

Multi-wavelength photometric variation of PG 1605+072

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Abstract

In a large coordinated attempt to further our understanding of the p-mode pulsating sdB star PG 1605+072, the Multi-Site Spectroscopic Telescope (MSST) collaboration has obtained simultaneous time-resolved spectroscopic and photometric observations. The photometry was extended by additional WET data which increased the time base. This contribution outlines the analysis of the MSST photometric light curve, including the four-colour BUSCA data from which chromatic amplitudes have been derived, as well as supplementary FUV spectra and light curves from two different epochs. These results have the potential to complement the interpretation of the published spectroscopic information.

Individual Objects: PG 1605+072

Multi-Site Spectroscopic Telescope for PG 1605+072

Introduction and MSST overview

PG 1605+072 is a pulsating subdwarf B star evolving off the EHB. Observationally, it may be considered a sibling among sdBs of the even brighter star Balloon 090100001; both stars are multiperiodic and pulsate each with the largest amplitude among the sdBs of $\approx 6\%$ in the strongest mode. Just as more recently for Balloon 090100001, the rich frequency spectrum has triggered extended photometric monitoring campaigns in the optical as well as the gathering of time-resolved colour and spectral information. The resulting literature that has been published, from the initial discoveries and campaigns all the way to the work in progress on analysing the repeated coordinated observational efforts, is too numerous to be cited comprehensively in this context.

The Multi-Site Spectroscopic Telescope (MSST) project in particular combined the following observational ingredients in order to simultaneously sample PG 1605+072's intensity and radial velocity variations: white light and multicolour light curves; low-resolution time-resolved spectroscopy (O'Toole et al. 2005, Tillich et al. 2007); and high-resolution time-resolved spectroscopy.

This report primarily makes mention of the photometric analysis, and furthermore discusses PG 1605+072 as observed with FUSE: light curves, radial velocities, and especially chromatic amplitudes as presented by Stahn (2005) and Lutz (2007).

In the spirit of this workshop, the focus is on the variety of data sets available and how to treat and potentially combine this data. For published results (in numbers) the relevant work is referenced; here we note that the immediate aim of MSST is mode identification (*l*) to complement future asteroseismic modelling. The changing power in the pulsation spectrum of PG 1605+072 may make this difficult, but may also hold clues to the details of the driving mechanism. The long-term motivation remains the clarification of the evolutionary status and origin of PG 1605+072 as one representative of the subdwarf B stars.

MSST and WET optical light curve, Fourier transforms and frequency fitting

The optical light curve consists of a total of 96 individual data sets, combining white light data from the MSST photometry and the WET Xcov22 campaign. The frequency solution for the white light curve has been obtained in an iterative manner. First of all, overlapping data sets were cross-correlated to check the timing and quality. On a trusted subset of the data obtained by bootstrapping from the overlapping data sets, first a four-, later an eleven-frequency model was constructed. The initial model was cross-correlated with all observations to uncover and correct for remaining timing errors, improved using the provisionally corrected full data set, and the procedure repeated with the second, more complex model. Finally, a 55-frequency model was fitted to the corrected data, using a non-linear least squares sine fit as in the steps before.

The final light curve documents this procedure by providing, for each data point, the time as raw truncated Julian Date, followed by the value of the barycentric correction, the time in BJD, the value of the corrections derived from the cross correlation, and finally the corrected time in BJD. This is followed by the modulation intensity with a mean value of zero, and an observation ID unique to each of the 96 data sets.

Chromatic amplitudes

MSST: BUSCA multicolour light curve

Tremblay et al. (2006) have compiled and analysed the optical multicolour photometry available for pulsating sdB stars at the time. This included the measurements by Falter et al. (2003) obtained in 2001 for PG 1605+072. Figure 1 shows the five nights of multicolour photometry obtained in 2002 with the BUSCA instrument at the Calar Alto 2.2m telescope. To construct the overplotted model, the BUSCA colours were first collapsed into one "white" light curve, which was fitted with a reduced set of frequencies from the simultaneous, more extended white light MSST photometry. The reduction of the number of frequencies was done by merging close frequencies, not resolved in the BUSCA data subset, assuming they belong to the same *l*. This may not be correct; if so, the chromatic amplitudes derived for these merged frequencies will be meaningless. Chromatic amplitudes were obtained by fixing the 30 frequencies fitted to the BUSCA "white" light curve and re-determining amplitudes and phases on the individual *uv*, *b*, *r*, and *nir* light curves. The result for the twelve strongest frequencies is shown in Fig. 2. In a plot where the chromatic amplitudes are normalised to the *uv* amplitude (not shown), the curves roughly fall into three groups with different slopes, indicative of the expected grouping according to common *l* values.

FUSE far-UV light curve

As shown by Fontaine & Chayer (2006), far-UV light curves for PG 1605+072 may be obtained by collapsing FUSE spectra extracted in bins from time-tagged data producing a time series.

