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The Whole Earth Telescope: An International Adventure in Asteroseismology

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Abstract. Today, we are beginning to probe the interior of stars through the new science of stellar seismology. Certain stars, ranging from our own Sun to white dwarfs, undergo natural vibrations that can be detected with sensitive time-series photometry and/or spectroscopy. Since the signal we seek is an unbroken time-series to allow determination of the vibration frequencies, data from a single-site is usually incapable of uniquely identifying the pulsation modes, no matter how large the telescope being used. In many cases, the observational goals can be achieved using small-ish telescopes in well-coordinated global networks. Here, I briefly describe the work of one such international network of observatories and scientists known as the Whole Earth Telescope (WET). With the WET, we have sounded out the interiors of a large number of nonradially pulsating stars. Over the past 14 years, WET has observed dozens of stars in 20 separate observing campaigns. Our team has wide span of interests, and has observed several other classes of objects such as delta Scuti stars, CV stars, pulsating sdB stars, and rapidly oscillating Ap stars.

1. Introduction - a Little WET History

In 1986, astronomers from the University of Texas established a world–wide network of cooperating astronomical observatories to obtain uninterrupted time–series measurements of variable stars. The technological goal was to resolve the multi-periodic oscillations observed in these objects into their individual components; the scientific goal was to construct accurate theoretical models of the target objects, constrained by their observed behavior, from which their fundamental astrophysical parameters could be derived (Nather et al. 1990). This approach has been extremely successful, and has placed the fledgling science of stellar seismology at the forefront of stellar astrophysics.

This network, now known as the Whole Earth Telescope (WET), is run as a single astronomical instrument with many operators. The collaboration includes scientists from around the globe in data acquisition, reduction, analysis, and theoretical interpretation. For the first decade of its existence, the WET was headquartered at the University of Texas in Austin. After 1994, with Dr. J. Christopher Clemens as a Hubble Fellow at Iowa State University, and with support from the International Institute of Theoretical and Applied Physics

(IITAP), headquarters for WET runs began to be held at Iowa State. Tables 1 and 2 list all WET observing runs through 2000.

Table 1. WET runs 1988 – 1994

Run / Date	Target	Type	PI	Status
Xcov 1	PG 1346	CV	Winget, Provencal	Published
Mar 88	V803 Cen	O'Donoghue	Published	
Xcov 2	G29-38	ZZ Ceti	Winget	Published
Nov 88	V471 Tau	CV	Clemens	Published
Xcov 3	PG 1159	GW Vir	Winget	Published
Mar 89				
Xcov 4	AM CVn	CV	Solheim, Provencal	Published
Mar 90	G117-B15A	ZZ Ceti	Kepler	Published
Xcov 5	GD 358	DB	Winget	Published
May 90	GD 165	ZZ Ceti	Bergeron	Published
Xcov 6	PG 1707	GW Vir	Clemens	In analysis
May 91	GD 154	ZZ Ceti	Vauclair	Published
Xcov 7	PG 1115	DB	Barstow	in analysis
Feb 92	G226-29	ZZ Ceti	Kepler	Published
	WET-0856	δ Scuti	Handler	Published
Xcov 8	PG 2131	GW Vir	Kawaler, Nather	Published
Sep 92	G185-32	ZZ Ceti	Moskalik	in analysis
Xcov 9	PG 1159	GW Vir	Winget	Published
Mar 93	FG Vir	δ Scuti	Breger	Published
Xcov 10	GD 358	DB	Nather, Bradley	Published
May 94				
Xcov 11	RX J2117	PNN	Vauclair, Moskalik	in prep
Aug 94				

WET co–founder Dr. Edward Nather retired as director in 1997. The directorship is now shared by Darragh O'Donoghue (at SAAO) and the author; responsibility for coordinating WET runs moved to Iowa State University. Fortunately, the founders, Drs. Ed Nather and Don Winget, continue active involvement in WET science.

Through December 2000, the WET has managed 20 observing runs (called "Xcovs"). The principal targets have been pulsating white dwarfs, ranging from the coolest (ZZ Ceti stars) through the pulsating central stars of planetary nebulae. WET has also observed a pulsating sdB star (PG 1336). In November 2000, the WET observed a rapidly oscillating Ap star - the pre-est of pre-white dwarfs to be observed by this collaboration.

