



$l=0, m=0$



$l=1, m=0$



$l=1, m=1$



$l=2, m=0$



$l=2, m=1$



$l=2, m=2$



$l=3, m=0$



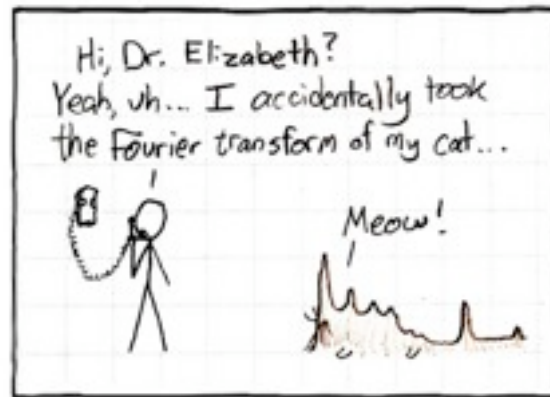
$l=3, m=1$

$l=3, m=2$



$l=3, m=3$



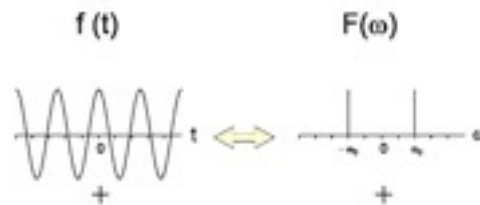


THE FOURIER TRANSFORM

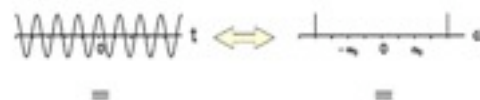
Your friend, really!

Fourier Transform

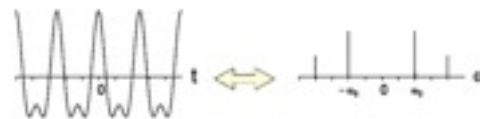
Decomposition of a function into a sum of sinusoidal functions that can be recombined to obtain the original function



Function of
 Amplitude
 Frequency



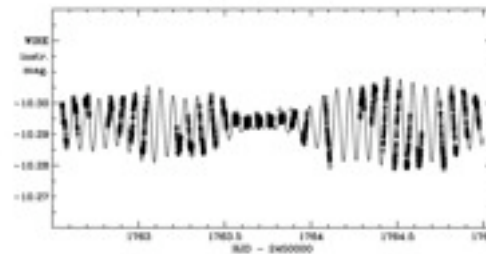
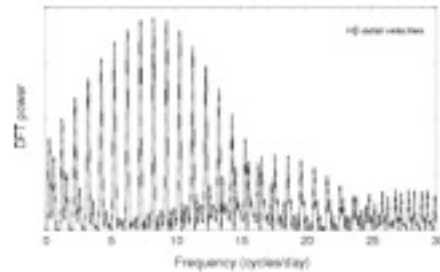
Perfect for measurement of periodic signals



Real oscillations not so simple
Periodic observations
Interference between oscillations
Instrument sensitivity
Target properties

