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# THE MSST CAMPAIGN: 4M SPECTROSCOPY OF PG1605+072

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**Abstract.**
The MultiSite Spectroscopic Telescope (MSST) campaign aimed to provide a detailed view of the the short-period pulsating subdwarf B star PG 1605+072. We present results from the part of the campaign undertaken on 4m telescopes in May/June 2002.

**Key words:** stars: variable: other – stars: oscillations – stars: individual (PG1605+072)

## 1. INTRODUCTION

The MultiSite Spectroscopic Telescope (MSST) campaign observed the non-radially pulsating subdwarf B star PG1605+072 in May/June 2002 (Heber et al 2003). Spectroscopic observations were obtained on a range of 2-m and 4-m class telescopes, supported by photometry from a large number of observatories, including the Whole Earth Telescope. Other papers describing the spectroscopic results from 2m telescopes (O'Toole et al. 2005) and the photometry (Schuh et al. 2003, Dreizler et al. 2006) are and will be published elsewhere.

Previous spectroscopic observations of PG 1605+072 with 4m telescopes had

**Table 1.** MSST 4m observing log.

| Date 2002 May | Obs | Start JD-2445000 | Finish | $t_{\rm exp}$ s | $N_{\rm obs}$ |
|---|---|---|---|---|---|
| 14 | APO | 409.324 | 409.446 | 3.6 | 1773 |
| 15 | APO | 410.183 | 410.331 | 4.8 | 1727 |
| 18 | APO | 413.296 | 413.329 | 4.8 | 471 |
| 22 | CA | 416.908 | 417.146 | 16.5 | 1065 |
| 23 | CA | 417.885 | 418.158 | 16.5 | 1213 |
| 29 | NTT | 424.161 | 424.359 | – | – |
| total | | | | | 10892 |

proved the feasibility and precision of a study of velocity variations (Woolf et al. 2002), compromised only by the quantity of data obtained and issues about timing. The main focus of this part of the MSST was to maximise the length and coverage of the observations in order to obtain higher resolution in both velocity and frequency, and hence to obtain material useful for identifying oscillation modes. As a consequence of the traditional traumas of observational astronomy (time allocation, instrument failure and bad weather), out of eighteen nights originally requested, 7.5 nights were awarded and 24.3 hours of time-resolved spectroscopy was obtained, of which 19.5 hours was usable. This paper introduces the observations, and presents the frequencies derived from the radial velocity measurements.

## 2. OBSERVATIONS

Time-resolved spectroscopy of spectral resolution $\sim 1$Å was carried out during six nights at the Calar Alto 3.5-m telescope (Spain), the European Southern Observatory 3.5-m New Technology Telescope (Chile) and the Apache Point Observatory 3.5m (New Mexico, USA).

At Apache Point (APO), we used the red arm of the Dual Imaging Spectrograph where it was anticipated that velocity changes would be observable in H$\alpha$. At Calar Alto 3.5m (CA) telescope, both arms of the TWIN spectrograph were used to obtain spectra simultaneously in the wavelength ranges 5785–6880Å and 3850–4950Å. At the NTT, the ESO Multi-Mode Instrument (EMMI) was used to obtain spectra in the wavelength range 6400–6700Å. However, atmospheric conditions were so poor that none of the EMMI data have proved to be usable.

In all cases, spectra were obtained by trailing the star along the slit (Falter et al., 2003) to give two-dimensional images representing wavelength dispersion in one axis and time in the other. The time resolution is given effectively by the trail-rate along the slit divided by the projected size of the stellar disk on the detector; a higher trail rate provides better time resolution, but lower S/N per resolution element. A summary of the observations is given in Table 1. The integrated sky background is estimated using regions at each end of the slit. Arc-lamp and standard-star calibration images were obtained in order to provide wavelength calibrations and geometric correction.

The data reduction methods have been described by Falter et al. (2003). With the image trailed along the slit at a uniform rate, each two-dimensional image has to be reduced to a series of discrete spectra, with each one accurately time-stamped. The choice of extraction interval is made at this stage to optimise

**Table 2.** MSST 4m frequencies and amplitudes.

| $F_{\rm b}$ mHz | $V_{\rm b}$ km s$^{-1}$ | P S | $F_{\rm r}$ mHz | $V_{\rm r}$ km s$^{-1}$ | $F_{\rm 2m}$ mHz | $V_{\rm 2m}$ km s$^{-1}$ |
|---|---|---|---|---|---|---|
| 1.705 | 6.0 | 586 | | | | |
| 1.756 | 5.4 | 569 | 1.767 | 8.5 | | |
| 1.867 | 7.2 | 536 | 1.867 | 6.5 | 1.891 | 2.3 |
| 2.095 | 5.4 | 477 | | | 2.076 | 15.4 |

both the signal to noise ratio in individual spectra and the sampling rate. The reduced data products consist of a two-dimensional FITS file containing a series of wavelength calibrated time-tagged spectra for each long-slit trailed spectrum.

Spectra were read directly from the reduced FITS files and resampled onto a logarithmic wavelength scale. Velocities were determined by cross-correlating each spectrum with a template created by summing all spectra from a given series. Problems with the wavelength calibrations, evident from substantial offsets for individual frames, were corrected by demanding the mean velocity for each frame to be 0 km s$^{-1}$.

