PHOTOMETRIC AND SPECTROSCOPIC MONITORING OF THE SDBV STAR PG 1605+072:

The Multi-Site Spectroscopic Telescope (MSST) Project

U. HEBER[1], S. DREIZLER[2], S.L. SCHUH[2], S. O'TOOLE[1,3], C.S. JEFFERY[4] ,
S. FALTER[1], V. WOOLF[4], A. AHMAD[4], M. BILLERES[5], S. CHARPINET[6] ,
O.-M. CORDES[7], B.-Q. FOR[8], E. GREEN[8], E.A. HYDE[8], A. JACOB[3] ,
H. KJELDSEN[9], S. KLEINMAN[10], J. KRZESINSKI[10], I. LOPES[11,12] ,
S. MARINONI[13], T. MAUCH[3], A. NITTA[10], D. O'DONOGHUE[14], R. OESTENSEN[15], ,
D. POLLACCO[16], R. PEREIRA[12], T. PEREIRA[12], M.D. REED[17], R. SILVOTTI[18] AND
R. TOWNSEND[19], M. VUCKOVIC[20], B. A. WHITE[8], J. XIAOJUN[21]

[1]*Dr. Remeis-Sternwarte, Univ. Erlangen-Nürnberg, Bamberg, D*
[2]*Universität Tübingen, D,* [3]*University of Sydney, AUS*
[4]*Armagh Observatory, UK,* [5]*European Southern Observatory, Chile*
[6]*Observatoire Midi-Pyrenees, Toulouse, F*
[7]*Universität Bonn, D,* [8]*Steward Observatory, USA*
[9]*University of Aarhus, DK,* [10]*Apache Point Observatory, USA*
[11]*Oxford University, UK,* [12]*Instituto Superior Tecnico, Lisbon, P*
[13]*Bologna University, I,* [14]*SAAO, South Africa*
[15]*ING, La Palma, Spain,* [16]*Queens University Belfast, UK*
[17]*Southwest Missouri State University, USA*
[18]*Osservatorio Astronomico di Capodimonte, Naples, I*
[19]*University College London, UK,* [20]*Iowa State University, USA*
[21]*Beijing Astronomical Observatory, China*

Introduction. A small fraction of sdB stars show short-period, multi-periodic light variations and form the new class of pulsating star known as EC 14026 variables, after the prototype, or, alternately, as sdBV stars. Until recently, time-series observations of pulsating sdB stars have been limited to photometry (for a review see Charpinet et al., 2001). While emphasizing the great potential of asteroseismology with sdB variables (sdBV), Charpinet et al. also clearly demonstrate that the difficult process of mode identification, necessarily required for an asteroseismological study, is even more complicated for sdBV stars than for objects such as pulsating white dwarfs. While the latter tend to show a nearly equidistant mode pattern for consecutive overtones, no such relation is evident for sdBV stars. Consequently, observational methods beyond photometry alone are needed to further progress the interpretation of the sdBVs' pulsational behaviour.

Pulsations not only produce photometric variations but also spectroscopic variations. PG 1605+072 is the ideal target amongst the sdBV stars to search for such variations. It has the longest pulsation periods (∼500s), the largest amplitude variations (0.2 mag in the optical) and the richest frequency spectrum (> 50 modes) of all sdBVs. The long periods maximise the S/N that can be acquired within any given pulsation cycle. However, PG 1605+072 is rotating rather rapidly at $v \sin i = 39\mathrm{km\ s}^{-1}$ (Heber et al. 1999), which makes the mode identification more complicated due to significant rotational splitting. Therefore it has so far been impossible to identify the modes from optical light curves.

O'Toole et al. (2000) were the first to detect radial velocity shifts in PG 1605+072 with an amplitude of 14 km/s (at H β) from time-resolved spectroscopy at medium resolution. Time-resolved spectroscopy was subsequently carried out at higher spectral and temporal resolution in 2000 May (Woolf et al. 2002). Three pulsation periods were resolved by these authors and also by Falter et al. (2002) one year later. However, the amplitude ratios of the modes detected spectroscopically in 2000 differed from those derived photometrically in 1998. This was also found in a medium-resolution study by O'Toole et al. (2002a), using observations taken at approximately the same time as those of Woolf et al. Observations at higher spectral resolution obtained in 2001 May (Falter et al. 2002) indicate that the amplitudes are consistent with those of the 1998 photometry again. This means that there has been a switch in power between modes over the years. Falter et al. (2002) were also able to obtain multicolour photometry simultaneous with the spectroscopy for the first time, demonstrating that the pulsation amplitudes in the different passbands show a wavelength dependency and provides information on the continuum variations. Last but not least, O'Toole et al. (2002) were able to measure Balmer line equivalent width variations which increase with Balmer sequence number.

The spectroscopic observations described above all suffer from limited frequency resolution and aliasing problems associated with finite time series or single-site observations. Therefore an international collaboration has been formed to carry out observations of sufficient length to resolve the more than 50 modes of PG 1605+072 known. The campaign has become known as the Multi-Site Spectroscopic Telescope (MSST).