WET observations have played a central role in over 12 Ph.D. dissertations, generated over 30 refereed publications, and been highlighted in 5 dedicated international workshops. Proceedings from the past four have been published by the journal *Baltic Astronomy.* Active WET members number approximately 50, with home institutions in 16 countries.

Table 2. WET runs 1994 – 2000

Run / Date	Target	Type	PI	Status
Xcov 12	PG 1351	DB	Hansen	In analysis
Apr 95	L19-2	ZZ Ceti	Sullivan	in prep
Xcov 13	RE 0571+14	CV	Marar, Seetha	in prep
Feb 96	CD-24 7599	δ Scuti	Handler	published
Xcov 14	PG 0122	GW Vir	O'Brien	published
Sep 96	WZ Sge	CV	Nather	in clouds
Xcov 15	DQ Her	CV	Nather	In analysis
Jul 97	EC 20058	DB	O'Donoghue	in analysis
Xcov 16	BPM 37093	ZZ Ceti	Kanaan, Nitta	in analysis
May 98				
Xcov 17	PG 1336 (N)	sdB	Kilkenny, Reed	in prep
Apr 99	BPM 37093 (S)	ZZ Ceti	Nitta	in analysis
Xcov 18	HL Tau 76	ZZ Ceti	Dolez	in analysis
Nov 99	PG 0122	GW Vir	O'Brien	in analysis
Xcov 19	GD 358	DB	Kepler	in analysis
Apr 00	PG 1159	GW Vir	Kepler	in analysis
Xcov 20	HR 1217	roAp	Kurtz	in analysis
Nov 00				

2. WET Science Goals and Technical Challenges

The science goals of WET revolve around fully resolving the pulsation spectra of multiperiodic nonradially pulsating stars. Once fully resolved, we attempt to match the observed pulsation periods with those of stellar models. Success in doing so provides a determination of global properties of the pulsating stars (such as mass, rotation rate, luminosity, and distance) and, more importantly, gives us a window into the stellar interior structure.

For us to succeed in meeting these goals for the stars we are interested in, several technical requirements need to be met. To avoid the unresolvable confusion caused by 1 cycle/day aliases in data from a single terrestrial site, we must obtain uninterrupted time-series photometry of these rapidly variable stars. Our "instrument" must be sensitive in the temporal frequency range between 700 and 50,000 μHz (i.e. to periods between 20 and 1400 seconds). To obtain a frequency resolution of 1 μHz (though we sometimes wish for even better) a run must last at least 1 week. To see the pulsations, which are small amplitude, we require an amplitude sensitivity of less than 1 millimagnitude for $V < 17$ - that is, we need telescopes, at good sites, of 1 meter aperture or more. Finally, we try to keep the maximum 1 cycle/day alias amplitudes below 20%

We meet these technical challenges by attempting to obtain global coverage through coordinated observations at up to 15 observatories. If the weather cooperates, we can obtain 24 hour/day coverage and squash the 1 cycle/day alias. The weather rarely cooperates to this degree. However, the weather is a random variable - and with persistence, we can obtain data from all sites around the globe in a typical 2–week WET run. This means that while the coverage may not be continuous, we still can get a high duty cycle (frequently better than 70%) and, most importantly, cover all phases of the 24-hour rotation period of our Earth. Nather et al. (1990) illustrate the significant reduction of these 1 cycle/day alias structures that we can achieve with WET.

Success also requires using detectors of uniform wavelength sensitivity, and care in combining data from different telescopes. These chores are minimized with a "standard" photometer design (Kleinman et al. 1996) and a standard set of software tools. By working with astronomers who are interested in the science of the WET and who are also those at the telescopes during the observations, we are able to meet the technical challenges. Because of the sensitive nature of the signal and instrumentation needed to measure it, we have found that automating the data collection is not practical or wise. We really need to have observers – observers who care about the data – at the telescopes.

3. WET Operations

The WET is an organization that allows astronomers from around the world work together — first in planning an observing run, next in obtaining the data during the actual observing campaign, and finally in analyzing the data and publishing the results. With over 50 astronomers from more than a dozen countries, this mode of operation would be nearly impossible without the use of the Internet to link observers and scientists. By using computers linked through the Internet, such "virtual collaborations" are viable. In the case of the WET, we have shown that not only can we have a virtual collaboration, we can actually do the science in a networked fashion - thus the term "virtual collaboratory."

