Evidence of Hot-Bottom-Burning in Extreme OH/IR Stars

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ABSTRACT

Observations by *Herschel Space Observatory* of extreme OH/IR stars indicate that these objects currently undergo a phase of very high mass loss – superwind. We derived relatively low $^{12}C/^{13}C$ ratios which is indicative of the hot-bottom burning process. Further evidence from the observed oxygen isotopes ($^{16}O/^{17}O/^{18}O$) also support this idea. We conclude that these stars are massive ($M \geq 5\,M_{\odot}$) AGB stars. With *SPICA*-SAFARI, it will be possible to observe these isotopic ratios in a number of these stars as they contribute significant gas and dust mass return to the interstellar medium of our galaxy.

1. INTRODUCTION

One of the important characteristics of a star which evolves onto the asymptotic giant branch (AGB) is the star is losing much of its initial mass in a form of cool, low-velocity stellar wind. As a result, it develops an extended circumstellar envelope of dust and gas and eventually evolve to become a planetary nebula (e.g., Iben & Renzini 1983; Habing 1996). It has been postulated that towards the end of the AGB phase, mass loss rate increases (Vassiliadis & Wood 1993).

Since all stars with an initial mass between 0.8–8 $M_{\odot}$ pass through the AGB phase. It is difficult to determine the initial stellar mass of an AGB star. However, chemistry in the circumstellar envelope gives clues to rough initial masses. For stars with a mass below $\sim 3\,M_{\odot}$, the third dredge-up can convert initially oxygen-rich star to a carbon star, i.e., C/O is larger than 1. Stars with a mass larger than $\sim 4\,M_{\odot}$, the hot-bottom burning (HBB) starts and convert carbon to nitrogen hence reducing the C/O ratio to below unity (Boothroyd et al. 1993). Signatures of HBB are the low $^{12}C/^{13}C$ and $^{18}O/^{16}O$ ratios as well as Li overabundance in circumstellar envelopes (Sackmann & Boothroyd 1992; Lattanzio et al. 1996).

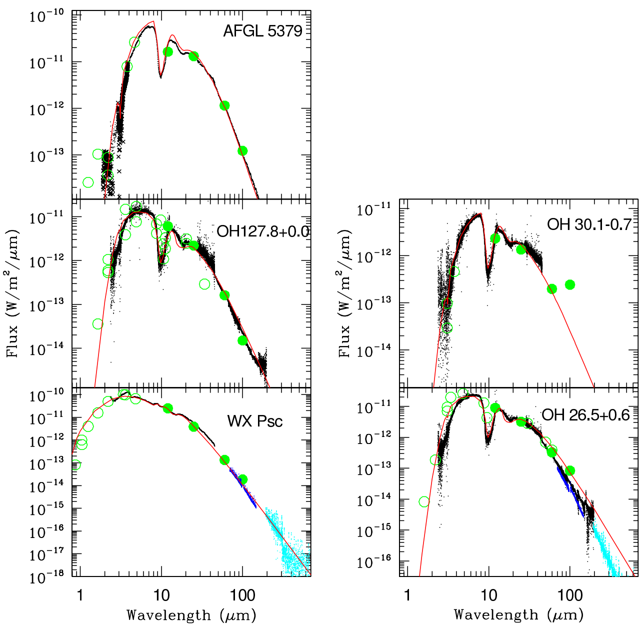

Figure 1. Spectral energy distributions of the sampled stars. The solid lines are the model, dots are observations from *IRAS* LRS, *ISO* and *Herschel*-PACS and SPIRE while the filled circles are from IRAS PSC and open circles and crosses are ground based observations.

Table 1. Parameters for modelling the dust and gas mass loss rates in the sample stars, the radii of the superwind (r_{sw}), and the derived $^{12}C/^{13}C$ ratios.

	WX Psc	OH 127.8+0.0	AFGL 5379	OH 26.5+0.6	OH 30.1−0.7
T_* (K)	2200	2300	2200	2200	2200
R_* (cm)	4.8×10^{13}	9.0×10^{13}	5.0×10^{13}	6.0×10^{13}	5.0×10^{13}
v_e (km s^{-1})	19.8	12.7	18.3	15.0	18.1
D(kpc)	0.68	2.8	0.58	1.37	1.75
$\dot{M}$ ($M_\odot$ yr^{-1})	1.8×10^{-7}	2.0×10^{-6}	1.6×10^{-6}	2.0×10^{-6}	1.8×10^{-6}
$\dot{M}_{dyn}$ ($M_\odot$ yr^{-1})	1.9×10^{-5}	9.2×10^{-4}	1.6×10^{-4}	3.2×10^{-4}	1.8×10^{-4}
r_{sw} (cm)	—	1.2×10^{16}	1.0×10^{16}	9.0×10^{15}	2.5×10^{16}
$^{12}C/^{13}C$	10 ± 4	2 ± 1	27 ± 11	10 ± 16	4 ± 1

