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ON DEAD OH/IR STARS

B. M. Lewis
Arecibo Observatory, HC3, Box 53995, Arecibo, PR 00612; blewis@naic.edu
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ABSTRACT

Because the net duration of all 1612 MHz emission phases from $|b| > 10°$ OH/IR stars is ∼1700 yr, one "death," as evidenced by the disappearance of all 1612 MHz masers, should occur in a sample of 170 every 10 yr, on average, if they have only one emission phase. We report here on the reobservation after 12 yr of the 328 OH/IR stars in the Arecibo sky with a peak first-epoch $I_{1612} > 100$ mJy. Four of these now have undetectable 1612 MHz masers, while those from a fifth, FV Boo, appear to be in terminal decline. The blue IR colors, 315 day period of FV Boo, and presence of water and SiO masers in several of the newly identified dead OH/IR stars all suggest that these objects are still asymptotic giant branch (AGB) stars rather than proto–planetary nebulae. This conclusion suggests that most oxygen-rich AGB stars pass through the OH/IR star phase more than once. The positions of the dead OH/IR stars on first-epoch plots of I_{1612} versus $S(25)$ and on plots of the ratio of these quantities versus IR color are entirely normal. However, all of the dead OH/IR stars have small, less than 12 km s^{-1}, expansion velocities, and all but one have blue IR colors. When these criteria are used to further delimit the sample, the five dead OH/IR stars in a sample of 112 imply a mean 1612 MHz emission life $t_e \sim 314$ (+387, −97) yr. The short duration of this emission phase is readily understood if oxygen-rich AGB stars toward the end of the AGB pass through a brief OH/IR star phase after a thermal pulse, when, as often happens, they are not bright enough to support heavy mass loss on the luminosity ascent to a thermal pulse. Copious AGB mass loss is thus frequently triggered by events that follow a thermal pulse.

Subject headings: circumstellar matter — radio lines: stars — stars: AGB and post-AGB — stars: mass loss — stars: variables: other — surveys

1. INTRODUCTION

First, a word on terminology. An important fraction of any sample of *IRAS* sources, selected to match the IR colors of known OH/IR stars, does not exhibit a detectable 1612 MHz maser, even when the colors are those of very thick circumstellar shells (Lewis 1992). However, some of these objects do *exhibit* mainline OH and/or 22 GHz masers. These IR sources are called OH/IR star color mimics. The existence of bona fide mimics makes it necessary to restrict the use of the OH/IR star label to asymptotic giant branch (AGB) stars exhibiting 1612 MHz masers, a usage that also avoids confusing them with Mira variables that have OH mainline masers, thin shells, and colors that are rarely associated with 1612 MHz masers. The "death" of an OH/IR star occurs when it is no longer expected to have detectable 1612 MHz masers.

There are two evolutionary scenarios for dead OH/IR stars. The first follows soon after the complete loss of a stellar envelope, when, in consequence, the circumstellar shell can no longer be replenished by ongoing mass loss. These stars then contract to become the central stars of planetary nebulae and so first become proto–planetary nebulae (PPN) before, some thousands of years later, evolving into planetary nebulae. The prototypical object for this scenario is IRAS 18455+0448, which had a 2.1 Jy maser in 1988 that had faded to a 0.1 Jy maser by 1998; its final, smooth, exponential decline was followed for 2 yr by Lewis, Oppenheimer, & Daubar (2001), until its peak intensity $I_{1612} < 2$ mJy. In this case, the lack of a long-period pulsational signature in the declining maser and the red IR colors of the shell both suggest that 18455+0448 had become a PPN. Such deaths are normally irrevocable. By contrast, the second scenario for dead OH/IR stars occurs when mass loss into a circumstellar shell declines sharply as the extra luminosity available after a He shell flash ebbs away, even though the star still has a stellar envelope. The subsequent evolution in the case of a *low-mass* AGB star is a retracing of its prior mass-loss history en route to its next thermal pulse, after which it is resurrected as an OH/IR star (Wood & Vassiliadis 1992; Lewis 2001a).

