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WOCS 9005: A Barium Blue Straggler in M67 and Photometric Detection of Its White Dwarf Companion

Introduction

1 Significance of s-process Elements

- Slow neutron capture process, in AGB stars

2 What are Barium Stars?

- Stars in early evolutionary phases like the MS, SG, RG that show ba or other s-process elements (McCLURE 1984).

3 Case C Post Mass Transfer Binary systems

- MT, after the donor star in binary has evolved into the AGB phase

4 Importance of UV observations and Previously found such systems.

- Gray et al. (2011)
- (Miszalski et al. 2012, 2013; Siegel et al. 2012; Merle et al. 2016).

5 Importance of M67 Cluster

- Messier 67 (M67; NGC 2682) is an old, rich open cluster with solar-like age and metallicity, making it ideal for studying stellar evolution, dynamics, and binary systems.

6 Importance of the Study's Findings

- This study is significant as it provides the direct detection of a hidden WD companion in a post-MT system and estimates its parameters using SED fitting.

Data sets

UVIT Data (AstroSat)

M67 catalog (**Jadhav et al. 2021**).

FUV Filters: F148W, F154W, F169M.

UVOT Data (Swift)

M67 catalog **(Siegel et al. 2019)**.

Filters: NUV; UVW1, UVM2, UVW2, and Optical; U.

GALAH optical Spectroscopic data

GALAH Survey (**Buder et al. 2021**)

Using HERMES spectrograph (R = 28,000).

- **Radial Velocity** Time series Data and Orbital parameters from WOCS (Geller et al. 2021).
- **Archival Data** to create multiwavelength SEDs (explored later)

