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Results from the Whole Earth Telescope – Indian Contributions

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Abstract. The Indian team at ISRO has been part of the Whole Earth Telescope (WET) team since 1988 when we first participated in the campaign on V471 Tau. We have been part of many other observing campaigns over the last decade. This presentation traces the circumstances leading to our joining the WET team and how useful the coverage from the Indian longitude has been. The results of several pulsators from the WET runs during which we participated are also described. These include PG1159-035 the prototype of the GW Vir type of stars, RE J 0751+14 a cataclysmic variable, PG 1336-018 a binary with an sdB pulsator and finally HR 1217 a roAp star. The paper concludes with what the limitations are in our observations and how we can overcome them in the future.

Key words. Stars: pulsating—stars: individual: PG1159-035—stars: individual: RE J 0751+14—stars: individual: PG 1336-018—stars: individual: HR 1217.

1. Introduction

The Whole Earth Telescope (WET) is a world wide network of astronomers whose main goal is to study pulsating stars and to resolve the pulsations at the best ever frequency resolution. In order to achieve this purpose, the members of this collaboration try to obtain uninterrupted data with an improved signal to noise ratio on specific target stars. This leads to the detection of multiple frequencies to very low amplitude levels (a few millimag going down to a few micromag) and the resolving of closely spaced (to few μHertz) frequencies. The data set appears as though the observations on the star was a continuation from one observing site to another as the star moved westwards and as though the whole Earth served as an observing site — hence the name. The concept of WET was mooted in 1986 and originated in the precincts of the University of Texas at Austin, USA. In 1995, it was affiliated to the IITAP – International Institute of Theoretical Physics – at Iowa State University. The WET is headed by a Director who is assisted in all decision matters by the Council Of Wise (COW) (see *http://wet.physics.iastate.edu*). However, it is a fairly democratic body with provision for all collaborators to interact and have their say. The first observational campaign was conducted in 1988 on PG 1346+082 with six observatories participating. Over the years there have been astronomers from 20 observatories who have participated in various campaigns and 24 campaigns have so far been been conducted. The WET campaigns are denoted by XCOVn where '*n*' is the number of the campaign. The Asian longitudes are very crucial because almost half of this area in terms of latitude is covered by the Indian Ocean and in the remaining land area there are not sufficient numbers of observatories with the necessary observing conditions. Hence, the observational coverage from the Asian longitudes are exigent to fill critical gaps in the data sets. India joined the WET organisation during the second campaign in November 1988 (XCOV2) to observe V 471 Tau. Since then we have contributed data sets during 7 campaigns.

2. Indian participation

Many astronomers in India have been involved in the observation of variable stars at various observatories. Members of our division (SAID; earlier known as Technical Physics Division) at ISRO Satellite Centre were involved in fast photometry of cataclysmic variables. Well aware of the problems connected with single channel photometers, we decided to build a two-star photometer. Our preliminary design was made in 1984. During the IAU general assembly held at New Delhi, India, in 1985, we got the chance to meet other astronomers who had built or were planning to build two/three channel photometers. Some of them are the founder members of WET. Having realised the two-star photometer in 1987 (Venkat Rao *et al.* 1990; also see Ashoka *et al.* 2001) we were in a position to test it in 1988. With the provision of the interface card and the Quilt-9 software (Nather *et al.* 1990) from our WET colleagues and the availability of PCs around the same time, everything fell into place for our joining the WET campaigns. Variable star photometry became fun with the capability to observe the light curve in real time. Since then we have participated in over 7 campaigns and have used telescopes at Vainu Bappu Observatory at Kavalur in South India (lat $= 12°34'.5$, long $= 78°49'.5$) as well as at ARIES (lat $= 29°, 22'$, long $= 79°, 27'$; erstwhile State Observatory Nainital).