Periodic gaps in signals
Single site data
Large aliasing problem

Continuous data flow
Breaks aliasing problem
Increases signal to noise



An Observational Problem

Observations at a single terrestrial site produce periodic time series gaps

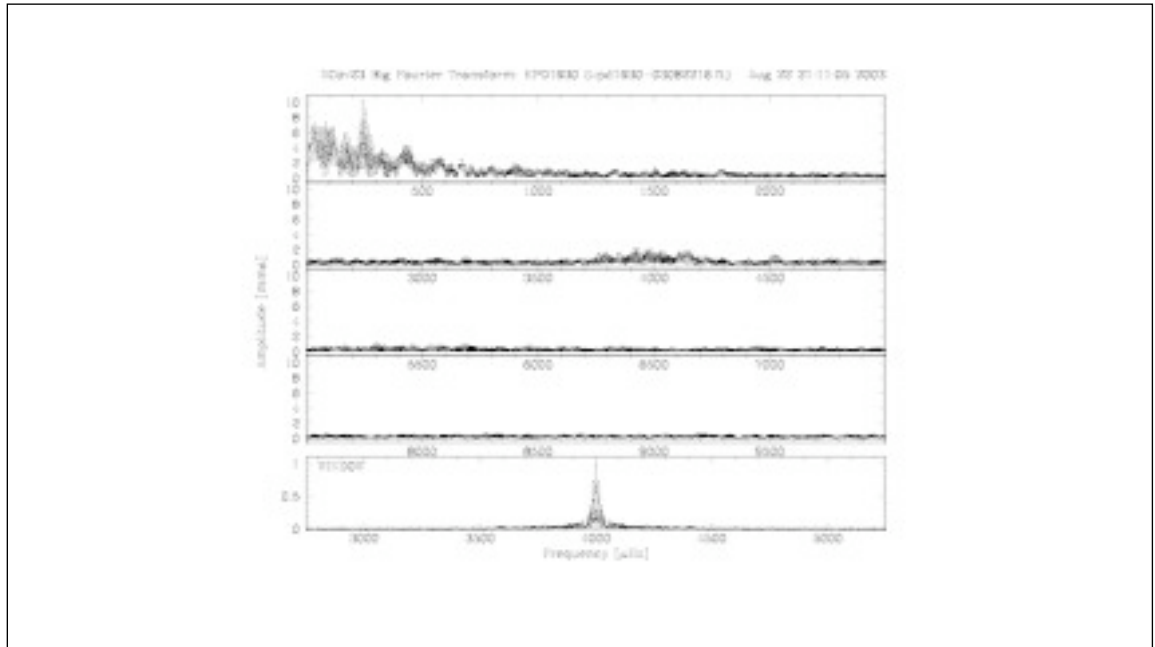
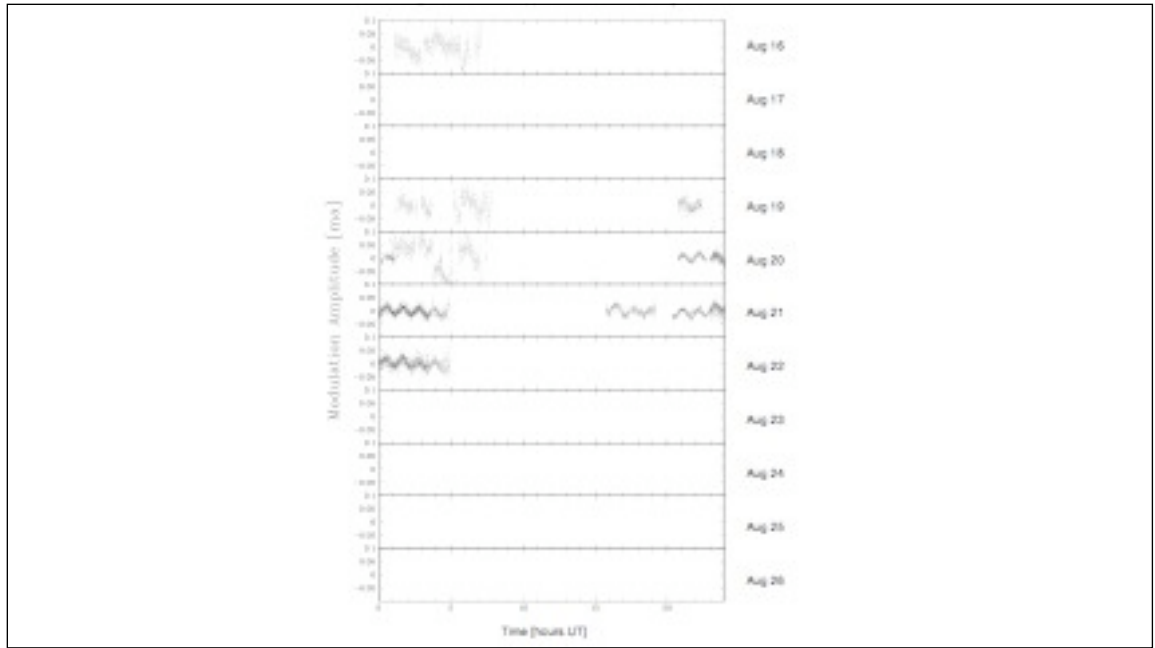
The oscillation spectrum is convolved with the temporal window spectrum
Contaminates oscillation spectrum with spurious peaks

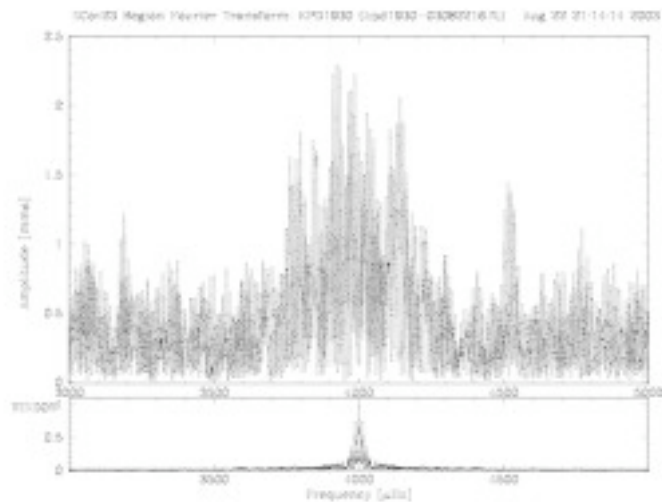
Solutions

Antarctica
max 6 month duration

Network
needs data merging, but maintainable

Space
expensive, difficult





Oscillation networks

Solar Oscillations:

- Global Oscillation Network Group (GONG)
- Birmingham Solar Oscillations Network (BiSON)

Stellar Oscillations:

