1993ASPC...45..185P

Luminous High-Latitude Stars
ASP Conference Series, Vol. 45, 1993
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THE CHEMICAL COMPOSITION OF POST AGB STARS

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ABSTRACT The abundance ratios [C/Fe], [N/Fe], [O/Fe] and [S/Fe] in post AGB A-F supergiant-like stars are large and cannot be easily explained by nucleosynthesis and/or mixing. The large ratios of [C/Fe], [N/Fe], [O/Fe] and [S/Fe] is due to the depletion of Fe but not of C, N, O and S elements. The depletion of refractory elements and the lack of depletions in CNO and S in the atmosphere of these post AGB stars is similar to that observed in the interstellar medium. Since most of these stars have circumstellar dust shells the depleted refractory elements appear to be locked up in dust grains. The results suggest that in the recent past (possibly during the OH−IR stars stage) the outer atmospheres of these stars expanded and cooled to the limit of the condensation temperature of refractory elements. Formation of cores of dust grains very close to the stars and the resulting dust driven mass loss which drives out mostly the dust may be able to explain the observed abundance peculiarities in these post AGB stars.

1. INTRODUCTION

From the far-infrared IRAS observations circumstellar dust shells have been detected from the high galactic latitude A and F supergiants (Parthasarathy and Pottasch 1986; Lamers et al 1986). This result has lead to the detection and identification of several IRAS sources showing optical region spectra and far IR colours similar to the high galactic latitude A and F supergiants. These stars have circumstellar dust shells with far infrared colours and flux distributions similar to the dust shells of planetary nebulae (PNe) and in the optical region they show A, F, G, K supergiant like spectra (Parthasarathy and Pottasch 1986., Lamers et al 1986). Parthasarathy and Pottasch (1986) interpreted that the dust shells around these objects are the result of severe mass loss experienced by these objects during their AGB stage of evolution and now they are in post AGB stage of evolution, evolving from the tip of the AGB towards left in the HR diagram into the region of PNe. It is likely that these objects are a small part of hitherto unseen phase of stellar evolution.

The AGB phase of evolution of intermediate and low mass stars is terminated by the ejection of the most of the hydrogen rich outer envelope resulting in a planetary nebula (Iben and Renzini, 1983). As post AGB stars/proto-planetary nebulae evolve into early stages of planetary nebulae, part of the dust shell begins to be ionized. The post AGB stars detected from IRAS data extend from non-variable OH/IR stars to M, K, G, F, A supergiant like stars with circumstellar dust shells. This sequence appears to represent the evolution of the post AGB stars towards hotter spectral types (Parthasarathy and Pottasch 1989, Parthasarathy 1989, 1990).

Detailed chemical composition analysis of all these stars is important to further understand their evolutionary stage, nucleosynthesis, mixing and mass loss processes experienced by these stars.

2. CHEMICAL COMPOSITION

The chemical composition determinations of high galactic latitude post AGB A and F supergiants were made by Kodaira et al 1970, Kodaira 1973 (BD +39°4926), Luck et al 1983 (HR 4912), Luck and Bond (1984), and Bond and Luck 1987 (HR 46703)., Lambert et al (1988) (HR 4049)., Luck et al (1990). More recently Waelkens et al (1991, 1992) and Parthasarathy et al (1992) derived the chemical composition of HD 52961, HD 44179 (Red-Rectangle) and HD 56126 respectively.

2.1 ABUNDANCE OF FE AND RELATED ELEMENTS

The [Fe/H] abundance values of several post AGB stars are given in Table 1. The low [Fe/H] values, high galactic latitudes and high velocities (HD 46703, HD 56126) of some of these stars suggests that these are low mass stars in an advanced stage of evolution with metallicities characteristic of halo stars. The iron abundance in HR 4049, HD 52961, HD 44179 and BD +39°4926 is extremely low (Table 1). In addition to the underabundance of Fe; Ca, Al, Ti, Mg, Si etc are also found to be under-abundant.

