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Discovery of Fluorine in Cool Extreme Helium Stars

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ABSTRACT

Neutral fluorine (F I) lines are identified in the optical spectra of cool EHe stars. These are the first identification of F I lines in a star's spectrum, and provide the first measurement of fluorine abundances in EHe stars. The results show that fluorine is overabundant in EHe stars. The overabundance of fluorine provides evidence for the synthesis of fluorine in these stars, that is discussed in the light of asymptotic giant branch (AGB) evolution, and the expectation from accretion of an He white dwarf by a C-O white dwarf.

Subject headings: stars: abundances – stars: chemically peculiar – stars: evolution

1. Introduction

The solar system, for a long time, has been the only source of information about the fluorine abundance in the Galaxy (Hall & Noyes 1969). The astrophysical origin of solar system's fluorine is not yet identified from the known theories of stellar nucleosynthesis. The major problem with fluorine production is that, the element has only one stable, yet rather fragile, isotope, ^{19}F. In stellar interiors it is readily destroyed by hydrogen via ^{19}F(p,α)^{16}O and helium via ^{19}F(α,p)^{22}Ne. The high F abundances which were measured, using infrared HF vibration-rotation transitions, in the asymptotic giant branch (AGB) stars from the Jorissen, Smith & Lambert (1992) sample, provided clues for fluorine production in AGB stars. The Cunha et al. (2003) study measured F abundances in different populations: in galactic red giants (a subset of Jorissen et al. sample), in red giants in the Large Magellanic Cloud (LMC), as well as in a few stars in the globular cluster Omega Centauri. Concerning ω Cen, the F abundances found in that study were quite low. One possible interpretation

was that the AGB stars in ω Cen did not contribute significantly to the fluorine. However, this conclusion assumes that there has been effective AGB pollution in ω Cen.

Apart from the third dredge-up of AGB stars, the other two sources of fluorine are Type II supernovae (SNe) explosions, and stellar winds from Wolf-Rayet (W-R) stars. Woosley & Weaver (1995) showed that in Type II SNe, ^{19}F can be created by spallation of ^{20}Ne by neutrinos. In massive or W-R stars, ^{19}F is probably produced during He-burning phase and, before it gets annihilated, is ejected into space by strong stellar winds (Maynet & Arnould 2000). In AGB stars ^{19}F is predicted to be produced in the convective He-rich intershell and then dredged-up to the surface during the He-burning thermal pulses (Forestini et al. 1992). The reaction chain for F production in the He-burning environments of AGB and W-R stars is: ^{14}N$(\alpha,\gamma)^{18}$F$(\beta^{+})^{18}$O$(p,\alpha)^{15}$N$(\alpha,\gamma)^{19}$F. Protons are provided by the ^{14}N$(n,p)^{14}$C reaction with neutrons liberated from ^{13}C$(\alpha,n)^{16}$O. The ^{14}N and ^{13}C nuclei are the result of H-burning by CNO cycling, and the initial ^{13}C stock acts as a limiting factor for the ^{19}F yield.

The Cunha et al.'s same fluorine abundance results for the Milky Way were later discussed in Renda et al. (2004) in light of a chemical evolution model for the Galaxy that took into account all possible sources for fluorine production. This chemical evolution model, however, cannot be applied to the peculiar globular cluster ω Cen and the low fluorine abundance results for ω Cen remain puzzling. Renda et al. suggest that both W-R and AGB stars are significant sources of fluorine, and that is supported by the evidence of enhanced F abundance from F v and F vi absorption lines in the far-UV spectra of hot post-AGB PG 1159 stars (Werner, Rauch & Kruk 2005). Also, Zhang & Liu (2005) determine F abundances from the nebular emission lines: [F ii] line at 4789Å and [F iv] line at 4060Å, for a sample of Planetary nebulae (PNe). Fluorine is abundant in PNe, and this provides evidence for the synthesis of fluorine in the AGB phase. No evidence of enhanced fluorine resulting from spallation in Type II SNe is suggested by the observations of F i interstellar absorption line at 955Å in two sight lines towards the Cep OB2 association using *Far Ultraviolet Spectroscopic Explorer* (Federman et al. 2005).

