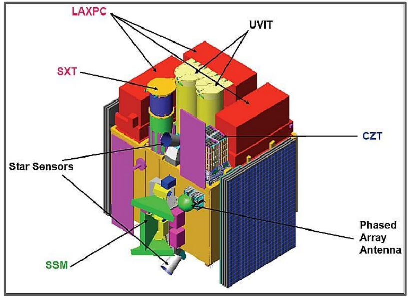
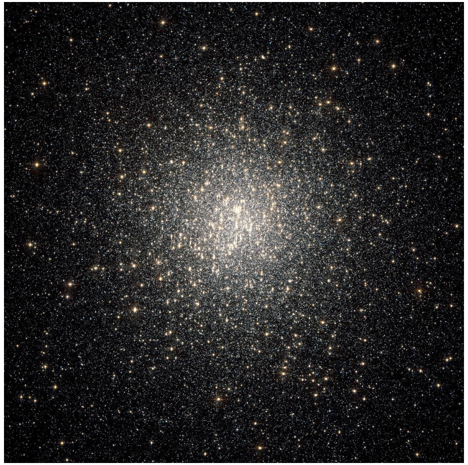


A census of UV-bright stars in the dense globular cluster NGC 2808 using UVIT-HST-GAIA

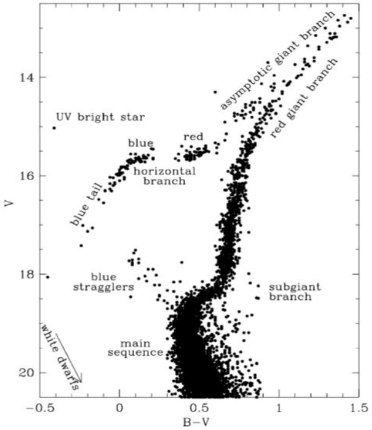


Deepthi S. Prabhu
Indian Institute of Astrophysics, Bengaluru.

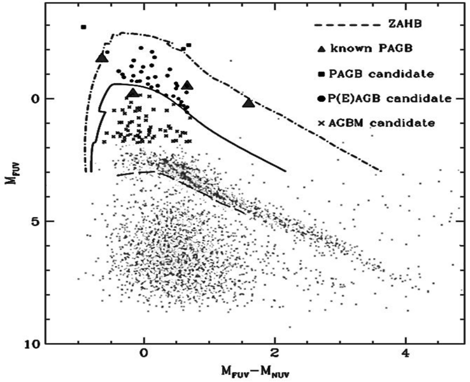
NUVA eMeeting
26th & 27th Oct. 2021

UV-bright stars in globular clusters

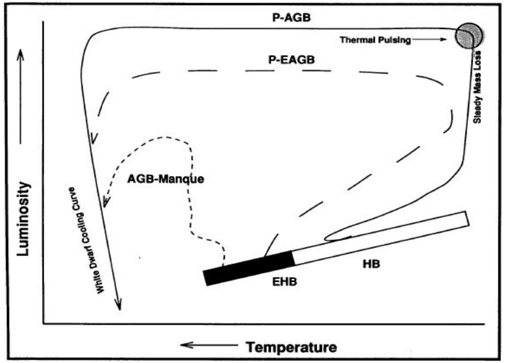
- Stars brighter than the zero-age horizontal branch (ZAHB) by 1 mag or more in FUV and hotter than 7000 K (*Moehler et al. 2019*).
- Theoretically, these are post-HB (pHB) or post-He-core-burning (pHeCB) stars.
- pHB evolution depends on strongly on the mass of the stellar envelope after core-He exhaustion.



Buonanno et al. 1994



Schiavon et al. 2012



Dorman et al. 1993

pHB type	Log L/L_{sun}	Lifetime
pAGB	≥ 3.1	< 10^5 yrs
peAGB	2.65 – 3.1	~ 10^5 yrs
AGB manqué	1.8 – 2.65	20 – 40 Myrs

Dorman et al. 1993

Why study UV-bright stars ?