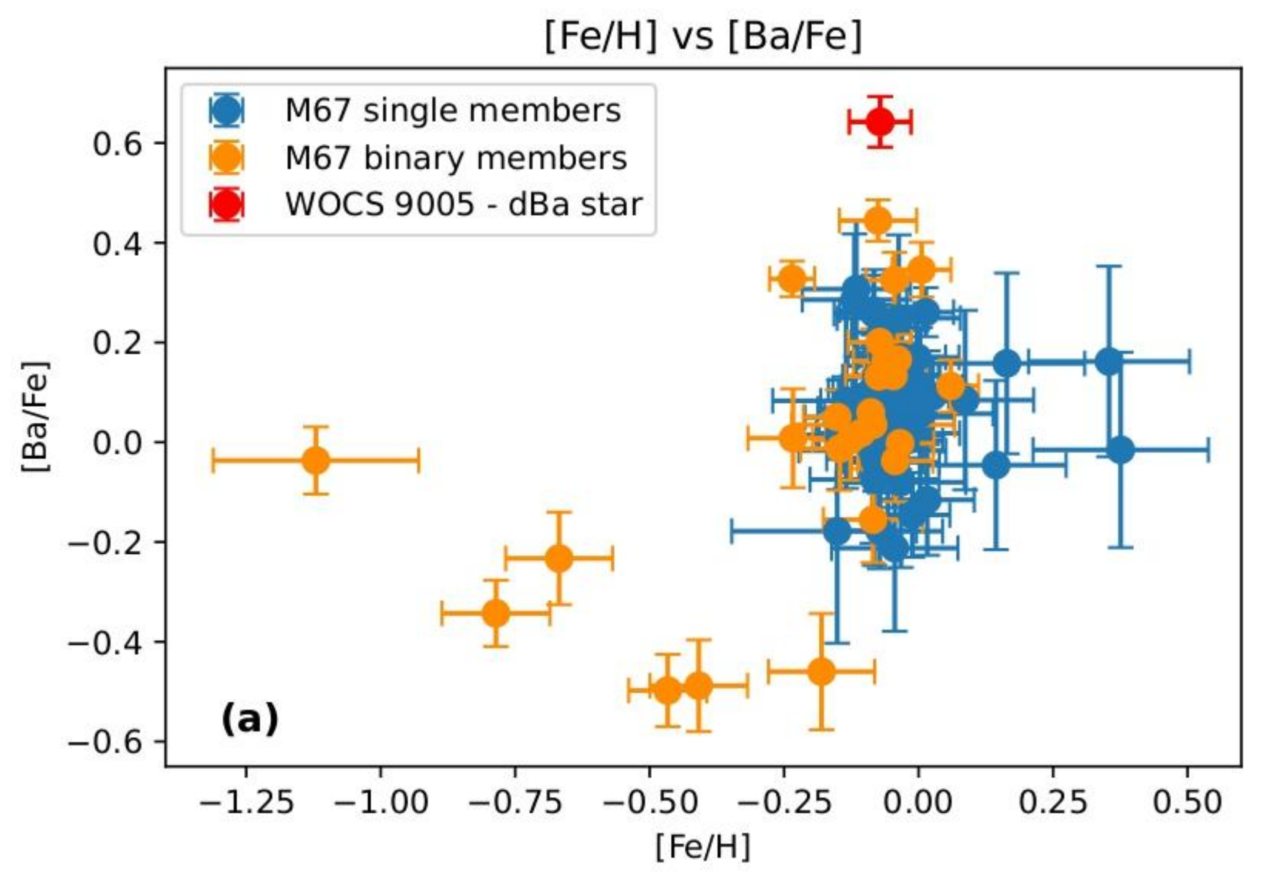
Target Selection

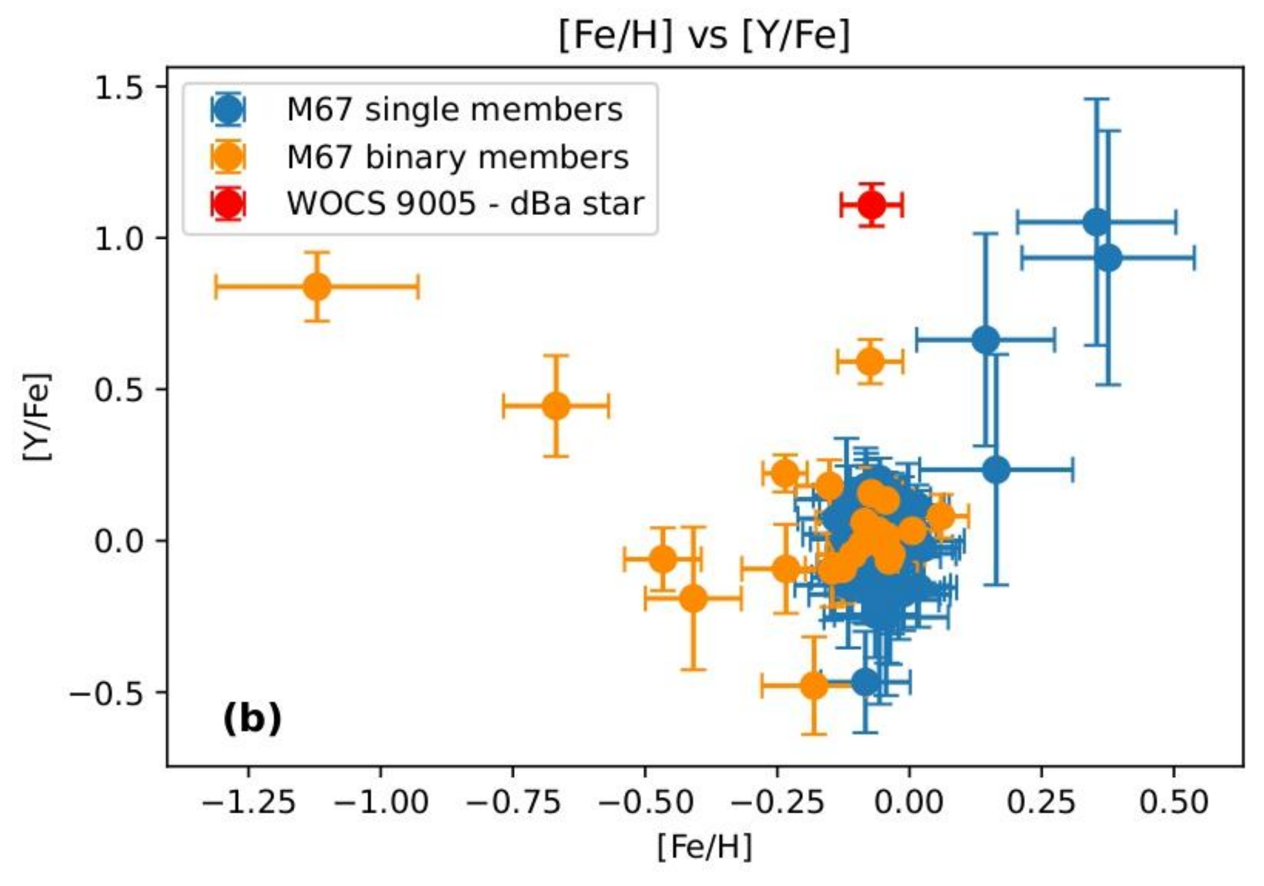
1. Detected in UVIT images with high SNR.
2. Confirmed M67 membership (Geller et al. 2021).
3. High [Ba/Fe] and [Y/Fe] from GALAH.

Detected Elements:

i. Yttrium (Y): First s-process peak.

ii. Barium (Ba): Second s-process peak.

