The peculiar abundances of fluorine in hydrogen-deficient stars

Anirban Bhowmick
(anirban.phy91@gmail.com)

Indian Institute of Astrophysics

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Introduction

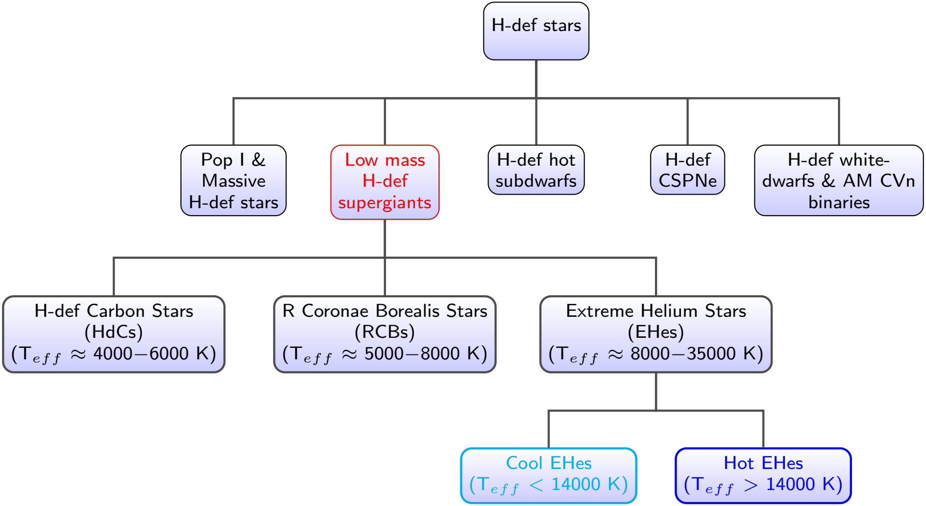
- Fluorine $\rightarrow$ 9th element of periodic table $\rightarrow$ cosmic origins still under scrutiny.
- Highly reactive to p and α- captures .. easily destroyed in stellar atmospheres $\rightarrow$ cosmic abundance orders of magnitude lower than neighbouring elements of periodic table.
- Most common line for astrophysical detection - line of **HF** in NIR **2.3358 μm**

Solar $\log \epsilon(\mathrm{F})_\odot$=4.40$\pm$0.25 ; $\log \epsilon(\mathrm{Fe})_\odot$ = 7.5 (Maiorca et al. 2014) , [F/Fe]$_\odot$ = 0 as reference

F for red giants in our Galaxy from HF lines $\rightarrow$ [F/Fe] $\leq$ 0.0 for the range of [Fe/H] 0 to -1.5 (Jonsson et al. 2017, Guerco et al. 2019) and slightly enhanced in AGBs – maximum 20-30 times solar (Jorissen 1992, Abia 2015).

- Predicted sources of formation based on cosmic abundance - rapidly rotating massive stars, ν-process nucleosynthesis in SNIIe, nucleosynthesis in He-burning Wolf-Rayet star atmospheres, TP pulsating AGBs and novae (Prantzos et al. 2018, Woosley et al. 1990, Palacios et al. 2005, Jorissen et al. 1992, Abia et al. 2015, Ryde et al. 2020).
- There exist a class of hydrogen-deficient stars in which F is overabundant by more than 1000 times!!! $\rightarrow$ *new sources of F production?*

Classification of hydrogen-deficient stars



- Hydrogen-deficient stars – **hence no detection of HF!**
- Werner et al. (2006) and Werner & Herwig (2006) detected ionised **F** V and **F** VI in the spectra of a class of hot hydrogen-deficient central stars of planetary nebula **PG 1159 stars** with an enhancement of 10-250 times.
- Pandey (2006) and Pandey et al. (2008) detected neutral **F** I lines in two classes of H-deficient supergiants – *the cool Extreme Helium Stars and the R Coronae Borealis stars* with an enrichment of 800-8000 times!
- Focus of my talk - status of F in H-deficient supergiants and our investigations on it (**Bhowmick et al. 2020**).