Extreme helium (EHe) stars, see for Pandey et al. (2006a) and the references therein, are suggested to have gone through AGB phase in their earlier evolution, hence, fluorine should be present in their atmospheres. Presence of fluorine in EHe's atmosphere can serve as a test bed for fluorine production in AGB stars. In this letter, we present fluorine abundances for the sample of cool EHe stars from F i lines.

2. Observations

High-resolution optical spectra of four cool EHes: FQ Aqr, LS IV-14° 109, BD -1° 3438, and LS IV-1° 2, were obtained at the W. J. McDonald Observatory's 2.7-m telescope with the coudé cross-dispersed echelle spectrograph (Tull et al. 1995) at a 2-pixel resolving power (R $=\lambda/\Delta\lambda$) of 60,000. The details of these observations are described in Pandey et al. (2001). The observations of the cool EHe LSS 3378, described in Pandey & Reddy (2006), were acquired at CTIO.

Finally, spectra of HD 168476 = PV Tel, the coolest member of the hot EHe stars, were obtained with the Vainu Bappu Telescope (VBT) of the Indian Institute of Astrophysics with a fiber-fed cross-dispersed echelle spectrometer (Rao et al. 2004, 2005). These spectra with a resolving power of about 30,000 were recorded on a 2048 × 4096 pixels CCD camera exclusively built for the spectrometer. The signal-to-noise (S/N) per pixel of the final co-added spectrum, from the exposures obtained on 2006 April 22 and 2006 May 15, is ∼40 at about 6902Å.

In addition, McDonald spectra of HR 2074, a normal A0 Ia-type supergiant, and KS Per, a H-deficient hot primary of a spectroscopic binary, were available for examination. The telluric absorption lines from the spectra of the programme stars were removed interactively using early-type rapidly rotating stars. We have used the Image Reduction and Analysis Facility (IRAF) software packages to reduce the spectra, and the task *telluric* within IRAF to remove the telluric absorption lines. In Figure 1, the telluric absorption lines from the spectrum of the cool EHe LSS 3378 are not removed just to show their presence.

3. F I Lines

The multiplets numbered 1, 2, 4, and 6 by Moore (1972) are potential contributors of F I absorption lines to cool EHe stars' spectra. Complete listings of the wavelengths for lines of these multiplets from the $3s - 3p$ transition array were compiled from the NIST database[1]. Measured gf-values were taken from Musielok et al. (1999) who show that their results are in fair agreement not only with the semiempirical calculations of Kurucz & Peytremann (1975) but also with earlier experimental determinations; the latter on a relative scale. Table 1 gives a partial list of these multiplets; lines of very small gf-value are omitted on the ground that their F I contribution must be very small.