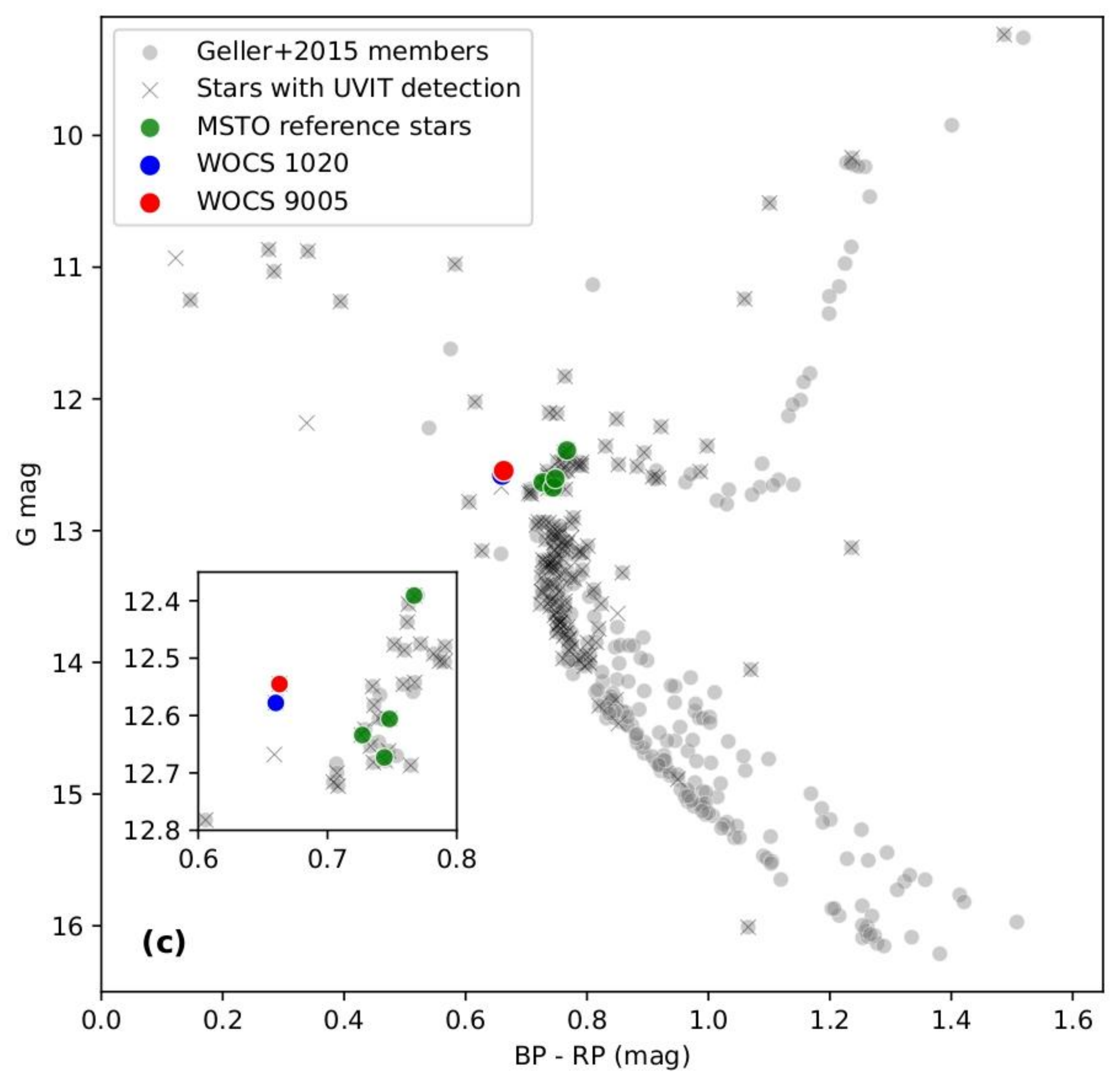




WOCS 9005

1. Highest barium and yttrium abundances.
2. Classified as SB1 and BSS (confirmed via Gaia CMD).
3. Binary Member with Period = 2769 ± 18, e = 0.15 ± 0.05
4. Likely formed through Case C mass transfer (MT), indicating s-process enrichment.

WOCS 1020, and four main-sequence turn-off (MSTO) stars in M67: WOCS 4021, 5009, 4004, and 7010



