Title: Investigating the Structure of the Largest Pulsating Crystallized White Dwarf WD J004917.14-252556.8

PI: Kaylah B. McGowan
Instrument: Gemini South (GMOS)
PI institution: Vanderbilt University
PI e-mail: kaylah.b.mcgowan@vanderbilt.edu
Co-Investigators: Jessie Runnoe, Vanderbilt University— jessie.c.runnoe@vanderbilt.edu

Abstract

This proposal presents a comprehensive observational study utilizing (GMOS) Gemini South time-series photometry of WD J004917.14-252556.81, an ultramassive DA white dwarf displaying significant variability at two frequencies. This white dwarf, J0049-2525, stands as the most massive known pulsating white dwarf to date, estimated at M* = 1.31 Msun (for a CO core) or 1.26 Msun (for an ONe core) Kilic et al. (2023). Remarkably, lacking indicators of binary mergers, magnetism, high tangential velocity, or rapid rotation, this star is likely a product of single-star evolution, possibly harboring an ONe core. The interior of this white dwarf, identified as over $\gtrsim$ 99 percent crystallized based on evolutionary models, poses a unique opportunity for asteroseismology to delve into its structural properties Kilic et al. (2023). However, due to the limited detection of pulsation modes, robust seismic solutions remain challenging. To address this, we aim to conduct extensive follow-up high precision time-series photometry, targeting this extraordinary star. This prolonged observational campaign holds the potential to unveil a substantial number of additional pulsation modes, crucial in overcoming uncertainties in asteroseismic fits. Exploring the interior of this $\approx$ 1.3 Msun crystallized white dwarf, will provide insights into its structural composition and evolution. This proposal requests GMOS time to observe this white dwarf for a multi-day period.

Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

The discovery of WD J004917.14-252556.8, the largest known pulsating white dwarf, has opened a compelling avenue for scientific exploration. Our proposed investigation aims to leverage Gemini time-series photometry over consecutive days to validate and comprehend the pulsar timing of this celestial object. Previous investigations show the presence of multi-periodic variability that requires further study to quantize. Through a systematic collection of extensive follow-up time-series photometric data on this exceptional target, we anticipate uncovering a considerable array of additional pulsation modes. These newfound modes hold the promise to address the existing challenges posed by degeneracies in asteroseismic fits, allowing for a more precise understanding of the internal structure of a 1.3 solar mass crystallized white dwarf. This unique target has a crystallized fraction that is expected to be 99%. By probing the interior of this unique stellar remnant, our study aims to offer invaluable insights into the fundamental mechanisms governing the evolution and behavior of ultramassive DA white dwarfs.

(Rowan et al., 2019) and (Vincent et al., 2020) have identified three additional potential pulsating white dwarf candidates, each with a mass exceeding 1.05 solar masses. However, these candidates lack follow-up spectroscopic analysis in existing literature, displaying variations at singular dominant periods of 330, 357, and 809 seconds, respectively. This observed behavior aligns with the known photometric variations exhibited by rapidly rotating white dwarfs (as noted by (Pshirkov et al., 2020) and (Caiazzo et al., 2021)), potentially mimicking ZZ Ceti white dwarfs (as suggested by (Kilic et al., 2021)). To conclusively ascertain whether these three targets are indeed DA white dwarfs demonstrating multi-periodic photometric variations due to pulsations, further spectroscopic analysis and time-series photometry are imperative.

Understanding the evolutionary pathways of stars is crucial. Most stars evolving in isolation culminate as CO core white dwarfs ((Fontaine et al., 2001)). However, mass transfer within binary systems can alter a star's evolution, resulting in the formation of low-mass white dwarfs featuring helium cores and masses below approximately 0.45 solar masses. Conversely, stars with off-center carbon ignition in a degenerate CO core exceeding 1.06 solar masses should lead to the creation of ONe core white dwarfs ((Murai et al., 1968)). Nonetheless, binary mergers may also yield CO core white dwarfs within the same mass range (as discussed by (Althaus et al., 2021), albeit contested by Schwab (2021)). Unfortunately, observational constraints regarding the core composition of white dwarfs remain incredibly challenging.

Astroseismology

A comprehensive study incorporating spectroscopic analysis and detailed time-series photometry is vital to confirm the nature of these potential pulsating white dwarf candidates and shed light on the diverse evolutionary pathways leading to the formation of white dwarfs with varied core compositions and masses.The study of asteroseismology presents an unparalleled opportunity to delve into the internal structure of massive, crystallized white dwarfs. This exploration, however, hinges on detecting a substantial number of g-modes with consecutive radial orders. The variations in periods and their spacings are contingent upon factors like mass, effective temperature, hydrogen envelope mass, and the proportion of crystallized mass. In the case of J0049-2525, previous observations from APO and Gemini have revealed only two prominent modes, rendering the identification of a singular seismic solution impossible. Consequently, there are several plausible solutions that align with the observed characteristics of this star. To resolve the ambiguities in the asteroseismic interpretations, it's imperative to detect a significant number of additional pulsation modes.

