Asteroseismology of Przybylski’s Star with HARPS

David Mkrtichian\textsuperscript{1,2}, Artie Hatzes\textsuperscript{3}, and Hideyuki Saio\textsuperscript{4}

\textsuperscript{1} ARCSEC, Sejong University, Seoul, South Korea
\textsuperscript{2} Astronomical Observatory, Odessa National University, Odessa, Ukraine
\textsuperscript{3} Thüringer Landessternwarte Tautenburg, Germany
\textsuperscript{4} Tohoku University, Japan

E-mail: davidm@sejong.ac.kr, artie@tls-tautenburg.de, saio@astr.tohoku.ac.jp

Abstract.
We present the detection of a rich $\ell=0-2$ p-mode oscillation spectrum in the most chemically-peculiar roAp star HD 101065 (Przybylski’s star). Constructed echelle-diagrams exhibit both large ($\Delta \nu = 64.07$ $\mu$Hz) and small (5-7 $\mu$Hz) frequency spacings. We have calculated the nonadiabatic frequencies of axisymmetric high-order p-modes using main sequence models with dipole magnetic fields and masses ranging from 1.5 to 1.7 $M_\odot$. Two sets of chemical composition (X,Z)= (0.7, 0.02) and (0.695, 0.025) were adopted. We find the model with Z=0.02, log $T_{\text{eff}}$= 3.8150, log $L/L_\odot$= 0.7710, M= 1.50 $M_\odot$, Age= 1.6 $10^9$yr, B$_p$= 9.00 kG fits the observed oscillation spectrum very well. Further progress in improving the asteroseismic modelling of Przybylski’s star requires increasing the accuracy of determination of oscillation spectrum with mode spacings less than 1 $\mu$Hz.

1. Introduction
The star HD 101065 was discovered by Przybylski [1] as an extremely chemically peculiar star with a strong spectral lines of rare-earth elements. The first magnetic field measurements by [2] show a longitudinal magnetic field in the range of $H_z = -2100$ to $-2500 \pm 450$ Gauss which firmly established the magnetic nature of this Ap star. In earlier investigations, [3] found the spectral lines of 51 chemical elements. [4] extended the abundance determination for 54 elements and confirmed the extraordinary +4–5 dex chemical overabundances of lanthanides. Recent investigations show the presence of lines of Tc, the short-lived (half-lifetime $t=17.7$ years) element Pm, and other radioactive elements ([4], [5], [6]) in the spectrum of HD 101065. Diffusion theory cannot be invoked to explain these short-lived radioactive species. This has possible implications for the understanding of the origin and evolution of chemical elements. The nature of the strong abundance anomalies in Ap stars and in particular HD 101065 as the key star from this class, is one of the great unsolved problems of stellar astrophysics. In spite of 44 years-long history of investigations, more than half of spectral lines in the spectrum are not identified and the extraordinary chemical anomalies of Przybylski’s star remain unexplained.

The rapid oscillations of HD 101065 were found by [6] and it become a prototype star of a new class of high-overtone rapidly-oscillating Ap (roAp) stars exhibiting non-radial acoustic oscillations aligned with magnetic axis (oblique pulsator). Spectroscopic studies using precise stellar radial velocity (RV) measurements have yielded important new clues as to the nature of the oscillations in roAp stars. [7] established conclusively the presence of a standing wave with a radial node and running wave in the roAp 33 Lib and gave a prescription for the study of vertical
chemical inhomogeneities in roAp stars with the aid of a new technique of multi-mode acoustic tomography. This technique used the multi-mode acoustic phase and amplitude cross-sections of the atmosphere as a function of geometric depth. This technique exploits the fact that for a vertical wave in the stellar atmosphere there should be a one-to-one mapping between the pulsation phase and amplitude of a mode and the atmospheric geometric depth. The traditional correspondence (for normal atmospheres) between line strength and optical depth may not hold for roAp stars due to strong vertical stratification of elements. In roAp stars the pulsation phase (and amplitude) is thus the only true link between a spectral line and its depth of formation. Increasing of the accuracy of the measured pulsation phase and hence the geometrical depth determination for line-forming layers in atmosphere we can, in turn, find the accurate profile of the chemical stratifications and physical model of atmosphere.

In this paper we present the first step in the application of such a state-of-the-art technique to HD 101065 that is aimed at finding an accurate acoustic oscillation spectrum using the precise radial velocities taken with the HARPS spectrograph.

2. The precise radial velocities
Spectroscopic observations of HD 101065 aimed at detecting and identifying the low amplitude p-mode oscillations were obtained on the nights 3–6 March 2004 at the European Southern Observatory (ESO) under program 072.D-0286 using the HARPS echelle-spectrometer of the 3.6-m telescope. The instrument provides a resolving power $R(=\lambda/\Delta\lambda) = 110,000$ with a wavelength coverage of 4700–7400 Å. Exposure times were typically 60 secs with a readout time of about 30 secs. The stellar radial velocity (RV) measurements presented here were obtained for all spectral lines in the wavelength ranges $\lambda$4700–5000 Å and $\lambda$6300–7400 Å. These RVs were more accurate than that was based the spectral lines in the iodine absorption cell spectral range 5000–6300 Å initially presented by [8] due the denser number of spectral lines in the blue regions of the spectrum. The typical accuracy of a new individual measurements was 3-4 m/s.

3. Oscillation spectrum of Przybylski's star
The most detailed photometric investigation of oscillation spectrum of HD 101065 using the data spanning 10 years were reported by [9] who found three oscillation frequencies: the principal
The schematic of oscillation spectrum of HD 101065. The large and small spacings in the oscillation spectrum are well visible.

mode $\nu_1 = 1.37289$ mHz (with first harmonic at $2\nu_1 = 2.74567$ mHz), $\nu_2 = 1.36963$ mHz and $\nu_3 = 1.31507$ mHz.

