THE WHOLE EARTH TELESCOPE

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ABSTRACT

The history of our galaxy and the detailed history of star formation in the early universe is written in the white dwarf stars. Recently we have learned how to reach beneath their exposed surfaces by observing white dwarfs that are intrinsic variables. We use the stellar equivalent of seismology to probe their interiors, and thus to unravel the history they hold inside. We have designed and placed into operation an observational technique that uses the whole earth as a telescope platform, defeating the effects of daylight which, until now, had seriously limited the length of a single light curve, and therefore the amount of information we could hope to extract from it. This paper describes our new telescope and presents preliminary results from our first observing run in March, 1988.

TELESCOPE DESCRIPTION

The Multi-Mirror telescope at the University of Arizona, and other multi-mirror designs in various stages of development, collect their mirrors closely in space so they can cooperate to increase the brightness of their optical images. Our new telescope, in contrast, has its several mirrors distributed in longitude around the earth, so they can cooperate in time rather than in space, to increase the resolution (rather than the intensity) of the spectra they obtain. Rather than the traditional spectra in wavelength, we obtain spectra in frequency — power spectra or amplitude spectra — from the time-series data recorded for a single object. We study the regular changes in light level of close binaries and the intrinsic periodic oscillations of white dwarf stars.

The resolution in frequency is determined primarily by the length of the light curve. We use existing telescopes equipped with high speed photometers to obtain light curves of our target objects with as few gaps as possible: as the object is setting for one observer it is rising for another located farther west. The distributed nature of our telescope allows it to remain in darkness as the earth turns on its axis, and thus to keep a single object under continuous study for days, rather than hours.

Figure 1 shows the locations of the different existing optical telescopes we used in March, 1988, for our first observing run using this technique, and Figure 2 lists the observers involved. The overall operation was coordinated in real time from our command post in Austin, Texas, using telex machines and long distance telephone calls for communication. We operate the process as if we were operating a single telescope, so we have come to think of it that way. It may not have the largest light-gathering power in the world — it had the equivalent of a single 3.8m mirror on its first run — but it certainly has the largest telescope mounting (hence its name). And unlike some other telescope designs, additional mirrors can be added quite easily.

In a curious way this is an invisible telescope: it was there all the time, unnoticed, and it disappears again in between scheduled operations. It's very hard to run because administrative overhead is large — planning and coordination of observations and observing techniques, as well as data reduction and analysis. Uniformity of instrumentation is difficult to arrange. The telescope is also difficult to fund because no single monument exists that can be named after a donor; almost all the cost lies in the instrumentation and in operating expenses. But its power to gather scientific data of unprecedented value makes it unlikely that it will return permanently to its earlier, invisible state.

FIRST LIGHT

Figure 3 shows a graph of the time-series photometric coverge during our first operation of the Whole Earth Telescope in March, 1988. Additional spectroscopic coverage of the primary target, PG1346+082, was obtained at the the M.M.T. telescope in Arizona, the 1.8m telescope in Sutherland,

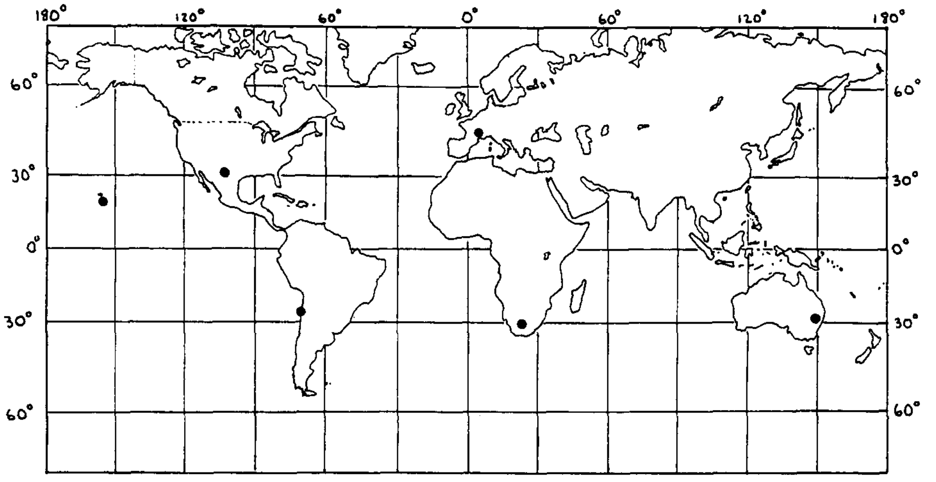

Figure 1: The Whole Earth Telescope. The observatories involved are denoted by the •.