Observed Spectra of WOCS 9005

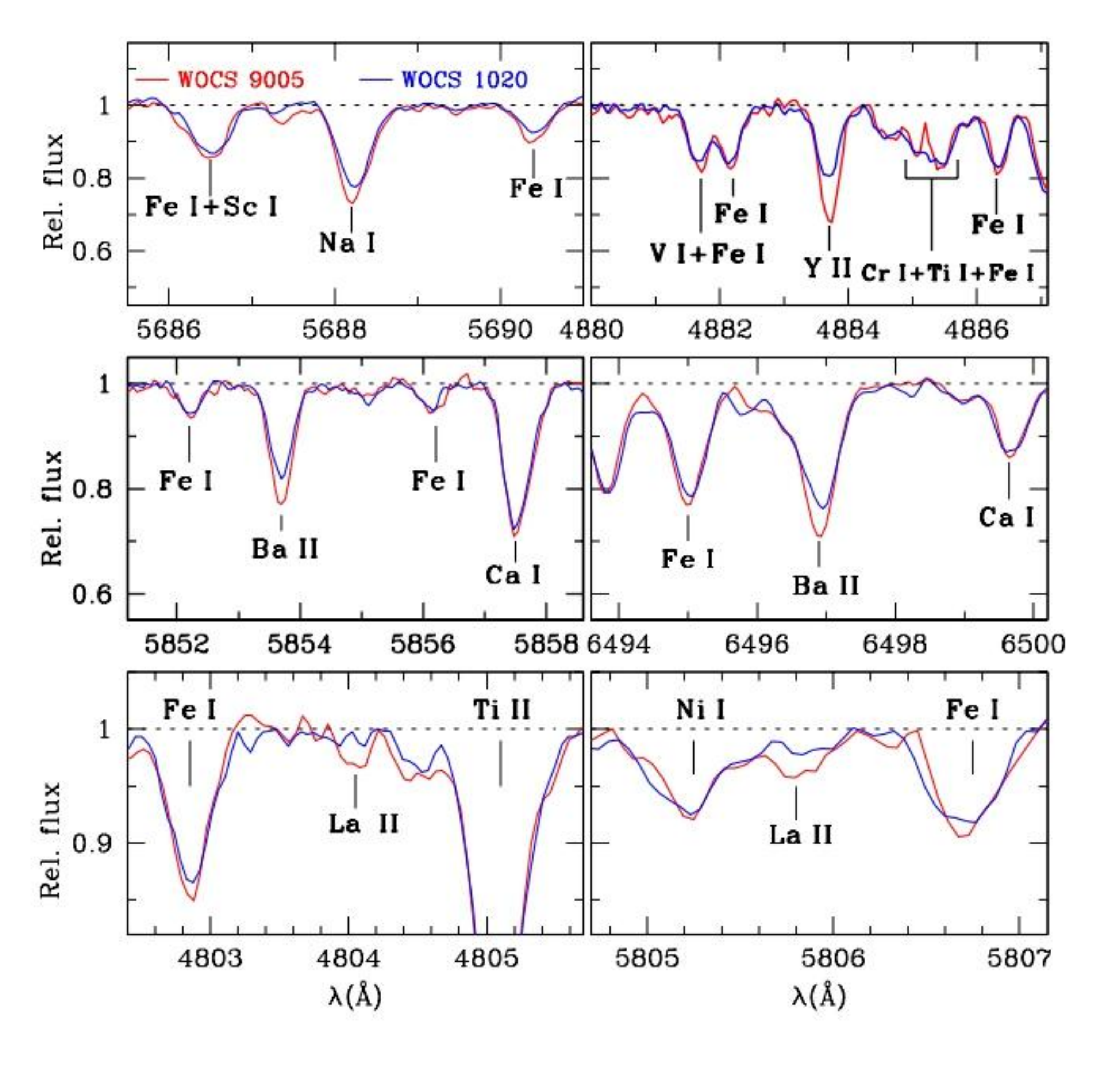


Figure shows a direct comparison of WOCS 9005 with WOCS 1020 spectra.

Data Source:

- Spectra retrieved from the GALAH DR3 Spectral Library.
- Spectral resolution: 28,000.
- Signal-to-noise ratio (SNR): higher than 100 over the wavelength range, observed with the HERMES spectrograph.

Differential Abundance Analysis:

- Performed relative to the Sun using the abfind driver of MOOG (Sneden 1973).
- ATLAS9 one-dimensional, plane-parallel LTE model photospheres were used, adopting updated opacity distribution functions (Castelli & Kurucz 2003).
- Stellar parameters (Teff, logg, ξt, [Fe/H]) were derived by force-fitting iron line equivalent widths (EWs) to the observed values, ensuring excitation and ionization equilibrium.