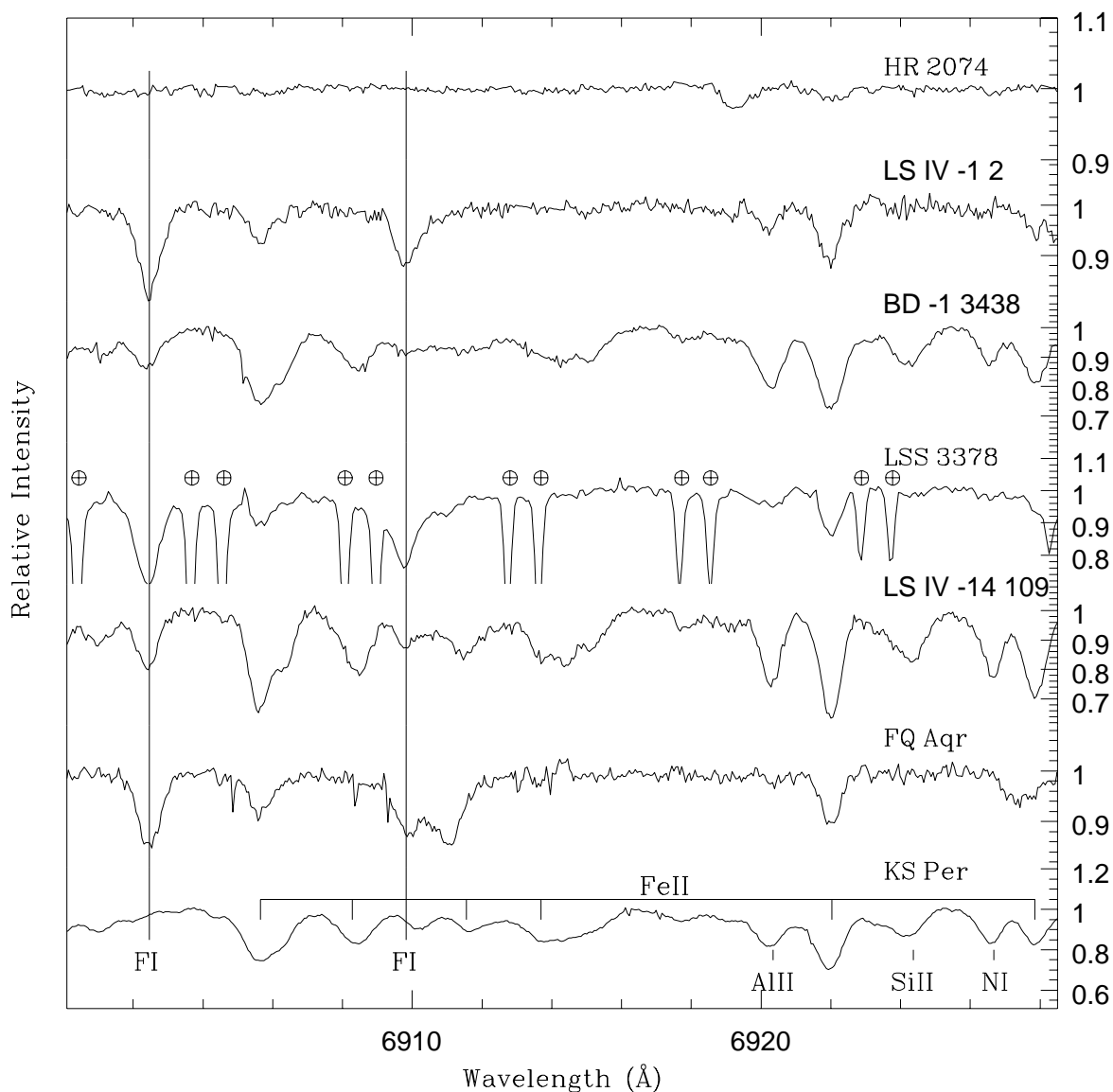[1]http://physics.nist.gov/PhysRefData/ASD/lines_form.html

Fig. 1.— A sample of F I lines, that are indicated by vertical solid lines, region of the spectra of cool EHe stars that are plotted with their effective temperatures increasing from bottom to top. The positions of the key lines are identified in this window from 6900 Å to 6928 Å. The telluric absorption lines in the spectrum of LSS 3378 are shown marked ⊕. The spectra of KS Per and HR 2074 are also plotted.

Table 1

F I lines from $2s^2 2p^4(^3\mathrm{P})3s - 2s^2 2p^4(^3\mathrm{P})3p$ transition array detected in the spectra of the analysed stars. The F I lines used in abundance determination for all the analysed cool EHes are shown in bold