Shared peculiarities of cool EHes and RCBs:

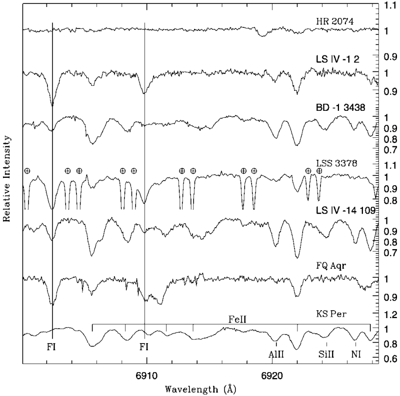


Figure: F I lines in Cool EHes (Pandey 2006).

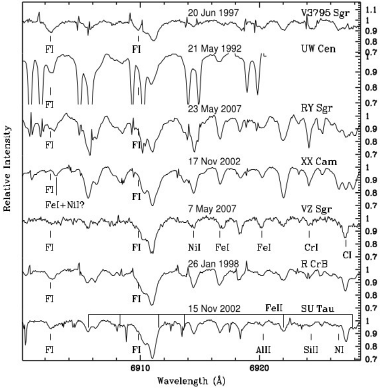


Figure: F I lines in RCBs (Pandey et al. 2008).

Table: F abundances of sample of cool EHes/RCBs:

Star name	(T_{eff}, logg, ξ)	logϵ(Fe)	logϵ(F)	Star type
FQ Aqr	(8750, 0.75, 8.0)	5.4	6.5	cool EHe
NO Ser	(11750, 2.3, 10.0)	6.7	6.2	cool EHe
UV Cas	(7250, 0.5, 7.0)	6.9	6.2	maj RCB
V3795 Sgr	(8000, 1.0, 10.0)	5.6	6.7	min RCB
Sakurai's object	(7500, 0.0, 8.0)	6.2	< 5.4	FF object

logϵ(Fe)$_\odot$ = 7.5 ; logϵ(F)$_\odot$ = 4.4 ; Taking ref: [F/Fe]$_\odot$ = 0 ;

Avg [F/Fe]$_{sample}$ = 3.3 !! *almost 2000 times higher !!*

Table: Previous status of F in H-deficient supergiants

HdC	RCBs	cool EHes	hot EHes
F (??) (T_{eff} too low for F I formation)	F detected in form of F I lines (Pandey et al. 2008)	F detected in form of F I lines Pandey, G. (2006)	??

Possible formation scenarios:

Unique chemical compositions, age and population in our galaxy → two proposed formation scenarios : the double degenerate (DD) merger and the final helium-shell flash (FF) model.

- **Final flash** (Iben 1983) → involves a late or final He-shell flash in a post-AGB star on the white dwarf cooling track, converting it to a H-poor cool supergiant (i.e., a HdC or RCB star) which then further evolves at about constant luminosity (i.e., as a EHe star) back to the white dwarf cooling track (Iben et al. 1983, Herwig 2001) → *Also known as Born-Again AGBs.*

- **DD scenario** (Webbink 1984, Iben & Tutukov 1984), involves merger of two low mass degenerate white dwarfs (He+He or more favourably He+CO) in a closed binary system , with episodes of nucleosynthesis accompanying the immediate phase of the merger and/or the post-merger phase.

- *FF scenario fails to account for the observed F over-abundance which is supported by non-detection of F in Sakurai's object (Eyres 1998, Pandey et al. 2008)*

- *CO+He WD DD merger can account for the exceptional F-overabundances. (Clayton 2007, Menon et al. 2013, 2019)*

Final flash scenario

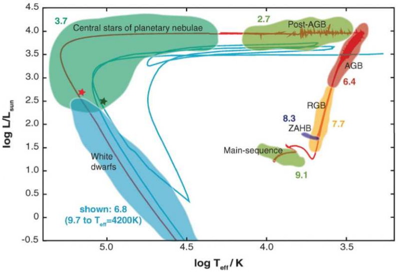


Figure: Evolution of a $2M_{\odot}$ star from Herwig et al. (2005) with different phases of evolution marked in different colours and labeled. The blue line traces the evolutionary path of a 'born-again' AGB after experiencing a final He-shell flash.

