MSST observations of the pulsating sdB star PG 1605+072

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Abstract. We present the first results from the MultiSite Spectroscopic Telescope (MSST) observations of the sdBV star PG 1605+072. Pulsating sdB stars (also known as EC 14026 stars) offer the chance to gain new insights into the formation and evolution of extreme Horizontal Branch stars using the tools of asteroseismology. PG 1605+072 is an outstanding object in its class, with the richest frequency spectrum, the longest periods, and the largest variations.

The MSST campaign took place in May/June 2002 immediately following the Whole Earth Telescope Xcov22 run, which observed PG 1605+072 as an alternate target. We will first give an overview of the project and its feasibility, after which we will present the massive data set, made up of 399 hours of photometry and 151 hours of spectroscopy. The overall aims of the project are to examine light/velocity amplitude ratios and phase differences, changes in equivalent width/line index, and λ-dependence of photometric amplitudes, and to use these properties for mode identification.

Keywords: stars: oscillations — subdwarfs — stars: individual: PG 1605+072

1. Motivation

Of all the short-period sdB pulsators currently known, PG 1605+072 stands out. It is perhaps the most evolved, it has the highest amplitudes and longest periods, and it is the only apparently single sdB star that shows significant rotation. Its rich pulsation spectrum and relative brightness make it an ideal target for multisite observing campaigns such as the Whole Earth Telescope (WET). After the discovery observations showed a complex amplitude spectrum with many modes (Koen

* see http://astro.uni-tuebingen.de/~schuh/msst/astronomers.html and http://wet.iitap.iastate.edu/xcov22/people.html

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et al. 1998), a two week multisite photometric campaign was organised, and more than 55 frequencies were detected, as well as evidence for amplitude variation (Kilkenny et al. 1999). Models by Kawaler (1999) suggested that part of the complexity of PG 1605+072’s amplitude spectrum may be due to rapid rotation with an equatorial velocity of about 130 km s$^{-1}$, thereby causing rotational splitting of the oscillation modes. When Heber et al. (1999) carried out a spectral analysis, they measured $v \sin i$ to be 39 km s$^{-1}$, which fit nicely into this picture. Both Heber et al. (1999) and Koen et al. (1998) found that PG 1605+072 has evolved off the extreme Horizontal Branch (EHB), making it an important link between the EHB and the white dwarf cooling curve. An analysis by Reed (2001) showed that the amplitude spectrum is too complex to measure mode stability.

O’Toole et al. (2000) were the first to detect velocity variations in the Balmer lines of PG 1605+072, measuring amplitudes of 14 km s$^{-1}$ in H$\beta$ using 2 m telescopes. Woolf et al. (2002) showed the advantage of using 4 m class telescopes, with much better velocity accuracy than 2 m telescopes. They also used moments of the cross-correlation function to detect line shape variations. O’Toole et al. (2002), using a larger data set than O’Toole et al. (2000), did a detailed analysis of two-site spectroscopy, and found evidence for amplitude variation and closely spaced modes. O’Toole et al. (2003) examined Balmer line indices and found an amplitude dependence on Balmer line number, which they used to derive the amplitudes of the effective temperature and surface gravity variations. Falter et al. (2003) were the first to attempt simultaneous multicolour photometry and spectroscopy, and found no phase difference between different filters. Using spectrophotometry, O’Toole (2003) obtained the same result, and found the velocity/intensity phase difference to be $\sim 110^\circ$ for all 8 modes detected (for purely adiabatic oscillations, this phase difference should be $90^\circ$).

These analyses showed that one and two site spectroscopic campaigns are not enough to understand the complex nature of PG 1605+072, and that even multisite photometry would not do the job. Considering the potentially huge amount of information that can be obtained from this star, we decided to undertake a multisite spectroscopic and photometric campaign in May/June 2002. Here we present the initial results from this ambitious project.