- Most uncertain phases in the evolution of low-mass single stars because of :

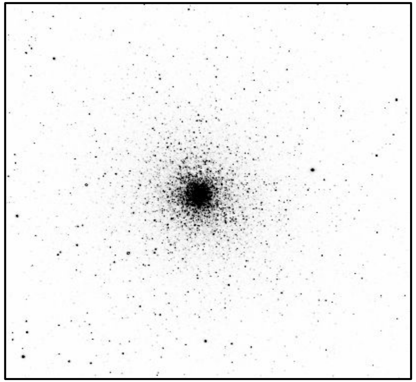
  a). Uncertainties in the size of C/O core and loosely constrained mass of H-rich envelope.

  b). Lack of understanding of winds in the RGB phase.

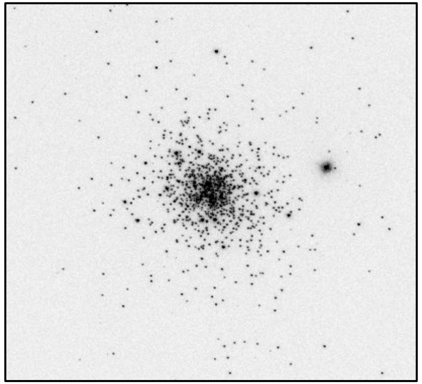
- Relatively fast evolving, short-lived phase of single stellar evolution -- statistically scarce sample.
- Speculated reason for UV-upturn phenomenon in the spectra of elliptical galaxies.

Importance of Ultraviolet observations

- Optical searches --- biased towards hot, luminous pAGB stars and extremely affected by crowding in the cores of globular clusters.
- The cool stellar populations are suppressed in the ultraviolet wavebands -- reduces crowding in globular cluster cores.

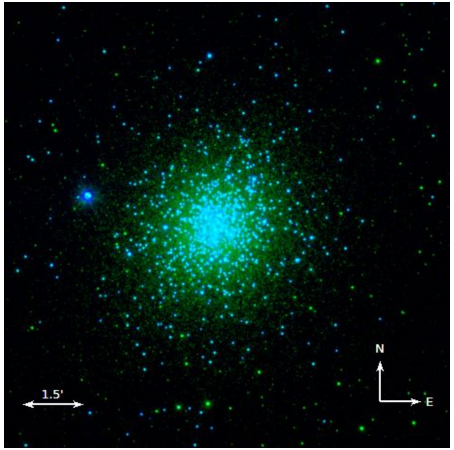


R band image of
GC NGC 2808



UVIT F154W image of
GC NGC 2808

Target : Globular Cluster NGC 2808

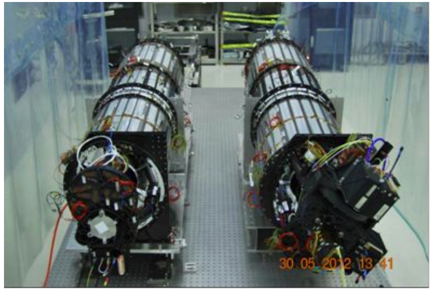


UVIT image of NGC 2808

- RA = 09h 12m 03.1s
- DEC = -64d 51m 48.6s
- Distance = 9.6 kpc
- E(B-V) = 0.22 mag
- [Fe/H] = -1.14 dex
- Distance modulus = 15.59 mag
  (Harris 1996, 2010 edition)
- Age = 10.9 ± 0.7 Gyr
  (Massari et al. 2016)

Data used

UVIT	*HST*	*Gaia*	Ground-based
F154W F169M N242W N245M N263M N279N	WFC3/UVIS F275W WFC3/UVIS F336W WFC3/UVIS F438W ACS/WFC F606W ACS/WFC F814W	G_{BP} G_{RP} G	Johnson U Johnson B Johnson V Cousins R Cousins I
	Membership info. ✔	Membership info. ✔	
Reduced from L1 to L2 using CCDLAB	*(Nardiello+2018, Piotto+2015)*	*(Helmi+2018), (Singh+2020)*	*(Stetson+2019)*



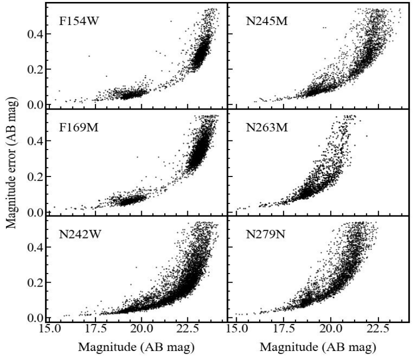
- UVIT, with the following features is an excellent facility for the study of UV-bright stars.

