Investigating Pulsating Lambda Boötis Stars

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Introduction: λ Boo stars are a rare spectral class (~2%) of late-B to early-F stars, whose origin remains a puzzle after their isolation as peculiar over 70 years ago. They have a selective deficiency of the refractory elements while the volatile elements (C, N, O, S) show solar abundances. This abundance pattern appears to be caused by the accretion of material onto the star's surface from either the interstellar medium or a circumstellar disk, but the alternative that the star is metal-weak throughout needs to be definitively addressed. Since many later-type λ Boo stars pulsate as δ Sct, γ Dor, or hybrids, asteroseismology can help distinguish between the two compositional profiles.

Identification is made through classification resolution spectra, and confirmed by detailed abundance analysis. The optical characteristics of λ Boo stars are broad hydrogen lines from late-B to early-F, weak metallic-lines as compared with the MK standard corresponding to the hydrogen lines, coupled with a particularly weak Mg II 4481 line (**Figure 1**).

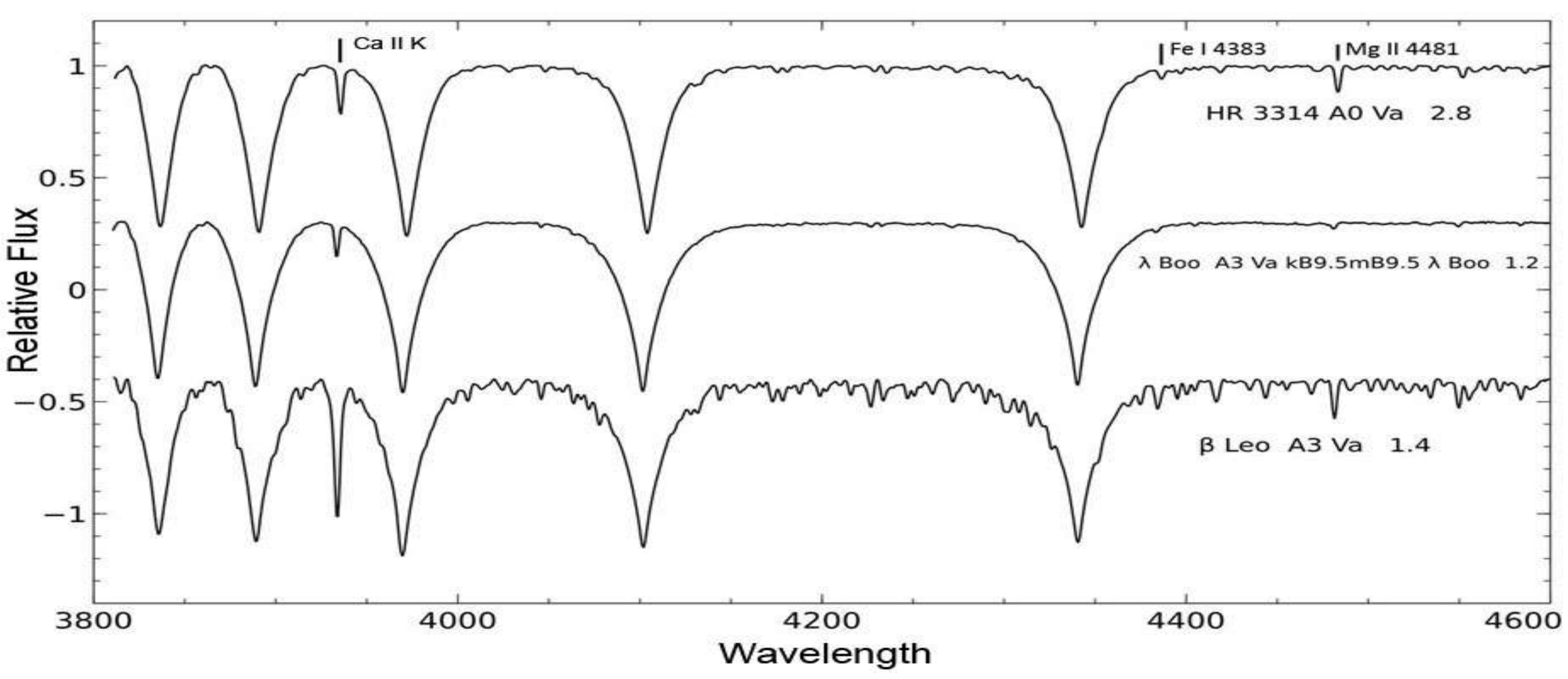

***Figure 1**: Montage of the prototype λ Boo with an MK standard star above and below. The spectra are from the Dark Sky Observatory.*

Members: Since the classification of a star as λ Boo was not well established for some time and is a task requiring some skill, a heterogeneous literature for membership developed. A recent re-evaluation of 212 objects, recorded in the literature as λ Boo candidates, led to 67 being considered by Murphy et al. (2015, PASA 32, 36) to be genuine members of the class.