Until now, we have only had evidence for the death of one OH/IR star, so confirmation of the second scenario depends on discovering more. This is practical, as the net duration of all 1612 MHz emission phases for an OH/IR star with a low progenitor mass is ∼1670 (+1680, −554) yr, a value derived from their frequency relative to associated PPN and the shell-expansion age of the PPN 18095+2704 (Lewis 2000). We should thus, on average, witness the death of one such OH/IR star every 10 yr from a sample of 170 if the 1612 MHz emission phase usually occurs as a single episode, with most deaths conforming to the first scenario. However, more deaths are expected if stars evolve through an emission phase several times, as the second scenario anticipates. We accordingly report here on the results of reobserving the Arecibo sample of OH/IR stars after ∼12 yr.

2. OBSERVATIONS

OH/IR stars commonly exhibit factor of 2–3 variations in the intensity of their 1612 MHz masers around their pulsation cycles (Harvey et al. 1974; Herman & Habing 1985), although systemic factor of 10 changes are sometimes seen in individual features of hypergiant stars such as IRC +10420. There is also a possibility of secular changes in the intensity of masers, as was seen for instance with the 20 yr fading of the mainline masers of Mira (Gerard & Bourgois 1992), which was probably due to changes in the orientation of our line of sight with respect to the evolving orbit of its degenerate companion. To have confidence in the final disappearance of all 1612 MHz masers, we therefore need to show that they have faded by a factor greater than 20. This survey for dead OH/IR stars using the 305 m Arecibo telescope is thus restricted to those with a discovery epoch $I_{1612} > 100$ mJy.

A complete sample of OH/IR stars in the Arecibo sky ($0° \leq \delta \leq 38°$) was obtained between 1985 and 1988 by searching for the 1612 MHz masers exhibited by color-selected *IRAS* sources having $S(25\ \mu\mathrm{m}) > 2$ Jy. This resulted in a tally of 435 stars (Lewis 1994) and includes stars from the full range of progenitor masses. Of these, the 328 that had a discovery epoch $I_{1612} > 100$ mJy constitute our master sample; all have been reobserved since 1999 March.

The new observations are 10 minute, ON source integrations taken simultaneously in the 1612, 1665, and 1667 MHz OH lines, most at a resolution of 0.07 km s^{-1}, with left-circular polarization and right-circular polarization signals being fed to separate 1024 lag correlators. The baselines are flattened by subtracting a polynomial fit to channels without signal. Table 1 provides details on observations of the four objects that no longer have detectable 1612 MHz masers. Each of these has been reobserved several times, so the accumulated 3 σ limits on the presence of 1612 MHz emission listed in Table 2 show that all of their masers are at least a factor of 60 weaker than their first-epoch I_{1612}. In addition, Table 1 contains some details on IRAS 15060+0947 (=FV Boo=NSV 20253), which still has masers in the last stages of an exponential decline. Our current tally of deaths thus stands at ~5.

IRAS 15060+0947 needs particular discussion. The *IRAS* Point Source Catalog (1985) accords it an $S(25) = 26.9$ Jy, while its *IRAS* low-resolution spectrograph type of 28 shows that it had a strong 9.7 μm silicate feature in emission. It has an M9 III spectral type. Its 1612 MHz masers were first detected in 1985 May by Eder, Lewis, & Terzian (1988) when they had a classic morphology, with blue- and redshifted peaks of 142 and 370 mJy, respectively. Moreover, they still had peak intensities of 146 and 185 mJy when first reobserved in 1999 July, although they have always been much weaker since. Indeed, FV Boo had an $I_{1612} < 10$ mJy in 2001 September, when it was 37 times weaker than its I_{1612} in 1985. The 1612 MHz light curve is shown in Figure 1 with a linear fit to the log of the intensity of each of its peaks; this shows that an exponential decline underlies an oscillating intensity. The decline has an e-folding time of ~560 days. A Lomb periodogram analysis of the light curve from each peak, after rectifying for the log decline, gives a period of 318 ± 3 days, which is consistent with the 315 day optical period (Takamizawa 1998). FV Boo is thus an OH/IR star whose 1612 MHz masers appear to be in terminal decline even as it exhibits the long-period variability of an AGB star.