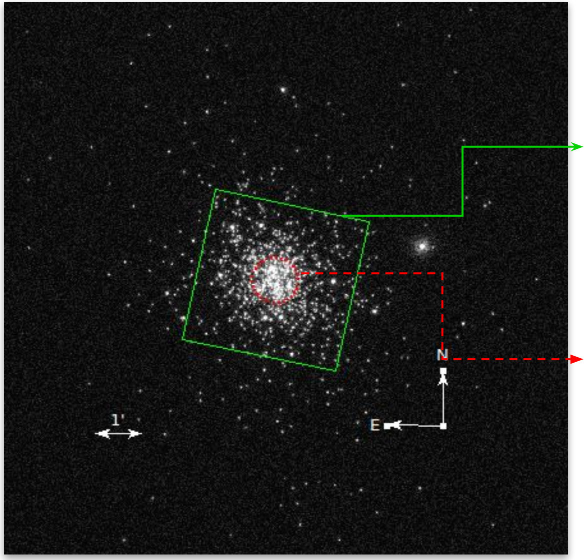
✔ Field of View : 28’
✔ Spatial resolution : ~ 1.5”
✔ Multiple filters in FUV & NUV bands

Data Analysis

- Image Reduction and Analysis facility (IRAF) was used to perform PSF photometry on the 6 UVIT images.

Filter	λ_{mean} (Å)	$\Delta\lambda$ (Å)	Zero point (mag)	Exp. time (s)	No. of stars	FWHM of model PSF (arcsec)
F154W	1541	380	17.77	4987.34	2692	1.47
F169M	1608	290	17.45	4220.36	3996	1.45
N242W	2418	785	19.81	1040.99	5056	1.41
N245M	2447	280	18.50	886.42	2686	1.64
N263M	2632	275	18.18	354.46	1309	1.58
N279N	2792	90	16.50	2629.94	2868	1.42

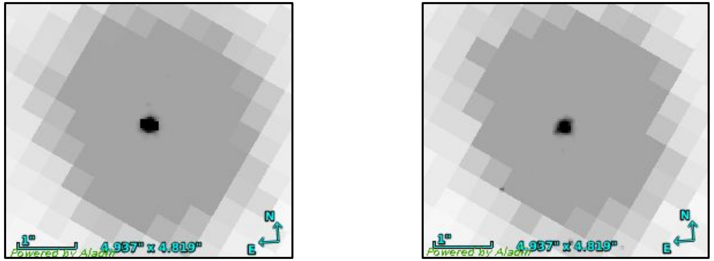




HST FOV (2.7' X 2.7')

Unresolved by UVIT : excluded (1' diameter)

- UVIT data were uniquely cross-matched with *HST* data for the inner region and *Gaia* and ground-based data in the outer region to identify various stars and to select cluster members.



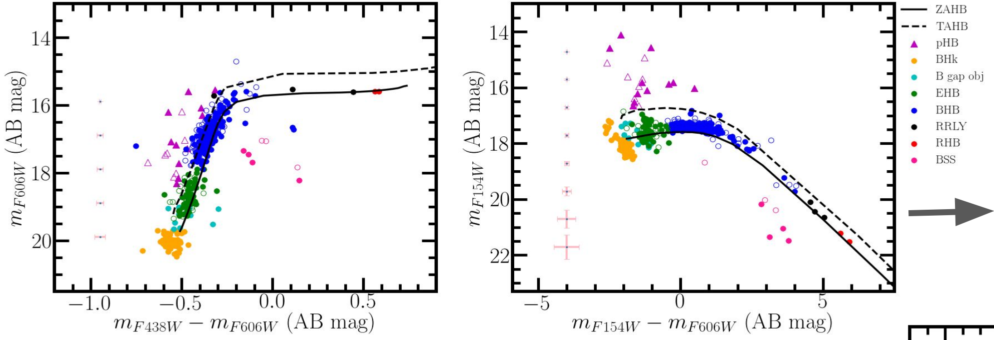
UVIT F154W image is overlaid with *HST* F275W image. The grey patch shows the UVIT PSF and the dark patches are the stars detected by *HST.*

Colour-magnitude diagrams (CMDs)

- The standard B,V,I magnitudes for stars in the outer region were transformed to the corresponding *HST* filters (F438W, F606W and F814W) using the transformation equations given in *Harris+2018, Sirianni+2005*.