3. Asteroseismology with the WET

The main goal of the WET has been asteroseismological studies of pulsating variables. Many of these variables pulsate in non-radial modes exhibiting multiple, closely-spaced frequencies. The aim is to resolve these frequencies and evolve a theoretical model which simulates the observed frequencies. Essentially, the observationally resolved frequencies can help to fine tune theoretical models to fit observations so that various physical parameters of these pulsating stars can be estimated. For most classes of variables, the same estimates can be extended to non-variables also as a class. The physical parameters which can thus be estimated using asteroseismological tools and which have been best demonstrated for the '*g*' modes exhibited in white dwarf pulsators are as follows:

- The rotation rate of the star: by the '*m*' splitting or rotational modulation of pulsations.
- The magnetic field strength: by the asymmetry in '*m*' spacing.
- Differential rotation rate: change in '*m*' splitting for different modes (different locations in the star).

- The stellar mass: from the mean period spacing of same 'l' but different 'k'.
- Core composition by the mean period spacing of different adjacent 'k' values.
- Surface layer masses: by deviations from the mean period spacing.

Although the maximum success rate of applying asteroseismological methods has been achieved with white dwarfs, several other pulsation studies have been possible with WET used to observe other classes of pulsating variables also. We will describe in this paper a few of the results from WET on different classes of objects, selecting stars which were observed from the Indian longitudes. This however is NOT a summary of the overall results of the WET. We choose for the purpose of this paper, four targets:

- PG 1159-035 – a DOV white dwarf; first target for which most of the results of asteroseismology were demonstrated.
- PG 1336-018 – an eclipsing sdBV system where the sensitivity limits of the WET enabled the detection of very low amplitude pulsations even during eclipse.
- REJ 0751+14 – a cataclysmic variable, where long duration allowed for observing changes in the pulse profile.
- HR 1217 – a roAp star, where a theoretically predicted frequency was searched for and found.

3.1 *PG 1159-035*

PG1159-035 also known as GW Vir, or McGraw's star was discovered to be a variable in 1979 (McGraw *et al.* 1979). It exhibits a predominant period at 516s. Further co-ordinated observations demonstrated that although the 516s is the predominant frequency, there are several groups of distinct frequencies clearly indicating that the star is multiperiodic. (Winget *et al.* 1985; Winget 1988). Based on these observations it was proposed that the star is pulsating in the '$l = 1$' or '$l = 3$' mode for a 0.6 solar mass white dwarf (Kawaler 1988). The change in period of the 516s or dp/dt was estimated to be $(-2.4 \pm 0.4) \times 10^{-11} \mathrm{ss}^{-1}$ (Winget and Kepler 1988).

Knowing well that this star is multiperiodic, a Whole Earth Telescope campaign was conducted in March 1988 (XCOV3) in which 9 observatories were involved and the results were published by Winget *et al.* (1991). It was proven with this campaign that the star is indeed a rich multimode pulsator. Over 121 peaks were evident in the Fourier transform of which 101 modes were identified (Winget *et al.* 1991). Several '$l = 1$' modes and a few '$l = 2$' modes were identified. The fine splitting for both these sets indicated that the rotation period of the star is $1.38 \pm 0.01d$.

The non-uniformity in the splitting, which was less than 5%, was attributed to a magnetic field strength of less than 6000G. The determination of the mean period spacing for modes with the same 'l' but different values of 'k', enabled us to estimate the mass to be 0.586 ± 0.003 solar mass.

It was also concluded that the atmosphere of PG 1159-035 is compositionally stratified with a very thin layer of helium and even a thinner layer of hydrogen. Although the 516s period was identified to be an '$m = +1$' mode the dp/dt derived from earlier data was consistent with the WET observations and the value of dp/dt was refined to be $(-2.49 \pm 0.06) \times 10^{-11} \mathrm{ss}^{-1}$); PG1159-035 has been observed several times after this campaign, using WET in 1993, 2000 and 2002. The frequencies of the resolved modes appear stable, although the amplitudes do vary, as is the case with several pulsators. However, all issues of PG1159-035 are not completely solved. Evolutionary