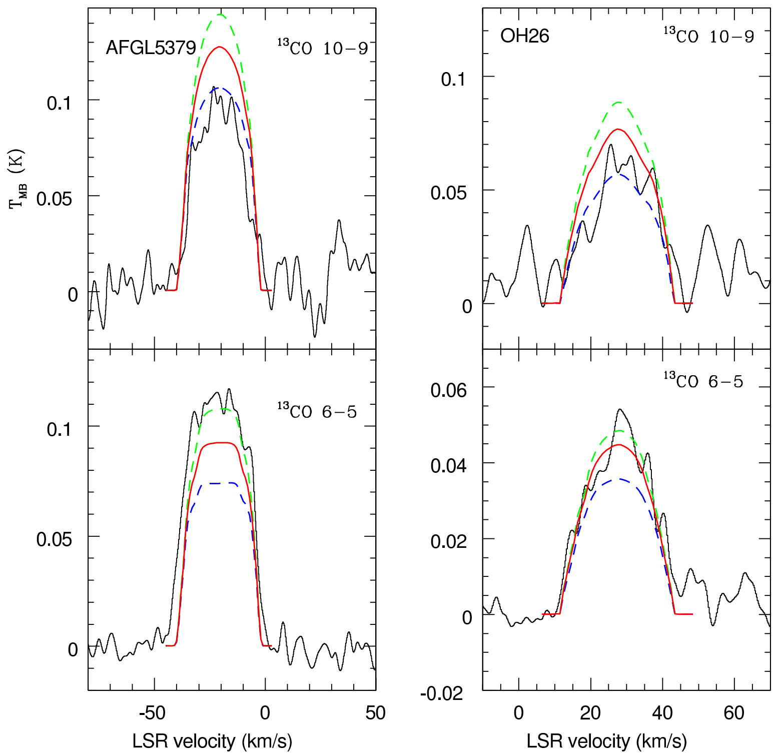

Figure 2. Observations of ^{13}CO (histogram) using HIFI for two of our sample stars. The smoothed lines are the best fit $^{13}CO/H_2$ abundance. The dashed lines show the range of uncertainty in the abundance.

In this paper, we present observations of a few extreme OH/IR stars, AGB stars which show deep silicate dust absorption at 10 and 20 μm as well as strong OH maser emission, observed by *Herschel Space Observatory* (hereafter *Herschel*, Pilbratt et al. 2010) using the heterodyne instrument HIFI (de Graauw et al. 2010).

2. MASS LOSS RATES

By fitting the spectral energy distributions (Figure 1), we derived high dust mass loss rates for our sample stars (See Table 1). Assuming that mass loss is due to a momentum-driven wind, we calculate the (dynamical) gas mass loss rate which is driven by the dust to the observed terminal velocity, $\dot{M}_{dyn}$. As can be seen, these values are a few 10^{-4} $M_\odot$ yr^{-1}, except for WX Psc which has the silicate 10 μm in self-absorption.

In modelling the gas mass loss rate, we fit the CO rotational emission lines obtained with *Herschel*-HIFI, as well as complementary ground-based observations to probe the warm inner part and cool outer envelope, respectively. A constant mass loss rate derived from a dust-driven wind hugely overestimate the line fluxes for low transitions (e.g., J =1–0 and 2–1). In order to reconcile the model with the infrared and CO observations, we conclude that 4 out of 5 stars have undergone a recent increase in their mass loss rates, a superwind. This increase results in the high dust optical depth as