Observed Spectra of WOCS 9005

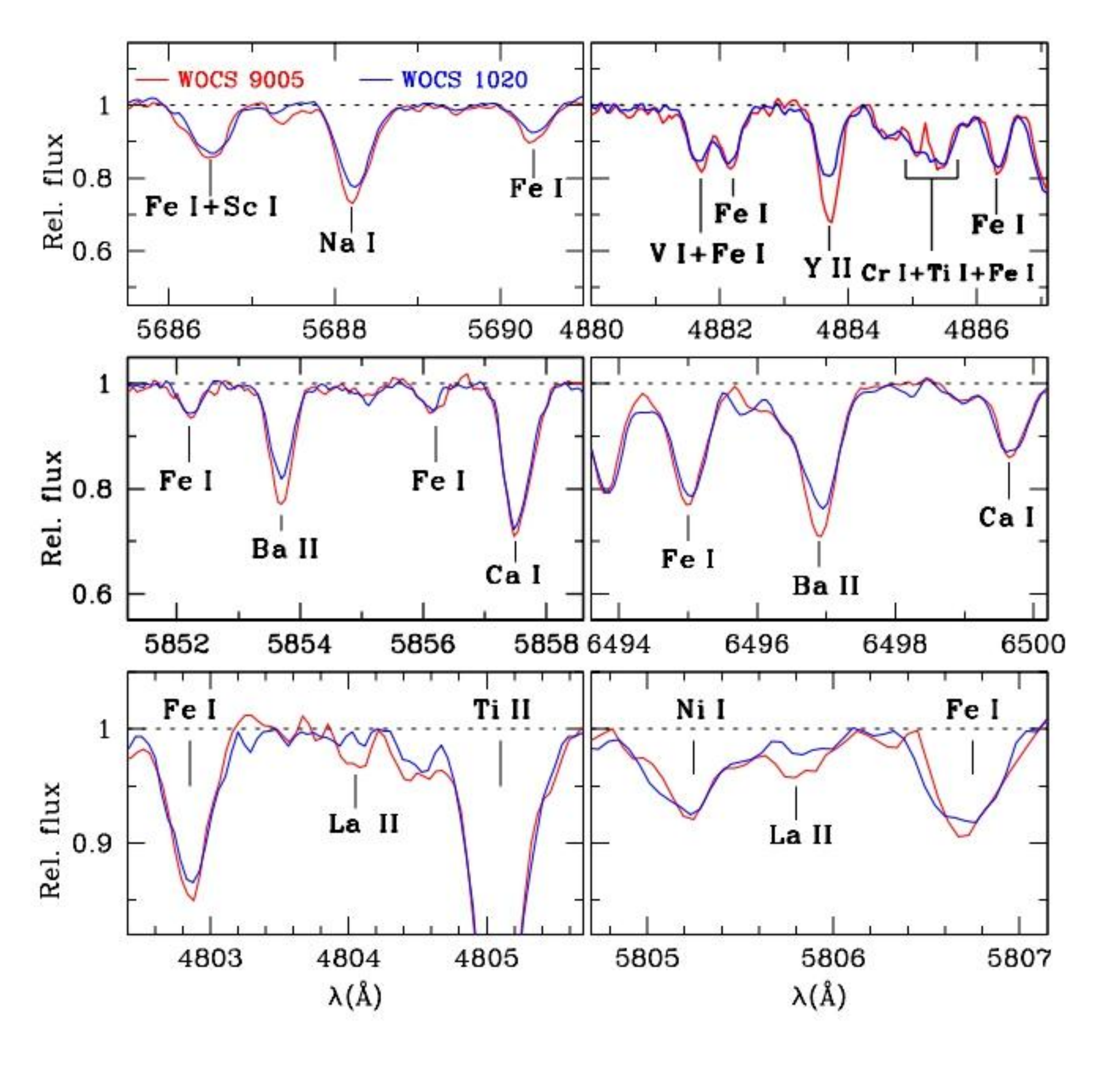


Figure shows a direct comparison of WOCS 9005 with WOCS 1020 spectra.

Element Abundance Measurements:

- Abundances for Na and s-process elements (Y II, Ba II, La II) were determined using synthetic profile fitting.
- Lines analyzed:
  - Na: 5688 Å
  - Y II: 4884 Å, 5729 Å
  - Ba II: 5854 Å, 6497 Å
  - La II: 4804 Å, 5806 Å.

Spectral Line Fitting:

- Synthetic profiles were smoothed with Gaussian profiles to match observed spectra, accounting for instrumental and rotational (v sini) broadening.

Elemental Abundances and Stellar Parameters for WOCS 9005 and WOCS 1020 and the Average [X/Fe]