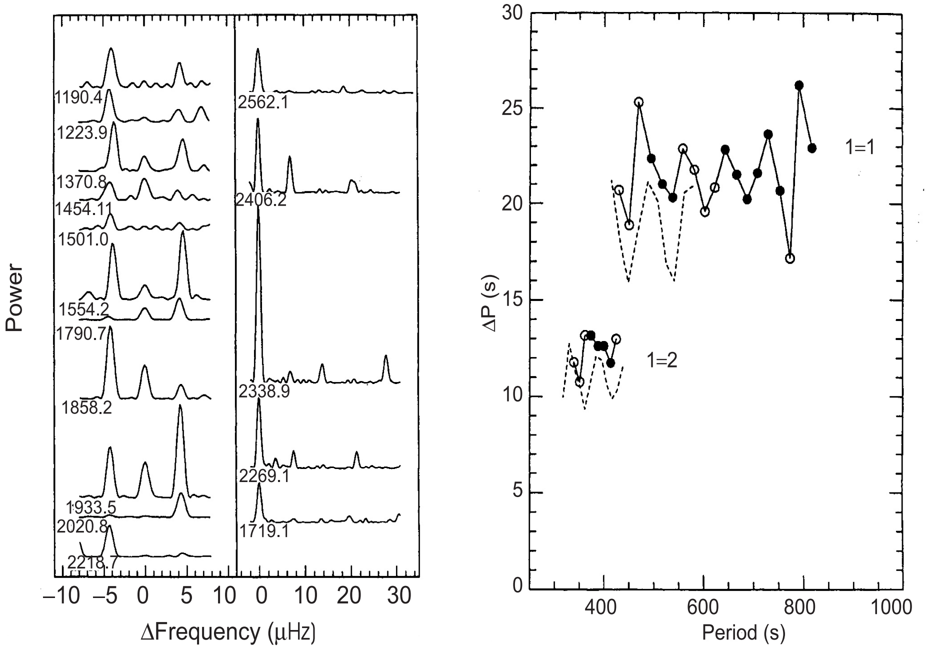

Figure 1. Figure on the left shows the $l = 1$ and $l = 2$ splittings of different modes stacked one above the other for viewing convenience. The figure on the right shows the same modes on period scales to show the approximately equal period spacing of the *g* modes (from Winget *et al.* 1991).

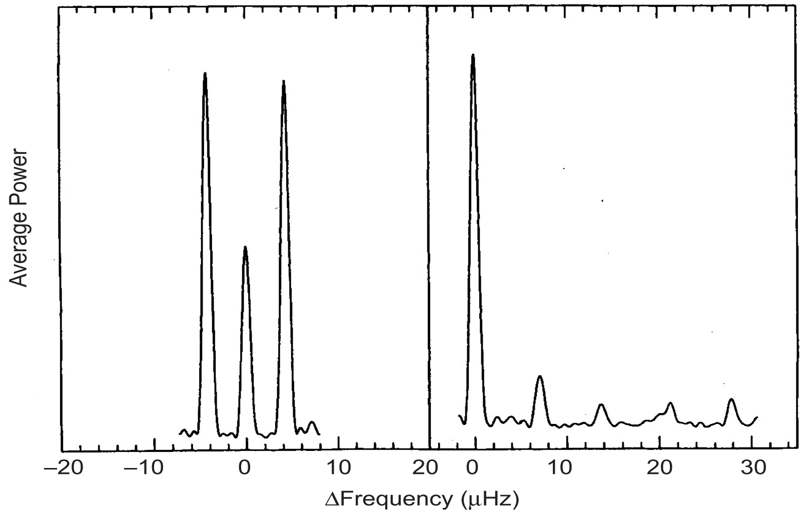

Figure 2. The average of all the $l = 1$ and $l = 2$ modes (from Winget *et al.* 1991).

models predict that dp/dt would be negative for trapped modes like the 516s and the 539s modes but would be positive for non-trapped like the 495s and 451s modes (Kawaler and Bradley 1994). Later direct measures (Costa and Kepler 1997) of phase of 516s period indicate that dp/dt for the 516s period itself could be positive and very large (($(+13 \pm 2.6) \times 10^{-11}$ss^{-1}). The evolution of the periods with time is an issue which will need many more observations before it is settled.