Pulsation data are incomplete for these 67 members, but two space missions are helping. There is a ready goldmine of such data in the Kepler field stars, among which 107 have been classified from LAMOST spectra with the expert computer classification program MKCLASS as new λ Boo candidates (Gray et al. 2016, AJ 151, 13). We are also conducting a spectroscopic survey of known metal-poor stars to find additional λ Boo candidates for which asteroseismic data will be accessible from the upcoming all-sky Transiting Exoplanet Survey Satellite (TESS) mission.

The LAMOST-Kepler λ Boo stars: A motivation to search for λ Boo stars in the Kepler field comes from an expectation that their circumstellar disks will give them a higher incidence of planets, in addition to the availability of high-precision photometry for astero-seismology.

Out of 34 LAMOST-Kepler candidates observed recently with VATTSpec (*right*), 15 proved to be λ Boo type. Classifications are given, together with their pulsation analysis in **Table 1**. That 8 of the 11 with Kepler data do pulsate supports Murphy's (2014, *Investigating the A-Type Stars Using Kepler Data*, Springer) contention that λ Boos are more likely to pulsate than normal stars, and/or will show richer pulsation spectra than normal δ Sct stars.

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The four hybrid δ Sct/γ Dor pulsators are specially important for testing λ Boo models with asteroseismology. They allow simultaneous probing of (1) the outer layers of the envelope where the p-modes propagate, and (2) the deeper interior layers between the convective core and the envelope, where the g-modes propagate.

The hybrid KIC9828226, if an uncontaminated star, becomes very unusual in being a pulsator outside the instability strip. Full analysis of a high-resolution HERMES/Mercator spectrum (Niemczura et al. 2015, MNRAS 450, 2764) revealed $T_{\rm eff}$ = 9000 ±100 K, log g = 4.0 ±0.1, $v$sin$i$ = 88 ±9 km/s and [Fe/H] = -1.23 ±0.21 dex, and with typical λ Boo abundance patterns: [C/H], [N/H] and [O/H] are -0.05 ±0.14, -0.18 ± 0.14 and +0.93 ±0.14 dex, respectively. Meanwhile, [Mg/H] = -1.46 ±0.14 (i.e., 10 σ deficient) and [Si/H] is 9 σ below solar at -1.3 ±0.14 dex.

Further LAMOST-Kepler λ Boo candidates' spectra will be observed, and asteroseismic analysis of the hybrids' pulsations is planned.

KIC number	Spectral type (CC, SJM)	Kepler photometry analysis (SJM)
KIC03727221	A8 V kA4mA4 lam Boo	no Kepler photometry (not on silicon)
KIC04840675	F0 Vn kA6mA6 lam Boo	δSct, and two fainter solar-type companions (Balona+2012)
KIC04998035	F0 IVn kA6mA6 lam Boo	no Kepler photometry (not on silicon)
KIC05959352	A0 Vb kB9mB7 (lam Boo)	no Kepler photometry (not on silicon)
KIC06280902	F1 Vn kF0mA8 (lam Boo)	low-amp δSct (0.1 mmag peaks)
KIC06463047	A6 V kA1mA1 (lam Boo)	δSct-γDor hybrid.
KIC08246833	F0 V kA6mA6 lam Boo	δSct. The low frequencies are probably g modes, too.
KIC08560996	A9 V kA3mA4 lam Boo	PM binary with ~1700-d period. $m_2$sin$i$ is ~0.07 $M_{\rm sun}$.
KIC09289960	F0 V kA6mA6 lam Boo	δSct, high amplitudes exceeding 10 mmag.
KIC09646944	A9 Vn kA4mA4 lam Boo	no Kepler photometry (not on silicon)
KIC09656348	A9 V kA3mA4 lam Boo	γDor, also with single p-mode (hence γDor-δSct hybrid)
KIC09828226	A1 V kB9.5mB8 lam Boo	δSct-γDor hybrid, despite being well outside the instability strip at A1.
KIC10226388	F1 V kA6mA6 (lam Boo)	1.5-d ellipsoidal variable. PM triple system, with ~1000-d tertiary.
KIC10394576	A7 V kA3mA5 lam Boo	non-pulsating. No g modes or p modes.
KIC11973705	F0 V kA2mA2 lam Boo	δSct-γDor hybrid.

***Table 1**: λ Boötis stars in the LAMOST-Kepler Field.*