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2.2 THE CNO ABUNDANCES

The [Fe/H], [C/Fe], [O/Fe], [N/Fe] abundances in HD 56126 are similar to the abundances in the high velocity metal poor F supergiant HD 46703 (Table 3). The [C/Fe], [N/Fe], [O/Fe] values are very much larger than those expected in metal poor stars. Similar values were found by Luck et al (1990) and Waelkens et al. (1990) from an analysis of several post AGB stars (Table 1). In metal poor dwarfs the [C/Fe]=0.0 and at [Fe/H]=-2.5, [C/Fe] $\simeq +0.2$; [N/Fe] $\simeq -0.2$ for [Fe/H]=-2.5 to -1.0, and [N/Fe]=0.0 for [Fe/H]=0.0; and [O/Fe]=+0.4 for [Fe/H] in the range -1.0 to -3.0 (see Wheeler et al 1989). The [C/Fe], [N/Fe] and [O/Fe] ratios observed in post AGB stars (Table 1) are much larger than expected in extreme metal poor stars. The relation between [Fe/H] and [C/Fe] and similar relations between [N/Fe] and [O/Fe] can not be explained easily in terms of nucleosynthesis or galactic chemical evolution. The CNO abundances in these post AGB stars are nearly solar or slightly different from solar values. The abundance results shown for extremely metal poor post AGB stars are from Lambert et al (1988) (HR 4049), Waelkens et al (1991, 1992) (HR 4049 and HD 52961), Takada-Hidai (1990) (HR 4049) and Kodaira (1973) (BD $+39^o4926$). In most of the post AGB stars (Table 1) the carbon abundance [C/H] is in the range 0.0 to -0.5, [N/H]=0.0 to +0.5, [O/H]=0.0 to -0.5 and [S/H]=0.0 to -0.5. For HR 4912 Luck et al (1984) give [Fe/H]=-1.2 and [C/H]=-1.1. A redetermination of C abundance in HR 4912 using several C lines is needed. Recently Waelkens et al (1992) derived the photospheric abundances of HD 44179 the central star of Red-Rectangle. They find [Fe/H] ≤ -3.2 but the CNO abundances are nearly solar. The abundances in HD 44179 are similar to the abundances in other metal poor post AGB stars HD 46703, BD $+39^o4926$, HD 52961, and HR 4049. The large ratios of [C/Fe], [N/Fe] and [O/Fe] are due to under-abundance of Fe. The [C/H]. [N/H] and [O/H] are nearly normal.

The C/N/O abundance ratios which are more meaningful in understanding the evolutionary aspects are also given in Table 1. The CNO abundances and C/N/O ratios in these stars suggests that they are evolved and nitrogen is overabundant. Figure 1 shows the position in the C/N - O/N plane of various types of evolved stars (For details see Nussbaumer et al. 1988) and the post AGB stars. The points clearly form two regions: the sun, all the G, K, M giants and supergiants and symbiotic stars lie to the left of the C/O=1 line. Separated by a gap we see the carbon stars on a small strip to the right of the C/O=1 line. In descending order of C/N, O/N ratios we first find G and K giants, then M, MS, S giants and symbiotic stars, and in the lowest the supergiants. In this order they increasingly exhibit the products of CNO-cycling (enhancement of N at the expenses of C and O). The carbon stars are clearly separated from the other giants and supergiants. By definition they lie to the right of the C/O=1 line. The carbon stars do not peter out to the right of the C/O=1 line but lie in a narrow strip close to the C/O=1 line. All carbon stars have O/N $\geq$ 3. Their location in Fig 1 indicates that the helium burning products have been brought to the stellar surface. The location of post AGB stars HD 52961, HD 213985, HR 4049, and 89 Her in Fig. 1 is the same as that of carbon stars suggests that these stars also have helium burning products on their surfaces and may be related to carbon stars. In the log O/N against log C/N diagram (Fig 1) HD 161796, HD 46703, BD +39°4926 and HD 56126 are in the region occupied by G, K, M giants.