The first-epoch plots of I_{1612} versus $S(25)$ and the ratio of these quantities versus IR color are shown in Figures 2 and 3 for the whole Arecibo sample. This color is defined from the *IRAS* fluxes, adjusted for a 300 K blackbody, as $(25-12)\ \mu\mathrm{m} = \log_{10}[S(25) \times 12 \times 0.89/S(12) \times 25 \times 1.09]$.

TABLE 1

Observations of Dead OH/IR Stars

IRAS	Epoch	σ or I_{1612} (mJy)
18455+0448	1988 May	2086
	2000 Dec	1.31
	2001 Mar	1.48
	2001 Apr	2.95
	2001 May	2.31
	2001 Aug	2.13
	2001 Nov	1.82
	2002 Jan	2.27
19479+2111	1987 May	271
	2000 Jun	2.29
	2001 May	1.73
	2001 Oct	1.68
	2001 Nov	1.17
	2002 Feb	1.87
19529+3634	1987 May	280
	2001 Aug	2.35
	2001 Nov	1.73
	2002 Feb	1.53
20547+0247	1988 May	540 (=U Equ)
	1999 Apr	2.55
	2000 Dec	1.42
	2001 Feb	1.80
	2001 May	2.14
	2001 Aug	2.22
15060+0947	1985 May 16	342 (=FV Boo)
	1999 Jul 3	167
	1999 Dec 25	41
	2000 Oct 22	12
	2001 Sep 23	08
	2002 Jan 21	33

In both figures, the positions of dead OH/IR stars at the time of their discovery lie on the densest loci of stars, rather than amidst objects with weaker-than-average I_{1612} for their $S(25)$ or color, so the imminent demise of these stars cannot be predicted from the plots. Nevertheless, all four of our new dead or dying objects have blue IR colors and, as Table 2 shows, expansion velocities $V_e < 12$ km s^{-1}.

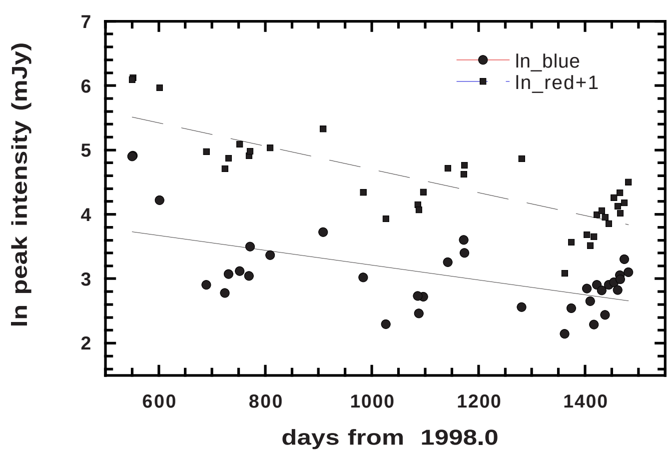

Fig. 1.—Light curve defined by the blue- and redshifted 1612 MHz peak intensities of FV Boo. The curve for the red peak is displaced vertically by 1.0 units for clarity.

TABLE 2
DEAD OH/IR STAR PARAMETERS

IRAS	Limit I_{1612} (mJy)	Epoch	(25–12) μm	V_e (km s^{-1})	Factor Change	H_2O[d] Status	SiO Status
15060 + 0947[a].......	~10	2001 Oct 6	−0.52	9.1	~37	D	D[e]
18455 + 0448[b]	< 2.1	2000 Dec–2001 Nov	−0.28	6.4	1000	N	N[f]
19479+ 2111[c]........	< 2.6	2000 Jun–2001 Nov	−0.64	3.4	104	D	D[f]
19529 + 3634[c].......	< 3.3	2001 Aug-Nov	−0.60	4.3	85	N	. . .
20547 + 0247[b]	< 3.2	1999 Apr–2001 Aug	−0.54	2.1	165	D	. . .