South Africa and the I.U.E. satellite in space. The star rose about three hours after twilight and the early part of the run had more moonlight than was desirable, but these disadvantages were more than offset by unprecedented luck with the weather: most of the sites were photometric most of the time. We give priority to targets which can be seen from observatories in either hemisphere, both to increase coverage and to minimize data loss from atmospheric opacity (clouds). We are unlikely to be this lucky with the weather again and do not require it, but we will not complain if it happens.

Our primary target object, PG1346+082, was one we had studied extensively from a single observatory (Wood *et al.* 1987) but were not satisfied we understood it. Our working model for the system describes it as a close pair of interacting stars, both of which are degenerate. Mass is being stripped from the less massive of the pair by Roche lobe overflow, forms an accretion disk around its orbital companion, and accretes in episodic fashion much like a dwarf nova. The material is pure helium: hydrogen is notable by its total absence. We believe we are seeing revealed the inner core of a star that was once much more massive, burned hydrogen to helium on the main sequence but never initiated helium burning, and later collapsed to form a helium-core white dwarf when hydrogen burning could no longer be sustained. The average rate of mass transfer in the system is set by the effects of gravitational radiation, which removes orbital momentum and forces the two objects to interact.

The episodic nature of the accretion process causes the system to vary from magnitude 17.2, when accretion flow is minimal, to magnitude 13 when it is at a maximum. It behaves much like a yo-yo (or a computer): it's sometimes up but mostly down. We had hoped it would stay near maximum brightness most of the time, because we were convinced our smallest telescope — the 0.6m on Mauna Kea in Hawaii — would be unable to gather useful data should the object stay near minimum. We were wrong. Our observer there got accurate offset measurements from a bright guide star when PG1346 was at magnitude 14, and set on it "blind" for the subsequent nights of the run when it was much fainter. To our astonishment the data were quite usable, if somewhat noisy, a tribute to the dark sky and excellent seeing that permitted use of a very small isolating aperture.

THE SPECTRAL WINDOW

If a star exhibits a single, pure sine wave modulation in brightness, then the Fourier transform of its light curve will show a single delta function at its frequency of modulation — if we can watch it for an infinite amount of time. We can't, of course, so all real light curves have some finite length, and their Fourier transforms show a spike with some finite width for each periodicity present. The shorter the run, the poorer is our ability to resolve two periodicities close together in frequency.

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WHOLE EARTH TELESCOPE XCOV-I MARCH 1988

Dramatis Personae

PHOTOMETRIC OBSERVATIONS

Texas, Command Central
D. E. Winget
J. C. Clemens
C. F. Claver
Hawaii, Mauna Kea Observatory
B. P. Hine
Australia, Siding Spring & Mt. Stromlo Observatories
A. D. Grauer
Lilia Ferrario
South Africa, Sutherland Observatory
Brian Warner
Darragh O'Donoghue
Peter Martinez
France, Haute-Province Observatory
Gerard Vauclair
Michel Chevreton
Chile, Cerro Tololo Interamerican Observatory
Greg Henry
S. O. Kepler
Texas, McDonald Observatory
R. E. Nather
M. A. Wood

DATA REDUCTION AND ANALYSIS

Judi Provencal
D. E. Winget
S. O. Kepler
Brian Warner
C. F. Claver

Figure 2: Participants in XCOV-1.