2. Observations and Reductions

The MSST campaign obtained both photometry and spectroscopy. The photometric part of the campaign was divided into two parts. As part
of the WET Xcov22 campaign, PG 1605+072 was observed as an alternative target, and ~127 hours of observations were obtained (Heber et al. 2003). All photomultiplier (PMT) data were reduced using the WET reduction software QED. Most CCD data were reduced using standard aperture photometry routines in IRAF. Some data remains unreduced. From the main part of the MSST campaign ~272 hours of observations were obtained, giving a total of ~399 hours, or roughly 54% temporal coverage. This is by far the most data acquired for any sdB during a single observing campaign. Again PMT data were reduced using QED, while most CCD data was reduced using TRIPP (Time Resolved Imaging Photometry Package, see Schuh et al. 1999), and some data were reduced using IRAF. We also have 5 nights of multicolour photometry, using BUSCA on the Calar Alto 2.2 m telescope, which has yet to be reduced.

There were also two parts to the spectroscopic contribution to the MSST campaign, using 4 m and 2 m telescopes. Several of the 4 m telescopes applied for did not receive time or were clouded out, so coverage was poor at only ~7% (around 27 hours total). All 3 telescopes (Apache Point 3.5 m, Calar Alto 3.5 m and the ESO NTT 3.5 m) acquired spectra by trailing the star along the slit. This allows for variable exposure times, depending on conditions. An example of the quality of data possible using this technique is shown in Figure 1. The high velocity precision achievable with this technique suggests that it can be used
on fainter and/or lower amplitude targets. Not all of the data has been
analysed, although everything has been reduced using SPEX (long-
slit SPectrum EXtraction package)\(^1\), a package which allows for
the reduction of trailed spectra. Poor weather conditions during the
NTT observations means that data may not be useful.

The observations using 2 m telescopes were somewhat more suc-
cessful, although the timing of the allocations was not always optimum,
meaning there were two halves to the campaign, separated by about 2
weeks. The first half of the campaign had good coverage on paper,
but bad weather at both La Silla and Siding Spring Observatories
meant around 70-75% of allocated time was lost, leading to 58 hours of
observations or \(~22\%\) coverage. The second half of the campaign was
much more successful, with 93 hours of observations, or around 32%
coverage. All of the 2 m spectroscopy data were reduced using standard
routines in IRAF for bias subtraction, flat fielding, sky correction, and
order extraction, however the velocities were determined using a double
precision version of the rv package\(^2\). The raw velocities are shown in
Figure 2. The higher apparent scatter in the second half of the campaign
is mainly due to long term drifts in the velocity curves. These drifts
seem to be inherent in both the DFOSC and ALFOSC spectrographs. A

\(^1\) see \url{http://astro.uni-tuebingen.de/~schuh/spex/index.html}
\(^2\) available from \url{http://iraf.noao.edu/scripts/extern/rvx.pl}
Figure 3. Amplitude spectrum of MSST photometry from SAAO, SSO and the JKT. The 2075.8 $\mu$Hz mode is dominant again. The inset shows the spectral window.

A similar problem is seen in observations of PG 1325+101 using ALFOSC (Østensen, these proceedings).

3. First Results

Although great care was taken to make sure that the timing of each observation was accurate, inevitably we ran into some problems. These mainly occurred during analysis of the photometry, where the addition of several sites to the main campaign data caused strange aliasing effects. In some cases a large reduction in oscillation amplitudes was also seen (up to $\sim$25%), despite the data from single sites analysed individually showing similar amplitudes. This might indicate a timing problem. As a start, we show in Figure 3 the amplitude spectrum of 3 sites where timing does not seem to cause problems (SAAO, JKT and SSO). Fortunately PG 1605+072 was observed for at least 6 nights from each of these observatories, constituting a large fraction of the data. Other sites appear to have deviating timing, and the reasons are still under investigation. As mentioned above, some data (from BAO) have not been reduced yet, and are not included.

One of the most striking things about Figure 3 is the dominance of the mode at 2075.8 $\mu$Hz. This mode had the highest amplitude in the observations of Koen et al. (1998) and Kilkenny et al. (1999), how-
Figure 4. Velocity amplitude spectrum of PG 1605+072 (top); after prewhitening 5 frequencies (middle); after prewhitening by 10 frequencies (bottom).

