J. Astrophys. Astr. (2020)41:40
https://doi.org/10.1007/s12036-020-09659-2

Fluorine detection in hot extreme helium stars

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MS received 5 September 2020; accepted 5 October 2020

Abstract. The origin and evolution of hydrogen-deficient stars are not yet adequately understood. Their chemical peculiarities, along with hydrogen-deficiency, makes them stand out from the rest and sheds light on their possible origin. Severe fluorine enrichment (of the order of 800–8000) is one such characteristic feature of a class of hydrogen deficient stars, mainly the RCBs (R Coronae Borealis stars) and cool EHes (Extreme Helium stars) which enforces their close connection. For hot EHes, this relationship with the cooler EHes, based on their fluorine abundance is unexplored. Here, first estimates of fluorine abundances in hot EHes are presented and discussed in the light of their cooler counterparts to try to establish an evolutionary connection. The relation between these fluorine estimates with the other elemental abundances observed in these stars plays a pivotal role to predict the formation and evolution of these exotic stars.

Keyword. Hydrogen-deficient stars—chemical peculiarity—cxtreme helium stars.

1. Introduction

Extreme helium stars (EHes) are helium rich, A- and B-type, hydrogen deficient supergiants having effective temperatures in the range of 8000−35000 K. The observed surface composition of these stars are similar to the cooler H-deficient stars, namely the R Coronae Borealis (RCB) and hydrogen-deficient carbon (HdC) stars. Apart from sharing extreme hydrogen deficiency, EHe, RCB and HdC stars also exhibit typical chemical peculiarities.

The two most extraordinary peculiarities observed in the surface compositions of these H-deficient stars are (i) the extreme overabundance of ^{18}O in HdC and cool RCBs such that $^{18}O/^{16}O > 1$ (Clayton *et al.* 2007) and (ii) a startling overabundance of F in RCBs and cool EHes such that F relative to Fe is enhanced by 800 to 8000 times (Pandey 2006; Pandey *et al.* 2008; Hema *et al.* 2017). The status of these anomalies in hot EHes are unknown. This work addresses the F abundance of the hot EHes, and hence determine if these peculiarities extend to the hot EHes.

EHes are extremely rare in the Galaxy, with 22 discovered till date (Jeffery *et al.* 1996; Jeffery 2017). There are about 17 known EHes, having effective temperatures hotter than about 14000 K and are classified as hot EHes. In this work, ten hot EHes are examined. For the hot EHes, sufficient knowledge about the two notable chemical peculiarities of the cool H-deficient stars, i.e., ^{18}O and F were unexplored. Since the O isotopic abundances were determined from CO molecular lines in the infrared spectrum and CO molecules cannot exist in the atmospheres of hot (or cool) EHes due to higher effective temperature, the O isotopic abundances are unobtainable for EHes. Fluorine abundances are, however, obtainable for EHes.

The observed chemical composition suggests a hydrogen-deficient atmosphere, including material exposed to both H- and He-burning. Based on their observed surface composition, two main formation

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This article is part of the Topical Collection: Chemical Elements in the Universe: Origin and Evolution.

scenarios are proposed: "double-degenerate" (DD) merger scenario involving the merger of a He white dwarf with a more massive C–O white dwarf (Iben & Tutukov 1984; Webbink 1984) and the "final-flash" (FF) model involving a late or final He-shell flash in a post-AGB star transforming the star into a hydrogen-deficient supergiant (Iben *et al.*1983). Based primarily on the F, Ne, ^{13}C and ^{18}O abundances, there is a growing consensus for the DD scenario; however, a small fraction may be produced by FF scenario.

If the pattern of chemical peculiarities appears common across the HdC, RCB and EHe, primarily a sequence of increasing effective temperature, a common formation scenario would seem likely. As mentioned above, the ^{18}O abundance anomaly cannot be investigated in EHes, but the F anomaly is determinable across the sequence. For warm RCBs and the cooler EHes, neutral fluorine (F I) lines were detected which provided the high-F overabundances (Pandey *et al.* 2006, 2008; Hema *et al.* 2017). For hot EHes, the F I lines are undetectable in optical spectra, but lines of ionized fluorine should be present in the ultraviolet (3500–3900 Å) if the F abundance is anomalous and overabundant. To date, the only confirmed detection of F II lines in an H-deficient star is Pandey *et al.* (2014)'s detection of F II lines at 3500–3510 Å in the spectrum of hot EHe/hot RCB DY Cen. However, DY Cen is an odd H-deficient star having relatively high hydrogen abundance. Detection of fluorine in other hot EHes is yet to be explored. Here we report F abundances (or upper limits) for ten hot EHes. The knowledge of the fluorine abundance and its relation to the other abundant species found in these stars plays an important role in discovering the nucleosynthesis processes taking place which in turn helps to determine their origin and evolution.