DD merger scenario

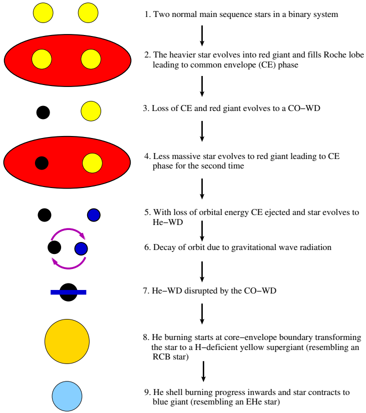


Figure: Illustration of formation for an RCB/EHe through DD merger scenario involving a CO-WD and a He-WD

Motivation of our work (Bhowmick et al. 2020)

Motivation:

- Cool EHes and warm RCBs $\rightarrow$ F overabundance.
- Severe F enrichment common to both warm RCBs and cool EHes was not observed in hot EHes.
- Peculiarities in hot EHes common with cool EHes and RCBs $\rightarrow$ *Possible evolutionary connection*! RCB $\rightarrow$ cool EHe $\rightarrow$ hot EHe !! $\rightarrow$ *DD merger most likely formation scenario.*

Idea:

- F detected in form of F I lines in cool EHes and warm RCBs $\rightarrow$ undetectable/weak in hot EHes due to hot effective temperatures, $\mathbf{T}_{eff} \geq$ **14000** K
- Singly ionized F lines (F II) appears in optical blue, 3500 Å and 3850 Å . observable using IIA HESP (High Resolution Echelle Spectrograph) on 2m HCT, Hanle.
- Availability of high resolution optical spectroscopic data of sample of hot EHes from ESO archives (ESO-UVES, ESO-FEROS).

Observation and selection of sample

- High-res optical Echelle spectra obtained for **10** hot EHes ($\mathbf{T}_{eff}$ $\geq$**14000** K)using HCT-HESP , ESO-FEROS, ESO-UVES and McDonald Observatory.

Table: Log of observations of the EHe stars.

Star name	Date of observation	Exposure time(secs)	V-mag	S/N (3500Å)	S/N(3800Å)	Source of spectra	$R = \lambda/\Delta\lambda$
LS IV+6° 2	2006-03-31	2000	12.2	120		UVES	40000
	2006-04-21	2980	12.2		175	FEROS	45000
V652 Her	2005-03-01	600	10.5		110	FEROS	45000
	2017-06-04	2700(5)	10.5		65	HESP	28000
	2018-04-22	2700(3)	10.5		40	HESP	28000
DY Cen	2010-02-27	1800	12.5	140	120	UVES	40000
V2205 Oph	2005-02-26	600	10.5		100	FEROS	45000
	2017-06-04	2400(4)	10.5		60	HESP	28000
	2018-05-09	2400(3)	10.5		50	HESP	29000
	2018-05-10	2400(3)	10.5		38	HESP	29000
HD 144941	2006-04-10	780	10.1	270		UVES	40000
	2006-01-08	3000	10.1		250	FEROS	45000
LSE 78	2006-01-10	1500	11.2	155		UVES	40000
	2006-04-09	2400	11.2		170	FEROS	45000
BD+10° 2179	2006-05-10	1000	10.0	220		UVES	40000
	2006-04-12	2820	10.0		210	FEROS	45000
	2018-01-13	2400(3)	10.0		95	HESP	29000
	2018-02-10	2400(3)	10.0		110	HESP	29000
	2018-03-27	2400(3)	10.0		80	HESP	29000
V1920 Cyg	1996-07-25	1800	10.3		110	McDonald	48000
HD 124448	2006-04-10	975	10.0	190		UVES	40000
	2006-04-08	2820	10.0		200	FEROS	45000
PV Tel	2006-04-08	1500	9.3		180	FEROS	45000

Targeted lines:

Table: F II lines from 3s − 3p and 3p − 3d transition array contributing to the spectra of the analysed stars. The F II lines used in abundance determinations are shown in bold.

