J., C. Aerts, D. Buzasi, J. Catanzarite, T. Conrow, and R. Laher. "Asteroseismology on a WIRE," in Proceedings of the First Eddington Workshop: Stellar Structure and Habitable Planet Finding.