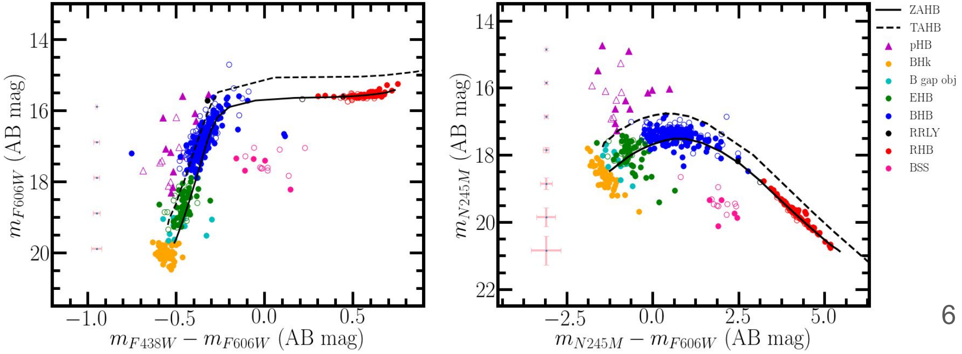
Updated BaSTI ZAHB & TAHB models (Hidalgo+2018)

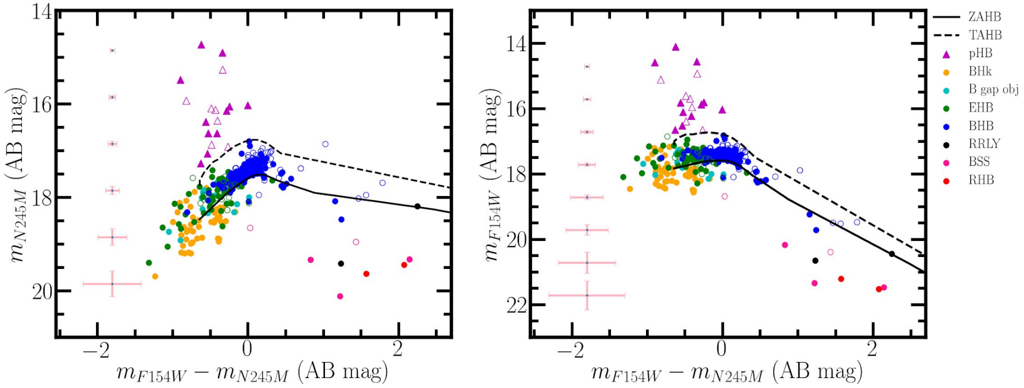
[Fe/H] = −0.9 dex
He abundance = 0.249 dex
solar scaled [α/Fe] = 0.0 dex
Convective overshoot - No
Diffusion - Yes