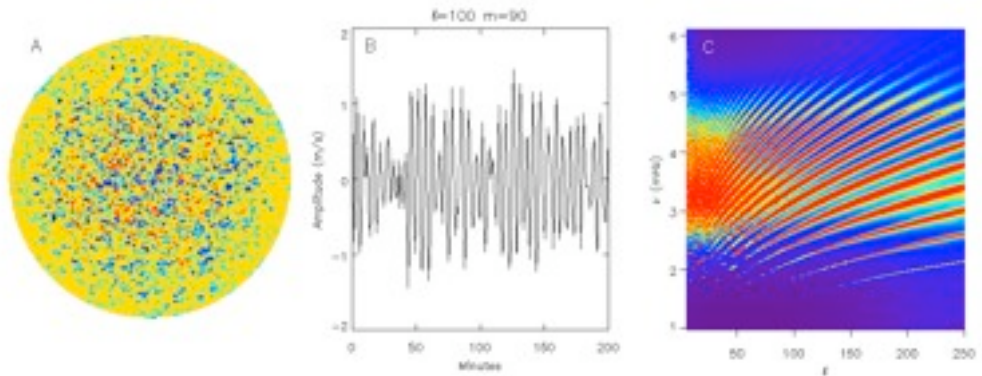
- Stellar Oscillations Network Group (SONG)
- MUSICOS (Multi-Site Continuous Spectroscopy)
- Delta Scuti Network - δ Scuti stars
- Whole Earth Telescope (WET) - White Dwarfs

Space Missions:

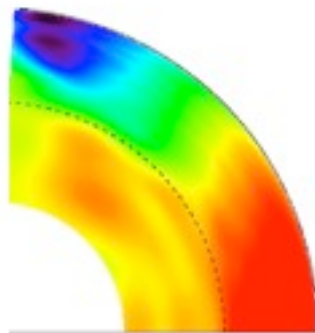
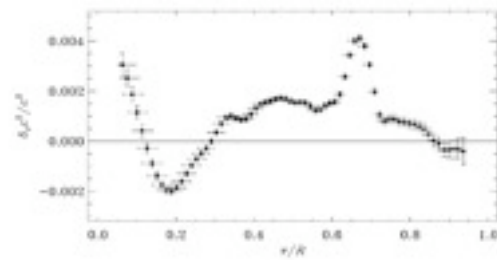
- SOLar and Heliospheric Observatory (SOHO)
- Kepler

Helioseismology: measuring waves on the surface of the Sun
Discovery of propagating waves on Sun (Leighton et al, 1962)

Doppler Map ==> Time Series ==> Fourier Transform ==> Spherical Harmonics



Confirmation of convection zone boundary



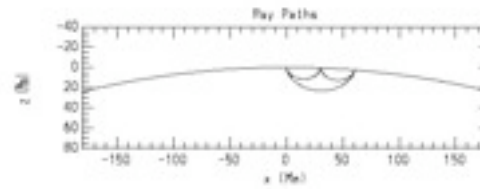
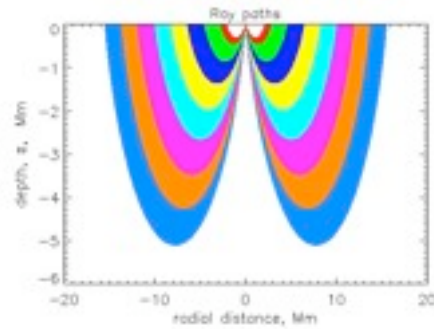
Differential rotation of layers of Sun
in convection zone below surface

Core and convection rotation
different

Modes turn at depth where sound speed = horizontal phase speed = v/ℓ

All modes with same v/ℓ must take same time to make one trip between reflections

Basis of Time-Distance (or Local) Helioseismology

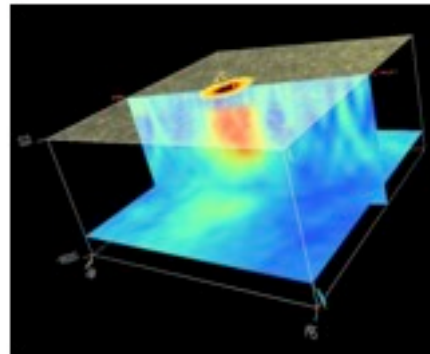
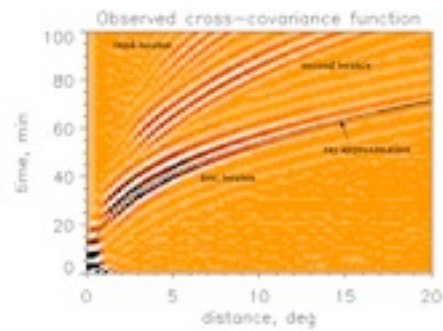


Interesting new results

Images of activity in the far side of the Sun

Flare prediction

Emerging active regions



WET founded in 1986
University of Texas at Austin



Worldwide collaboration of astronomers interested in
observations of oscillating stars

Technological goal:

To resolve the multi-periodic oscillations observed in white
dwarfs (and other objects) into their individual components

Scientific goal:

To construct accurate theoretical models, constrained by
observed behavior, from which fundamental astrophysical
parameters could be derived

Headquartered at
UT Austin 1986 - 1996
Ed Nather, Director

Iowa State University 1997 - 2006
Steve Kawaler, Director
Chris Clemens, Scot Kleinman, Reed Riddle, ADWOs

Delaware Asteroseismic Research Center (DARC)
Judi Provencal, Director; Harry Shipman, Financial director
Mike Montgomery, Science Director; Susan Thompson, Assoc. Dir.