3.1. Target Selection and Observing Time

The WET can only obtain high–quality data on one (or maybe two) targets at a time. The resources (in both time and money) needed for a WET run are considerable. Given these facts, we can only observe a limited number of targets, and selection of which stars to observe is an important and difficult assignment.

Approximately 8 WET members serve on a "Council of the Wise" or simply COW. Once or twice a year, proposals for WET targets are solicited from the entire community by the COW. The COW then decides, based on the science case as well as the case for the need of the peculiar strengths of the WET - which targets are to be observed. The successful proposer becomes the PI for that target, and prepares a generic scientific justification for use in applying for telescope time. The PI works with the Associate Director for WET Operations (or ADWO) in coordinating proposals for the various WET sites.

The WET has no dedicated telescopes. When the target is approved, all members of the WET collaboration prepare and submit proposals to their local observing facility for time to participate in the run. These proposals are coordinated so that the separate time allocation committees are aware of the collaborative nature of each proposal. Observing sites range from smaller instruments that are local to the home research institutions, through national facilities such as KPNO, CTIO, OHP, and SAAO.

3.2. The WET Control Center

With up to 15 observers around the world observing the same target, there is ample room for confusion and waste of resources. To maximize the effectiveness of our collaborative observations, during a WET run (which typically lasts 2-3 weeks) we maintain a continually staffed control center. At the control center (or HQ) are WET members with significant experience in observing, data reduction and analysis. HQ personnel usually include the PI for the target of the run.

The HQ staff communicate with all observers daily to update them on the progress of the run, and to help solve any problems that may arise at a site. They also provide an independent test of the observatory and data acquisition clocks. Throughout the run, as an observer completes his/her night of data collection, s/he sends the data via e-mail or ftp to the HQ. HQ staff then reduce the data and examine it for quality, timing errors, etc.

With a fully staffed HQ, we can maintain an up-do-date light curve and compute current pulsation spectra for analysis. The reductions and analysis are made available to all members of the WET team, including those not directly involved in the run, via the WWW. The WWW site for the run–in–progress, linked to the main WET website (currently http://wet.iitap.iastate.edu), shows the log of each individual run, the combined lightcurve, and amplitude spectrum. To help plan the immediate future, and assess the run, the website also has weather updates and other status variables from each site. An open discussion page allows collaborators to discuss the results so far, speculate on new discoveries, etc.

Another important role of the HQ staff is allocating observatories to secondary targets. When overlapping sites are both active, the HQ staff can move one of the observers to a secondary target, allowing the WET to obtain data on more than one target at a time. Occasionally, we have been able to get nearly 48 hours of data in one 24 hour period!

At the end of a run, the HQ computers have accumulated all of the raw data. In addition to the raw data, we archive the first–look reductions by the HQ staff, plots of light curves, spectra, and other reductions, e-mail messages from all sites pertaining to the run, and the current version of all reduction and