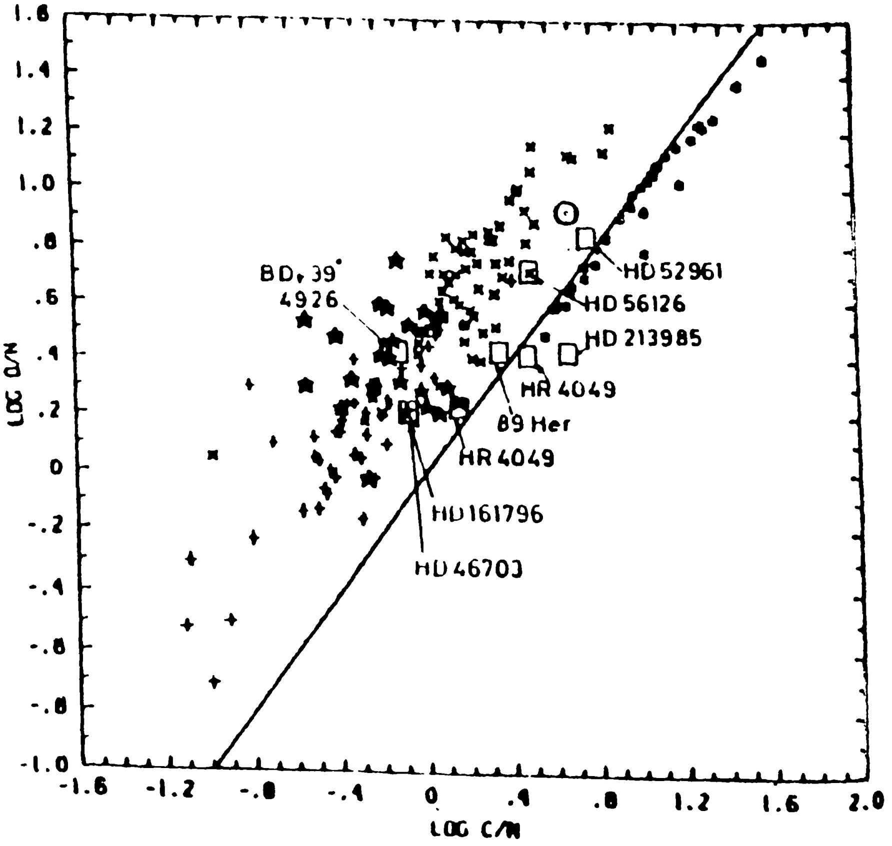

Fig. 1 Relative abundance O/N against C/N for post AGB stars (□), G, K, M, MS and S giants (×), carbon stars (∗) and intermediate supergiants (+), symbiotic stars (⋆). The symbol (⊙) shows the Sun. The data on symbiotic stars G, K, M, MS and S giants, carbon stars, and intrmediate supergiants are from Nussbaumer et al. (1988).

In the log O/N against C/N diagram (Fig 1) none of the post AGB stars given in Table 1 is in the region defined by intermediate mass supergiants indicating that progenitors of the post AGB stars (Fig 1, Table 1) originated from low mass stars. The C/N/O ratios (Table 1) and location in the O/N against C/N diagram (Figure 1) suggests that they have products of CNO-cycling on their surface and also some of them may also have helium burning products on their surfaces. HD 213985 (C/N=4.79), HD 52961 (C/N=6.03) and HD 56126 (C/N=3.16) have relatively high C/N ratios. However these are high galactic latitude supergiants and HD 56126 is a high velocity star belonging to the old disk. Cottrell and Sneden (1986) found solar C/N ratios and enhanced O/Fe ratios in evolved high velocity giant stars (metal poor members of the disk population).