To achieve this, we advocate for extensive follow-up time-series photometry campaigns specifically targeting this unique celestial target. The acquisition of a more comprehensive dataset, featuring a diverse array of pulsation modes, holds the key to overcoming the degeneracies encountered in the asteroseismic fits. This concerted effort will not only enable a more refined understanding of the internal structure of J0049-2525 but also pave the way for breakthroughs in our comprehension of massive, crystallized white dwarfs through the lens of asteroseismology.

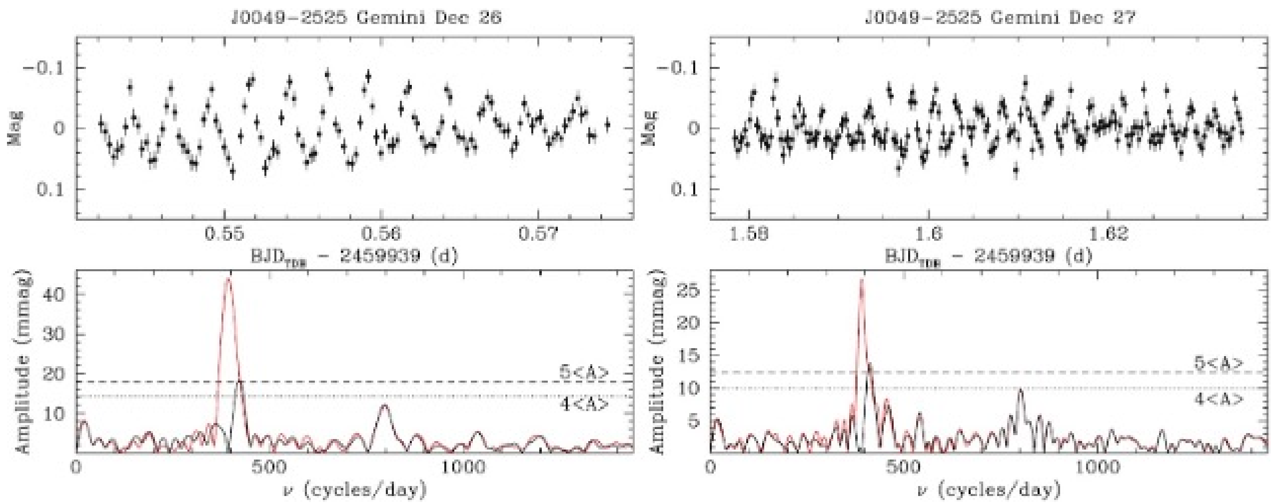

Figure 1: Gemini time-series photometry of J0049-2525 obtained over two consecutive nights.The panels and labels are the same as in Figure 2. The observations span 47 (left) and 81 min (right), respectively.Mon Not R Astron Soc, Volume 522, Issue 2, June 2023, Pages 2181-2187, https://doi.org/10.1093/mnras/stad1113