Cluster members detected in UVIT F154W

Cluster members detected in UVIT N245M

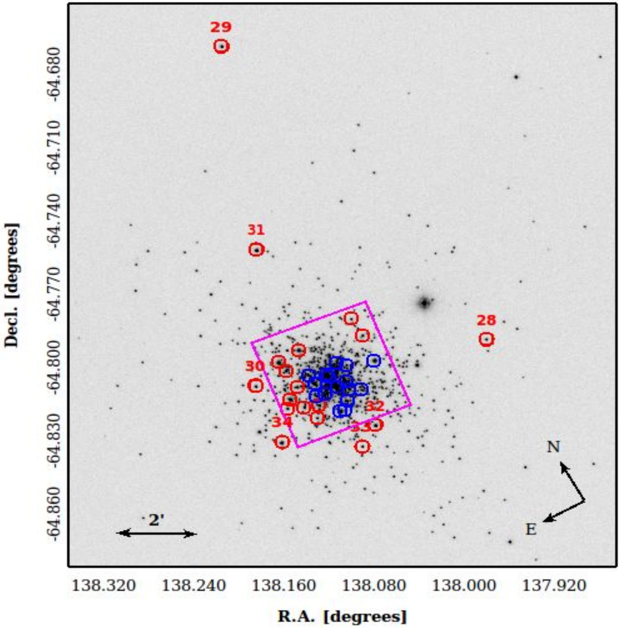




Cluster members common to UVIT F154W & N245M

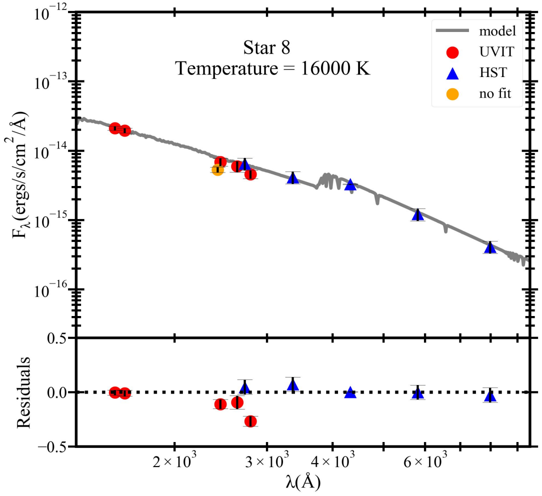
Filter	N_{pHB}	N_{BHk}	N_{Bgap}	N_{EHB}	N_{BHB}	$N_{RRLyrae}$	N_{RHB}	N_{BSS}
F154W	11(7)	53(0)	12(0)	48(21)	147(65)	3(0)	2(0)	4(3)
F169M	11(7)	52(0)	12(0)	49(21)	146(64)	2(1)	1(0)	3(1)
N242W	11(7)	49(0)	11(0)	45(21)	146(66)	4(1)	119(124)	9(28)
N245M	11(7)	48(0)	12(0)	45(20)	146(66)	2(1)	65(23)	5(10)
N263M	11(7)	23(0)	8(0)	29(17)	140(66)	3(1)	38(4)	4(1)
N279N	11(7)	40(0)	10(0)	40(17)	147(64)	5(1)	103(49)	8(2)

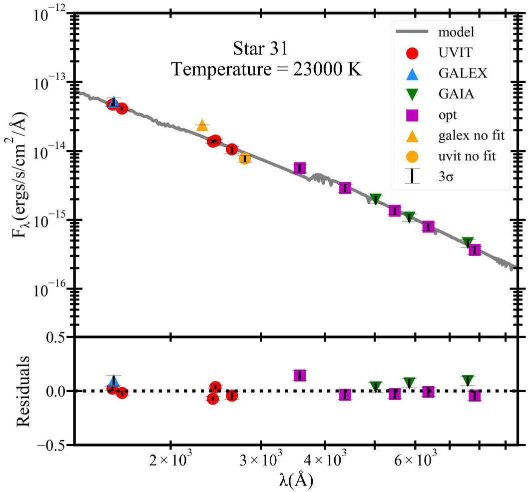
- 18 UV-bright member stars are detected using UVIT photometry. All these are 1 mag or more brighter than the ZAHB in FUV and have FUV - NUV < 0.6 mag.
- 16 additional UV-bright stars (located within 30” from cluster center) are identified using *HST* photometry.
- Total of 34 UV-bright stars are identified.

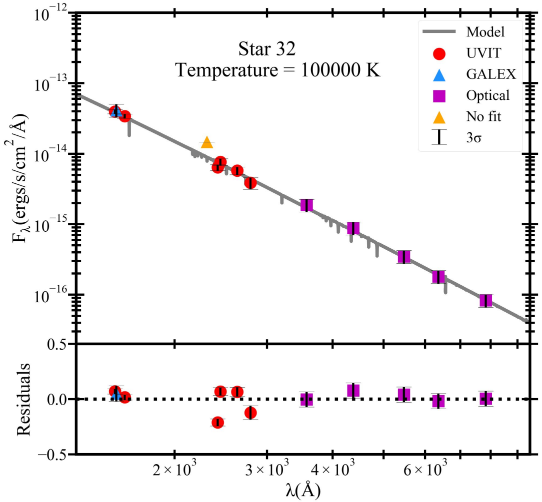


Spectral Energy Distributions

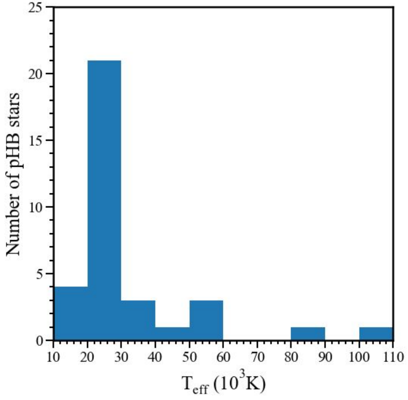
- SEDs were constructed by combining photometry from UVIT, *HST, Gaia* and ground-based optical data using the virtual observatory tool VOSA (VO SED Analyser) *(Bayo et al. 2008)*.
- Extinction coefficients were estimated in VOSA following the Fitzpatrick reddening law.