2. Observation

High-resolution optical echelle spectra of ten hot EHes were obtained from the following telescopes/spectrograph combination: HCT-HESP, ESO-FEROS and ESO-UVES, and McDonald Observatory.

Three hot EHes: V652 Her, V2205 Oph and BD +10° 2179 were observed using Hanle Echelle Spectrograph (HESP) mounted on the 2-m Himalayana Chandra Telescope (HCT) at the Indian Astronomical Observatory (IAO) in Hanle, Ladakh, India. Spectra of stars inaccessible from HESP were obtained from ESO data archives involving spectra from ESO-FEROS and ESO-UVES telescope/spectrograph combination. Spectrum of the hot EHe V1920 Cyg was obtained from W. J. McDonald Observatory. All but two stars (DY Cen and V1920 Cyg) were complemented with more than one telescope/spectrograph combination.

3. Identification

In hot EHes, fluorine if present will appear as singly-ionized fluorine lines, F II. Multiplets 1–5, in the Revised Multiplet Table (RMT) of Moore (1972) and by Wiese *et al.* (1996) are the potential contributors of F II absorption lines in the spectra. The adopted log *gf* values were compiled from the NIST database. The following four F II lines were identified as a significant contributor to stellar profiles: 3847.086 Å, 3849.986 Å and 3851.667 Å and the fourth line centred at 3505.614 Å (a blend of 3 components 3505.614 Å, 3505.52 Å and 3505.37 Å). To account for the contribution of blending components and to accurately determine F II line's contribution, spectrum synthesis was done using the code SYNSPEC (Hubeny *et al.* 1994) with LTE model atmospheres of individual stars from Pandey *et al.* (2006), Pandey *et al.* (2014) and Pandey Lambert (2011), Pandey Lambert (2017). The measured fluorine abundances (Table 1) are given as $\log\epsilon(X)$ normalised to $\log\sum\mu_i\epsilon(i) = 12.15$, where μ_i is the atomic weight of the element i.

4. Results and discussion

The main results summarised from Bhowmick *et al.* (2020) are as follows:

- F II lines were strongly detected in 6 out of 10 hot EHes. Upper limits were obtained for two C-poor EHes, V652 Her and HD 144941, and the two coolest members of this group, HD 124448 and PV Tel, which does not show confirmed detection.
- F is found to be highly enriched in atmospheres of hot EHes, and excluding the four stars having uncertain F detection, the mean F abundance is around 6.9 which is very similar to those of cool EHes and RCBs reported earlier.
- While the Galactic F abundance measurements from red giants follow [F/Fe] $\simeq$ 0.0 (Maiorca *et al.* 2014; Jönsson *et al.* 2014, 2017; Guerço *et al.* 2019) over the [Fe/H] interval 0 to −1.5,

Table 1. Derived fluorine abundances in hot EHes.

		log ϵ(F)						
Star name	($T_{\rm eff}$, log g, ξ)	3847.086 Å	3849.986 Å	3851.667 Å	3505.614 Å	Mean	$\sigma_1^{\rm a}$	$\sigma_2^{\rm b}$
LS IV+6° 2	(32000, 4.20, 9.0)[1]	6.5	6.4	6.4	6.6	6.5	0.1	±0.1
V652 Her	(25300, 3.25, 13.0)[2]	<5.7	<5.5	<5.6	–	<5.6	–	–
V2205 Oph	(24800, 2.85, 23.0)[1]	7.0	7.0	7.0	–	7.0	0.1	± 0.1
DY Cen	(24750, 2.65, 24.0)[3]	6.7	6.9	6.8	7.0	6.9	0.1	± 0.2
HD 144941	(21000, 3.35, 10.0)[2]	<5.5	<5.7	<5.5	<5.5	<5.6	–	–
LSE 78	(18300, 2.2, 16.0)[4]	7.4	7.4	7.4	7.3	7.4	0.1	± 0.2
BD +10° 2179	(17000, 2.6, 7.5)[1]	6.4	6.5	6.4	< 6.5	6.4	0.2	± 0.1
V1920 Cyg	(16300, 1.8, 20)[4]	7.5	7.6	7.5	–	7.5	0.2	± 0.1
HD 124448	(15500, 2.0, 12)[4]	<6.0	<6.0	<6.0	<6.0	<6.0	–	–
PV Tel	(13750, 1.6, 25.0)[1]	<6.5	<6.5	<6.5	–	<6.5	–	–