Parameter	WOCS 9005	WOCS 1020	Average_TO
[Na I/Fe]	+0.28 ± 0.05(1)	0.00 ± 0.05(1)	+0.08 ± 0.07
[Mg I/Fe]	+0.07 ± 0.04(1)	+0.03 ± 0.05(2)	+0.05 ± 0.06
[Al I/Fe]	+0.07 ± 0.05(4)	+0.09 ± 0.03(3)	+0.08 ± 0.02
[Si I/Fe]	−0.04 ± 0.04(4)	−0.02 ± 0.02(3)	0.00 ± 0.06
[Ca I/Fe]	−0.01 ± 0.06(4)	−0.01 ± 0.05(3)	+0.03 ± 0.02
[Ti I/Fe]	−0.01 ± 0.05(3)	+0.02 ± 0.04(2)	0.00 ± 0.03
[Cr I/Fe]	−0.05 ± 0.03(1)	−0.02 ± 0.03(1)	−0.02 ± 0.03
[Fe I/H]	−0.10 ± 0.05(21)	−0.11 ± 0.06(18)	−0.14 ± 0.02
[Fe II/H]	−0.11 ± 0.07(3)	−0.09 ± 0.07(2)	−0.14 ± 0.02
[Ni I/Fe]	−0.04 ± 0.05(9)	0.00 ± 0.05(7)	0.00 ± 0.04
[Y II/Fe]	+1.09 ± 0.07(2)	+0.05 ± 0.08(2)	+0.08 ± 0.02
[Ba II/Fe]	+0.75 ± 0.08(2)	+0.12 ± 0.09(2)	+0.14 ± 0.04
[La II/Fe]	+0.65 ± 0.06(2)	+0.09 ± 0.06(2)	+0.05 ± 0.07
T_{eff} (K)[a]	6350 ± 50	6350 ± 50	...
log g (cm s^{-2})[a]	4.2 ± 0.2	4.2 ± 0.2	...
ξ_t (km s^{-1})[a]	1.47 ± 0.1	1.70 ± 0.1	...
[Fe/H] (dex)[a]	−0.10 ± 0.05	−0.11 ± 0.06	...
$v \sin i$ (km s^{-1})[a]	15.0 ± 2.0	14.0 ± 2.0	...
M ($M_\odot$)[b]	1.37 ± 0.04	1.30 ± 0.05	...
R ($R_\odot$)[b]	1.99 ± 0.06	1.80 ± 0.05	...

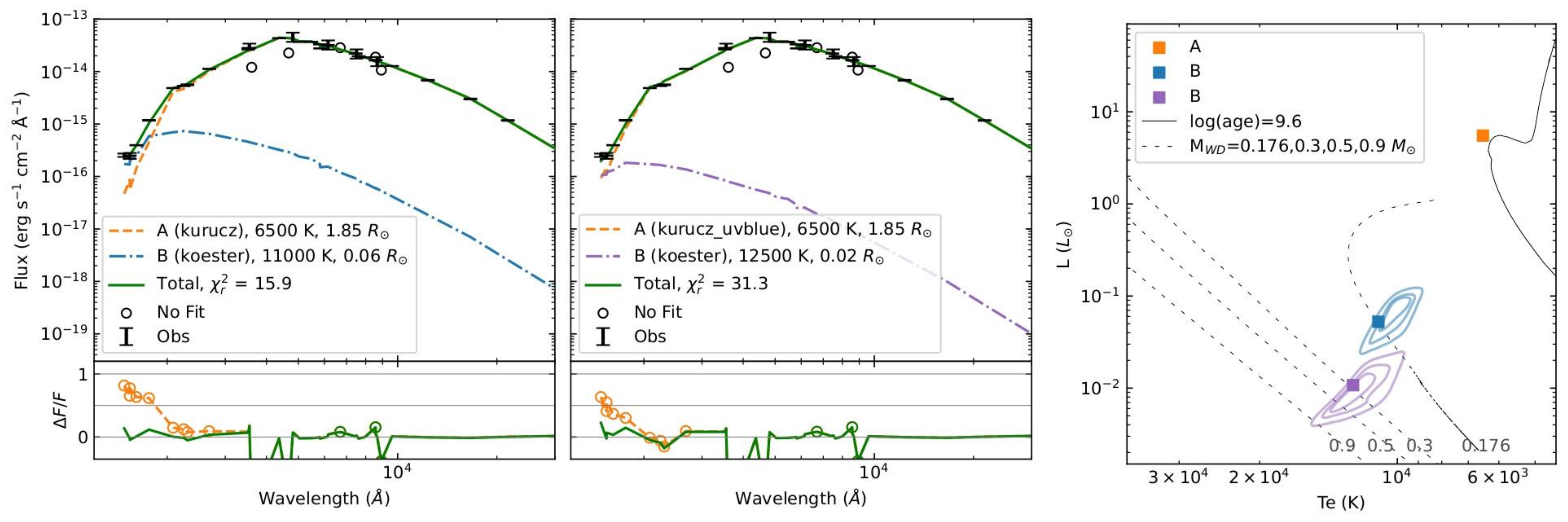
RV_{COM} (km s^{-1})	Period (days)	RV_{semi} (km s^{-1})	e	$f(m)$ ($10^{-2} M_\odot$)	a sini (10^{11} m)	M_1 ($M_\odot$)	M_{WD} ($M_\odot$)
32.91 ± 0.16	2769 ± 18	5.1 ± 0.3	0.15 ± 0.05	3.7 ± 0.6	1.92 ± 0.11	1.37 ± 0.04	0.5

a: Estimated through spectral analysis.

b: Obtained via PARAM, a web interface for the Bayesian estimation of stellar parameters.