NOTE.—D = detection; N = nondetection.
[a] Eder et al. 1988.
[b] Chengalur et al. 1993.
[c] Lewis et al. 1990.
[d] Engels & Lewis 1996.
[e] Ita et al. 2001.
[f] Unpublished.

3. DISCUSSION

We currently know of four dead OH/IR stars in which all of the previously strong 1612 MHz masers in the systems have faded below our detectability limit in less than 12 yr. While a single instance of the systemwide extinction of masers, first noticed in 18455+0448, might at a pinch be attributed to some ad hoc condition that simultaneously affects the two 1612 MHz gain paths along our line of sight through an otherwise normal shell, this is difficult to accept for four systems. Moreover, the inverse process is also seen, in which substantial 1612 MHz masers (and both 1665 and 1667 MHz masers also) have grown from nothing over an appreciable velocity range in 6 yr within the shell of the hypergiant candidate OH/IR star, IRAS 19566+3423 (Lewis 2001b). Our data thus suggest that a surprisingly short, less than 10 yr, timescale characterizes these dramatic, systemwide changes to the set of masers. And because large changes must eventually occur to a shell's whole complement of masers whenever a persistent, large change in $\dot{M}$ affects a shell, this circumstance provides a robust explanation for the "birth" and the "death" of OH/IR stars.

Our four dead OH/IR stars were isolated from just 328 OH/IR stars observed twice, with a mean epoch difference of ~12 yr. The simplest pro tem treatment is to presume (1) that all 328 have low-mass progenitors and (2) that every dead OH/IR star follows the first scenario in immediately becoming a PPN. In this case, the death rate of stars from the total sample implies a mean 1612 MHz emission life, t_e, of $328 \times 12/4 \sim 984$ yr, which is less than 60% of the $t_e \sim 1700$ yr from the $|b| > 10°$ OH/IR stars that provide the shortest anticipated rate. Moreover, the $|b| > 10°$ stars, whenever they are not also PPN, all have (25–12) μm < -0.38 (Lewis, Eder, & Terzian 1990; Lewis 2000), as do the newly identified dead OH/IR stars. When the parent sample is restricted to the subset of 195 with (25–12) μm < -0.38, t_e drops to 780 (+571, −285) yr. But this t_e is still exaggerated in size, as an important fraction of the subset does not have low-mass progenitors. Because all of these estimates for t_e are less than 1700 yr, however, we must tentatively conclude that assumption 2 above is wrong. Most of our dead OH/IR stars are therefore following the second death scenario, in which they remain on the AGB as long-period variables while they retrace their mass-loss history and can exhibit water and/or SiO masers.

The blue IR color of the dead OH/IR stars is significant. This arises as the radius, R_{OH}, of maximum OH number density in the shell supporting 1612 MHz masers is typically $(1–10) \times 10^{16}$ cm (Netzer & Knapp 1987), which implies a

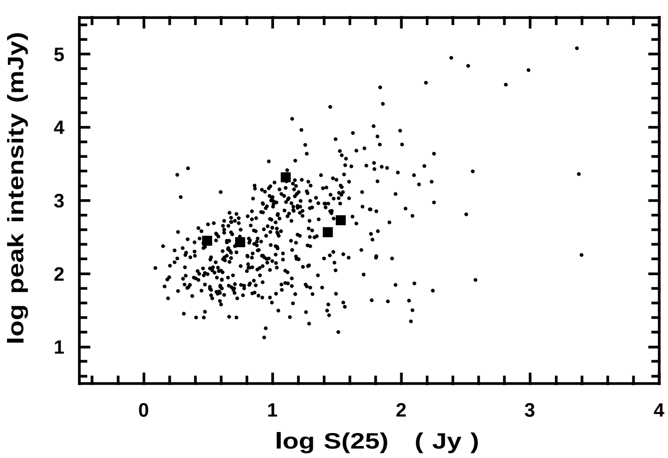

FIG. 2.—Log-log plot from the complete set of Arecibo OH/IR stars of the intensity of the largest 1612 MHz peak in the first-epoch observation against the 25 μm flux. The dead OH/IR stars are overplotted as squares.

