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THE APPROACHING DEATH OF THE OH/IR STAR IRAS 18455+0448

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ABSTRACT

1612 MHz observations of the OH/IR star IRAS 18455+0448 in 1998 June showed that its peak intensity had faded by a factor of 20 from its 2.09 Jy discovery intensity in 1988. Its peak intensity, when observed at constant resolution, has faded exponentially since by a further factor of 10, with an *e*-folding time of 319 days. This decline is seemingly inexorable, even though the main line OH masers are as yet largely unaffected, as the correlation between the expansion velocities and periods of OH/IR stars suggests a likely period of ∼400 days for 18455+0448 as a long-period variable, and our observations cover 706 days. We argue that extant data are best understood if we are witnessing an early stage in the expansion of a fossil circumstellar shell around 18455+0448, prior to it becoming a planetary nebula.

Subject headings: circumstellar matter — masers — radio lines: stars — stars: AGB and post-AGB

1. INTRODUCTION

One of the shakedown projects on the refurbished Arecibo telescope in 1998 June was to begin collecting simultaneous 1612, 1665, and 1667 MHz spectra of the Arecibo set of OH/IR stars. OH/IR stars are late-type stars with circumstellar shells exhibiting 1612 MHz masers. This is in contradistinction to the OH/IR star color mimics, which are similar objects that were expected to exhibit 1612 MHz masers but do not, although some mimics do exhibit main line masers. The Arecibo OH/IR stars were originally identified by color selection from the *IRAS* Point Source Catalog (1985) and confirmed by detection of their 1612 MHz masers (Eder, Lewis, & Terzian 1988). However, to our surprise, the peak 1612 MHz intensity of IRAS 18455+0448, one of 18 randomly chosen objects surveyed in 1998, had faded by a factor of 20 (Oppenheimer & Daubar 1998) from the 2.09 Jy reported at its discovery in 1988 (or by a factor of 13 if ringing in the profile is removed with a Hanning filter), while its second (0.64 Jy) peak had disappeared. These are exceptional changes. Past monitoring of pulsation-cycle–related changes in intensity of 1612 MHz masers shows that a factor of 2–3 variation is usual (Harvey et al. 1974; Herman & Habing 1985), although factor of 10 changes are seen from time to time in individual features of hypergiant stars such as IRC +10420. We report here on follow-up monitoring observations of IRAS 18455+0448 (alias MSX 5C_G036.8745+02.9676), which show that the peak intensity of its 1612 MHz maser has now faded by a further factor of 3. This heralds the imminent demise of the object as an OH/IR star.

2. OBSERVATIONS

2.1. OH *Observations*

The 1612 MHz masers of 18455+0448 were first detected in mid-1988: its discovery spectrum at the search resolution of 0.44 km s^{-1} is in Chengalur et al. (1993), its 0.22 km s^{-1} resolution 1665 and 1667 MHz spectra in Lewis (1997). There are no detected water masers (Engels & Lewis 1996). All three OH spectra have a classic OH/IR star morphology, with just two prominent peaks in each line, although these do have a small, $\Delta V = 2V_e = 12.7$ km s^{-1} separation for its red IR colors. Moreover, its original 2.1 Jy peak is very close to the ∼3 Jy upper limit implied for it by the general correlation between 1612 MHz and 25 μm flux (cf. Fig. 10 of Eder et al. 1988). Thus, 18455+0448 appeared in 1988 to be a typical OH/IR star.

The new observations of 18455+0448 were taken with the upgraded Arecibo telescope at a variety of velocity resolutions as time progressed, using nine-level sampling; Table 1 contains the instrumental details. These observations are simple ON-source integrations, with left- and right- circularly polarized signals fed to separate 1024 lag correlators. They are calibrated via 10 s ON/OFF measurements of a noise tube having an intensity of ∼30% of system temperature, while the noise tube is calibrated by intercomparisons with a set of 0.25–3 Jy continuum sources in fields not listed as complex by the NRAO VLA Sky Survey (Condon et al. 1998). The baselines are flattened by subtracting a polynomial fit to channels without signal.

Figure 1 documents the decline in the 1612 MHz intensity of 18455+0448. A log of the OH feature intensities, *at the observed resolution of each*, is listed for extant spectra in Table 2, where the routine detection of main line masers provides independent confirmation on the pointing. Figure 2 shows the history of the 1612 MHz maser, after its intensity has been averaged over adjacent bins to a consistent resolution of 0.57 km s^{-1}. This maser has decayed exponentially since 1998, with an *e*-folding time of 318.5 days. Since the decline has been monitored for 706 days, which is longer than the probable pulsation period of ∼400 (maximum 560) days inferred from correlations between ΔV and the periods of OH/IR stars (e.g., Fig. 6*a* of Lewis 1991), the decline cannot be attributed to changes in the pulsation cycle. We presume it permanent. It thus took less than 12 yr for a seemingly normal OH/IR star to be almost completely extinguished.