Planetary nebulae lie on both sides of C/O=1 line (Nussbaumer et al. 1988). However majority of them lie on the side of the carbon stars. Some of them seem to display only CNO processed material and coincide with F-M giants whereas others clearly show He burning products and are located near the carbon stars. Post AGB stars also show both these aspects. Recently Perinotto (1991) evaluated average chemical abundances for planetary nebulae (PN) of type I and types II-III of Peimbert. He used the chemical abundances of 209 well studied planetary nebulae. For type I PN he found C/H=8.72, N/H=8.60 and O/H=8.66 and for types II-III PN, C/H=8.82, N/H=8.07, O/H=8.66. The C/H abundances clearly show that the carbon abundance in type I and types II-III PN is nearly solar or within 0.1 dex of solar carbon abundance. Type I PN show 0.6 dex overabundance of nitrogen. The oxygen is 0.25 dex underabundant in type I and type II-III. The abundances in PN are consistent with the possibility that the enrichment of nitrogen in type I PN is due mostly to the ON cycle, while that in PN of types II-III it is due mostly to the CN cycle. The C/N/O abundance ratios in PN are given in Table 1. The C/H, N/H and O/H abundances in post AGB stars are not very different from the average C/H, N/H and O/H abundances of PN derived by Perimotto (1991). The C/O ratio of PN is in the range of 1.15 to 1.45 (Table 1). Some of the post AGB stars also show C/O ratio close to 1. Type I PN are helium and nitrogen rich and may have progeniters with initial mass $\geq 2.4 M_{\odot}$. Type II PN may have progenetors with initial masses 1.2 to 2.4 $M_{\odot}$, and type III 1 to 1.2 $M_{\odot}$. The O/N ratio of several post AGB stars given in Table 4 are comparable to the O/N ratio of type II-III PN. However some of the post AGB stars appear to be nitrogen rich and some have C/N ratio comparable to that of type II-III PN. We have no idea of the helium abundances in the atmospheres of these stars. There are several uncertainties such as the initial main sequence masses, path of evolution and mixing and mass loss stages of these stars. However in addition to the CNO abundances, high galactic latitude position and high velocities of some of these stars suggest that they have evolved from low mass stars.

2.3 THE SULFUR ABUNDANCES

The sulfur abundances in several post AGB stars are given in Table 1. The [S/Fe] ratios are much larger than expected from metal poor stars. In metal poor dwarfs sulfur is found to be slightly overabundant [S/Fe] = +0.4 (Wheeler et al 1989). However in the post AGB stars the [S/Fe] ranges up to +3.6 (Table 1., Luck et al 1990., Bond 1991). Such large [S/Fe] values cannot be accounted in terms of nucleosynthesis (Luck et al 1990., Bond and Luck 1987). The large ratios of [S/Fe] is due to underabundance of Fe. The [S/H] values are nearly normal.

3. DISCUSSION

The deficiency of refractory elements such as Mg, Al, Si, Ca, Ti and Fe and the lack of such deficiency in CNO and S in post AGB A-F supergiants is similar to that observed in the abundances of interstellar medium. The abundances in the interstellar medium (lower column density, diffuse clouds) and in BD +39°4926 (Kodaira 1973) are compared (Parthasarathy et al 1992). The abundance trends in BD +39°4926, (Kodaira 1973), HD 46703 (Luck and Bond 1984; Bond and Luck 1987) HR 4049 and HD 52961 (Waelkens et al 1990) and HD 56126 (Parthasarathy et al 1992) are similar to that observed in the interstellar medium. Since most of the post AGB stars discussed here show evidence for the presence of warm and/or cold circumstellar dust shells lends strong support to the idea that the depleted elements are locked up in the dust grains. Hoyle and Wickramasinghe (1962) (see also Kamijo 1963) were the first to suggest that the dust grains tend to be formed in the atmospheres of cool red giants and supergiants at temperatures less than 2700 K. They suggested that the dust grains that have formed in the atmospheres of these cool stars have significant effect on the photospheric opacity causing the photospheric density to decrease very markedly as the temperature falls towards 2000 K. They further suggested that it is this fall of density that allows the grains to be repelled outwards by radiation pressure and to leave the star altogether in spite of the frictional resistance of the photospheric gases and these dust grains do not evaporate as they leave the atmosphere of the star.