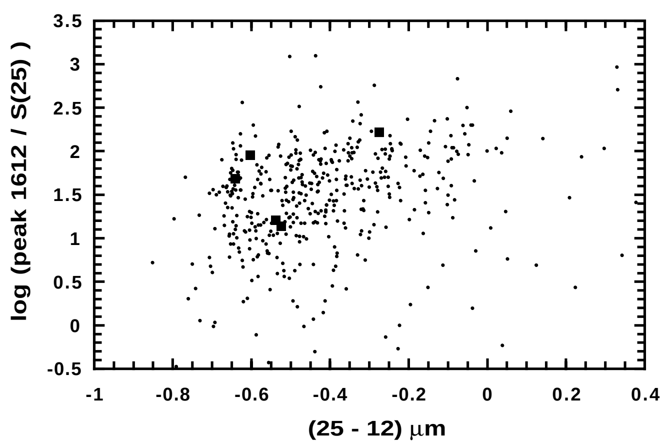

FIG. 3.—Ratio of the largest first-epoch 1612 MHz peak with the 25 μm flux plotted against the IR color for the complete set of Arecibo OH/IR stars. The dead OH/IR stars are overplotted as squares.

wind travel time, $\tau = R_{\rm OH}/V_e$, of several hundred years for the movement of mass from the star to $R_{\rm OH}$. Thus, gross changes in the complement of masers must lag behind those in $\dot{M}$ by $\sim\tau$ yr. The IR colors of the circumstellar shell at the time when the 1612 MHz masers disappear are, in consequence, already modified by the accumulated effect of a decreased $\dot{M}$ in the near environs of the star from colors obtaining τ yr in the past. For dead OH/IR stars following the second scenario, the color evolution of a shell soon turns toward bluer IR colors, as the dominant contribution to the 12 μm flux begins to come from the newest, hottest dust near the star; this eventually pushes their (25–12) μm color to ~ -0.85, as modeled by Steffen, Szczerba, & Schönberner (1998). Thus, a relatively blue IR color is expected for dead OH/IR stars following the second scenario, whereas a redder color is expected for those following the first.

FV Boo provides the most direct observational validation of the second scenario, as it has its three hallmark characteristics. These are (1) an exponential decline of similar magnitude in both the red and blue 1612 MHz peaks, (2) the long pulsation period of an AGB star, and (3) a blue IR color. It also exhibits water and SiO masers, which are far less likely to be exhibited by a PPN (Lewis 1989). FV Boo will thus become the prototype for the second scenario once its masers have faded beyond detectability in 2–4 yr time, when the tally of dead OH/IR stars from an $\sim$14 yr epoch interval will be 5. The initial, most brusque treatment of these death statistics then implies that the mean duration of a 1612 MHz emission phase in a *general* population of OH/IR stars is $t_e \sim (328 \times 14/5) \sim 920\ (+1133, -693)$ yr.

To understand a $t_e \sim 920$ yr, we need to recognize the difference between the classical OH/IR stars known before *IRAS*, which are almost all located near the Galactic plane, and those identified from color-selected *IRAS* sources, which have a far broader distribution in the Galaxy. The *classic* stars in general have much larger progenitor masses, have periods of 1000–2000 days, have $V_e > 12$ km s^{-1}, attain redder IR colors, and so have thicker shells; they presumptively occur when their degenerate cores are massive enough to drive a superwind for thousands of years without help from the extra luminosity of a He shell flash. By contrast, the multitude of low-mass OH/IR stars found by *IRAS* have periods shorter than 700 days, have bluer IR colors, and most have $V_e < 12$ km s^{-1}; they appear to achieve a superwind status only with the help of the added fillip provided by a He shell flash, which restricts their OH/IR star phase to a few hundred years (Lewis 2001a). This last property is expected to arise should these stars lose a significant fraction of their mass during ascent to the tip of the red giant branch (Fusi-Pecci & Renzini 1976), which would prevent them from having enough envelope mass to ever support an extended superwind episode on the AGB. Similarly brief 1612 MHz emission phases also occur in the more massive stars before their degenerate cores are able to sustain a superwind during the luminosity ascent to a He shell flash. Most oxygen-rich AGB stars should in consequence pass through a series of brief OH/IR star phases (Wood & Vassiliadis 1992), when they will have circumstellar shells resembling those of low-mass stars, although the OH/IR star phase recurs after $\sim$5000 yr in massive stars, and after $\sim$70,000 yr in low-mass stars.