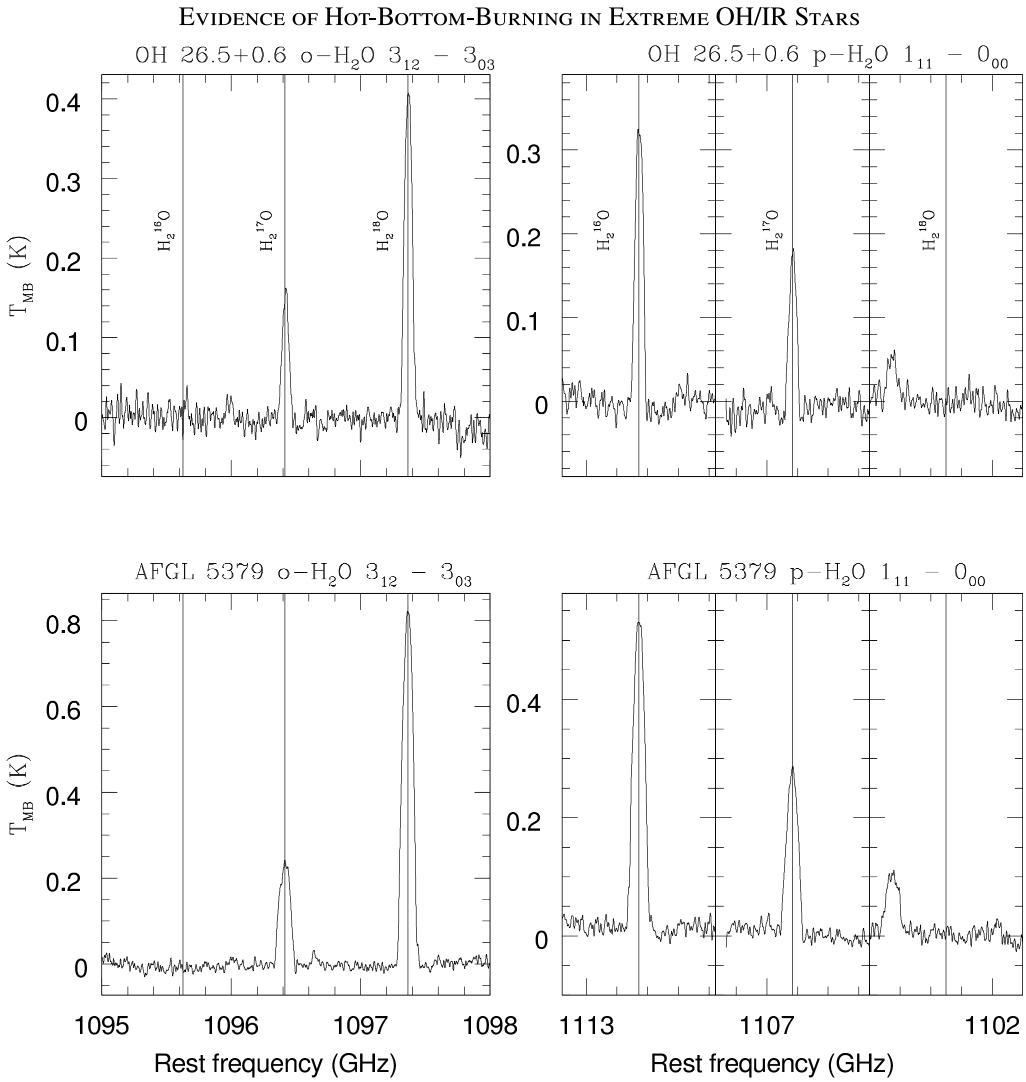

Figure 3. *Herschel*-HIFI spectra of three main isotopologues of an ortho-H_2O (left) and a para-H_2O (right) for AFGL 5379 (bottom) and OH 26.5+0.6 (top). The vertical line marks the rest frequency of the H_2O emission lines. Note the absence of the $H_2^{18}O$ in both transitions.

seen in the silicate absorption bands while the outer, cooler part of the circumstellar envelope is due to tenuous mass loss prior to the superwind.

3. ISOTOPIC RATIOS

We also obtained spectra of ^{13}CO for some of our stars. Delfosse et al. (1997) observed a number of extreme OH/IR stars with the IRAM telescope which we used to derive the carbon isotopic ratios. Due to the high optical depth of the ^{12}CO (and possibly ^{13}CO) lines, these values have large uncertainties. However, these numbers are close to the equilibrium value for the CNO cycle of 4. It is noted that although CNO cycle operates in low mass stars, it is more efficient in higher mass stars.

Our HIFI observations included frequency settings which admitted three isotopologues of the same transition of an ortho-H_2O $3_{1,2}$–$3_{0,3}$ and the ground state para-H_2O $1_{1,1}$–$0_{0,0}$ for OH 26.5+0.6 and AFGL 5379 (Figure 3). Both transitions show strong emission from the $H_2^{16}O$ and $H_2^{17}O$ while the $H_2^{18}O$ lines are not detected above the noise. This is also a consequence of HBB which quickly destroys the ^{18}O isotope leaving the other two isotopes unchanged.

Lattanzio et al. (1996) showed a calculation for a $6\,M_\odot$ with a solar composition which has a similar outcome that we observed in these two stars. We conclude then that these OH/IR stars are massive ($M_* \geq 5\,M_\odot$) AGB stars.

4. FUTURE OBSERVATIONS WITH *SPICA*

It is almost impossible to observe H_2O from the ground hence *Herschel* has been instrumental in the study of this molecules in evolved stars. With *SPICA*, we will be able to extend our study to cover many more objects which are losing mass at a very high rate. The SAFARI instrument will be able to resolve most of the strong H_2O isotopologues which is inaccessible from the ground, as well as CO lines. These stars are important since their mass loss affects the chemical evolution of our galaxy, both in terms of molecular and dust enrichment.

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