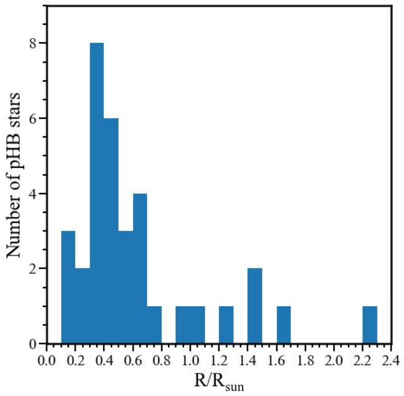






Derived fundamental parameters





ID	R.A. (deg)	Decl. (deg)	Model	T_{eff} (K)	ΔT_{eff} (K)	$\frac{L}{L_\odot}$	$\Delta\frac{L}{L_\odot}$	$\frac{R}{R_\odot}$	$\Delta\frac{R}{R_\odot}$	χ^2_{red}	N_{fit}	Phot. used
Star 1	137.96181	-64.84165	Kurucz	27000	500	50.80	0.27	0.33	0.01	7.58	11	FUV, NUV, opt.
Star 2	138.02575	-64.84307	Kurucz	21000	500	352.95	1.53	1.42	0.07	8.21	10	FUV, NUV, opt.
Star 3	138.06046	-64.86146	TMAP	80000	3750	2857.45	0.88	0.28	0.03	3.31	8	FUV, NUV, opt.
Star 4	138.05040	-64.84379	Kurucz	39000	500	781.10	0.95	0.61	0.02	4.51	9	FUV, NUV, opt.
Star 5	138.04719	-64.87492	Kurucz	27000	500	59.54	0.25	0.35	0.01	2.34	10	FUV, NUV, opt.
Star 6	138.06813	-64.86459	Kurucz	12500	125	108.50	1.11	2.20	0.04	6.86	11	FUV, NUV, opt.
Star 7	138.05264	-64.86779	Kurucz	22000	500	85.73	0.44	0.64	0.03	3.36	9	FUV, NUV, opt.
Star 8	138.04842	-64.84887	Kurucz	16000	500	117.20	0.96	1.41	0.09	6.44	10	FUV, NUV, opt.
Star 9	138.04760	-64.85790	Kurucz	17000	500	109.80	0.78	1.21	0.07	3.50	10	FUV, NUV, opt.
Star 10	138.03820	-64.87028	Kurucz	22000	500	106.20	0.62	0.71	0.03	5.78	10	FUV, NUV, opt.
Star 11	137.96088	-64.85092	Kurucz	26000	500	79.93	0.32	0.44	0.02	3.94	9	FUV, NUV, opt.
Star 12	138.02716	-64.86694	Kurucz	25000	500	102.60	0.87	0.54	0.02	0.10	7	FUV, NUV, opt.
Star 13	138.01470	-64.85891	Kurucz	15000	500	128.83	2.02	1.68	0.11	0.09	7	FUV, NUV, opt.
Star 14	138.01349	-64.86046	Kurucz	27000	500	86.65	0.09	0.42	0.02	4.86	7	FUV, NUV, opt.
Star 15	138.01173	-64.86674	Kurucz	26000	500	131.15	0.22	0.56	0.02	1.59	7	FUV, NUV, opt.
Star 16	138.03578	-64.86580	Kurucz	23000	500	54.90	0.04	0.47	0.02	1.39	5	NUV, opt.
Star 17	138.03122	-64.85554	Kurucz	25000	500	41.40	0.02	0.34	0.01	8.76	5	NUV, opt.
Star 18	138.03010	-64.86050	Kurucz	22000	500	211.00	0.07	1.00	0.05	6.01	5	NUV, opt.
Star 19	138.02244	-64.87728	Kurucz	45000	500	633.00	0.10	0.41	0.01	1.33	5	NUV, opt.
Star 20	138.01776	-64.87794	Kurucz	27000	500	72.00	0.03	0.39	0.01	1.98	5	NUV, opt.
Star 21	138.01103	-64.87463	Kurucz	24000	500	49.30	0.08	0.41	0.02	3.75	5	NUV, opt.
Star 22	138.00244	-64.87014	Kurucz	22000	500	102.00	0.69	0.69	0.03	0.02	5	NUV, opt.
Star 23	138.00133	-64.86623	Kurucz	50000	500	113.00	0.02	0.14	0.00	4.61	5	NUV, opt.
Star 24	137.99932	-64.85673	Kurucz	50000	500	97.80	0.13	0.13	0.00	3.77	5	NUV, opt.
Star 25	137.99187	-64.87307	Kurucz	35000	500	56.10	0.18	0.20	0.01	0.33	5	NUV, opt.
Star 26	137.99182	-64.85956	Kurucz	27000	500	67.70	0.32	0.38	0.01	0.11	5	NUV, opt.
Star 27	137.96443	-64.86377	Kurucz	50000	500	988.00	1.22	0.42	0.01	0.26	5	NUV, opt.
Star 28	137.85352	-64.87929	Kurucz	26000	500	65.36	0.97	0.39	0.02	2.58	15	FUV, NUV, opt.
Star 29	137.92453	-64.70158	Kurucz	32000	500	145.80	1.09	0.39	0.01	2.66	15	FUV, NUV, opt.
Star 30	138.08369	-64.84865	Kurucz	25000	500	98.59	1.03	0.52	0.02	2.89	13	FUV, NUV, opt.
Star 31	138.00728	-64.79293	Kurucz	23000	500	251.00	2.12	0.99	0.04	4.49	14	FUV, NUV, opt.
Star 32	137.99974	-64.89071	TMAP	100000	5000	3010.25	1.20	0.18	0.02	9.06	12	FUV, NUV, opt.
Star 33	138.02306	-64.89646	Kurucz	26000	500	53.26	0.51	0.36	0.01	2.39	11	FUV, NUV, opt.
Star 34	138.09187	-64.87727	Kurucz	24000	500	119.91	0.75	0.63	0.03	4.40	11	FUV, NUV, opt.