A better estimate for t_e can be obtained by restricting the host sample to the subset with shell properties common to those in the brief 1612 MHz emission phase [(25–12) μm < -0.38; $V_e < 12$ km s^{-1}]. This implies a $t_e = 112 \times 14/5 \sim 314\ (+387, -97)$ yr. Or, if the host sample is restricted to the intrinsically low-mass subset of 39 with $|b| > 10°$, in which there are two deaths (FV Boo and U Equ), $t_e \sim 273$ yr. These unanimously low estimates for t_e show that (1) for a low-mass star to accumulate a net $t_e \sim 1700$ yr, a brief 1612 MHz emission phase must recur several times, and (2) because the duration of the luminosity spike above ambient after a thermal pulse, t_s, is 400–500 yr, according to stellar evolution calculations (Wood & Zarro 1981), so $t_s \sim 2t_e$, the brief 1612 MHz emission phase for stars in our sample is indeed linked to the abrupt luminosity changes following after a He shell flash.

The transience of OH/IR stars evidenced in these death statistics has two corollaries, as (1) there should be about as many births as there are deaths, and (2) the periods of all transient OH/IR stars should be decreasing. The first corollary, which follows from our expectation of a steady-state population of OH/IR stars, is being confirmed by experience, as Lewis (2001c) identifies three new OH/IR stars (V1511 Cyg, IRAS 18432+1343, and IRAS 18280+0521) that did not exhibit 1612 MHz masers during first-epoch searches in 1985–1988. The second corollary is a consequence of the near 1:2 ratio in the magnitude of t_e and t_s, as a *newly expanding*, dense, circumstellar shell cannot exhibit 1612 MHz masers until there is enough dust protection to provide its molecules with sufficient longevity against photodissociation by interstellar UV. But constant $\dot{M}$ models of shells show that OH molecules quickly recombine at the densities and temperatures prevailing for $R < 10^{15}$ cm, so it takes $\geq$200 yr to grow an OH column density sufficient to support a 1612 MHz maser in the presence of an average UV flux (D. Howe 2000, private communication); it takes even longer for them to emerge in real shells that initially have an accelerating $\dot{M}$ for as long as the extra luminosity generated by the He shell flash is still increasing. Thus, 1612 MHz masers should be hosted in transient OH/IR stars only during the decline in the luminosity spike, while their periods are decreasing (Lewis 2001a).

4. CONCLUSIONS

This search for dead OH/IR stars has identified one in the process of dying, FV Boo, and three more that no longer exhibit 1612 MHz masers. Their blue IR colors, the presence in some of water and SiO masers, and the 315 day period of FV Boo suggest that these objects are all still AGB stars, whose immediate evolution is likely to retrace their previous mass-loss history until their next thermal pulse, rather than PPN. Their IR colors should thus loop back to a (25–12) μm ~ -0.85 before becoming redder again.

The short, $t_e \sim 314$ yr, average duration of the 1612 MHz emission phase implied by the frequency of dead OH/IR stars in our sample is readily understood if oxygen-rich AGB stars toward the end of the AGB pass through a brief OH/IR star phase after each thermal pulse, when they are not bright enough to support heavy mass loss on the luminosity ascent to a thermal pulse. This t_e is then the observational signature in oxygen-rich stars for the correlation between the $\dot{M}$ and period proposed by Wood & Vassiliadis (1992). Copious AGB mass loss is thus frequently triggered by the events that follow a thermal pulse. While an increase in shell density is an expected consequence of an increase in luminosity and period, Lewis (2001a) argues that the physical trigger for copious mass loss occurs when the density in the circumstellar shell rises past the threshold that abruptly causes newly formed dust grains to be slowed by collisions with gas molecules so that grains suddenly start to couple photon momentum to the shell.

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