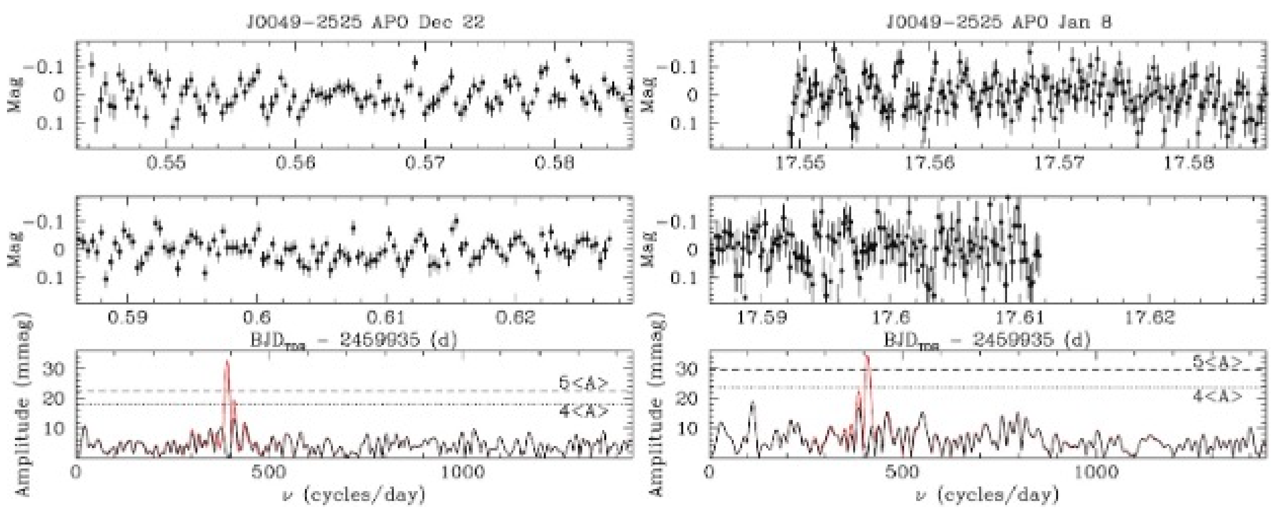

Figure 2: APO time-series photometry of J0049-2525 on two separate nights (top panels). The bottom panels show the Fourier transform of each light curve before (red) and after (black) pre-whitening of the dominant frequency. The dotted and dashed lines mark the 4 and 5¡A¿ level, where ¡A¿ is the average amplitude in the Fourier transform. Mon Not R Astron Soc, Volume 522, Issue 2, June 2023, Pages 2181-2187, https://doi.org/10.1093/mnras/stad1113

Experimental Design *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification?*

The proposed target has been selected because a) its the most massive known pulsating white dwarf to date, estimated at M* = 1.31 Msun (for a CO core) or 1.26 Msun (for an ONe core) Kilic et al. (2023), b) ultramassive DA white dwarf displaying significant variability at two frequencies c) the interior of this white dwarf is estimated to be $\gtrsim$ 99 percent crystallized based on evolutionary models. Fig 4 presents the physical parameters of WD J004917.14252556.81, which is a DA white dwarf with Teff = 13020 ± 460K and log g = 9.341 ± 0.036.

Fig. 1 shows the Gemini light curves of J0049-2525 from UT 2022 December 26 and 27 along with their Fourier transforms. The data quality is significantly better than APO, even though Gemini observations have a shorter baseline these light curves show peak-to-peak variations that vary over time. Fig. 2 demonstrates the shortcomings of APO observations which fall short of capturing the full multiperiodic photometric.

Gemini's large aperture size allows for high precision photometry, necessary for minute variability measurements, with high S/N. As detailed in the Technical Justification section, exposure times have been calculated to achieve a S/N ratios 100 for the target. Observations will be conducted with SDSS-g filter as done in previous observations. Fig 1. shows the need for high precision measurements with magnitude variations on the order of 0.1 with an uncertainty factor of 0.1 for each exposure. These multi-day measurements will provide precise variability measurements that are necessary to find additional g modes, provided that a sufficient number of g modes with consecutive radial order are detected. Enhancing the accuracy of these astroseismic models will provide crucial insight on the unique crystalline interior structure of J0049-2525 and single star stellar evolution models.