3.2 *PG 1336-018*

Also known as NY Vir, this system is a close eclipsing binary with a binary period of 2.4 hr (0.101d). One of the components of the binary is a pulsating B subdwarf (sdBV). These are also known as EC 14026 variables after the first prototype discovered in this group (Kilkenny *et al.* 1997). Pulsations were discovered in PG1336-018 with two frequencies at 5.4 mHz (184s) and 7.1 mHz (141s) being predominant (Kilkenny *et al.* 1998). Amplitude modulation and bands of power at other frequencies indicated that this star could be multiperiodic. PG 1336-018 was observed in April 1999 (XCOV17) with the WET and 172 hours of observation with 47% coverage was obtained. More than 28 frequencies were detected with 20 frequencies being identified in the frequency range of 4000 to 8000 μHz down to an amplitude of 0.003 modulation intensity (mi) level (Kilkenny *et al.* 2003). The predominant frequency around 5400 μHz itself was resolved into several frequencies. Frequency structure changes were observed on time scales as short as one day. This may be caused by unresolved modes or amplitude changes. Rotational effects were searched for and may have been present in two of the frequencies. Although 20 frequencies were identified, they could not be classified as specific modes due to the inadequacy in modeling. One of the aims of the WET campaign was to look for pulsations during eclipse and if well resolved, mode identification would be possible depending on the gradual decrease/increase in amplitude of the frequencies during ingress/egress.

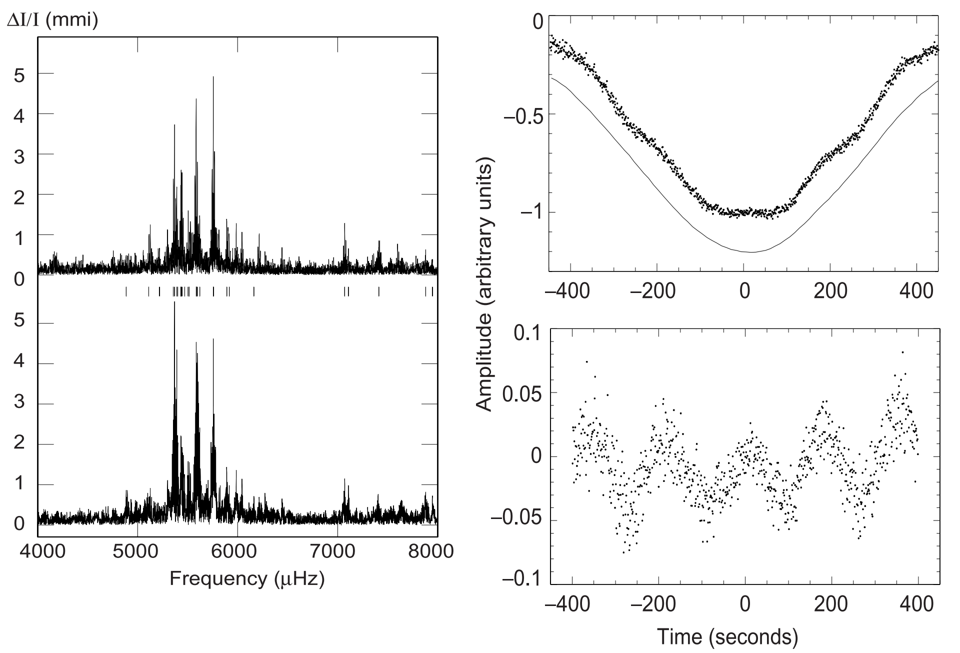

Figure 3. The figure on the left shows the frequency spectrum of PG 1336-018 obtained during two halves of the WET run in April 1999. The figure on the right shows the presence of pulsations during the eclipse after removing the eclipse profile using a fit (from Kilkenny *et al.* 2003).