Multiplet (No.)	λ (Å)	χ (eV)	$\log gf$	Contributors
$3s\ ^4\mathrm{P} - 3p\ ^4\mathrm{P}°$	**7482.72**	12.73	-0.66	F I, C I λ7483.445Å (red wing), Fe II λ7482.777Å (weak)
(1)	7514.93	12.75	-0.96	F I
	7331.95	12.70	-0.11	F I, N I λ7332.055Å, Fe II λ7332.115Å (weak)
	7425.64	12.73	-0.19	F I, Fe II λ7425.095Å
	7552.24	12.73	-0.34	F I
	7573.41	12.75	-0.34	F I
$3s\ ^4\mathrm{P} - 3p\ ^4\mathrm{D}°$	**6856.02**	12.70	$+0.44$	F I, Fe II λ6855.646Å
(2)	**6902.46**	12.73	$+0.18$	F I
	6909.82	12.75	-0.23	F I
	6773.97	12.70	-0.40	F I, Fe II λ6774.146Å, Fe II λ6774.473Å (red wing)
	6834.26	12.73	-0.21	F I
	6795.52	12.73	-1.09	F I
$3s\ ^2\mathrm{P} - 3p\ ^2\mathrm{D}°$	**7754.70**	12.98	$+0.24$	F I, Ti II λ7755.751Å (red wing)
(4)	**7800.22**	13.03	$+0.04$	F I, Si I λ7799.996Å (weak), Fe II λ7801.235Å (red wing)
$3s\ ^2\mathrm{P} - 3p\ ^2\mathrm{P}°$	**7037.45**	12.98	$+0.10$	F I, unknown blend (blue wing)
(6)	7127.88	13.03	-0.12	F I
	6966.35	12.98	-1.01	F I

Eleven F I lines were identified as the principal or leading contributor to a stellar line - see Table 1. Figure 1 illustrates the window from 6900Å to 6928Å that represents a couple of F I lines at 6902.46, and 6909.82Å, where the cool EHe stars are ordered from top to bottom in order of decreasing effective temperature. All spectra are alligned to the rest wavelengths of the well known lines, that fall in the wavelength regions. At the bottom, KS Per is added, which is known to be H-deficient (Wallerstein, Greene & Tomley 1967; Pandey et al. 2006b). The spectrum of KS Per very much resembles the spectrum of the cool EHe LS IV-14° 109, except for the C I lines which are extremely week or not present in the KS Per's spectrum (Wallerstein, Greene & Tomley 1967; Pandey et al. 2006b). Singly ionized metal lines (particularly Fe II) are identified as contributor to a stellar line at or about F I lines in KS Per's spectrum. Note the presence of almost no lines in the KS Per's spectrum at or about some contributing F I lines in cool EHes' spectra (Figure 1). Only these F I lines, if not blended by C I lines, are identified as the sole major contributor to a stellar line in a cool EHe's spectrum. The pattern to be contrasted is, for example, the C I and F I lines show little variation in these cool EHe stars when compared to the metal lines (e.g., Fe II) that show a considerable star to star variation (Figure 1). Finally, the spectrum of HR 2074, a normal A0 Ia-type supergiant is shown at the top. Lines of all elements expected and observed in the spectrum of a normal A0 Ia-type supergiant were found. Lines of ionized metals of the iron group are plentiful. These lines are much stronger when compared with those observed in HR 2074, a notable feature of the spectra of cool EHe stars and KS Per, and attributable to the lower opacity in the atmosphere due to hydrogen deficiency.

For all F I lines, an attempt was made to conduct a thorough search for blending lines. Databases examined included the Kurucz's database[2], tables of spectra of H, C, N, and O (Moore 1993), selected tables of atomic spectra of Si (Moore 1965, 1967), the NIST database, and the new Fe I multiplet table (Nave et al. 1994). These provided not only wavelengths of potential blends but also estimates of a line's gf-value. The spectrum of supergiant HR 2074 was also considered; F I is not represented in its spectrum.

The contributors to a stellar line at or about F I lines are listed in Table 1; the lines shown in bold are selected for abundance determination for all the analysed cool EHes. The additional F I lines listed in Table 1 are in the missing wavelength regions of the McDonald spectra, and, are only used in abundance determination for the cool EHe LSS 3378.

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[2]http://kurucz.harvard.edu

4.   Abundance analysis

The fluorine abundances were determined from the F I lines listed in Table 1, by adopting the same procedure described in Pandey et al. (2006a). A model atmosphere is used with the Armagh LTE code SPECTRUM (Jeffery, Woolf & Pollacco 2001) to compute the equivalent width of a F I line or a synthetic spectrum for a selected spectral window. The synthetic spectrum was convolved with a Gaussian profile, to account for the combined effects of the stellar macroturbulence and the intrumental profile, before matching with the observed spectrum. The fact that several F I lines are blended with other lines requires that the fluorine abundance be extracted by spectrum synthesis. However, most of the F I lines are only slightly blended in the iron poor cool EHe stars: FQ Aqr, LSS 3378, and LS IV-1° 2.