[a]R.m.s. error: $\Delta T_{\rm eff} = \pm 500$ K, $\Delta \log g = \pm 0.2$ cgs, [b]R.m.s error: line-to-line scatter. [1]Pandey & Lambert (2011), [2]Pandey & Lambert (2017), [3]Pandey *et al.* (2014), [4]Pandey *et al.* (2006).

F-rich hot EHes lying in the similar metallicity interval, show a range of [F/Fe] from 2.5 to 4.0 suggesting F-enhancement by a factor of 300 to 10000 times than normal stars.

- F II lines do not vary smoothly with effective temperature, and the F abundances can be significantly different in EHes having similar effective temperatures suggesting individual evolutionary processes.
- A check on non-LTE effects on F II was carried out by determining abundance estimates through F I lines, if present. Similar estimates from F II and F I lines and in some cases complementary upper limits from both F I and F II lines rule out non-LTE effects confirming the abundance estimates.
- There is no possible correlation between F and C, N, Fe and s-process elements. For EHes, O–F suggest a positive correlation whereas there may exist a positive correlation between Ne–F if non-LTE corrected neon abundances are made available for the entire sequence of cool and hot EHes.

The uncertainties of fluorine abundances in two C-poor EHes suggest a different evolutionary process which may be responsible for such compositions. In EHes, the observed N abundances are similar to the N predicted from H-burning via CNO cycle involving conversion of initial C, N, O to N. It is interesting to note that the observed Ne abundances are also equal to the Ne predicted from the complete conversion of N to Ne via α capture during He-burning. Interestingly, it was found that the EHes, where observed Ne is not similar to the predicted Ne, are F-poor. The case for simultaneous overproduction of Ne and F without any visible depletion of N is a fascinating topic and needs to be explored further.

5. DD merger scenario and fluorine abundance

The DD merger scenario cannot account for the extraordinary F abundances in RCBs and EHes without episodes of nucleosynthesis accompanying the immediate phase of the merger and/or the post-merger phase. The final compositions of the resulting H-deficient stars are dependent on the types of the merger (CO+He or He+He), on details of the progenitor (masses, compositions, etc.) and the (complex) physics of the whole merger process. Lauer *et al.* (2019) in his CO+He WD merger model predicts enrichment of F, though the predicted F abundance is less than the observed value by a factor of 3. Menon *et al.* (2013), Menon *et al.* (2019) successfully reported that their CO+He WD merger models, spanning the entire metallicity range occupied by the RCB/EHe stars, reproduces the observed F abundances in these stars. Menon *et al.* (2013) in their models noted that one of the principal sources of F is in the He-burning shell of the post-merger star, where $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ serves as a neutron source and $^{14}\mathrm{N}$ is both a neutron poison and an F source: $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}(p,\gamma)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$. Though the CO+He merger models of Menon *et al.* (2013), Menon *et al.* (2019) correctly predicts enhancement of F, yet there are few drawbacks like overestimation of the other surface compositions notably C and O, suggesting that the simulations of the merger/post-merger phases have yet to achieve the finality. Simulations of He+He white dwarf mergers by Zhang & Jeffery (2012) accounts for F enrichment in C-rich EHes, yet not enough to match with observed F abundances. For C-poor EHes, there is still no F prediction for He+He WD merger models. Hence it seems fair enough to conclude that, the present simulations considering the DD scenario with CO+He white dwarf mergers account well for the F abundance anomaly of RCB/EHes, without introducing further anomalies in the C, N, O and Ne abundances.

6. Conclusion

With the discovery of severe F-enrichment in hot EHes which is perfectly in line with the reported F-overabundances of RCB and cool EHes, it remains no doubt that they are evolutionarily connected and may have common origins. The observed F overabundances that match well with the prediction of DD merger models solve decade-old mystery about the origin and evolution of these exotic stars. However, questions such as these remain: “How can N and Ne both have the abundance implied by the total conversion of initial C, N and O?”

Acknowledgements

The authors thank the organizing committee of the ‘150 Years of Periodic Table’ conference, and IIA, Bengaluru for all their support.

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