The formation of brand new dust grains out of free atoms, ions and molecules via nucleation requires a very special environment. The density needs to be of the order of 10^9 cm^{-3} or higher while the temperatures around 1000 - 2000 K. These conditions exist primarily in outflows from evolved cool red giants and supergiants where cores of dust grains have formed (Salpeter 1977; Field 1974). The presence of dust shells, molecular envelopes, and photospheres showing depletions of refractory elements suggests that these post AGB stars once were very cool and had extended cool outer atmospheres ($T < 2000$ K). The depletion of Ti, Al, Ca, Si, Fe etc in the photospheres of these post AGB stars suggests that the condensation (formation of clusters and cores of dust grains with refractory elements) has taken place when the present post AGB stars had envelopes with T in the range 1000 to 1600 K. The refractory elements such as Ti, Al, Ca (1400-1600 K) condensed and locked up in the cores of dust grains when the temperature of the extended atmosphere was close to the condensation temperature of these elements (Field 1974)(Ti, Al, Ca (1400-1600 K); Si, Mg (1270-1320 K); Fe, Ni (1280 K)). Therefore we see the depletions of these elements in these post AGB stars. Volatile elements (C, N, O, Si, Zn) with low T_c (condensation temperature < 700 K) do not show significant depletions in the atmosphere of these stars indicating temperatures above 1000 K before the ejection of the dust shell or dust driven mass loss.

Observations and theory suggest that dust forms very close to the star (around 2 stellar radii); however the dust formation region may extend from two stellar radii to ten stellar radii (Dyck et al 1984; Zuckerman 1980; Lafon and Berruyer 1991). In the post AGB stars the dust seems to have formed close to the star during the expansion and cooling of the outer atmospheres of these stars. Tielens (1983) model of dust driven mass loss suggests that grains may attain large drift velocity with respect to gas and also the velocities of expansion and flow (dust driving) during rapid mass loss phase are not very high (< 30 km/sec). High velocity flows and shock waves destroy the dust grains and can also stop nucleation of dust grains. The conditions of temperatures, velocities in the outer expanding regions of the progenitors of present post AGB stars discussed here may be different from that of other stars with circumstellar dust shells. Some of the post AGB stars such as BD +39°4926, HR 4049, and HD 52961 are extremely deficient in Fe and most likely in other refractory elements. However their C, N, O and S abundance do not share this extreme deficiency. Why some of these objects show extreme deficiency of refractory elements while others do not suggests that some of them had very dense cool envelopes where dust formation was very efficient which has depleted large fraction of refractory elements, or these stars have gone through several cycles of envelope expansion, cooling to the limit of condensation temperature, dust formation close to the star.

The depletion of Fe, Mg, Si, Al but not of C, N, O was also noticed in planetary nebulae (Shields 1978; Pwa, Mo and Pottasch 1984; Harrington and Marionni 1981). In NGC 7027 shield found the gas phase iron abundance to be low [Fe/H]=−1.4, whereas oxygen has the solar abundance and suggested that the iron depletion results from grain formation. Shield found similar iron depletions in the gas phase abundances in several other planetary nebulae. He found the gas-phase Fe abundance to range $-2.0 \leq [\mathrm{Fe/O}] \leq -0.4$. In all these PN the oxygen abundances are essentially solar and show no correlation with [Fe/H]. In the planetary nebula NGC6543 Pwa et al. (1984) found for carbon and silicon lower than solar values by factors 2 and 4, but iron was found to be depleted by at least a factor of 70, and aluminium by a factor of 300. Harrington et al (1982) found similar depletions in the gas phase abundances of Mg, Fe, and Si in the planetary nebula NGC 7662. The absence of Mg II 2800 Å feature in several planetary nebulae implies that depletion of Mg is wide spread (Harrington and Marionni 1981; Flower and Penn 1981). IRAS data of all these planetary nebulae show evidence for the presence of dust shells. These results indicate that efficient condensation of iron and other refractory elements into dust grains in PN and post AGB stars.