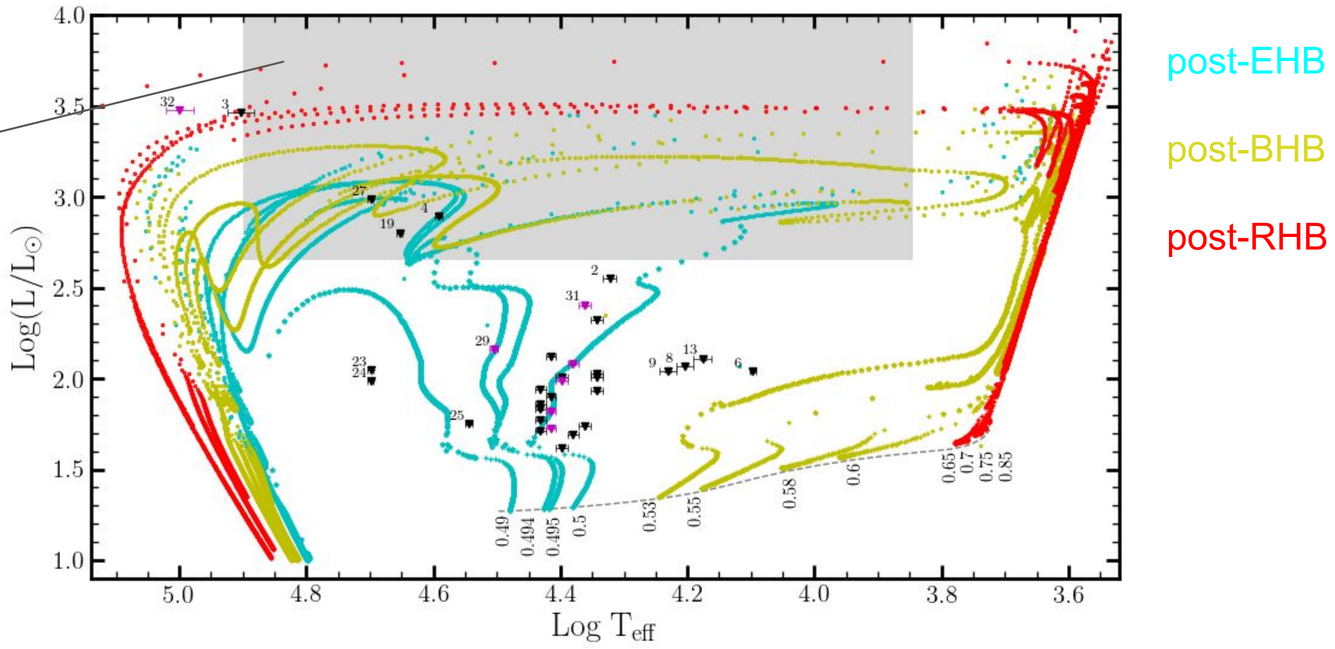
Comparison with literature values

ID	ID in literature	T_{eff} from literature (K)	T_{eff} from our analysis (K)	Reference
Star 13	AGBM1	14500	15500 ± 500	Brown et al. (2012)
Star 31	C4594	19900 ± 1600	23000 ± 500	Moehler et al. (2019)
Star 34	C2946	24900 ± 1800	24000 ± 500	Moehler et al. (2019)

Comparison with theoretical models

Expected location of hot p(e)AGB stars

- Most UV-bright stars are in the AGB-manque` phase with progenitor mass of M_{ZAHB} = $0.5 M_{sun}$
- Models suggest that all except 3 UV-bright stars have masses less than 0.53 M_{sun}.
- 2 hot p(e)AGB stars are observed and the hottest star has evolved off from this stage.



The post-HB evolutionary tracks from *Moehler et al. 2019* for [Fe/H] = -1 dex & age = 12 Gyr, corresponding to different ZAHB masses ranging from 0.49 M_{sun}- 0.85 M_{sun}.

Theoretical estimate of number of hot p(e)AGB stars

- The evolutionary flux method *(Greggio & Renzini 2011)* is used.
- The number of stars, N_i, in a particular stage of evolution *i*, in stellar population is given by the relation,

$$N_i = B(t) \times L_{total} \times t_i$$

where, *B(t)* is the specific evolutionary flux, L_{total} is the total luminosity of the stellar population and t_i is the duration of the evolutionary phase being analysed. For old systems like GCs, B(t) = 2 x 10^{-11} stars/yr/L_{sun}.

- The final expected number of hot p(e)AGB stars in the cluster is

$$N = (f_{RHB}.N^{RHB}) + (f_{BHB}.N^{BHB}) + (f_{EHB}.N^{EHB})$$