Orbital parameters and mass of the components of WOCS 9005 (Leiner et al. 2019; Geller et al. 2021)

SED Analysis - Photometric detection (“sighting”) of WD



SED Fitting: BINARY SED FITTING Python code (Jadhav et al. 2021a), based on χ^2 minimization:

1. Kurucz model (Castelli & Kurucz 2003).
2. Hybrid Kurucz_UVBLUE model; UVBLUE model spectra (Rodríguez-Merino et al. 2005)
3. Koester model (Koester 2010)

Residual flux showed a significant UV excess, with high fractional residuals (>50%), indicating the presence of a white dwarf (WD) component.

SED Analysis

Component	$T_{\rm eff}$ (K)	$R(R_\odot)$	$L(L_\odot)$	log g	χ^2_r	vgf^2_b
		Kurucz + Koester				
WOCS 9005A	6500^{+250}_{-250}	$1.85^{+0.03}_{-0.03}$	$5.52^{+1.15}_{-1.15}$	$3.5^{+0.5}_{-0.5}$	14.2	0.25
WOCS 9005B (Best fit)	$11,000^{+250}_{-250}$	$0.063^{+0.001}_{-0.001}$	$0.0525^{+0.0014}_{-0.0014}$	$9.50^{+0.00}_{-0.25}$	14.28	0.28
WOCS 9005B (Top 1 percentile)	9000–12,000	0.036–0.138	0.025–0.113	6.5–9.5	<30.94	<21.5
		Kurucz_UVBLUE + Koester				
WOCS 9005A	6500^{+500}_{-500}	$1.85^{+0.03}_{-0.03}$	$5.52^{+1.15}_{-1.15}$	$3.5^{+0.5}_{-0.5}$	14.1	0.17
WOCS 9005B (Best fit)	$12,500^{+250}_{-250}$	$0.0221^{+0.0022}_{-0.0004}$	$0.0108^{+0.0011}_{-0.0003}$	$9.50^{+0.00}_{-0.25}$	28.03	0.55
WOCS 9005B (Top 1 percentile)	9750–15,250	0.009–0.056	0.004–0.025	6.5–9.5	<29.86	<19.9

Table: Estimated parameters of the cooler and hotter companions from the SED fits.

The top 1 percentile of χ^2 fits show a wider WD mass range from the HRD: 0.17–0.9 Me.

Conclusion: Our SED analysis has successfully "sighted" the WD and characterized the hot companion.

Modeling MT scenario of WOCS 9005

Modelled the formation and evolution scenario of WOCS 9005 through MT from an AGB star by adopting the wind accretion model of Boffin & Jorissen (1988).

Before: [Ba/Fe] = 0, [Y/Fe] = 0, [La/Fe] = 0.

After: [Ba/Fe] = 0.75, [Y/Fe] = 1.09, [La/Fe] = 0.65.

Thermohaline mixing diluted the accreted material.

Semimajor axis was calculated as 7.12×10^{11} m from the given Orbital Information.

Accreted mass for a stellar wind velocity (Vwind) of 30 km/s is calculated using the MT formula from Boffin & Jorissen (1988) and Husti et al. (2009), yielding ≈ 0.15 $M_{\odot}$

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Discovery of a Barium Blue Straggler Star in M67 and "Sighting" of Its White Dwarf Companion*

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Abstract

We report the discovery of a barium blue straggler star (BSS) in M67, exhibiting enhancements in slow neutron-capture (*s*-)process elements. Spectroscopic analysis of two BSSs (WOCS 9005 & WOCS 1020) and four stars located near the main-sequence turn-off using GALAH spectra, showed that WOCS 9005 has a significantly high abundance of the *s*-process elements ([Ba/Fe] $= 0.75 \pm 0.08$, [Y/Fe] $= 1.09 \pm 0.07$, and [La/Fe] $= 0.65 \pm 0.06$). The BSS (WOCS 9005) is a spectroscopic binary with a known period, eccentricity, and a suspected white dwarf (WD) companion with a kinematic mass of 0.5 $M_{\odot}$. The first "sighting" of the WD in this barium BSS is achieved through multiwavelength spectral energy distribution (SED) with the crucial far-UV data from the UVIT/AstroSat. The parameters of the hot and cool companions are derived using binary fits of the SED using two combinations of models, yielding a WD with $T_{\rm eff}$ in the range 9750–15,250 K. Considering the kinematic mass limit, the cooling age of the WD is estimated as ∼60 Myr. The observed enhancements are attributed to a mass transfer (MT) from a companion asymptotic giant branch star, now a WD. We estimate the accreted mass to be 0.15 $M_{\odot}$, through wind accretion, which increased the envelope mass from 0.45 $M_{\odot}$. The detection of chemical enhancement, as well as the sighting of WD in this system, have been possible due to the recent MT in this binary, as suggested by the young WD.