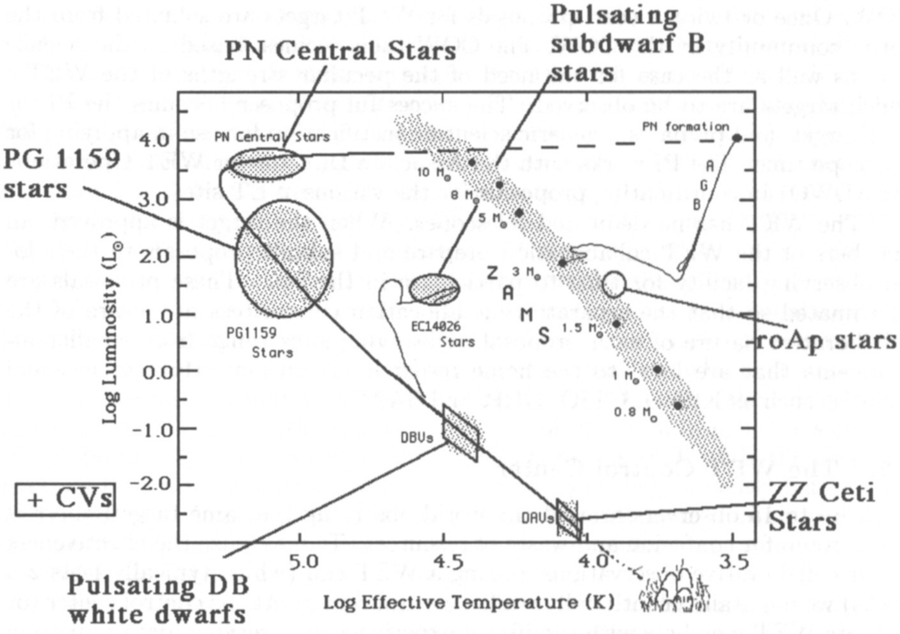

Figure 1. A schematic Hertzsprung-Russell diagram including representative main sequence and evolutionary tracks. Indicated on this diagram are the classes of variable stars that have been examined as targets of WET observations (after Kawaler 1986).

analysis software. A copy of this archive, which fits easily on a standard CD, is taken home by the PI for a more leisurely and thorough analysis.

3.3. Data and Publication

Despite the apparent simplicity of time–series photometry (i.e. low data volume compared to imaging or spectroscopy) correct reduction and analysis of WET data is very difficult. The PI has the responsibility to handle the data and draft a paper (or papers) for publication, but this can take years. To try to stimulate our members, the WET has adopted an 18 month proprietary period, wherein the PI has all rights to publishing the data. Typically the first paper based on a WET run will have as authors all observers and HQ staff that participated in the run. Author order questions are solved by the nature of the collaboration - first–author honors go to the PI and the person or people who did the analysis after the run was over. Authorship continues starting at the geographic location of the HQ, and working West. Subsequent papers that use the data have an author list that includes only those who participated in the additional analysis.

After the proprietary period is over, or the first paper is published, the rest of the collaboration is free to publish independent analysis of the data in whatever form they choose. Of course, all WET collaborators have free access to all the data from the time of the run forward. The raw data, and all reduction software are publicly available after the proprietary period is over.

4. WET Science

In this brief review, there is no chance to fully describe the many exciting science results of the WET, or to adequately describe the wide range of impact of WET (and WET-style) data. This section simply gives a few "headlines" about these sample targets, with references to papers in the literature. Reviews of many WET results can be found in the proceedings of the last three WET workshops (Meistas & Vauclair 2000, Meistas & Moskalik 1998, Meistas & Solheim 1995). See also Kawaler & Dahlstrom (2000) for a broad overview of white dwarf stars and the impact of WET.

Figure 1 illustrates the range of variable stars that the WET has investigated in terms of the H–R diagram. Clearly, we have covered a large portion of this map, with the inclusion of white dwarf stars over 6 orders of magnitude in luminosity, roAp and δ Scuti stars, and the pulsating sdB variables.

Sample amplitude spectra of WET observations are shown in Figure 2. This figure shows the remarkable uniformity in the pulsation spectra of a wide variety of stars. It is this similarity in photometric behavior that gives WET such a wide range of targets. It is an instrument designed with white dwarfs in mind, but applicable to a much larger range of targets.

4.1. PN Central Stars and Pre-White Dwarfs

WET has observed one central star in detail: RX J2117. This star, first identified as an evolved star by its identification as a ROSAT X-ray source, was found to be variable in 1993. This star is a complex pulsator - a paper with analysis of the WET data is in preparation (Moskalik et al. 2001).

Arguably the most productive WET target has been PG 1159, a pulsating hydrogen–deficient pre-white dwarf. Observations in this star from 1991 have yielded accurate determinations of its mass, distance, and subsurface composition profile (Winget et al. 1991, Kawaler & Bradley 1994). These data have been combined to reveal a secular period change that challenges theoretical models of these stars (Costa et al. 1999) We continue monitoring PG 1159 - and it continues to bear fruit.