Multiplet No.	λ Å	χ (ev)	log *gf*	Likely contributors
1	**3847.086**	21.88	0.31	F II, N II λ 3847.38
	3849.986	21.88	0.16	F II, Mg II(weak) λ 3850.40
	3851.667	21.88	−0.06	F II, O II λ 3851.47
2	4024.727	22.67	0.16	F II , He I , λ 4023.986 , 4026.189, 4026.362 (very strong)
	4025.010	22.67	−0.54	F II , He I , λ 4023.986 , 4026.189, 4026.362 (very strong)
	4025.495	22.67	−0.06	F II , He I , λ 4023.986 , 4026.189, 4026.362 (very strong)
3	**3505.614**	25.10	0.676	F II
	3505.520	25.10	0.09	F II
	3505.370	25.10	−0.757	F II
	3503.095	25.10	0.391	F II, Ne II λ 3503.61
	3502.954	25.10	0.187	F II, He I λ 3502.393 (strong)
	3501.416	25.10	0.074	F II, He I λ 3498.659 (very strong) , Fe III λ 3501.767
4	4103.525	25.75	0.559	F II, O II λ 4103.017, N III λ 4103.37 (strong)
	4103.085	25.75	0.289	F II, O II λ 4103.017, N III λ 4103.37 (strong)
	4103.724	25.75	−0.064	F II, N III λ 4103.37 (strong)
	4103.871	25.75	−0.19	F II N III λ 4103.37 (strong)
5	4109.173	26.26	0.45	F II, O II λ 4108.75 , Mg II, λ 4109.54
	4116.547	26.27	0.18	F II, Si IV λ 4116.104 (strong)
	4119.219	26.27	−0.01	F II, O II λ 4119.221 (strong)

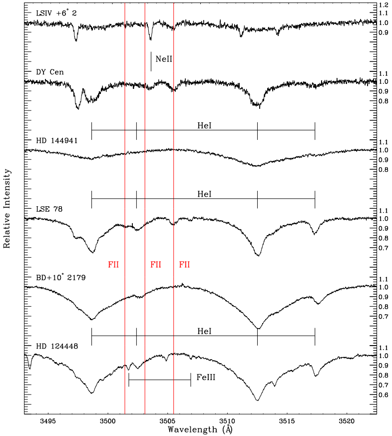


Figure: Comparison of the spectra with key identifications in 3500 Å region. F II lines of RMT 3 are represented by red.

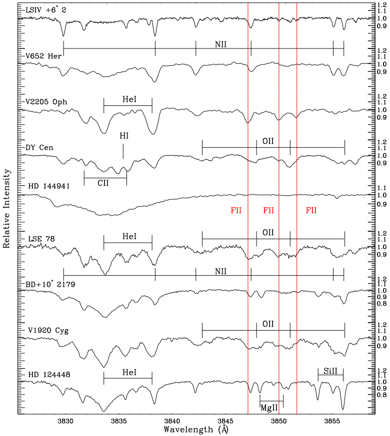


Figure: Comparison of the spectra with key identifications in 3850 Å region. F II lines of RMT 1 are represented by red.

Synthesis

- Spectrum synthesis code SYNSPEC (Hubeny et al. 1994) was used with the LTE model atmospheres of individual stars (from Pandey et al. (2006), Pandey et al. (2011), Pandey et al. (2014), & Pandey et al. (2017).

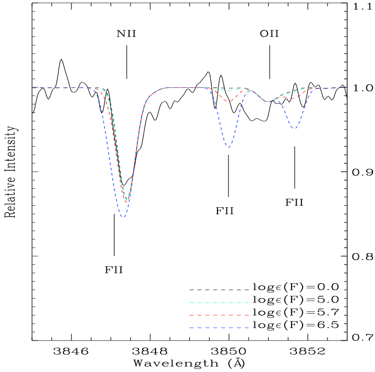


Figure: Observed F II in 3850Å of V652 Her (solid line) with key lines marked. Synthetic spectra are shown for four fluorine abundances.