H-deficient model atmospheres have been computed using the code STERNE (Jeffery, Woolf & Pollacco 2001) for the four stars with an effective temperature greater than 10,000 K (Table 2). For FQ Aqr with $T_{\mathrm{eff}} = 8750$ K, and LS IV-14° 109 with $T_{\mathrm{eff}} = 9500$ K, we adopt the Uppsala model atmospheres (Asplund et al. 1997).

The adopted stellar parameters: effective temperature (T_{eff}), surface gravity ($\log g$), microturbulent velocity (ξ) and a carbon-to-helium abundance ratio C/He, are from Pandey et al. (2001) for FQ Aqr, LS IV-14° 109, BD-1° 3438, and LS IV-1° 2, from Pandey & Reddy (2006) for LSS 3378, and from Pandey et al. (2006a) for PV Tel. Similarly, the elemental abundances affecting the blending lines were also taken from the above references. The contribution of the blends were varied within limits set by the abundances and the gf-values. The gf-values of the blending lines Si I, C I, and rest of the lines (see Table 1), are from the compilations by R. E. Luck (private communication), NIST database, and Kurucz's database, respectively. An example of the best fitting profiles, for 7 of the studied F I wavelength regions, is illustrated in Figure 2 for the sample cool EHe FQ Aqr. The measured mean fluorine abundances (Table 2) are given as $\log \epsilon(\mathrm{F})$, normalized such that $\log \Sigma \mu_i \epsilon(i) = 12.15$ where μ_i is the atomic weight of element i. An upper limit to the F abundance for PV Tel is obtained by comparing the synthetic and observed profiles of the F I line at 6902.46Å (Table 2). An upper limit to the F abundance for KS Per, the H-deficient binary that shows pure hydrogen burnt CN- and ON-cycled material, is also estimated from the nondetection of the F I line at 6902.46Å (Figure 1, Table 2). The line-to-line abundance scatter, and the number of lines used given within brackets, are in column 3 of Table 2. The effective error in F abundances due to uncertainty in the adopted stellar parameters, that are typically: $\Delta T_{\mathrm{eff}} = \pm 500$ K, $\Delta \log g = \pm 0.25$ cgs and $\Delta \xi = \pm 2$ km s^{-1}, is about 0.2 to 0.3 dex. Note that the derived fluorine abundances in LTE represent only the first step defining the absolute F abundance in these stars; more reliable values should, in principle, come from full non-LTE calculations.

Table 2.   The analysed EHe stars and the H-deficient binary KS Per, their stellar parameters, and fluorine abundances