## 3. FREQUENCY ANALYSIS

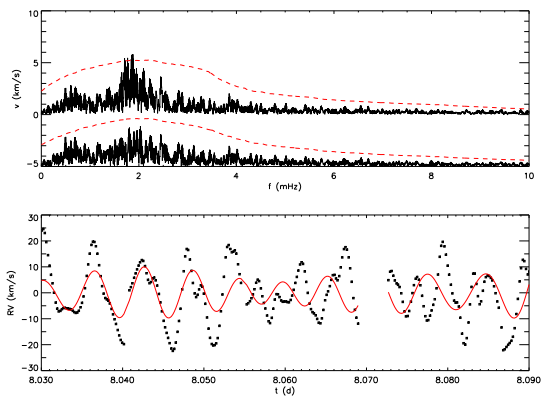


**Fig. 1.** Best solution for the CA blue spectroscopy. Top: the velocity amplitude spectrum (v) before (above) and after (below) subtraction of the four highest peaks. The dashed line shows the $4\sigma$ level in each case. Bottom: part of the radial velocity curve with the best four-frequency solution (solid) from Table 2. Times are in JD–2452410.

Velocity amplitude spectra for each dataset (CA blue, CA red, APO red and APO+CA red) were calculated using a simple Fourier transform. The limited overall coverage restricts the frequency information that can be extracted. All datasets show an excess of power in the range 1.5 – 2.5 mHz. Despite apparent similarities in the velocity curves, the amplitude spectra obtained from each arm of the TWIN spectrograph differ considerably from one another. A careful comparison was carried out to look for systematic correlations.

We have formally analyzed only the two CA datasets, which have a formal temporal resolution ($2/T$) of 18 mHz. A detection threshold was defined by a local $\sigma$. Any peak above $4\sigma$ was deemed real, a sinusoid was fitted and its frequency and amplitude recorded. The data was prewhitened by the fit and the procedure repeated until no peaks exceeded the $4\sigma$ level. The solutions are given in Table 2 for the blue ($F_{\rm b}$) and red ($F_{\rm r}$) arms, and also compared to the MSST 2m ($F_{\rm 2m}$) results.

These solutions are unsatisfactory. As we know from the 2m data, there are unresolved frequencies present which suggests that substantial errors should be attached to the amplitudes given in Table 1. It is interesting that neither signal at 1.71 and 1.76 mHz was detected in the MSST 2m campaign (O'Toole et al., 2005). Given the frequency resolution of our data, the signal at 1.76 mHz probably coincides with one at 1.744 mHz in the light curve of Kilkenny et al. (1999). It is also interesting that the signal at 2.076 mHz detected in the 2m campaign (O'Toole et al., 2005) has a much lower amplitude in the CA data. It may correspond with the 2.095 mHz identified here, but the referee's guess is that the latter may more properly correspond with the 2.101 and 2.102mHz peaks seen in the 2m data, or with some combination of all three. The weakness or absence of the 2.076 mHz peak in the CA data is significant because the 2m data extends for 1 week before and 5 weeks after the CA data.

O'Toole et al. (2005) note that this peak had a much reduced amplitude in early velocity studies (O'Toole et al., 2003; Woolf et al., 2002; O'Toole et al., 2002) compared with contemporary photometric studies (Kilkenny et al., 1999; Koen et al., 1998), but a larger velocity amplitude in the study by Falter et al. (2003). Such a variable amplitude may be intrinsic to the star or due to beating between two or more closely spaced frequencies. It is evident that a time-dependent study of the velocity amplitude of the 2.076 mHz peak in the 2m data will be instructive.

In conclusion, MSST 4m data provide a high-time and spectral resolution snapshot of the radial-velocity behaviour of PG1605+072 over short intervals during the more extended 2m campaign. Further analysis of the combined data from 2m, 4m and photometry campaigns will examine evidence of short-term variability in the frequency spectrum.

## REFERENCES

Dreizler, S., Schuh, S., Heber, U, et al. 2006, in prep.

Falter, S., Heber, U., Dreizler, S., et al. 2003, A&A, 401, 289

Heber, U., Dreizler, S., Schuh, S. L., et al. 2003, in *13th European Workshop on White Dwarfs*, eds. D. de Martino, R. Silvotti, J.-E. Solheim, & R. Kalytis (Kluwer), 105

Heber, U., Reid, I.N., & Werner, K. 1999, A&A, 348, L25

Heber, U., Napiwotski, R., & Reid, I.N. 1997, A&A, 323, 819

Jeffery C.S., Woolf V.M., & Pollacco D.L. 2001, A&A 376, 497

Kawaler, S.D. 1999, in *11th. European Workshop on White Dwarfs*, eds. J.-E. Solheim & E.G. Meistas, ASP Conf. Ser., 169, 158

Kilkenny, D., Koen, C., O'Donoghue, D., et al. 1999, MNRAS, 303, 525

Koen, C., O'Donoghue, D., Kilkenny, D., et al. 1998, MNRAS, 296, 317

Montañès Rodrìguez P., & Jeffery C.S. 2001, A&A, 375, 411

O'Toole, S.J., Bedding, T.R., Kjeldsen, H., Dall, T., & Stello, D. 2002, MNRAS, 334, 471

O'Toole, S.J., Jorgensen, M.A.S.G., Kjeldsen, H., et al. 2003, MNRAS, 340, 856

O'Toole, S.J., Heber, U., Jeffery, C.S., et al. 2005, A&A 440, 667

Schuh, S. L., Heber, U., Dreizler, S., et al. 2003, Baltic Astronomy, 12, 55

Woolf, V.M., Jeffery, C.S., & Pollacco, D.L. 2002a, MNRAS, 329, 497