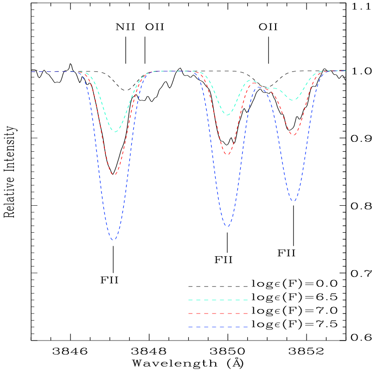


Figure: Observed F II in 3850Å of V2205 Oph (solid line) with key lines marked. Synthetic spectra are shown for four fluorine abundances.

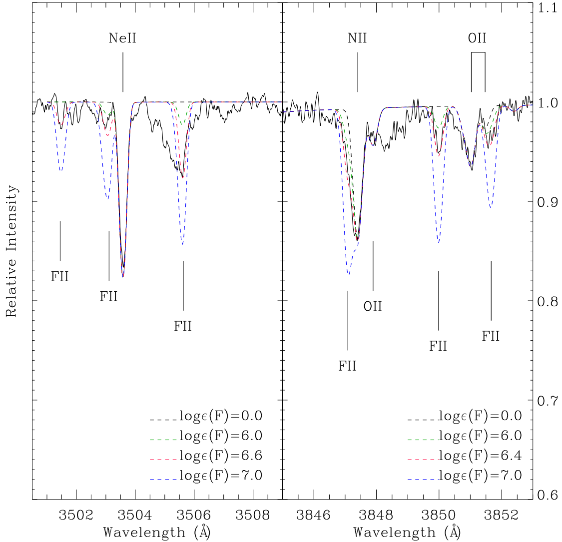


Figure: Observed F II in 3500Å and 3850Å of LS IV+6°2 (solid line) with key lines marked. Synthetic spectra are shown for four fluorine abundances.

Fluorine measurements

- F II lines are strongly detected in 6 of the 10 hot EHes.
- Upper limits are given for the two *carbon-poor* hots EHe V652 Her and HD 144941 and the two coolest member of the hot EHe group HD 124448 and PV Tel which doesn't show confirmed detection.

Table: Derived abundances of fluorine in hot EHes.

Star name	$(T_{eff}$, logg, $\xi)$	logϵ(F)						
		3847.086 Å	3849.986 Å	3851.667 Å	3505.614 Å	Mean	σ_1[a]	σ_2[b]
LS IV$+6^{\circ}$ 2	(32000, 4.20, 9.0) [2]	6.5	6.4	6.4	6.6	6.5	0.1	$\pm$0.1
V652 Her	(25300, 3.25, 13.0)[4]	$<$ 5.7	$<$ 5.5	$<$ 5.6	...	$<$ 5.6	...	...
V2205 Oph	(24800, 2.85, 23.0)[2]	7.0	7.0	7.0	...	7.0	0.1	$\pm$ 0.1
DY Cen	(24750, 2.65, 24.0)[3]	6.7	6.9	6.8	7.0	6.9	0.1	$\pm$ 0.2
HD 144941	(21000, 3.35, 10.0)[4]	$<$ 5.5	$<$ 5.7	$<$ 5.5	$<$ 5.5	$<$ 5.6	...	...
LSE 78	(18300, 2.2, 16.0)[1]	7.4	7.4	7.4	7.3	7.4	0.1	$\pm$ 0.2
BD$+10^{\circ}$ 2179	(17000, 2.6, 7.5)[2]	6.4	6.5	6.4	$<$ 6.5	6.4	0.2	$\pm$ 0.1
V1920 Cyg	(16300, 1.8, 20)[1]	7.5	7.6	7.5	...	7.5	0.2	$\pm$ 0.1
HD 124448	(15500, 2.0, 12)[1]	$<$ 6.0	$<$ 6.0	$<$ 6.0	$<$ 6.0	$<$ 6.0	...	...
PV Tel	(13750, 1.6, 25.0)[2]	$<$ 6.5	$<$ 6.5	$<$ 6.5	...	$<$ 6.5	...	...