The time series analysis of our new RV data was performed using discrete Fourier transforms (DFT). The least-square fitting of a signal and the “classical” consecutive pre-whitening procedure was employed. Through this sequential pre-whitening procedure we established 26 periodic signals in the data ranging from 217 m/s to 1.6 m/s. Among these 16 belong to a modal spectrum while the remaining signals are the first and second harmonics of oscillation modes. In the course of such a analysis we found two $11.574 \pm 0.91 \mu$Hz (1 c/d) mismatches among 16 frequencies corresponding to oscillation modes and two mismatches for the high-frequency harmonics of a real signal.

The schematic of RV oscillation spectrum for HD 101065 is shown in Figure 1. One can clearly see a regular frequency spacing in spectrum the low-degree modes. We find a $64.07 \pm 0.91 \mu$Hz spacing for consecutive overtones and $\approx 5$-$7 \mu$Hz for the small spacing. The presence of both the large and small frequency spacings in HD 101065 oscillation spectrum is a signature of excitation of consecutive overtones over the range of low degree p-modes.

4. The oscillation spectrum modelling and asteroseismology

Figure 2 shows the echelle diagram where the observed frequencies are plotted by solid points modular the large spacing. The frequency spacings and in particular the small separation in roAp stars are very sensitive to global magnetic field strength [10]. That permits us to determine asteroseismically the basic stellar parameters including the global magnetic field by direct modelling of theoretical oscillation spectrum and comparison with observations.

We have calculated nonadiabatic frequencies of axisymmetric high order p-modes under dipole magnetic fields as described by [10]. The main-sequence evolution models for masses ranging from $1.5M_\odot$ to $1.7M_\odot$ with an increment of 0.05$M_\odot$ were used. Two set of chemical compositions, $(X,Z) = (0.7, 0.02)$ and $(0.695, 0.025)$ are adopted, where X and Z stand for the mass fractions of hydrogen and heavy elements, respectively. The effective temperature (and luminosity) that gives frequencies most consistent with the observed ones was obtained by interpolating between two models on the evolutionary track of a given mass. The goodness of a model is judged by the mean deviation between the observed and model frequencies, in which we have used the logarithmic values of amplitudes (m/sec) as weight.

The best fit model with parameters $Z=0.02$, $\log T_{\text{eff}} = 3.815$, $\log L/L_\odot = 0.771$, $M = 1.50 M_\odot$,
Figure 3. Echelle-diagram of p-mode oscillation spectrum of HD101065 (dots) and of best fit theoretical model of $M = 1.50 \, M_\odot$, $\log T_{\text{eff}} = 3.8151$, $\log L/L_\odot = 0.7709$, Age$ = 1.6 \times 10^9 \, \text{yr}$, $B_p = 9.0 \, \text{kG}$ and the chemical composition $(X, Z) = (0.7, 0.02)$ (open symbols).

Age$ = 1.6 \times 10^9 \, \text{yr}$, $B_p = 9.0 \, \text{kG}$ showing the mean deviation of observed and theoretical frequencies $= 1.31 \, (\mu\text{Hz})$. The echelle diagram in Figure 2 shows the theoretical frequencies (open symbols) of this best fit model for HD 101065. It is remarkable that most of the theoretical frequencies for $l_m \leq 2$ in the observed frequency range correspond to observed frequencies.

The 9.0 kG polar magnetic field of HD 101065 together with the the most recent (2 March 2003) determination of the longitudinal magnetic field of $-1004 \pm 75 \, \text{G}$ [11] yielded $70.1 \pm 1.6^\circ$ as the aspect angle of the negative magnetic pole.

5. Conclusions
We detected a rich acoustic p-mode spectrum in HD101065 and found an accurate value for the general spacing between consecutive overtones of modes, $\Delta \nu = 64.07 \, \mu\text{Hz}$. For the first time for a roAp star we find a “small” spacing of modes that we interpret as the excitation of the complete spectrum of $l = 0$-2 modes. The asteroseismic tuning of the frequencies of the theoretical models to observed ones yielded the best fit model of an age $= 1.6 \times 10^9 \, \text{yr}$, mass $M = 1.50 \, M_\odot$, luminosity, $\log L/L_\odot = 0.771$, and magnetic field strength, $B_p = 9.00 \, \text{kG}$. This is one of the first asteroseismic determination of stellar model and magnetic field in a roAp star.

Acknowledgments
DM acknowledges his work as part of research activities of the Astrophysical Research Center of the Structure and Evolution of the Cosmos (ARCSEC) which is supported by the Korean Science and Engineering Foundation. APH acknowledges the support of grant 500W0204 from the Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR).
References

[1] Przybylski A. 1961 Nature 11 59
[2] Wolff S C, Hagen W. 1976 PASP 88 119
[3] Wegner G, Petford A D 1974 MNRAS 168 557
[4] Cowley C R, Ryabchikova T, Kupka F et al, 2000 MNRAS 317 299
[5] Gopka V F, Yushchenko A V, Shavrina A V et al 2004, in The A-Star Puzzle IAU Symp. 224, ed. Zverko J., Ziznovsky J, Adelman S J and Weiss W W, 734
[6] Kurtz D W 1978 IBVS 1436 1
[7] Mkrtichian D E, Hatzes A P, Kanaan A. 2003 MNRAS 345 781
[8] Mkrtichian D E, Hatzes A P 2005 JApA 26 185
[9] Martinez P, Kurtz D W, 1990 MNRAS 242 636
[10] Saio H, 2005, MNRAS 360 1022
[11] Hubrig S, Kurtz D W, Bangulo S et al 2004 A&A 415 661