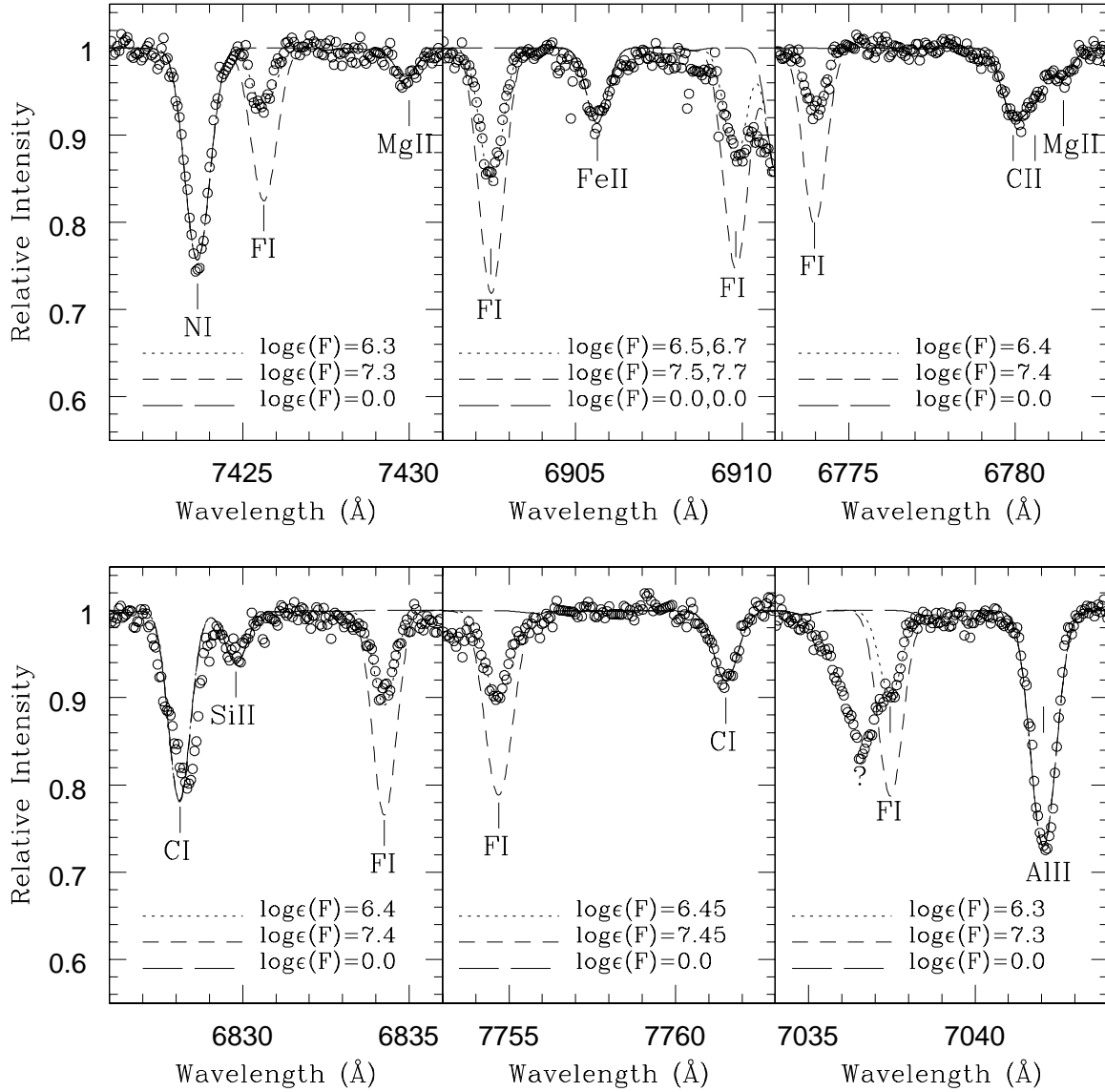| Star	$(T_{\mathrm{eff}},\ \log g,\ \xi)$	$\log \epsilon(\mathrm{F})$
BD+1° 4381 (=FQ Aqr)	(8750, 0.75, 8.0)	6.45±0.12(11)
V4732 Sgr (=LS IV-14° 109)	(9500, 1.0, 6.0)	6.52±0.19(11)
CoD -48° 10153 (=LSS 3378)	(10600, 0.4, 6.0)	7.30±0.17(17)
BD -1° 3438 (=NO Ser)	(11750, 2.3, 10.0)	6.24±0.18(11)
V2244 Oph (=LS IV-1° 2)	(12750, 1.75, 10.0)	7.15±0.14(11)
HD 168476 (=PV Tel)	(13750, 1.6, 10.0)	<7.20
HD 30353 (=KS Per)	(10500, 1.5, 10.0)[a]	<4.40

[a]from Pandey et al. (2006b)

Fig. 2.— Observed F I wavelength regions (open circles) of the sample cool EHe FQ Aqr with key lines marked. Synthetic spectra are shown for three fluorine abundaces, as shown on the figure.

