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On the cosmic origin of fluorine

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Abstract. The cosmic origin of fluorine, the ninth element of the periodic table, is still under debate. The reason for this fact is the large difficulties in observing stellar diagnostic lines, which can be used for the determination of the fluorine abundance in stars. Here we discuss some recent work on the chemical evolution of fluorine in the Milky Way and discuss the main contributors to the cosmic budget of fluorine.

Keywords. Abundances—fluorine—red giants.

1. Introduction

Since 2019 was the 150th anniversary of the Periodic Table of Chemical Elements, UNESCO proclaimed it as the 'International Year of the Periodic Table of Chemical Elements'. However, it was not until 2016, that the periodic table was completed up to period 7, with the identification of the element Oganesson with atomic number 118.

Much astrophysical work has been devoted to understanding the cosmic origin of the elements, with large success for a range of elements. However, one element that has escaped a full understanding of its origin is fluorine, which has an atomic number of 9. The reason for this lack of understanding is the very few measurements done of the abundance evolution of fluorine in the Universe.

Fluorine is interesting since it is the most electronegative element, extremely chemically reactive, as well as very nuclear reactive with p (H) and α (He) nuclei. On Earth, fluorine can be found in many minerals (such as the colourful calcium fluorite, a.k.a. fluorspar) and chemical compounds (such as the hazardous liquid hydrogen fluoride (HF)). Fluorine was first isolated in 1888 by Henri Moissan, which earned him the Nobel Prize in Chemistry in 1906.

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The cosmic abundance of fluorine is several orders of magnitude lower than that of the neighbouring elements in the periodic table. It is only the 24th most common element in the Universe. It is thus clear that stellar nucleosynthesis processes must by-pass it. Indeed, the nuclear reaction cross sections F(p), and F(α), in these processes are very high, which leads to the destruction of much of the newly formed fluorine.

The main cosmic formation processes and sites for the production of fluorine is reviewed in detail in Ryde *et al.* (2020), and are as follows:

(1) *In massive stars*: The contribution from non-rotating stars, from conventional Type II supernovae explosions (SNIIe), is negligible. However, rapidly rotating massive stars can produce primary fluorine from ^{14}N, via proton and alpha captures (Prantzos *et al.* 2018). Also, other processes have been suggested, such as the ν-process in SNIIe. In this process, neutrino-induced spallation reactions with ^{20}Ne in the expelled shell, can form fluorine. Also, contributions from Wolf–Rayet stars during the core-helium burning phase, and with the subsequent ejection through the strong, metal line-driven wind, have been suggested, but is highly uncertain.

(2) *In low-mass, thermal-pulsing AGB stars* (2–4$M_\odot$). In these stars fluorine is formed through a chain of reactions involving neutrons and protons. Fluorine

is expelled through stellar winds. These AGB stars also form s-process elements like Ce.

(3) *In novae*: Fluorine is formed from reactions starting with proton captures on ^{17}O nuclei.

So, which processes were the ones that succeeded in producing fluorine in the Universe, so that it survived to contribute to the cosmic build up of the element? Here, we will discuss how to find this out and what has been done lately in this respect.

2. Determination of the cosmic origin of fluorine

No useful atomic lines are available for use in an abundance determination in cool stars. In hot stars, it is possible to observe highly ionized far-UV lines (Werner *et al.* 2005) and highly excited optical F I lines (Pandey 2006; Pandey *et al.* 2008). The only readily useful diagnostics are instead the lines from the hydrogen fluoride molecule, lines that lie in the 2.1–2.4 (vibration-rotational lines) and 8–13 μm (pure rotational lines) regions. Only one single useful line, namely the HF ($v = 1$–0) R9 line at $\lambda_{\rm air} = 23\,358$ Å, has been used in most investigations in the literature. We note that there has been a confusion about zero-point energy of the energy levels of the HF molecule in the literature, see Jönsson *et al.* (2014).

The way the fluorine abundance is retrieved is, in general, by comparing synthetic spectra with observed spectra. In order to calculate these synthetic spectra, the stellar parameters of the star observed has to be known accurately. Especially, the effective temperatures of the stars have to be known accurately since the HF lines are very temperature-sensitive. For example, in the recent study by Ryde *et al.* (2020) special care was taken to analyse a homogeneous set of stars with well-determined stellar parameters. In that study, they determined the fluorine abundances for 51 stars spanning a range of metallicities, from $[{\rm Fe/H}] = -1.1$ to $+0.4$. The stars were observed with high-resolution, near-IR spectrographs at $R \sim 45000$. The accurate and precise stellar parameters were determined by the method described in Jönsson *et al.* (2017). In this method, the stellar parameters are determined simultaneously by fitting unsaturated and unblended lines from Fe I, Fe II, and Ca I lines and $\log g$ sensitive Ca I wings.