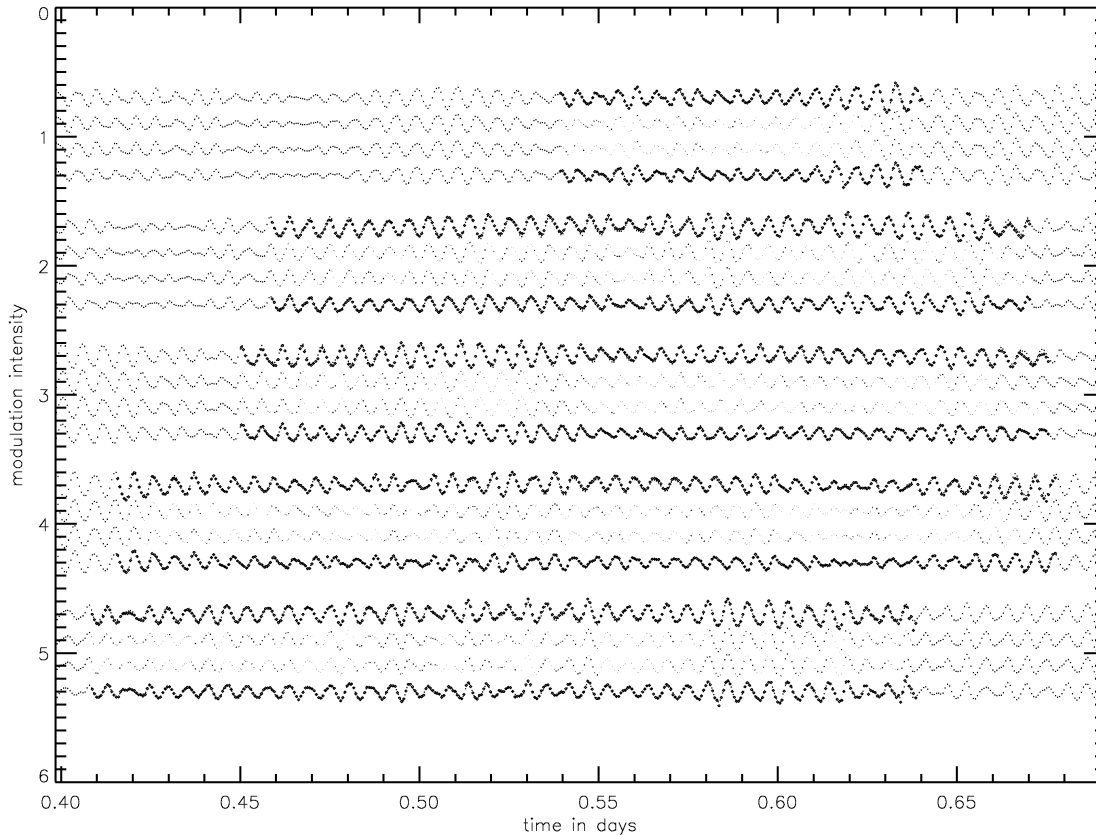


Figure 1: Five nights of multicolour photometry obtained in (2002) with the BUSCA instrument attached to the Calar Alto 2.2m telescope. The data points in the top four curves correspond (in descending order) to the unfiltered *uv*, *b*, *r*, *nir* light curves of May 14, followed by the data sets corresponding to May 18, 19, 20, and 21. A continuous model light curve containing 30 frequencies is overplotted.

If the collapsing process is applied to a subset of wavelength bins, chromatic amplitudes for the far-UV spectral range can be determined from the resulting individual intensity time series. This has been done by Stahn (2005) for the 07/2001 data (see also Lutz (2007) for the 04/2004 data). Again, a smaller subset of merged frequencies was used when deriving the chromatic amplitudes, with close frequencies not resolved in the FUSE Fourier spectrum merged together. The observed wavelength dependency of the pulsation amplitudes was compared to model predictions, but did not allow a reliable mode identification.

Radial velocities and spectroscopic parameters

FUSE radial velocities

The time series of uncollapsed FUSE spectra can be subjected to a cross-correlation analysis which yields pulsational radial velocities. The 07/2001 radial velocity curve has been analysed by Stahn (2005) in a similar way to the analysis done on the FUV intensity. In a direct comparison of the full curves, Stahn (2005) finds that the light to radial velocity phase shift amounts to $\pi/3$, a result which differs from that published by Kuassivi et al. (2005) who find $\pi/2$. When the comparison is done for individual frequencies, Stahn (2005) notices that the $\pi/3$ phase shift basically reflects the value corresponding to the strongest frequency, and derives differing values for two further frequencies. These results are indicative of a non-adiabatic pulsational behaviour of PG 1605+072.