Council of the Wise (CoW)
Oversees WET
Charts scientific direction

eXtended Coverage campaigns (XCov)

Run	Date	Target	Type	PI	Status
XCov 1	Mar 1998	PG 1344-092	BRG	Winget, Provençal	Published
		1803 Can	BRG	O'Donoghue	Published
XCov 2	Nov 1998	GG-38	DAV	Winget	Published
		1471 Tau	ICBS	Clemens	Published
XCov 3	Mar 1999	PG 1159-035	GR Vr	Winget	Published
XCov 4	Mar 1999	AM CVe	BRG	Solheim, Provençal	Published
		G117-015A	DAV	Kaper	Published
XCov 5	May 1999	GG38	DBV	Winget	Published
		GD-65	DAV	Bergsten	Published
		HD 195473	rsAb	Kurtz	learning experience
XCov 6	May 1999	PG 1767	GR Vr	Clemens, Neffler	Published
		GD-94	DAV	Vauclair	Published
		195857	CV	Buckley	in analysis
XCov 7	Feb 1999	PG 1115	DBV	Barstow, Clemens	in analysis
		GG38-29	DAV	Kaper	Published
		WET-0855	e Sou	Breger, Handler	Published
		PG 2131-088	GR Vr	Kawaler, Neffler	Published
XCov 8	Sep 1999	G185-32	DAV	Moskalk	Published
		RX J2117	GR Vr	Vauclair, Moskalk	Published
XCov 9	Mar 1999	PG 1159-035	GR Vr	Winget	Published
		PG Vr	e Sou	Breger	Published
XCov 10	May 1994	GG38	DBV	Nather, Bradley	Published
XCov 11	Aug 1994	RX J2117	GR Vr	Vauclair, Moskalk	Published
XCov 12	Apr 1995	PG 1351	DBV	Hansen	in analysis
		L19-2	DAV	Sullivan, Clemens	in analysis
XCov 13	Feb 1998	RE 079+14	CV	Marrat, Seetha	Published
		CD-24 799	e Sou	Breger, Handler	Published
XCov 14	Sep 1998	PG 0132+298	GR Vr	O'Brien	Published
		WZ Sgr	CV	Nather	in-issues
XCov 15	Jul 1997	DQ Her	CV	Nather	Published
		IC 2020B	DBV	O'Donoghue	Published
XCov 16	May 1998	BPM 37993	DAV	Kanaan, Kaper, Nita, Winget	Published
		Semulex 3	PRVr	Kawaler, O'Brien	No data
XCov 17	Apr 1999	PG 1336	eSB	Kilkenny	Published
		BPM 37993	DAV	Kanaan, Kaper, Nita, Winget	Published
XCov 18	Nov 1999	PS Tau 75	ZZ Cat	Dokez, Vauclair, Klemm	Published
		PG-0122	DDV	Vauclair, O'Brien	Published
XCov 19	June 2000	GG 38B	DBV	Kaper, Nita	Published
		PG 1159	GR Vr	Kaper, Nita	Published
XCov 20	Nov 2000	HR 1217	rsAb	Kurtz	Published
		KU V	DBV	Handler, Nita	Published
		R 548	ZZ Cat	Mukadam	Published
XCov 21	Apr 2001	PG 1336	eSB	Reed, Kilkenny	Reed Ph.D. thesis
		PG 1604-160	DBV	Handler	Published
		Feige 45	eSB	Reed, Kawaler	Reed Ph.D. thesis + Published
		MA 501	AGN	Walter, Koenigk	learning experience
XCov 22	May 2002	PG 1458+193	DBV	Handler	Published
		PG 1159-035	GR Vr	O'Brien	Published
		Feige 45	eSB	Reed, Kawaler	Published
		PG 1605-072	eSB	Schuh, et. al. & MSST	Published
XCov 23	August 2003	KPS	eSB	Chagnat, Reed	in analysis
		G 23-38	DAV	Klemm	Master's thesis
		PG 2207+2810	eSB	Shull	Published