Another pre-white dwarf, PG 2131, has provided an important test of asteroseismological analysis method (Reed et al. 2000). Perhaps the acme of asteroseismological inference is the distance to the pulsating star. All of the many analysis steps must be correct to derive an accurate distance. PG 2131 has a close companion that is a low-mass main sequence star. The companion has been resolved (with a separation of 0.3 arc seconds) in a pair of images obtained by the Hubble Space Telescope. Reed et al. (2000) analyze these images and obtain a spectroscopic parallax distance to the system that they compare with the seismological distance determined through a reanalysis of the WET data of Kawaler et al. (1995). Reed et al. (2000) find that the two distance agree within the 1 σ level, with the seismological distance having a small formal error of about 10 %.

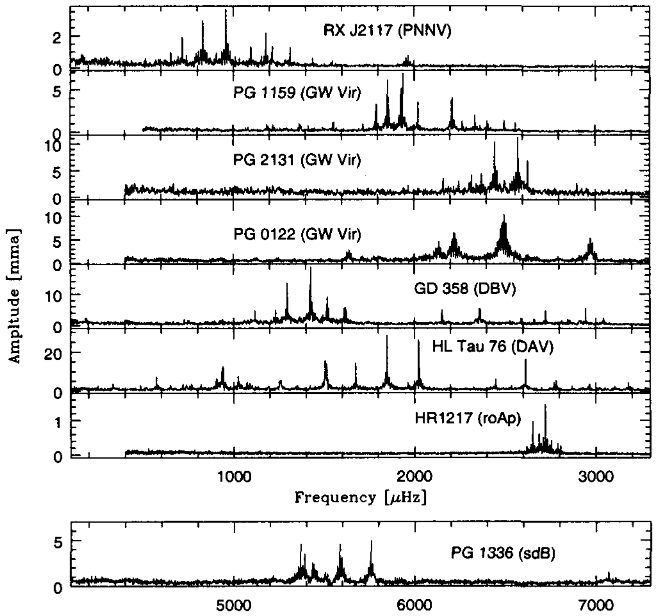

Figure 2. Pulsation spectra from WET. Panels show a PN central star (PNNV), pre-white dwarfs (GW Vir stars), pulsating DB white dwarf (DBV), and ZZ Ceti star (DAV). Bottom two panels show spectra for a rapidly oscillating Ap star and subdwarf B star.

Stellar probes of other areas of physics now include the coolest of the pre-white dwarfs, PG 0122. The evolution of this star should be dominated by energy loss through neutrino emission - the neutrino luminosity exceeds its photon luminosity by a factor of about three. O'Brien & Kawaler (2000) show how to use WET observations of this star, coupled with single–site monitoring, to measure the influence of neutrinos on the change of the pulsation periods.

4.2. Cooler White Dwarfs: the DB and DA (ZZ Ceti) Pulsators

For the pulsating DB white dwarfs, the principal object has been GD 358, first observed with the WET in 1990 (Winget et al. 1994). Results for GD 358 show it to be the most prolific of the pulsators, with over 185 separate modes visible. This high density of modes provides a good probe of the outer layers (Bradley & Winget 1994, Metcalfe et al. 2000), and constraints on models of white dwarf chemical evolution (Dehner & Kawaler 1995) Its pulsation patterns change dramatically from year to year, providing grist for the nonlinear pulsation theorist's mill (Vuille et al. 2000)

ZZ Ceti stars have been observed throughout the history of the WET. Results for ZZ Ceti stars at the hot end of the instability strip are collected in Clemens (1994), while Kleinman (1995) did a comprehensive study of those at the cool end of the strip. One of the most exciting individual targets has been BPM 37095, a ZZ Ceti star with a mass high enough for it to have a crystalline C/O core (Montgomery & Winget 1999); observations by WET are included in the Ph.D. dissertation of A. Nitta (2000). Finally, WET observations have played a key role in the determination of the cooling rate of the ZZ Ceti star G117-B15A by Kepler et al. (2000b).

4.3. Cataclysmic Variables, Subdwarf B Stars, and Main Sequence Stars

One of the early class of targets were CVs that showed short-period phenomena. See, for example, the results for PG 1346 (Provencal et al. 1997), and AM CVn (Solheim et al. 1998).

WET has been used to look at short–period δ Scuti stars - because we do relative photometry, our pulsation spectra are unreliable for periods longer than 20 minutes or so. Table 1 lists those stars that have had successful observations, including one ("WET-0856") that was discovered to be a variable during a WET run because it was used as a comparison star (Handler et al. 1996). In 1999, we observed a pulsating sdB star within a short-period eclipsing binary. The most recent WET run had as its target the rapidly oscillating Ap star HR 1217.

