MSST observations of the pulsating sdB star PG 1605+072

S. J. O'Toole (otoole@sternwarte.uni-erlangen.de), S. Falter and U. Heber

Dr Remus-Sternwarte, Astronomisches Institut der Universität Erlangen-Nürnberg, Sternwartestr. 7, Bamberg D-96049, Germany

C. S. Jeffery

Armagh Observatory, College Hül, Armagh BT61 9DG, Northern Ireland, UK

S. Dreizler and S. L. Schuh

Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, D-72076 Tübingen, Germany

Universitätssternwarte, Universität Göttingen, Geismarlandstrasse 11, D-37083 Göttingen, Germany

and the MSST+WET Teams*

Abstract. We present the first results from the MultiSite Spectroscopic Telescope (MSST) observations of the sdB star PG 1605+072. Pulsating sdB stars (also known as EC14026 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 Xc022 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 $\lambda$-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.litap.iastate.edu/xcov22/people.html

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 \( \sim 127 \) 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 \( \sim 272 \) hours of observations were obtained, giving a total of \( \sim 399 \) 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 \( \sim 7\% \) (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

---

*

*Figure 1.* Velocity curve from the Calar Alto 3.5 m with the TWIN spectrograph. Variations with a period of \( \sim 8 \) minutes are clear.
Figure 2. Coverage of the 2 m spectroscopy part of the campaign. The 2 weeks gap in the observations causes ~0.8 μHz alias peaks as well as those caused by daily gaps.

on fainter and/or lower amplitude targets. Not all of the data has been analysed, although everything has been reduced using SPES (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 successful, 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 http://astro.uni-tuebingen.de/~schuh/spes/index.html

\(^2\) available from http://iraf.noao.edu/scripts/extern/rvz.pl
Figure 3. Amplitude spectrum of MSST photometry from SAAO, SSO and the JKT. The 2075.8 μHz mode is dominant again. The inset shows the spectral window.

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 ~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 μHz. This mode had the highest amplitude in the observations of Koen et al. (1998) and Kilkenney et al. (1999), how-
ever, in the radial velocity studies of O'Toole et al. (2000, 2002) and Woelf 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 ~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 ~230 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 μHz, with a velocity amplitude of ~13.5 km s⁻¹. From our preliminary frequency analysis, we have detected 17 frequencies with a S/N of 4 or better. Of

\textit{Figure 4.} Velocity amplitude spectrum of PG 1605+072 (top); after prewhitening 5 frequencies (middle); after prewhitening by 10 frequencies (bottom).
these, one frequency is 0.12 μHz away from the 2075.8 μHz peak. Since
this is less than the frequency resolution (~0.4 μHz), we must question
its reality. There are no noticeable problems caused by the 2 week gap
(which causes a splitting of ~0.8 μHz). 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 spec-
troscopy, 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 ~1 μHz) 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 zero-point), 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 photome-
try and analysis of the 4 m spectroscopy needs to be completed. The
timing problems need to be investigated and then corrected for, af-
fter 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!

References

Heber et al., 2003, 13th European Workshop on White Dwarfs. NATO-ARW Workshop Series, p. 105
O’Toole S. J., 2003, PhD thesis, University of Sydney