The inclination of the system is estimated to be 81 degrees, and therefore even during primary eclipse, pulsations were expected. One important result obtained from the WET campaign was that during the eclipse, pulsations were indeed observed. However, they could not be resolved into modes due to insufficient coverage of eclipses during the campaign.

3.3 *RE J0751+14*

Also known as PQ Gem, this is an intermediate polar and has been extensively observed in both optical and x-ray bands (Mason *et al.* 1992; Duck *et al.* 1994; Rosen *et al.* 1993; Hellier *et al.* 1994). The rotation period of the white dwarf in this binary system was determined to be 13.9 min with its harmonic also at 6.9 min observed in R and I bands. The presence of a beat period was evident but the period of the beat was observed to be 14.5 min or 15.2 min. The polarisation studies in this system indicated that it is more like a polar with the estimated magnetic field to be as high as 8–18 MG using cyclotron models (Piirola *et al.* 1993; see also Vath *et al.* 1996; Potter *et al.* 1997). This object was observed with the WET during February 1996 (XCOV13). The spin period and the synodic period were clearly identified at 833.39s (13.9 min; frequency = 1.199 mHz) and 872.25s (14.5 min; frequency = 1.146 mHz) (Marar *et al.* 1998). The harmonics of these two periods were also observed. Both these periods were stable during the WET run. Based on this, the orbital period was estimated to be 5.19 h.

The spin profile and the beat pulse profile as a function of the orbital period was calculated which showed changes in the accretion geometry. The object was studied extensively almost simultaneously by many of the authors mentioned above. The white dwarf in the system was found to be spinning down at a rate of ($+1.1 \times 10^{-10}$ss^{-1}) by Mason (1997), which was confirmed in the WET data set ($dp/dt = 9.2 \times 10^{-11}$ss^{-1}).

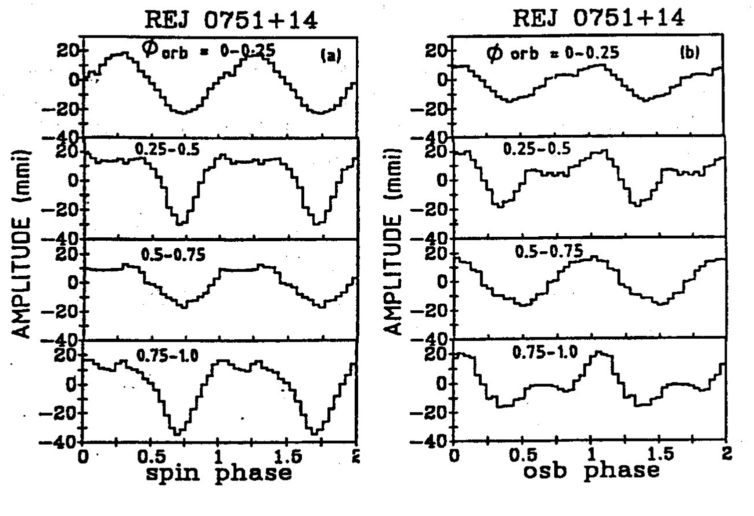

Figure 4. The variation in the profiles of the spin and orbital side band modulation as a function of orbital period for REJ 0751+14 (from Marar *et al.* 1998).

The object was studied by Potter *et al.* (1997) and extensively by spectroscopic methods by Hellier (1997). The spectroscopic results indicate that the system is indeed disc fed.

3.4 *HR 1217*

HR 1217 is a well studied rapidly oscillating Ap (roAp) star which exhibited six oscillation frequencies each of these showing rotational modulation (Kurtz *et al.* 1989). The spacing between the adjacent modes was found to be 34 μHz. This could be explained either as alternate even and odd modes which would imply a real splitting of 68 μHz for the same values of 'l'; or the adjacent modes could be different radial orders ('n' values) of the same 'l' which would imply a real spitting of 34 microHz. This was resolved (Mathews *et al.* 1999) using the Hipparcos data and the asteroseismic and the Hipparcos luminosity matched only for alternate odd/even modes implying a real splitting of 68 μHz. This result however showed that whereas 5 adjacent frequency groups in the earlier data of the star could be explained by this splitting, the 6th frequency was at a frequency of only 3/4 of this splitting frequency.