26 XCov campaigns completed

XCov 27 in May

http://www.physics.udel.edu/darc/2009_targets/2009_targets.html

WET campaigns

2 to 4 weeks long

10 to 20 observatories per campaign

Different sets of telescopes each time

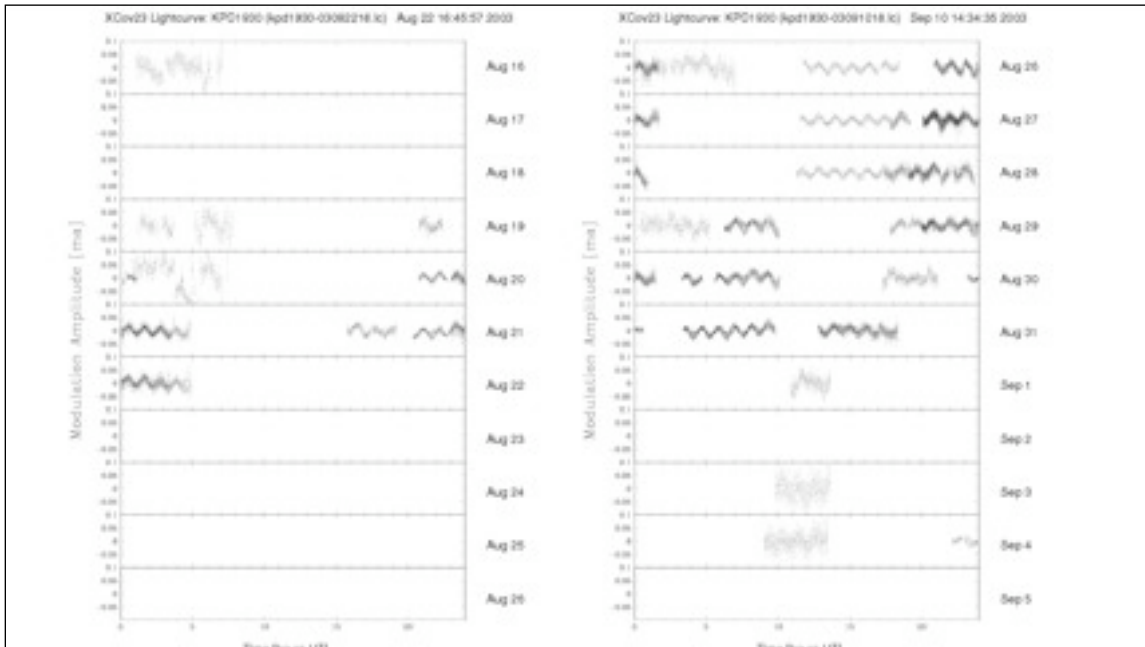
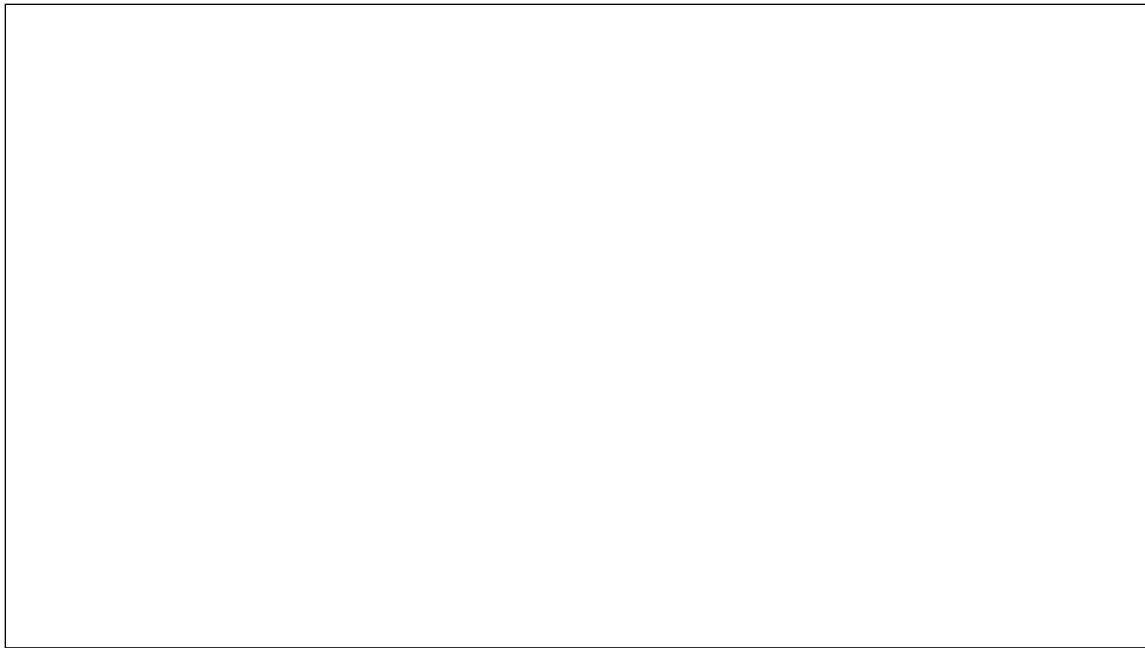
Overlap with special guests (HST)