[a] r.m.s error: $\Delta T_{eff} = \pm$ 500K , Δlogg $= \pm$ 0.2 cgs

[b] r.m.s error: line-to-line scatter

[1] Pandey et al. 2006

[2] Pandey et al. 2011

[3] Pandey et al. 2014

[4] Pandey et al. 2017

Fluorine enrichment:

Table: Elemental abundances of hot EHes.

Star name	$\log\epsilon$(X)							Ref
	C	N	O	Ne	Fe	F	Zr	
LS IV$+6^\circ$ 2	9.4	8.3	8.2	8.7	7.1	6.5	...	P11[2]
V652 Her	7.0	8.7	7.6	8.1	7.1	$\leq$ 5.6	...	P17[4]
V2205 Oph	9.1	7.8	8.0	8.2	6.6	7.0	...	P11[2]
DY Cen	9.6	7.8	9.0	8.0	6.0	6.9	...	P14[3]
HD 144941	6.9	6.4	7.1	7.2	$\leq$ 6.6	$\leq$ 5.6	...	P17[4]
LSE 78	9.4	8.3	9.4	8.7	6.8	7.4	3.5	P11[2], P06a[1]
BD$+10^\circ$ 2179	9.3	8.1	7.9	7.9	6.2	6.4	$\leq$ 2.6	P11[2], P06a[1]
V1920 Cyg	9.6	8.6	9.9	8.5	6.8	7.5	3.7	P11[2], P06a[1]
HD 124448	9.1	8.7	8.3	7.7	7.2	$\leq$ 6.0	2.7	P11[2], P06a[1]
PV Tel	9.2	8.6	8.8	7.6	7.0	$\leq$ 6.5	3.1	P11[2], P06a[1]

[1] Pandey et al. 2006
[2] Pandey et al. 2011
[3] Pandey et al. 2014
[4] Pandey et al. 2017

- Taking $\log\epsilon(\mathrm{F})_\odot = 4.40 \pm 0.25$ (Maiorca et al. 2014) for $\log\epsilon(\mathrm{Fe})_\odot = 7.5$ as reference; [F/Fe] = 0
- F for red giants in our Galaxy from HF lines → [F/Fe] $\leq$ 0.0 for the range of [Fe/H] 0 to -1.5 (Jonsson et al. 2017, Guerco et al. 2019)
- Average **[F/Fe]$_{hotEHes}$ = 3.5!** Remarkable overabundances of F!
- Overabundance of F in hot EHes similar to warm RCBs and cool EHes.

Test for non-LTE

- Compared with -**Neon** having similar atomic structure like F.
- Ne I suffers non-LTE effects: Abundance from Ne I $\sim$ 0.8 dex higher than those from Ne II (Pandey et al. 2011).
- Search for F I lines in the cooler counterparts of hot EHes and F II lines on previously reported cool EHes.
- F I line at 6856.02 Å V1920 Cyg $\rightarrow$ 7.8 ; LSE 78 $\rightarrow$ 7.5 .
- F II lines for LSS 3378 and PV Tel gives upper limit of 8.0 and 6.5 respectively.

Non-LTE effects!

Even if non-LTE effects are present comparable to Neon, a factor of 10, the level of the F overabundances in the EHes $\rightarrow$ *1000* !!! Overabundance of F in EHes and RCBs are *not in doubt*.

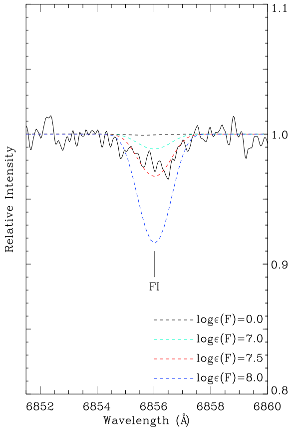


Figure: Observed F I in 6856 Å of LSE 78 (solid line) with key lines marked. Synthetic spectra are shown for four fluorine abundances.