5. Discussion

A good number of F I lines were identified for the first time in the optical spectra of the sample of cool EHe stars. An abundance analyses of these spectra provide the first abundances of fluorine for cool EHe stars. The enhanced F abundances (see Figure 4) in cool EHes are evidence of nucleosynthesis in their earlier evolution. The abundances for the other elements presented in Figure 4 are adopted from Pandey et al. (2001) for FQ Aqr, LS IV-14° 109, BD -1° 3438, and LS IV-1° 2, from Pandey & Reddy (2006) for LSS 3378, and from Wallerstein, Greene & Tomley (1967) and Pandey et al. (2006b) for KS Per. The F, C, and O abundances in cool EHes are independent of the star's initial metallicity (Fe abundance); the N abundances, however, show a clear trend with Fe (see Figure 4). These trends clearly suggest that F, C, and O abundances in cool EHes are associated with He-burnt material, and the N abundances are the result of H-burning via CNO cycling; the almost complete conversion of the initial C, N, and O to N is shown in the plot [N] vs [Fe] of Figure 4. During the He-burning thermal pulses ^{19}F is produced, and the initial ^{13}C supply then acts as a limiting factor for the ^{19}F yield. To account for the enhanced F abundances, in cool EHes, with no trend with Fe, requires a primary ^{13}C supply instead of the secondary ^{13}C supply from the CNO cycle ashes. Note the [F] vs [H] trend of Figure 4.

The F abundances in H-deficient PG 1159 stars show a strong variation from star to star, ranging from solar to 250 times solar (Werner, Rauch & Kruk 2005). The sample cool EHes show F enhancements about 100 times solar. Note that the models of Lugaro, Ugalde & Karakas (2004), for thermally pulsating AGB stars, predict that the F enrichment in the intershell is a strong function of the initial stellar mass; for solar metallicity models, $\log \epsilon(\mathrm{F})$, which is about 100 times solar, is maximal at $\mathrm{M} = 3 M_{\odot}$. Lugaro et al. conclude that their F intershell abundances are not high enough to explain the enhanced F abundances which were measured in the AGB stars from the Jorissen et al. sample. The surface composition of these H-deficient stars: PG 1159 and EHe, could be a result of final He-shell flash in a single post-AGB star (FF scenario), or a merger of two white dwarfs (DD scenario). Although the FF scenario accounts for PG 1159 stars, present theoretical calculations (Herwig et al. 1999) imply higher C/He and O/He ratios than are observed in EHe stars. However, DD scenario can account for the observed surface abundances of most of the elements in EHes (Pandey et al. 2006a).