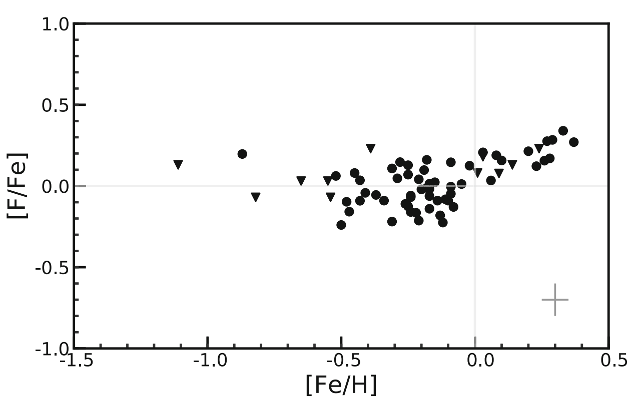

Figure 1. [F/Fe] ratio as a function of metallicity is shown for the stars observed in Ryde *et al.* (2020). Typical error bars are indicated in the lower right corner.

3. The Ryde *et al.* (2020) study

Of the 51 stars in the Ryde *et al.* (2020) study, 41 stars were observed with the Phoenix spectrograph (Hinkle *et al.* 1998, 2003) mounted on the 4-m Mayall telescope at Kitt Peak National Observatory (KPNO). Another 10 stars were observed with the IGRINS spectrograph at the 4.3-m Lowell Discovery Telescope (LDT; Mace *et al.* 2018), or on the 2.7-m Harlan J. Smith Telescope at McDonald Observatory (Mace *et al.* 2016). All in all, there were 51 spectra useful for the determination of the stellar fluorine abundances.

From these spectra, Ryde *et al.* (2020) determined not only the fluorine abundance, but also those of oxygen and Ce. In Figure 1, the [F/Fe] trend is shown as a function of the metallicity, [Fe/H]. The stellar abundances are normalized to the solar value, which is very uncertain. Since there is no detectable HF in the solar photosphere, the solar abundance value is determined from meteoritic measurements ($A_\odot({\rm F}) = 4.43$; Lodders 2003).

For metallicities below that of the Sun, a flat relation is found, with a smaller scatter compared to earlier results. At supersolar metallicities, a clear increasing relation is found. Furthermore, Ryde *et al.* (2020) found that the fluorine increase with metallicity shows a clear secondary behavior.

They also found that the [F/Ce] ratio was relatively flat for $-0.6 < [{\rm Fe/H}] < 0$. For two s-process element-enhanced giants at $[{\rm Fe/H}] < -0.8$, they did not detect an elevated fluorine abundance. Based on their full data set, and also their oxygen abundances which are compared to that of fluorine, Ryde *et al.* (2020) concluded that several major processes must be at play for the cosmic budget of fluorine over time. At lowest metallicities, massive stars are most important and for

$-0.6 < [\mathrm{Fe\ H}] < 0$, the asymptotic giant branch (AGB) star contribution must be large. At supersolar metallicities, there seems to be a need for processes with increasing yields with metallicity. The origins of the latter, and whether or not Wolf–Rayet stars and/or novae could contribute at supersolar metallicities, is currently not known.

4. The Grisoni *et al.* (2020) study

In order to investigate the origin and evolution of fluorine based on the data from the Ryde *et al.* (2020) study, Grison *et al.* (2020) investigated the trends with detailed chemical evolution models. They indeed found that rotating massive stars should be major contributors to the fluorine budget setting a plateau in the fluorine abundance trends below $[\mathrm{Fe/H}] = -0.5$. For the increase at higher metallicities or later times, a contribution from low-mass stars is needed, in the form of single AGB stars and/or novae.

5. Conclusion

The cosmic origin of the 9th element in the periodic table, fluorine, is still enigmatic. The light elements are the first to form in stellar nucleosynthetic processes, but fluorine is easily destroyed by nuclear reactions with the ubiquitous protons and alpha particles. Therefore, the cosmic abundance of fluorine is much lower tgab that of the neighbouring elements in the periodic table. A few observational studies have recently appeared. For example, the Ryde *et al.* (2020) study showed clearly a flat [F/Fe] trend at a solar value, with increasing fluorine abundance ratios at super solar metallicities. Their results also indicated that the fluorine slope shows a clear secondary behavior. Furthermore, they showed that the [F/Ce] ratio is flat for $-0.6 < [\mathrm{Fe/H}] < 0.0$. Together with the fact that two metal-poor $[\mathrm{Fe/H}] < -0.8$, Ce-enhanced stars do not have enhanced fluorine ratios, AGB stars cannot be the main contributor at these metallicities. Their conclusion is that several processes are needed for different metallicities: from massive, rotating stars at the lowest metallicities to AGB stars at solar [Fe/H], to a processes with metallicity-dependent yields at super solar metallicities. The Galactic Chemical Evolution models presented in Grisoni *et al.* (2020) agree with these conclusions and they show that a contribution of novae might be necessary for the production of fluorine in the Universe.

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