Abundance trend of F with Fe

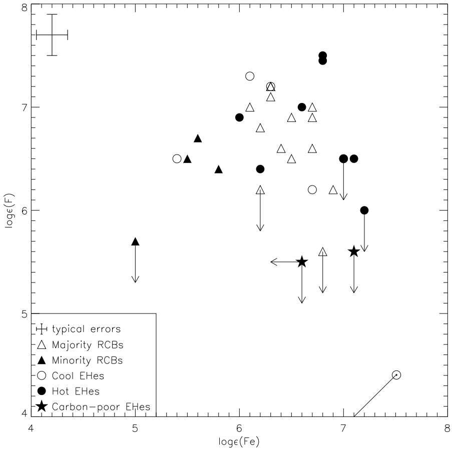


Figure: logϵ(F) versus logϵ(Fe) for hot EHes, cool EHes, and RCBs. The symbols representing different group of stars are showed. The encircled dot symbol represents the sun and the solid line represents locus of the solar ratio F/Fe.

- Remarkable F overabundance in hot EHes → from 250 to nearly 8000.

Abundance trends of F with C,N,O,Ne

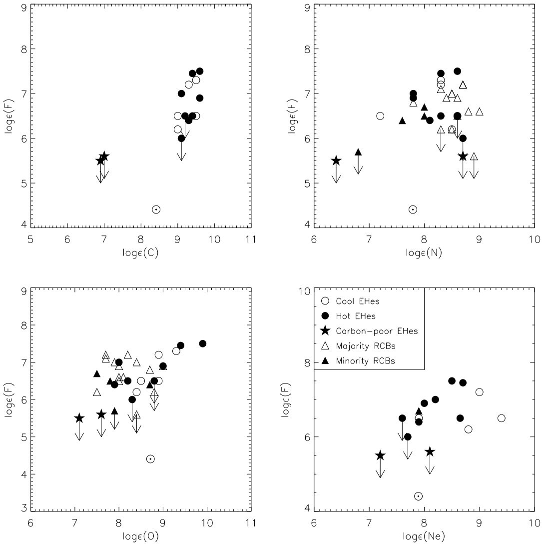


Figure: Observed logε(F) versus logε(X) for RCBs and EHes where X = C, N ,O and Ne respectively. The

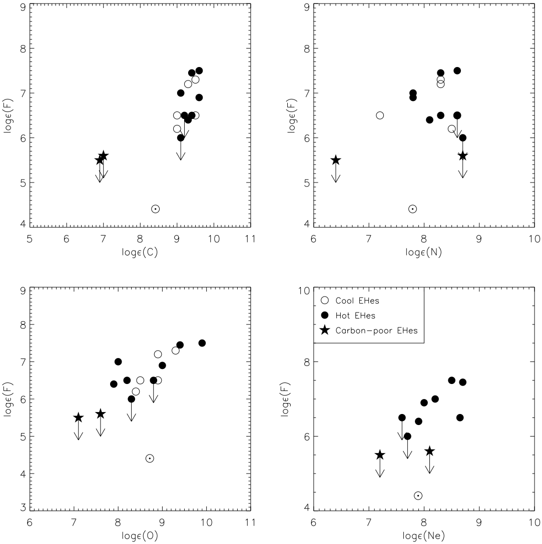


Figure: Observed logϵ(F) versus logϵ(X) for EHes where X = C, N ,O and Ne respectively. The encircled dot symbol represents the sun.

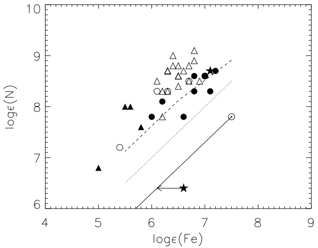
Reactions for F-synthesis

Reactions

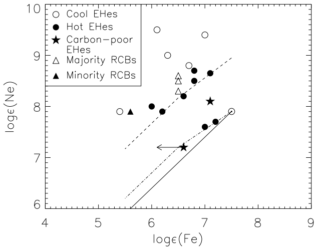
Two competing nucleosynthesis process are suggestion for over-production of ^{19}F:
$\Rightarrow$ ^{14}N$(\alpha,\gamma)^{18}$F$(\beta^{+}\nu)^{18}$O$(p,\gamma)^{19}$F by Clayton (2007) and Crawford (2020)
$\Rightarrow$ ^{14}N$(n,p)^{14}$C$(p,\gamma)^{15}$N$(\alpha,\gamma)^{19}$F by Menon et al. 2013, 2019.