Enrichment of s-process elements, and also fluorine, is not expected for the EHes resulting from a merger of a He with a C-O white dwarf (DD scenario) as discussed by Pandey et al. (2004, 2006a). However, synthesis of fluorine and s-process elements may occur during the merger and needs to be explored. The s-process elements are enriched in the cool EHe LSS 3378 (see for example, [Zr] vs [Fe] of Figure 4). The neutron source in EHes showing
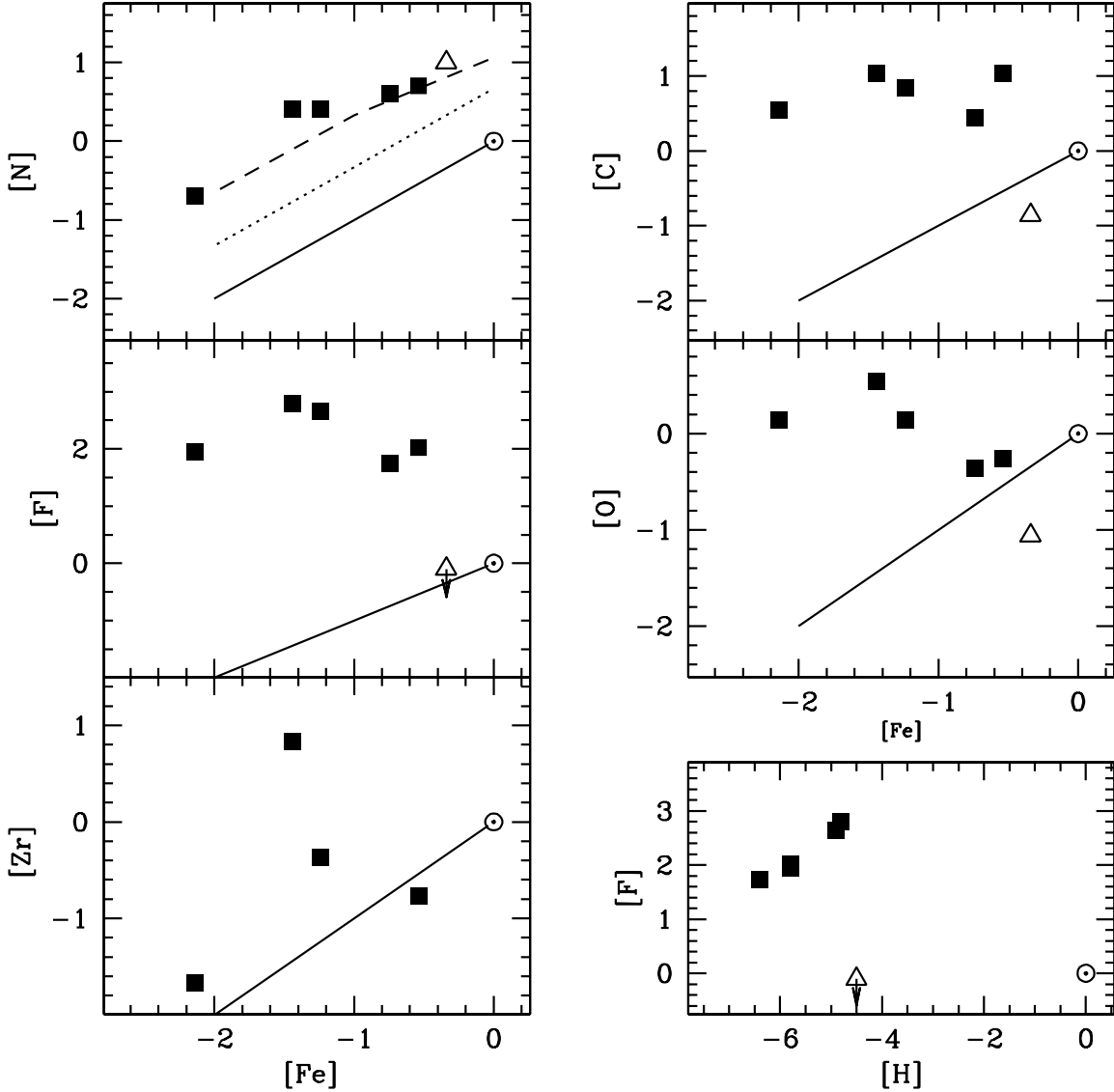
Fig. 3.— [N], [C], [F], [O], and [Zr] vs [Fe], and also [F] vs [H]. The sample of cool EHes is represented by filled squares; the abundances are from the references given in Section 4. KS Per is represented by open triangles; the abundances are from Wallerstein, Greene & Tomley (1967), and Pandey et al. (2006b) in preparation. ⊙ represents Sun; the adopted solar abundances are from Table 1 of Lodders (2003). The dotted line represents conversion of the initial sum of C and N to N. The dashed line represents the locus of the sum of initail C, N, and O converted to N. [X] = [Fe] are denoted by the solid lines where X represents N, C, F, O, and Zr.

enriched s-process elements is not known. $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ are the two possible sources. If the latter reaction dominates, then F is unlikely to survive in the He-rich intershell, as the reaction rate of $^{19}F(\alpha,n)^{22}Ne$ is much higher than that of $^{22}Ne(\alpha,n)^{25}Mg$ (Jorissen, Smith & Lambert 1992). Since ^{19}F is overabundant in cool EHes, [an upper limit to the F abundance for the coolest hot EHe PV Tel is also derived (see Table 2)], the reaction $^{22}Ne(\alpha,n)^{25}Mg$ is unlikely to be the neutron source in EHe stars. Non-LTE calculations should be performed for the key elements to further improve the chemical analysis.

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