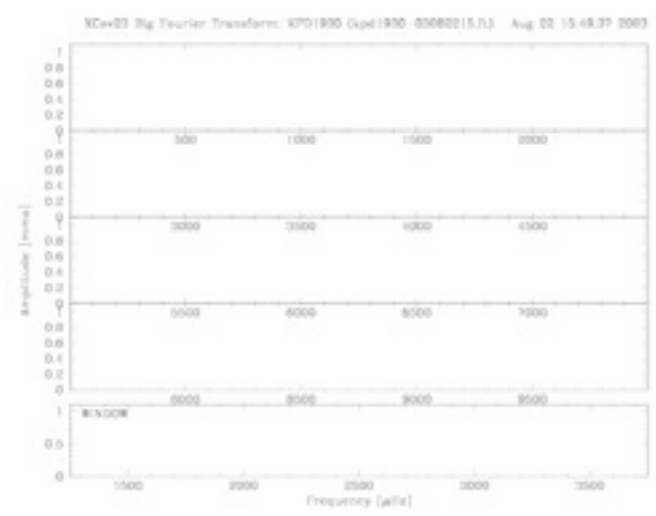
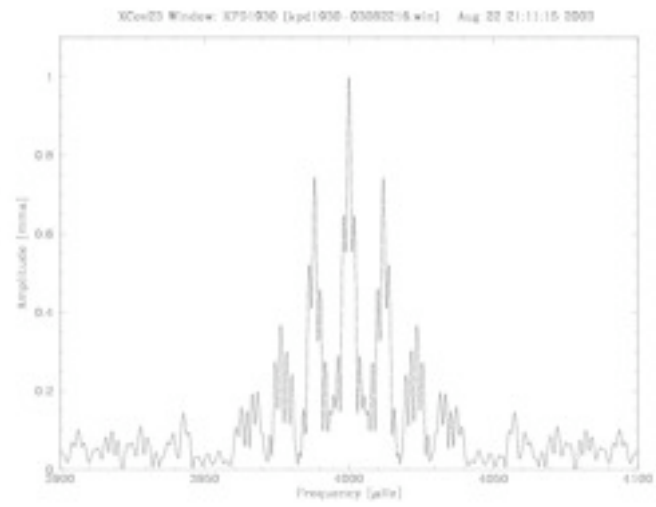
Manned headquarters to manage campaign

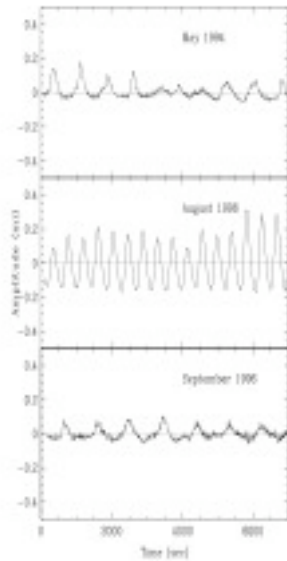
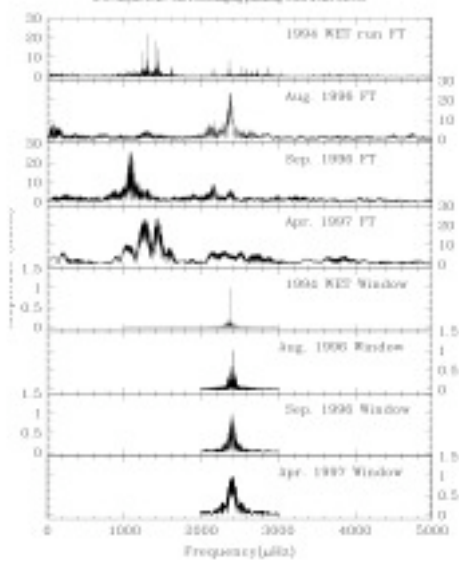
Only use WET for specific targets

Single site observations not good enough

Oscillation periods of "20 seconds to 20 minutes"

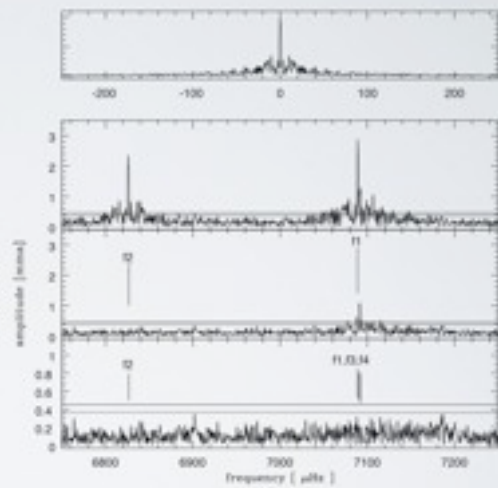
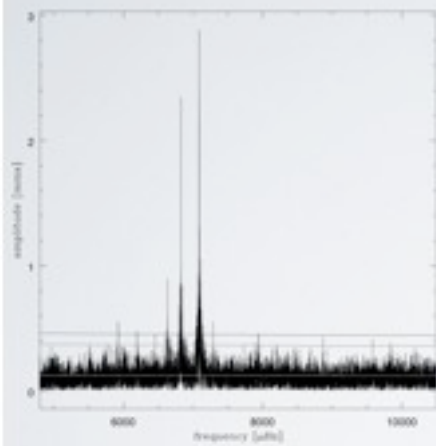






Kepler et al, A&A 401, 639–654 (2003)