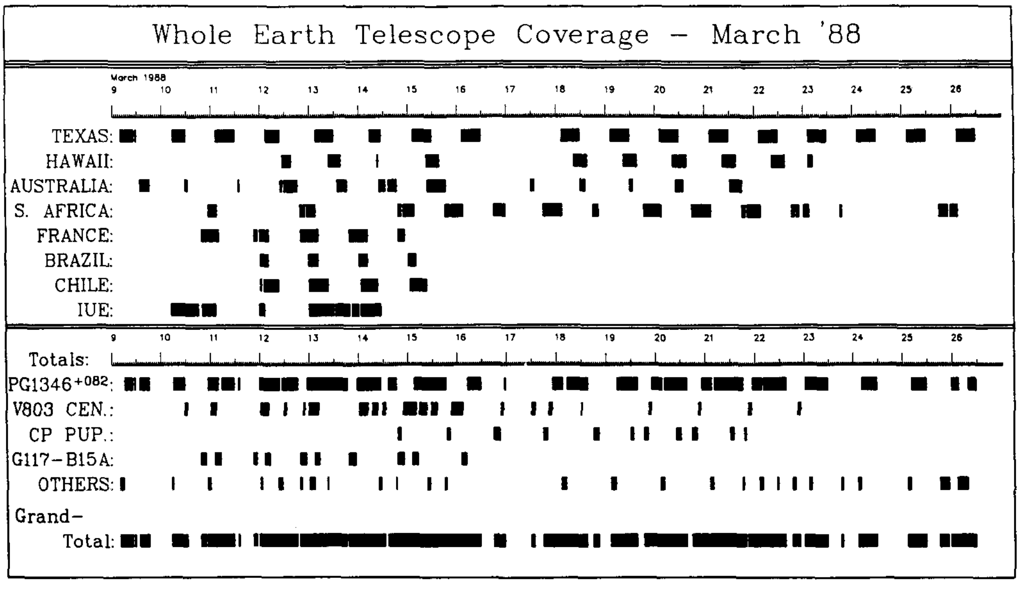

Figure 3: Whole Earth Telescope Coverage

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If a long light curve is sampled — that is, if it extends over several successive nights but is interrupted by daylight — then each single periodicity present becomes a forest of spikes in the power spectrum, each one representing a difference of one oscillation cycle from its nearest neighbor. We call this the "alias forest" and it is inevitable if data are obtained only from a single observatory. We can easily calculate the pattern of spikes we can expect for a single, noise-free sine wave by sampling it in just the way our data run was sampled, and then obtaining the Fourier transform of this artifical data. The result is not a pretty sight.

OBSERVATIONAL RESULTS

Figure 4 shows the product of such an exercise for the McDonald data on PG1346, sampled in just the way the original data were taken (Figure 3 shows the data intervals and the daytime gaps

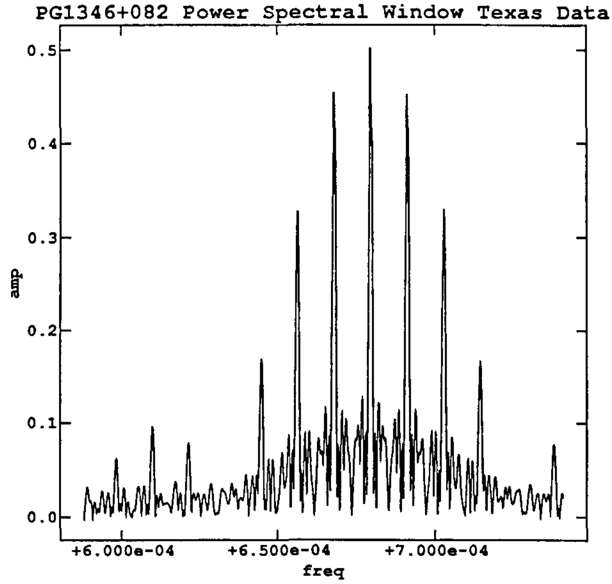

Figure 4: Power spectrum of a sine wave (Texas data only).

between them). Each separate periodicity present in the data will generate this ugly pattern, centered on its own frequency, and piled on top of all the others. While we might be able to identify two or three such patterns jumbled together, separating the multiple periodicities generated by g-mode pulsations is hopeless, particularly in the presence of the inevitable noise of measurment. Figure 5 shows a small portion of the time-series spectrum of PG1346, obtained by using only the data from the Texas observations. The small arrow indicates a periodicity of 1471s, the ninth largest of the group.

Figure 6 shows the spectral window for the complete data set. Ideally, it should contain only a single spike, and it would were our coverage complete. The flanking alias peaks arise because of a periodic gap in coverage at about −6h in longitude — we had not yet established collaboration with astronomers in India. We now have, and hope to reduce this effect on our next run, planned for November 1988. While flanking peaks can arise if one or another observatory is cloudy for part of the run, the most damaging gaps are those which appear regularly throughout the whole data set.

Figure 7 shows the same portion of the time-series spectrum, this time using the combined data from all of the observing sites. Note that the 1471s periodicity is now clearly the most prominent and other periodicities — marked with arrows — can be identified from the simpler patterns they generate in the spectrum. The large number of periodicities which are clearly well above the noise level was a real surprise. Unmarked peaks arise from combinations of the flanking alias peak patterns, so the

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interpretation is still a bit tentative. What is clear, though, is that far more than three periods are present in the system in this narrow range of frequencies.

Rotational effects in a binary system can be invoked to explain observed periodicities, but only a few of them. They might arise as rotation of one or both objects on their own axes, if they present non-uniform surfaces to our view, or they might arise from the orbital motion of the pair. Distortions from obscuration or other effects can produce harmonics but will not introduce new, incommensurate periods. The large number of observed peaks in this preliminary data suggest immediately that we are

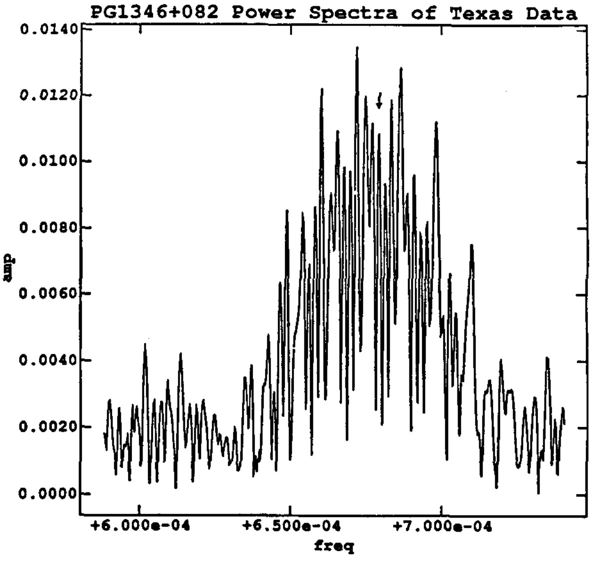

Figure 5: Power spectrum of PG1346+082 (Texas data only).