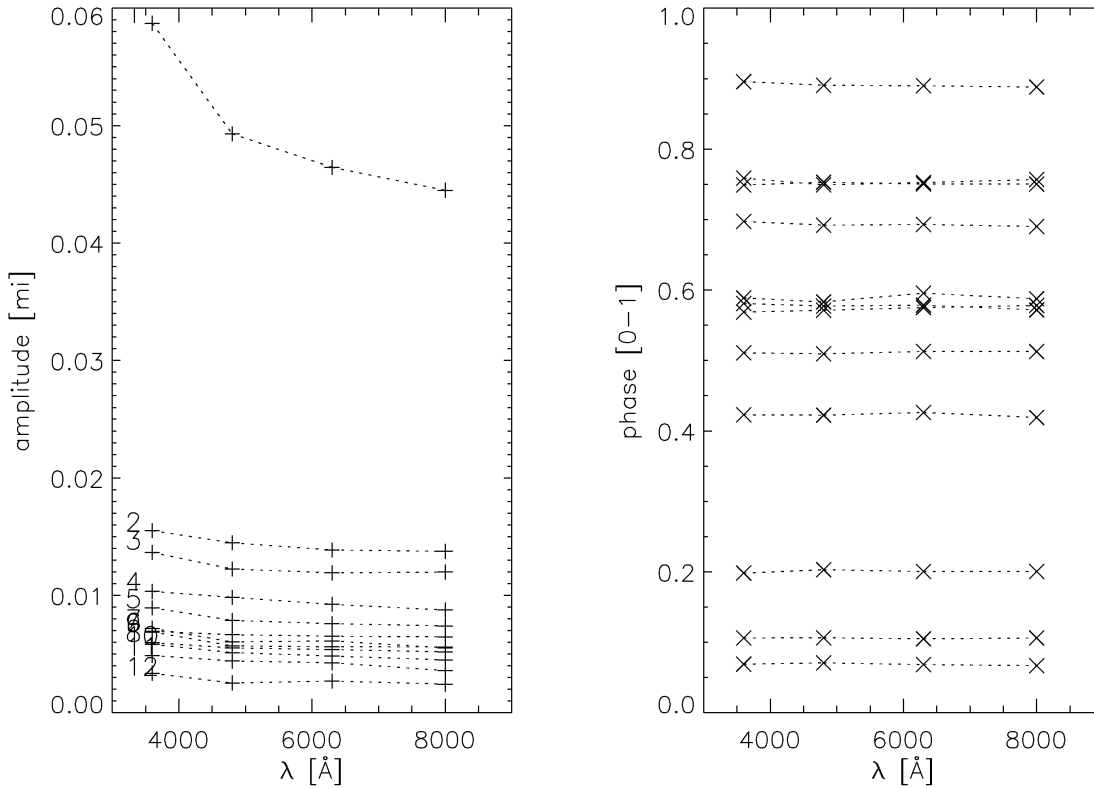


Figure 2: *Left panel:* Chromatic amplitudes derived from the 2002 BUSCA data shown in Fig. 1 for the twelve strongest frequencies in the model light curves. The error bars correspond roughly to the symbol size; beyond the 12th strongest frequency, error bars are larger than the measurable slope. *Right panel:* A quality check of the fit is obtained by inspecting the stability of the phase (free parameter; arbitrary zero point).

Optical radial velocities and spectroscopic parameters

O'Toole et al. (2005) derived the radial velocity variation from MSST low-resolution spectra. These results were used by Tillich et al. (2007) to produce RV-corrected, phase-resolved summed spectra for the strongest pulsation frequencies from the same optical spectroscopy. From these the variation in effective temperature and surface gravity corresponding to the individual pulsations could be determined. Phase relations were obtained for the photospheric parameters radial velocity versus $\log g$ and radial velocity versus temperature variation. As expected from geometrical considerations, the radial velocity versus $\log g$ variation results in a shift of $\pi/2$. The shift in radial velocity versus temperature variation of $\pi/3$ is fully consistent with the FUSE results if the intensity variation is assumed to be primarily due to changes in the effective temperature. Again, this points to the presence of non-adiabatic pulsational behaviour.

Challenges

To fully exploit the available observations briefly presented above, the following exercises remain to be carried out on the data. First, an in-depth analysis of the white light curve should be able to discriminate from the behaviour of phases if either genuine amplitude variations or instead unresolved modes are seen. This will also be of relevance for justifying the merging of frequencies when determining chromatic amplitudes; here the 2002 BUSCA

optical chromatic amplitude results need still to be compared to Falter et al. (2003) (2001 data). The same argument holds for the analysis of the short FUSE data sets that do not fully resolve the pulsation spectrum; some improvement can be expected when adding in the second (2004) FUSE data set. The challenge will then be to bring together the non-simultaneous optical and FUV chromatic amplitudes; the latter can in principle provide a very significant lever.

The next interesting step will be to bring together the optical light curves and the spectroscopy: will the same phase lags as found in the FUV, and similarly indicated by the variation in the spectroscopic parameters, be directly evident there? It also remains to be seen if the overall line profile variations will be matched by modelling attempts. Finally, it will be interesting to find out if the mode identification with these methods continues to remain a fundamental challenge despite the encouraging intermediate results.

References

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