M. Vuckovic et al, ApJ, 2006



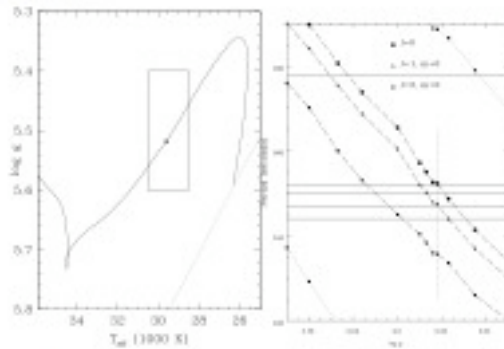
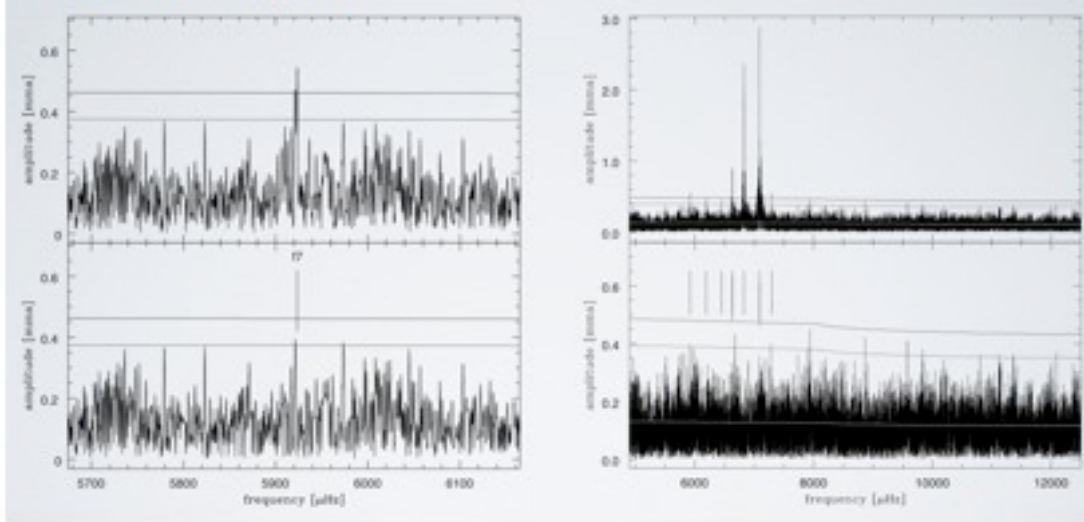


Figure 4. Comparison of the model with the observations. The left panel shows the evolutionary model track (solid line) containing our best-fitting model (dot). The dotted line is the 2M18 and its envelope in the spectroscopic or stars line. The right panel compares the model periods (points) to those observed (solid lines). The vertical dashed line indicates the best-fitting model.

Table 6. Comparison of observations with our best-fitting evolutionary model.

Number	Frequency μHz	Period (s)		Model		
		Obs	Model	n	l	m
1	364.99	376.909	274	0	0	0
2	367.66	372.624	322.260	0	0	0
3	2050.43	308.730	331.777	1	1	-1
4	3871.16	347.580	347.384	1	1	0
5	2968.24	331.824	344.890	1	1	-1

Mass	10 M_{\odot}	T_{eff}	$\log g$
Spectroscopy	1.00	2950 ± 200 K	3.31 ± 0.02
Model	0.470	0.070	0.00

explain all five observed frequencies in terms of period modes and rotational splitting. Though the model does predict an $l = 2, m = 0$ mode at the 378 s period, which is near the observed 376 s mode, we currently find no evidence to suggest that Pige 08 has $l = 2$. As such, we must conclude that our model does not reproduce this period without appealing to high v . Without further evidence (such as other observed members of the multiplet) for tracking high- l modes, we are forced to leave l as unattached by our model. Additionally, an $l = 2$ matches fitted five observed periods. Since we do not have a complete sample of models and this is really just an illustrative example, we are not alarmed. However, it could also indicate that our current models do not include enough physics to be accurate. The period spacing for the observed modes in our best-fitting model can be shown in Fig. 4. Thus, a small change to

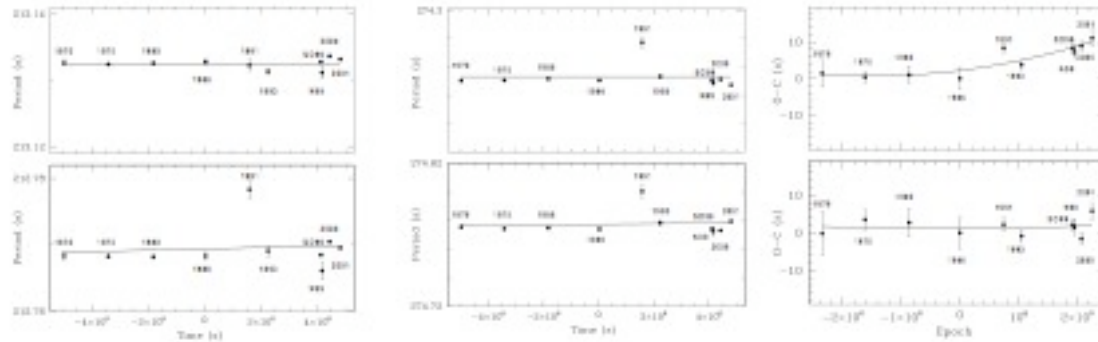


Fig. 2.—Direct method: best seasonal periods vs. time for the 203 α doublet. Top: Best-fit $P = (1.04 \pm 27) \times 10^{-11} \text{ s}^{-1}$ for $P_0 = 234.253 \pm 0.001$. Bottom: Best-fit $P = (1.0 \pm 10) \times 10^{-11} \text{ s}^{-1}$ for $P_0 = 232.7694 \pm 0.0004$. The 1991 data set spans over 5 days and contains only 21 hr of data, while other seasons span over a month on average.