The peak intensities of the main line masers vary in disparate ways. Apart from an isolated flarelike event in 1999 July, the 27 km s^{-1} 1667 MHz peak has declined linearly with time by a factor of ∼2, so that it now has an intensity below that of 1989. The 40 km s^{-1} peak, on the other hand, has exhibited a noisier, factor ∼2 increase over the same time, while the two 1665 MHz features have been approximately constant. None of the features exhibit any Mira-like periodicity.

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TABLE 1
OH OBSERVATIONS OF 18455+0448

Date	Resolution (m s^{-1})	rms[a] (mJy)
1988 May 05	440	15.6
1989 Aug 24	220	18.6
1998 Jul 08	284	7.6
1998 Nov 15	568	5.0
1999 Feb 14	142	2.1
1999 Jul 05	071	2.2
1999 Nov 25	071	3.3
1999 Dec 25	071	2.1
2000 Apr 18	071	2.5
2000 Jun 12	018	1.8

[a] At resolution of 568 m s^{-1}.

2.2. *Extant IR Observations*

Mid-IR fluxes are available from the *IRAS* and *Midcourse Space Experiment* (*MSX*) missions. 18455+0448 has a 25 μm flux, $S(25) = 12.7$ Jy, that usually ensures that *IRAS* accords a source a low-resolution spectrograph (LRS) type, but not in this case. Spectra delivered by the *IRAS* Software Telescope in Groningen (Assendorp et al. 1995) show little trace of a 9.7 μm silicate feature in our opinion, although they are reminiscent of an LRS type 73. Nevertheless, Kwok, Volk, & Bidelman (1997) advertise their AAS CD-ROM table of classifications, in which they list it as a type A (for silicate absorption) spectrum, which can be inspected on the World Wide Web.[3] However, *IRAS* does accord 18455+0448 a zero probability of being a variable IR source, which is confirmed now by the excellent agreement between the color-corrected *IRAS* and *MSX* fluxes, the latter coming from version 1.0 of the *MSX* Point Source Catalog distributed on-line by IPAC. Its moderately red IR colors [(25−12) μm = −0.275; (60−25) μm = −0.784] are defined from *IRAS* fluxes adjusted for a 300 K blackbody, via

$$(25 - 12)\ \mu\text{m} = \log [S(25) \times 12 \times 0.89/S(12) \times 25 \times 1.09] \quad (1)$$

and

$$(60 - 25)\ \mu\text{m} = \log [S(60) \times 25 \times 0.82/S(25) \times 60 \times 0.89]. \quad (2)$$

Since 18455+0448 has an untenably low blackbody IR luminosity of 400 $L_\odot$ for an OH/IR star if placed at its near

[3] See http://www.iras.ucalgary.ca/iras_database.html.

TABLE 2
OH MASERS[a] IN 18455+0448

Date	Line (MHz)	V_L (km s^{-1})	V_H (km s^{-1})	I_L (mJy)	I_H (mJy)
1988 May 05	1612	27.76	40.47	2086	641
1989 Aug 24	1665	27.64	40.39	863	304
	1667	27.64	40.17	846	153
1998 Jul 08	1612	27.47	...	110	...
	1665	27.77	40.47	498	126
	1667	27.52	40.07	1581	138
1998 Nov 15	1612	28.11	...	44.9	...
	1665	28.07	40.15	681	140
	1667	27.54	40.71	1237	101
1999 Feb 14	1612	27.86	...	47.2	...
	1665	27.78	40.42	562	148
	1667	27.65	40.27	1263	154
1999 Jul 05	1612	27.80	...	62.6	...
	1665	27.86	40.36	594	196
	1667	27.66	40.35	2236	244
1999 Nov 25	1612	27.79	...	42.8	...
	1665	27.85	40.35	675	179
	1667	27.65	40.34	997	223
1999 Dec 25	1612	27.79	...	27.6	...
	1665	27.86	40.41	596	148
	1667	27.47	40.52	810	180
2000 Apr 18	1612	27.79	...	33.1	...
	1665	27.85	40.42	548	166
	1667	27.65	40.34	920	224
2000 Jun 12	1612	27.77	...	39.5	...
	1665	27.85	40.35	454	137
	1667	27.72	40.34	733	169

[a] Peak intensities at observed resolution.