Since roAp stars have magnetic fields of several kilo Gauss, it was proposed that magneto-acoustic effects could be important and magnetic perturbation could result in variation in spacing (Cunha and Gough 2000; Bigot *et al.* 2000). Cunha (2001) predicted there would be an additional frequency with a splitting of around 34 μHz. This frequency was searched for during the WET run held in November 2000 (XCOV20).

An additional peak was detected at 2788.95 μHz, near the predicted frequency; this peak had an amplitude of 0.1 mma (Kurtz *et al.* 2002). It may be noted that this amplitude was well above the noise levels in the previous runs of 1986 and why it was not detected is still an open question. The amplitudes of various modes do change with time and this could be the reason for the non-detection of the new frequency in the 1986 dataset and its detection in 2000, which will be confirmed only with future observations. Meanwhile the MOST satellite has also observed this star and found almost the same frequency spectrum (see papers by Cunha; Kurtz; these proceedings and Kurtz *et al.* 2005).

4. Future of WET

It is clear that in the future we will need larger telescopes and will need to access fainter targets. At present, discussion groups are organised within WET to discuss the future of WET. This includes:

- Science issues which can be addressed by WET in the context of upcoming satellite experiments to observe pulsating variables; identification of niche problem areas in science which WET can address best;
- Funding issues as to how the WET should be operated in the future;
- Instrumentation issues as to whether all WET colleagues can be provided with identical instrumentation;
- Accessibility to fainter targets.

In particular the coverage of Asian longitudes has to be addressed, as this is becoming crucial from the point of view of gaps in data. The months of April to August are clouded over due to the monsoon in most parts of India. Alternate high altitude sites where weather patterns are different may prove very useful in this. For this purpose,

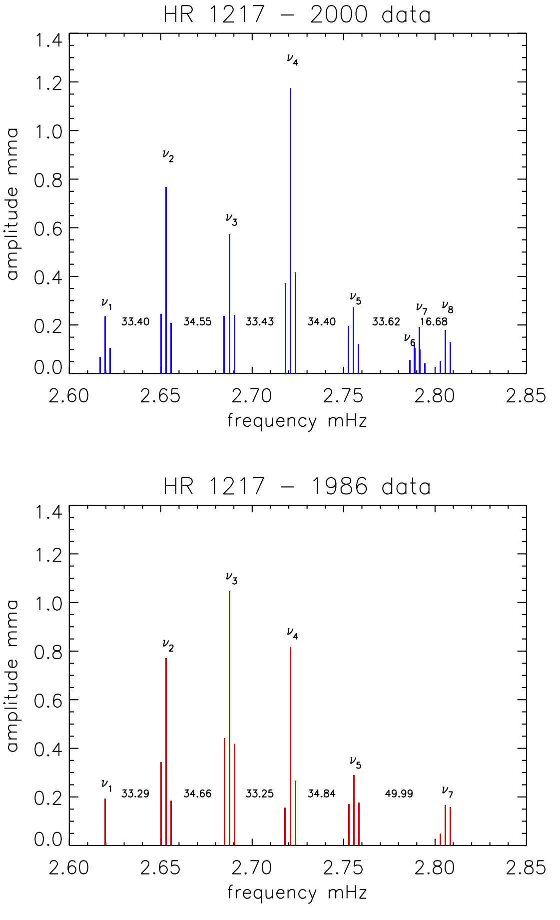

Figure 5. The difference in the Fourier spectra of the WET data set (top) and the 1986 dataset (bottom) (from Kurtz *et al.* 2002).

if bigger telescopes in better sites in India can be equipped with photometric specific instrumentation with good timekeeping (which is essential for time series photometry) and excellent tracking (since these objects are observed continuously for the whole night with as few breaks as possible), then these telescopes could all be included for future WET campaigns.

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