5. Conclusions

The WET, a network of "small" telescopes for global photometry of variable stars, has enabled a broad range of inquiry in stellar astronomy. The first 14 years of the WET have been extremely fruitful. This "new" way of observing produces front-line data using modest instrumentation . . . employed in creative ways. WET results have shaped our view of white dwarf evolution ranging from the formative stages down through the ZZ Ceti instability strip.

At the recent European Workshop on White Dwarfs, for example, most of a day contains papers directly related to WET observations and analysis, as well as results from WET that are directly incorporated into atmospheric and evolution studies. Many current white dwarf researchers earned their Ph.D.s working on WET or using WET data and results - and have gone on to expand their careers well beyond pulsating white dwarfs.

Sites on the WET network are testing CCD photometry systems that can provide rapid photometry (cycle times of 10 seconds or less) of much fainter stars for a given aperture. Additional "expansion" of the WET network has already included simultaneous observations with time-resolve Hubble Space Telescope spectroscopy (Kepler et al. 2000a). With new classes of objects, of which the WET has only made some tentative observations, there is great promise for it to continue its legacy of providing entirely new views of the interiors and environments of interesting stars.

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References

Bradley, P.A. & Winget, D.E. 1994, ApJ, 430, 850

Clemens, J.C. 1994, Ph.D. dissertation, University of Texas

Costa, J.E S., Kepler, S.O., & Winget, D. E. 1999, ApJ, 522, 973

Dehner, B.T. & Kawaler, S.D. 1995, ApJ, 445, L141

Dreizler, S. & Heber, U. 1998, å, 334, 618

Handler, G. et al. (the WET collaboration) 1996, å, 307, 329

Kawaler, S.D. 1986, Ph. D. dissertation, University of Texas

Kawaler, S.D. & Bradley, P.A. 1994, ApJ, 427, 415

Kawaler, S.D. et al. (The WET Collaboration) 1995, ApJ, 450, 350

Kawaler, S.D. & Dahlstrom, M. 2000, American Scientist, 88, 498

Kleinman, S.J., Nather, & T. Phillips, 1996, PASP, 108, 356

Kleinman, S.J. 1995, Ph.D. dissertation, University of Texas at Austin

Kepler, S.O., Robinson, E.L., Koester, D., Clemens, J.C., Nather, R.E., & Jiang, X.J. 2000a, ApJ, 539, 379

Kepler, S.O., Mukadam, A., Winget, D.E., Nather, R.E., Metcalfe, T.S., Reed, M.D., Kawaler, S.D., & Bradley, P.A. 2000b, ApJ, 543, 185

Meistas, E. & Solheim, J.-E. 1995, *The Third WET Workshop Proceedings*, Baltic Astron., 4, 104

Meistas, E. & Moskalik, P. 1998, *The Fourth WET Workshop Proceedings*, Baltic Astron., 7, 1

Meistas, E. & Vauclair, G. 2000, *The Fifth WET Workshop Proceedings*, Baltic Astron., 9, 1

Metcalfe, T.S., Nather, R.E., & Winget, D.E. 2000, ApJ, 545, 974

Montgomery, M.H. Winget, D.E. 1999, ApJ, 526, 976

Moskalik, P. et al. (the WET Collaboration) 2001, in preparation

Nather, R.E., Winget, D.E., Clemens, J.C., Hansen, C.J., & Hine, B.P. 1990, ApJ, 361, 309

Nitta, A. 2000, Ph.D. dissertation, University of Texas at Austin

O'Brien, M.S. & Kawaler, S.D. 2000, ApJ, 539, 372

Provencal, J. et al. (the WET Collaboration) 1997, ApJ, 480, 383

Reed, M.D., Kawaler, S.D., & O'Brien, M.S. 2000, ApJ, 545, 429

Solheim, J.-E. et al. (the WET Collaboration) 1998, å, 332, 939

Vuille, F. et al. (the WET Collaboration) 2000, MNRAS, 314, 689

Winget, D.E. et al. (the WET Collaboration) 1991, ApJ, 378, 326

Winget, D.E. et al. (the WET Collaboration) 1994, ApJ, 430, 839