The evidence for the condensation of refractory elements into dust grains comes from the presence of zinc in the photosphere of extremely metal poor post AGB star HD 52961 (Van Winckel, Mathis and Waelkens 1992). Zinc has a low grain condensation temperature. Zinc belongs to Fe group, and so its abundance should follow that of iron if underabundances are primordial. But if the iron group refractory elements are deficient because of depletion on to grains, then zinc will not show depletion because zinc has a low grain condensation and therefore least depleted. In the extremely Fe poor post AGB star HD 52961 Van Winckel et al 1992 find the zinc abundance to be −1.3 with respect to the Sun, and so it is more than three orders of magnitude less depleted than iron. This result confirms that in post AGB A, F supergiants the depleted refractory elements are locked up in dust grains. The extreme Fe deficiency is not primordial.

Parthasarathy, Garcia-Lario and Pottasch (1992) suggested that in the recent past (possibly during OH/IR stars stage) the outer atmospheres of these stars expanded and cooled to the limit of the condensation temperature of refractory elements. Formation of cores of dust grains very close to the stars and the resulting dust-driven mass loss which drives out mostly the dust may be able to explain the observed photospheric abundance peculiarities of post AGB stars.

Recently Mathis and Lamers (1992) suggested that the capture by the presently visible star of the depleted gas from a binary companions, or the rapid termination of vigorous stellar wind in a single star, so that the grains are blown outward through the expanding envelope to explain the extremely metal poor post AGB stars.

The circumstellar dust shells of some of the post AGB stars appear to be carbon rich (HR 4049, HD 44179, HD 56126). However the photospheric abundance of C and O indicate that they are oxygen rich. The oxygen rich photosphere with a carbon rich circumstellar dust shell is rather peculiar and is difficult to explain. Parthasarathy et al (1992) find that the photosphere of HD 56126 is oxygen rich and Kowok et al (1989) find that its circumstellar dust is carbon rich. This may be the result of formation of dust grains close to the star and driving out mostly the dust.

Some of the very metal poor post AGB supergiants were found to be long period single lined spectroscopic binary systems. The nature of the invisible secondary components is not clear. The extreme deficiency of Fe and other refractory elements and normal abundance of CNO, S and zinc may be due to an accretion of gas which is depleted in the refractory elements (Mathis and Lamers 1992). However most of the post AGB supergiants seem to be undergoing slow mass loss. Several of them show P-cygni type H_α profiles indicating mass loss rate of the order of $10^{-7} M_\odot$. There is no indication for accretion of circumstellar gas. In addition to the observational evidence for mass loss from these stars they also show long period pulsations. If the deficiency of refractory elements in the photospheres of these stars is due to the accretion of only the circumstellar gas (but not the dust) which is depleted in the refractory elements, then, because of mass loss and pulsations the photospheric abundance will be altered and they will not show the deficiency of refractory elements.

4. CONCLUSION

Formation of dust close to the star and the gas, dust separation during the AGB or post AGB mass loss phase and driving out mostly the dust may be able to explain the deficiency of refractory elements in the photospheres of the post AGB A-F supergiant-like stars.

Table 1. The Fe, C, N, O, S abundances in post AGB stars

	[Fe/H]	[C/Fe]	[N/Fe]	[O/Fe]	[S/Fe]	C/N	C/O	O/N
HD 161796	−0.3	+0.3	+1.1	+0.4	+0.7	0.76	0.44	1.66
89 Her	−0.4	+0.3	+0.6	+0.1	+0.1	2.40	0.89	2.63
HD 56126	−1.0	+1.0	+1.2	+1.0	+1.0	3.02	0.56	5.25
HD 46703	−1.6	+1.0	+1.8	+1.1	+1.3	0.76	0.44	1.66
BD +39 4926	−2.9	+2.5	+3.3	+2.8	+3.0	0.76	0.28	2.63
HD 44179	−3.5	+3.6	+3.4	+3.3	+3.3	7.59	1.12	6.61
HD 52961	−4.8	+4.3	+4.3	+4.3	+3.7	4.79	0.56	8.32
HR 4049	−4.8	+4.7	+4.9	+4.5	+4.4	3.02	0.89	3.31

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