MSST Observations. In 2002 May and June, a coordinated series of observations of PG 1605+072 were carried out using 15 telescopes at several longitudes. Because the pulsation modes of PG 1605+072 are known to be amplitude variable, any spectroscopic campaign has to be accompanied by photometric monitoring in order to measure velocity versus light variations. Closely spaced frequencies have to be resolved which require observations of several weeks with as few time gaps as possible. A fourfold observing

strategy has been developed.
1.) Time-resolved spectroscopy at 4-m class telescopes is used to measure the radial velocity curves with the highest accuracy possible. Due to limited availability of such telescopes this could only be done for a few nights, and is insufficient to resolve all of the modes.
2.) Time-resolved spectroscopy at 2-m class telescopes is used to measure the radial velocity curves and the variations of equivalent widths for a sufficient period of time to resolve all modes.
3.) Multi-band photometry is used to measure colour (and hence continuum) variations for a few nights, again too short to resolve all modes.
4.) Broad-band photometry is used to measure light curves for a period of time sufficiently long to resolve all modes.

Table 1 gives an overview of the data obtained for the individual types of observations (since some of the data overlap, the total is smaller than the sum of the contributions). The telescopes involved are listed below.

Table 1. Overall data in 2002; ff: filling factor.

type of observations		from	to	[h]	ff
high-resolution spectroscopy	**total**	05/14	05/29	**27**	7%
medium-resolution spectroscopy	May	05/19	05/28	58	22%
	June	06/14	06/26	94	30%
photometry	**total**	05/05	06/04	**328**	44%
	WET	05/05	05/21	127	31%
	MSST	05/14	06/04	272	51%
	multi-colour	05/19	05/22	21	22%

1.) Time-resolved spectroscopy of spectral resolution ~1Å was carried out during eight nights at the following telescopes: the Calar Alto 3.5-m (Spain), the European Southern Observatory 3.5-m NTT (Chile) and the Apache Point 3.5-m (New Mexico, USA). Spectra were taken by trailing the star along the slit (Falter et al. 2002) with a time resolution of typically 30 s. The data set corresponds to about 4000 individual spectra.
2.) Time resolved spectroscopy of resolution ~3Å was carried out during 40 nights at the following telescopes, the Mount Stromlo and Siding Spring Observatory 2.3-m (Australia), the Nordic Optical 2.56-m (La Palma, Spain), the European Southern Observatory 1.5-m Danish (La Silla, Chile), and the Steward Observatory 2.3-m Bok (Arizona, USA). About 10 000 spectra have been secured.
3.) PG 1605+072 was observed in four photometric bands with the BUSCA instrument (the instrumental "U","B","R","I" passbands are used) at the Calar Alto 2.2-m telescope for three nights.
4.) A combination of BG 39 filter, B-band and white light photometry

was carried out at the following telescopes: the Mount Stromlo and Siding Spring Observatory 1-m (Australia), the Beijing Astronomical Observatory 0.85-m (China), the South African Astronomical Observatory 1-m (South Africa), the Loiano 1.5-m (Italy), the Jacobus Kapteyn 1-m (La Palma, Spain), the Fick Observatory 0.6-m (Iowa, USA) and the McDonald Observatory 2.1-m (Texas, USA). Data were acquired covering more than 272 hours. In addition, the Whole Earth Telescope observed PG 1605+072 in 2002 May for 127 hours (Schuh et al. 2002).

Summary and Conclusion. The Multi-Site Spectroscopic Telescope is a virtual instrument and is also the name of a collaboration that aims to open up a new observational window to provide access to a mode identification for and an asteroseismological analysis of the pulsating sdB star PG 1605+072. Although the primary aim is to obtain time resolved spectroscopy it also includes the most extended photometric monitoring campaign for PG 1605+072.

The data gathered during the MSST campaign constitutes a huge improvement over earlier efforts. Its usefulness however depends in exactly the same way on the availability of good models for an interpretation of the data. The time dependent surface distribution of $T_{\rm eff}$, $\log g$ and the velocity field will be determined using Townsend's (1997) program BRUCE which also takes effects caused by rotation into account. Grids of synthetic spectra calculated from LTE and NLTE model atmospheres will be used to carry out the surface integration to derive phase-dependent flux spectra with a code developed by Falter (2001). Furthermore, detailed pulsation models (Charpinet et al., 2001) are at hand for the comparison with the observational frequency pattern.

ACKNOWLEDGEMENTS. We thank the various time allocation committees who awarded such a large amount of observing time. The Whole Earth Telescope collaboration is thanked for adopting PG 1605+072 as an alternate target during XCOV22. Finally we gratefully acknowledge the support of staff at the observatories involved in the campaign.

References

Charpinet S., Fontaine G., Brassard P. 2001, PASP 113,775
Falter S. 2001, Diploma Thesis, University of Erlangen-Nürnberg
Falter S., Heber, U., Dreizler S., Schuh, S.L., Cordes O. 2002, these Proceedings
Heber, U., Reid, I.N., Werner, K. 1999, A&A 348, L25
O'Toole, S.J., Bedding, T.R., Kjeldsen, H., *et al.* 2000, *ApJ*, **537**, L53
O'Toole, S.J., Bedding, T.R., Kjeldsen, H., *et al.* 2002a, *MNRAS*, **334**, 471
O'Toole, S.J., Jørgensen M.S., Kjeldsen, H., *et al.* 2002b, *MNRAS*, submitted.
Schuh, S.L., Heber, U., Dreizler, S., *et al.*, *The 6th Whole Earth Telescope Workshop*, eds. J.-E. Solheim and E. Meištas, *Baltic Astronomy*, in press
Townsend, R. H. D., 1997, *MNRAS*, **284**, 839
Woolf, V.M., Jeffery, C.S. and Pollacco, D.L. 2002, *MNRAS*, **329**, 497