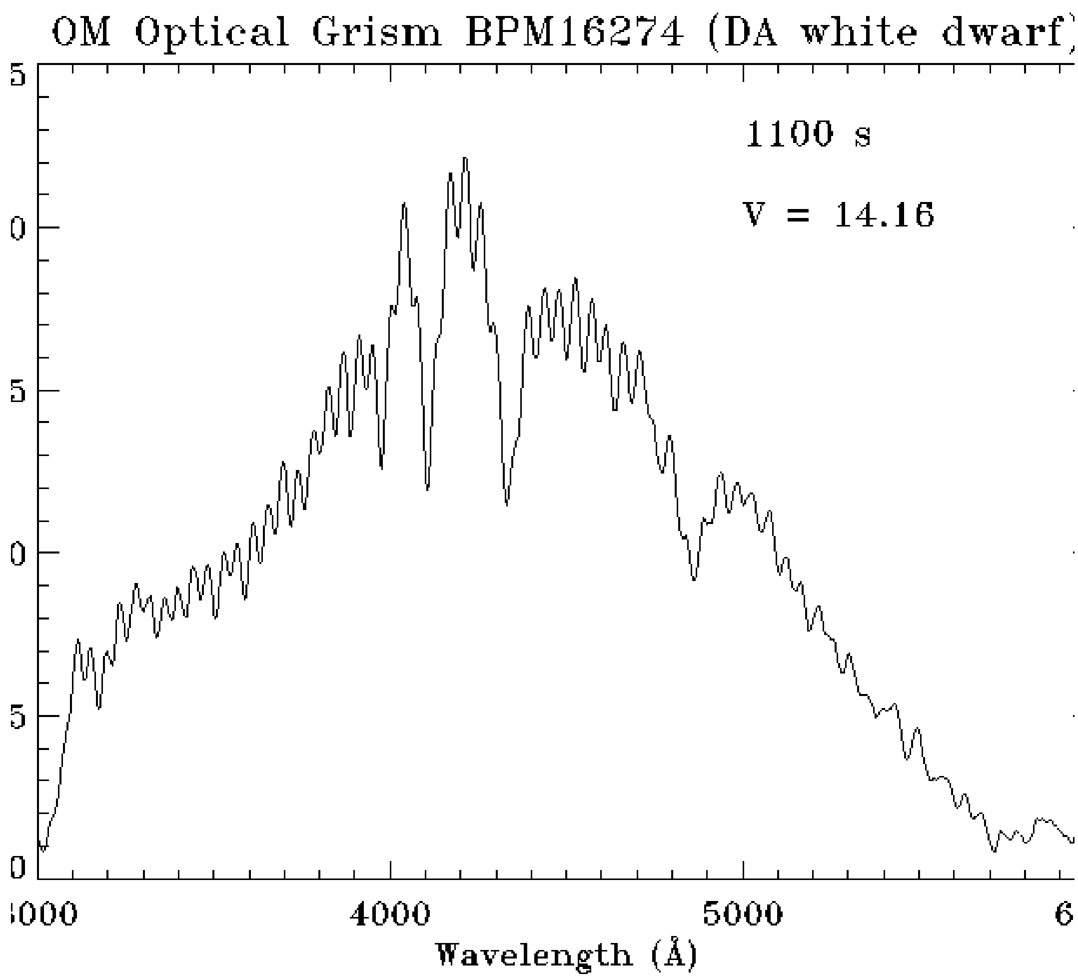

Figure 3: Spectrum of the white dwarf BPM16274 obtained using the visual grism Mason et al. (2000). The characteristics of this spectrum are close to the blackbody spectral distribution estimate made for this observation.

Parameter	Value
Spectral Type	DA
$T_{\rm eff}$ (K)	13020 ± 460
$\log g$	9.341 ± 0.036
Distance (pc)	$99.7^{+2.9}_{-2.7}$
Mass, ONe core ($M_\odot$)	1.263 ± 0.011
Cooling age, ONe core (Gyr)	1.94 ± 0.08
Mass, CO core ($M_\odot$)	1.312 ± 0.010
Cooling age, CO core (Gyr)	1.72 ± 0.09

Figure 4: Physical parameters of J004917.14-252556.81 Kilic et al. (2023).

Technical Justification *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification?*

The proposed observing run for J0049-2525 is designed to gather essential data for an extensive asteroseismic analysis. Leveraging the Gemini GMOS instrument in conjunction with the SDSS-g filter, and potentially utilizing the APO facility if relevant, the observations aim to provide critical insights into the pulsation behavior of this white dwarf.

Spanning over 4-5 nights, the observing strategy involves back-to-back exposures with a 7-second duration on each night, with observation overhead, the GMOS Integration Time Calculator estimates a cadence of 22.7 seconds. This approach ensures a comprehensive capture of the pulsation behavior exhibited by J0049-2525, utilizing a carefully considered CCD chip binning of 4x4 to optimize image quality while maintaining efficiency. Previous observations of 2 nights only provided enough data to produce 2 g modes in astrosesimic fits, though this is a short baseline observation, this cadence has proved its efficiency.

To complement the observations, a spectral density model black body spectrum with a temperature of 1142 Kelvin has been employed. This spectral model will contribute to refining the understanding of the object's characteristics and aid in the interpretation of the acquired photometric data. This chosen model is a close estimate to the actual spectra for a DA white dwarf.

Specific constraints have been requested to optimize observing conditions. The ideal scenario includes favorable seeing conditions to minimize atmospheric distortion, minimal cloud cover to prevent interference, low sky brightness for heightened sensitivity, and reduced water vapor content if applicable, particularly concerning specific wavelengths, to mitigate interference during data collection.

The photometric approach involves the selection of four reference stars brighter than J0049-2525 for relative photometry. These reference stars serve as essential guides, facilitating a detailed analysis of the luminosity variations exhibited by J0049-2525.

Following data collection, meticulous analysis employing standard calibration techniques, including bias subtraction, flat-fielding, and correction for instrumental effects, will ensure the accuracy and reliability of the obtained data. Subsequent analysis will focus on conducting precise relative photometry using the selected reference stars to quantify variations in J0049-2525's brightness. Furthermore, in-depth examination of the acquired light curves will be conducted to identify, characterize, and comprehend the observed pulsation modes.

The primary objective lies in detecting additional pulsation modes beyond the initially identified significant modes. Cataloging a broader range of pulsation frequencies is pivotal, aiming to overcome asteroseismic degeneracies and yield a comprehensive understanding of the internal structure and pulsation behavior of the white dwarf J0049-2525. The integration of the spectral density model black body spectrum, specifically with a temperature of 1124 Kelvin, enriches the dataset and aids in refining the interpretation of observed photometric variations.

Based on the acquired data and analysis, recommendations for follow-up observations, such as increased cadence or alternative filters, may be proposed for further investigating the white dwarf's pulsation behavior.

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