Fig. 3.—Direct method: best seasonal periods vs. time for the 274 α doublet. Top: Best-fit $P = (1.04 \pm 27) \times 10^{-11} \text{ s}^{-1}$ for $P_0 = 234.253 \pm 0.001$. Bottom: Best-fit $P = (1.0 \pm 10) \times 10^{-11} \text{ s}^{-1}$ for $P_0 = 232.7774 \pm 0.0009$.

same secondary component is also found in the O-C diagrams of the secondary pulsation frequency of the star (see Fig. 2 and 3 for more details). Any alternative interpretation of our results would have to be compatible with this fact. The secondary in the lower panels of Fig. 1, 2 and 3 suggest a circular orbit. From our observations we cannot set on a period upper limit on the eccentricity, but it must be close to zero.

Using the known characteristics of the V 993 Peg system, we can determine a first estimate of the planet's effective temperature by balancing the flux received from the star with the blackbody flux re-emitted by the planet (see Supplementary Information for more details). Assuming a Bondi albedo of 0.260 (similar to that of Jupiter¹⁷), we obtain an effective temperature for daylight of about 670 K, corresponding to a maximum of the blackbody radiation near 4.3 μm (Wien's law).

With a projected radius of about five light seconds, the outside of the habitable zone of V 993 Peg points towards a planet (for comparison, the amplitude of the solar fluxes varies around the distance of our Solar System in almost three light seconds). However, depending on the radiative inclination of the system, a dense cloud of neutral molecules and/or compression cannot be totally excluded. But the low inclination required (0.5° vs. 1° for a brown dwarf or 1° vs. 2.5° for a low-mass stellar companion) has a very low probability (3% and 0.2% respectively), assuming a random distribution of orbital plane inclinations.

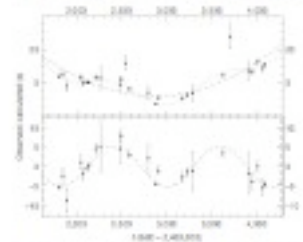


Figure 1.—The O-C diagram of the pulsation frequency of V 993 Peg. The O-C technique is a way of measuring the phase response of a periodic function, comparing the observed times of the maxima with those calculated from an ephemeris¹⁸. In our case what is compared is the time of the first maximum of each data set (obtained by fitting the data with the sinusoidal subharmonics), corresponding to the pulsation frequency with the best fit (obtained by fitting the whole series with one data set). The error bars are given by $(\sigma_1^2 + \sigma_2^2)^{1/2}$, where σ_1 and σ_2 are the 1- σ phase errors obtained from the two sinusoids respectively. The upper and lower panels

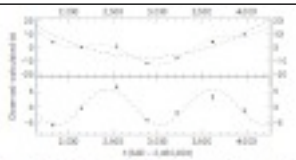


Figure 2.—The O-C diagram of V 993 Peg, in the context of the O-C diagrams of the two other observing seasons were considered and the phase was calculated on them (larger than one). This indicates the error that also values on the time resolution (or that represents O-C diagrams can be better resolved because frequency of a multiperiodic pulsation). In this case, if the observing star has a companion, both pulsations would undergo an independent combination of the periodic motion (around the center of mass). V 993 Peg has two or three pulsation periods (for more information see Supplementary Information) and it is not independent O-C diagrams can be obtained. As in Fig. 1, the upper and lower panels represent respectively the O-C diagrams of the observed component alone (the error bars are calculated as in Fig. 1).

and 0.2% respectively), assuming a random distribution of orbital plane inclinations.

Thus, with a 99% probability, V 993 Peg is the first recognized planet orbiting a post-main-sequence star, making this system a unique laboratory in which to test the evolution of planetary systems during and after the red-giant expansion. With a suitable age of the order of 10 Gyr (see Supplementary Information for more details), V 993 Peg is also one of the oldest planets known. An interesting case of a planet about the size and age of Earth (only a red-giant was recently present¹⁹), the calculation about whether low-mass companions to red-giant stars require an alternative to that system is complementary to that of V 993 Peg. Because the two systems are very different, the way that only for wandering planets of horizontal branch stars is it possible to

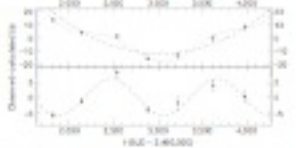


Figure 3.—The O-C diagram of V 993 Peg, in the context of the observed pulsation frequency. Considering the lower panels of Fig. 1 and 2, we can