However, in the radial velocity studies of O’Toole et al. (2000, 2002) and Woolf et al. (2002), with observations in 1999 and 2000, it was almost undetectable or had a much lower amplitude. It had returned to its former glory by the time Falter et al. (2003) observed it in 2001. Only a quick-and-dirty analysis of frequencies and amplitudes has been done, and this was mainly to investigate phase differences between each site. A full analysis will be done when all data is reduced and the timing problems are solved. Further discussion of the timing problems and possible solutions can be found in Section 4.

An example of what can be achieved with a 1200 lines/mm grating and a 3.5 m telescope has already been shown in Figure 1. Velocity variations are clearly visible with a period of $\sim 8$ minutes. These velocities will be combined with the 2 m observations once all of the data is fully reduced.

The 2 m spectroscopic observations appear to be free from timing difficulties, probably since the number of observatories used was less than for the photometry. The amplitude spectrum of all of the observations is shown in the top panel of Figure 4. The white noise level (measured at high frequencies) in this spectrum is only $\sim 230 \, \text{m s}^{-1}$. These data have been weighted by the inverse square of their velocity error. Once again the dominant frequency is at 2075.8 $\mu$Hz, with a velocity amplitude of $\sim 13.5 \, \text{km s}^{-1}$. From our preliminary frequency analysis, we have detected 17 frequencies with a S/N of 4 or better. Of
these, one frequency is $0.12 \mu Hz$ away from the 2075.8 $\mu Hz$ peak. Since this is less than the frequency resolution ($\sim 0.4 \mu Hz$), we must question its reality. There are no noticeable problems caused by the 2 week gap (which causes a splitting of $\sim 0.8 \mu Hz$). Two of the frequencies detected are combination frequencies, and if we relax our detection threshold of $S/N=4$ a little, we find a further combination frequency. Just what causes these combination frequencies is uncertain, although nonlinear effects caused by the rapid rotation of PG 1605+072 is one possibility. Four of the frequencies we have measured have not been seen before in velocity or photometry, so simulations will be required to determine whether they are real.

4. Some Problems

Some of the other problems encountered before, during and after the campaign have already been mentioned (the small amount of 4 m spectroscopy, bad weather at La Silla and Siding Spring Observatories), but the main problem has been the timing of the photometric observations. These errors create a kind of paranoia when it comes to dealing with low amplitude peaks very nearby (within $\sim 1 \mu Hz$) high amplitude ones. Which peak is due to amplitude variation, which is due to close mode spacing, and which is due to timing problems? Detailed simulations will hopefully answer these questions.

There are two possible ways to solve the timing problems, by manual iteration or by examining phases. The former method involves selecting sites with trustworthy times, systematically shifting the times of one of the affected data sets until the combination of the trustworthy data and the shifted data gives maximum amplitude. The second method consists of determining the frequencies and phases of the trustworthy data, fitting these frequencies to the affected data sets (all with common time zeropoint), comparing the phases, and then adjusting the times by the phase differences. This has been crudely done already to determine which sites had timing problems in the first place.

5. Conclusions and Future Work

There is still plenty of work to do before a proper and detailed analysis of the MSST observations can be done. Reduction of the photometry and analysis of the 4 m spectroscopy needs to be completed. The timing problems need to be investigated and then corrected for, after which combination of all photometric (MSST+WET) data can be
done. Only then, frequencies, amplitudes and phases from photometry and spectroscopy can be compared, and the identification of modes in PG 1605+072 can begin in earnest. We will call on the pulsation theorists to help explain some of our results.

We add a final comment on the feasibility of an MSST-like campaign on other pulsating sdBs. We have shown the feasibility of this kind of campaign beyond doubt for a bright sdB star with relatively long periods, but what about other targets? There are several other potential candidates for time-series spectroscopy, although they are typically fainter and/or have shorter periods. These include KPD 2109+4401, Feige 48 and PG 1219+534, which have less complicated amplitude spectra, but are still bright enough to observe, albeit with 4 m telescopes only. These stars have a lot fewer modes than PG 1605+072, but this is actually advantageous when looking for, and analysing, line profile variations. So in the future look out for MSST II!

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