- First one suffers from the availability of protons in a helium burning, H-deficient stellar atmosphere– Crawford (2020) $\rightarrow$ proton from mixing of remnant H-shell around the CO-WD, with the disrupted He-rich envelop during merger.
- For the 2nd case, by Menon (2013), the neutron required to initiate the reaction are given by ^{13}C$(\alpha,n)^{16}$O at onset of He burning and successfully reproduces the observed F abundances. ^{14}N acts as *neutron-poison* depleting neutrons available for *s-process*.
- For both the cases, ^{14}N is the principal seed for formation of ^{19}F.

Abundance trends of N and Ne vs Fe



- In the Figure of logϵ(N) vs logϵ(Fe) dashed line → $(\text{C+N+O})_{initial}$ with initial O obtained from the relation of $[\alpha/\text{Fe}]$ vs [Fe/H] for normal disk and halo stars given by Ryde & Lambert (2004)



- For logϵ(Ne) vs logϵ(Fe) dashed line → $(\text{C+N+O+Ne})_{initial}$ while the dot-dashed line → $\text{Ne}_{initial}$ from $[\alpha/\text{Fe}]$ vs [Fe/H] of Ryde & Lambert (2004)

Figure: Observed logϵ(N) and logϵ(Ne) versus logϵ(Fe)

Puzzle!!!

In EHes,

- $N_{observed} = (C+N+O)_{initial} \rightarrow N_{CNO}$ (during CNO cycling)
- $Ne_{observed} = (N+C+O+Ne)_{initial} = N_{CNO} + Ne_{initial} \rightarrow$ 100% conversion of CNO processed Nitrogen by α-captures to produce ^{22}Ne.
- Observed Ne $\uparrow$ without observed N $\downarrow$!!!! Simultaneous production of Ne and N ?
- Again where $Ne_{observed} = (N+C+O+Ne)_{initial} \rightarrow F \uparrow$
- If all of CNO-cycled **N** $\Rightarrow$ **Ne** then *how F is produced and overabundant? How observed nitrogen is not depleted?*
- *suggestion of existence of simultaneous regions of nucleosynthesis? history of binarity?*

Observed abundances in light of formation scenarios:

- CO+He WD merger models by Menon et al. (2013) & Menon et al. (2019) and Lauer et al. (2019) resulting in carbon-rich EHes accounts for F enrichment in EHes.
- He+He WD merger models by Zhang & Jeffery (2012a) account for the *carbon-poor* EHes (Pandey et al. 2017) don't predict fluorine. Observational result suggests carbon-poor EHes are F poor.
- Final compositions of the resulting single H-deficient stars are likely to depend on the type of the merger — CO+He or He+He — and on details of the stars (masses, compositions, ...)

Further proof of DD merger products enriched in F (??) → discovery of optical F II lines in hot subdwarf SB 744 (Nemeth 2021). *Hot subdwarfs are thought to be the result of binary mergers (Heber 2016)*

Summary

- **One of the first detections of F II lines in optical in any astrophysical spectra!!**
- Remarkable overabundance of F in hot EHes in comparison to solar determinations and normal stars (250 $\sim$ 10000)!
- Large F overabundances for hot EHe compatible with those for cool EHes and RCBs $\sim$ 6.7.
- Answers the decade old mystery about their formation and establishes a firm evolutionary connection between the H-def objects across a wide range of effective temperature.
- CO+He WD merger $\rightarrow$ carbon-rich EHes , F $\uparrow$,
  He+He WD merger $\rightarrow$ carbon-poor EHes, F $\downarrow$.
- Simultaneous overproduction of Ne and F without N getting depleted!! $\rightarrow$ *existence of different regions of nucleosynthesis? history of binary system?*
- *Can DD merger be considered one of the viable source for cosmic fluorine budget (??).* Rarity of such observed objects indicate otherwise.

THANK YOU

"I have loved the stars too fondly to be fearful of the night"

— Sarah Williams