Unified Astronomy Thesaurus concepts: Open star clusters (1160); Barium stars (135); Blue straggler stars (168); White dwarf stars (1799); S-process (1419); Spectroscopic binary stars (1557); Spectral energy distribution (2129)

1. Introduction

Star clusters are test beds to understand single and binary star evolution. Clusters host a good fraction of binaries (Jadhav

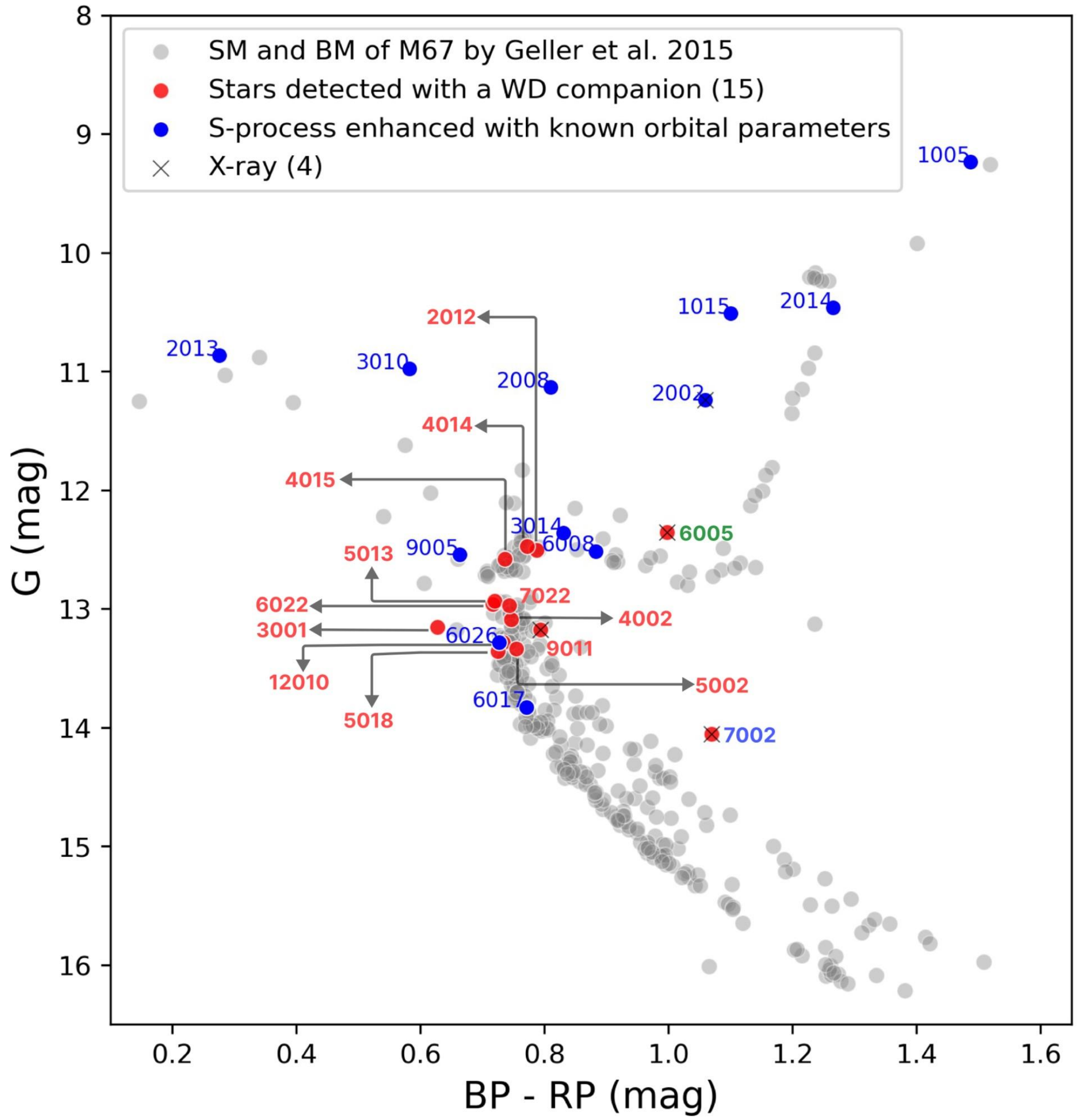
enhancement and four barium-enhanced BSSs with no radial velocity variations (Milliman et al. 2015). Mathys (1991) detected two Ba-enriched BSSs in M67 (S968 and S1263), which are found to be single members (Geller et al. 2015). This

Future/ongoing Work

- The future/ongoing work is to demonstrate that all types of mass transfer (MT) – Case A, B, and C – are actively occurring in M67 across different stages of stellar evolution, like MS (including BSSs, YSSs), SG, and RG stars.

- Case A/B MT was identified by detecting ELM WD companions alongside MS stars using multi-wavelength SED analysis.

- Case C MT were identified through the presence of long-period SB1 stars showing enhancements in s-process elements, further confirming the occurrence of all MT types in different phases of stars in this cluster.



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Thank you for listening!