where f_{RHB}, f_{BHB}, f_{EHB} are the fractions of RHB, BHB & EHB stars in the cluster. These are obtained from our observations.

The range of expected number of hot p(e)AGB stars obtained for NGC 2808 is, $N_{p(e)AGB}$ = 1.3 – 3.8.

Summary

1. A comprehensive study of the UV- bright member stars in the GC NGC 2808 was performed for the first time using the AstroSat/UVIT, *HST, Gaia* DR2 and ground-based optical data.

2. 34 UV-bright stars were detected based on their locations in the UV CMDs. Fundamental parameters such as T_{eff} (12500 K to 100,000 K), *R* (0.13 to 2.2 R_{sun}) and *L* (~ 40 to 3000 L_{sun}) of these stars were estimated through SED fitting technique.

3. By comparing the derived parameters with theoretical models, most UV-bright stars were found to have evolved from EHB stars with M_{ZAHB} = 0.5 M_{sun} , and these are in the AGB-manqué phase. Models suggested that all except the three hottest and the most luminous UV-bright stars have HB progenitors with M_{ZAHB} < 0.53 M_{sun}.

4. The expected number of hot p(e)AGB stars in NGC 2808 was estimated from stellar evolutionary models and was found to agree well with the observed number.

5. Seven pHB stars identified in the outer region using the AstroSat/UVIT images are ideal for further spectroscopic follow-up studies. This work thus demonstrates the capability of the UVIT in detecting and characterizing the UV-bright stars.

For more details, please see *Prabhu, D. S., Subramaniam, A., & Sahu, S. 2021, ApJ, 908, 66*

THANK YOU!