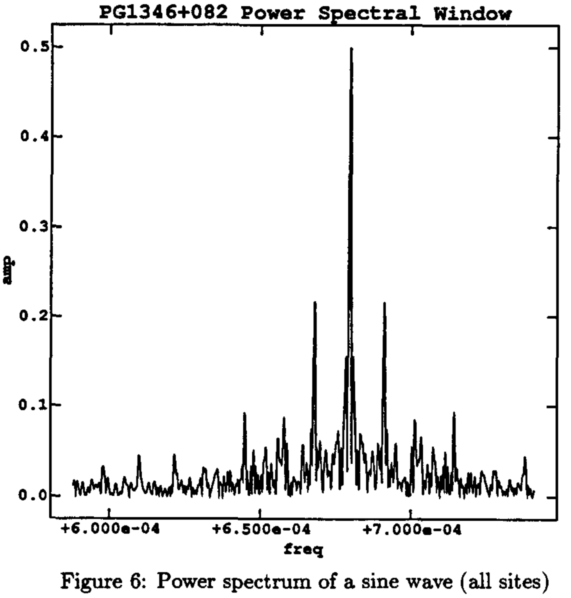

Figure 6: Power spectrum of a sine wave (all sites)

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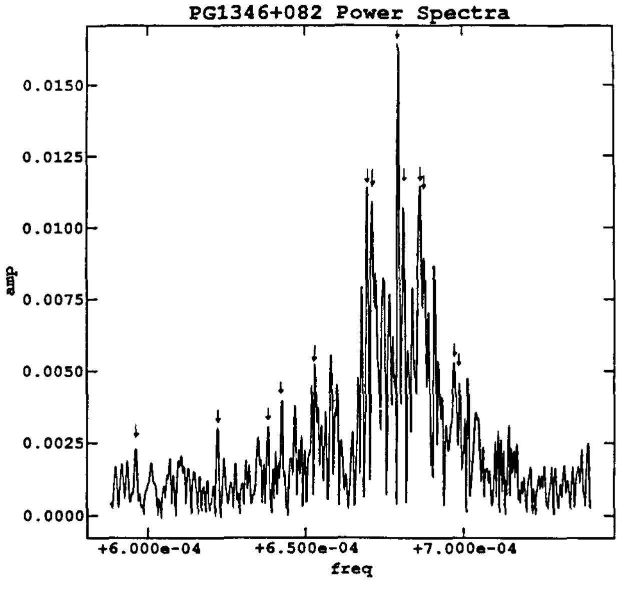

Figure 7: Power spectrum of PG1346+082 (all sites)

seeing g-mode pulsations from the surface of the more massive white dwarf.

This conclusion is quite plausible. The surface temperature of the accreting object lies comfortably within the instability strip for white dwarfs with atmospheres of helium (the DBV stars), and PG1346 spends most of its time in the low state, where light from a bright accretion disk would not drown out the modulation from g-mode oscillations. This wealth of oscillations was not seen by Wood *et al.* in PG1346 during its high state. The "flickering" they reported at minimum will need to be re-examined, however: beating among many periodicities might mimic the flickering seen in mass transfer binaries. It's just possible that mass transfer shuts off completely when PG1346 is at minimum light.

If this picture is correct, then PG1346+082 is the first known object to combine both g-mode pulsations in the accreting object and mass transfer from a degenerate donor — the two mechanisms we have identified that allow us to probe the internal structure of white dwarfs, and attempt to extract from them details about the early history of our galaxy, back when the universe was young.

CONCLUSIONS

Our results presented here are preliminary; a great deal more information can be extracted from the data in hand. We removed all of the slow excursions in brightness so we could better examine the rapid periodicities, and we have not examined all regions of the spectrum where signal power is evident. We have found that the harmonic structure is unexpectedly rich in detail (Provencal *et al.*, these proceedings) and may offer opportunities for exploring the structure of the (pure helium) accretion disk from modulations induced in it.

The development of instruments or techniques that can reveal new things, or can measure known things in a new way, has historically been the path to astronomical discovery and new astrophysical insight. We believe the Whole Earth Telescope is such a development.

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