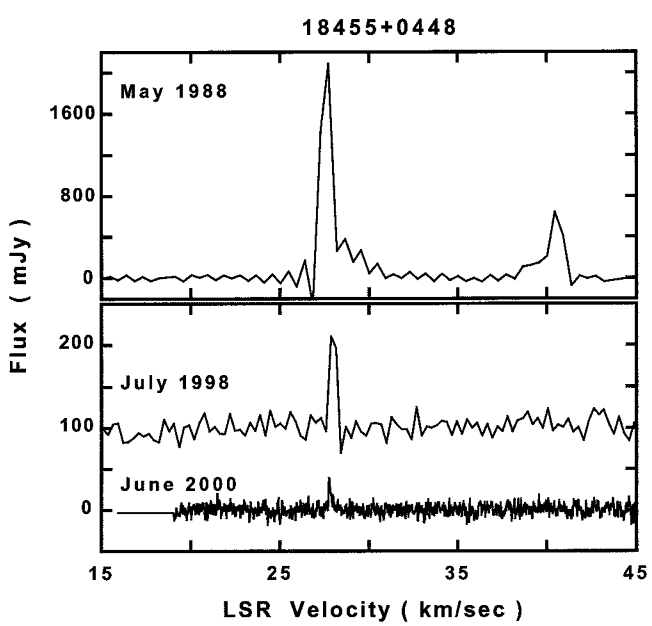

FIG. 1.—Selected unsmoothed 1612 MHz spectra of 18455+0448 from 1988 to 2000.

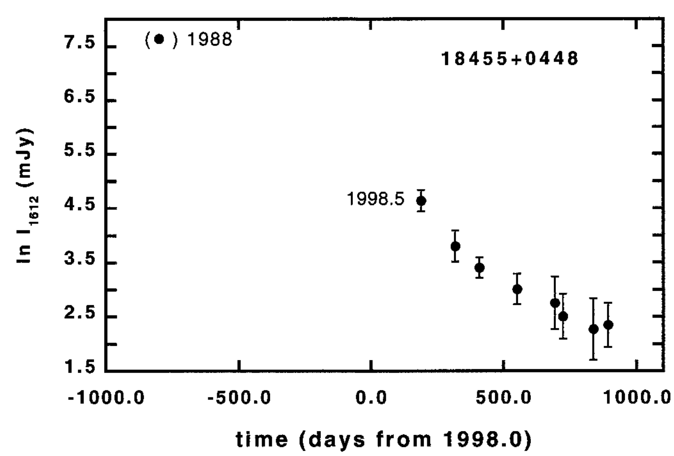

FIG. 2.—Decay of the 1612 MHz feature at 27.8 km s^{-1} from 1988 May to 2000 June, with 3 σ error bars. The peak intensity is plotted after averaging over adjacent channels to a resolution of 0.57 km s^{-1}. The 1988 observation, shown bracketed, is placed near the extrapolation of later observations, to emphasize the total range of intensity changes.

kinematic distance of 1.9 kpc, we use the 12 kpc far distance instead, despite it giving a rather large 15,800 $L_\odot$ IR luminosity.

3. DISCUSSION

The 1612 MHz masers of an OH/IR star must disappear sometime after the cessation of mass loss into its circumstellar shell, once the remnants of the shell have expanded sufficiently for interstellar UV to degrade its OH molecules. This occurs whenever $\dot{M} \rightarrow 0$, whether permanently, when the shell evolves first into a proto–planetary nebula (PPN) and then into a planetary nebula, or cyclically, when $\dot{M} \rightarrow 0$ for an extended time after a helium shell flash on the degenerate core of the OH/IR star. Masers can also be disrupted if the shell is subjected to a catastrophic event, such as the onset of a symbiotic nova, where a helium shell flash occurs at the surface of a white dwarf companion star after it has accreted enough mass from the enveloping wind. The ensuing intense UV flux quickly degrades OH molecules in the shell. However, such events are extremely rare and are entirely ruled out in the case of 18455+0448 by the close agreement between the recent (∼1996) *MSX* IR fluxes and those measured by *IRAS* in 1983–1984. We can thus be quite sure that the energetics of its shell have not changed over the last decade and so attribute the decline in its masers entirely to $\dot{M} \rightarrow 0$.

This diagnosis is consistent with the absence of water masers, as little gas is then expected within the zone that supports the maser. We are led both by theory (Field 1985) and by phenomenological surveys of masers (Lewis 1989) to anticipate that the 1612 MHz masers are the first of the OH masers to fade, as they depend on longer column densities of OH molecules (N_{OH}) than the main lines. Theory also predicts an exponential decline in a maser that is no longer saturated. These expectations match both the present weakening of the 1612 MHz maser and the relative constancy of the main line masers, as well as predicting the loss of main line masers over coming decades.

It is currently difficult to make a definitive determination as to whether 18455+0448 is a PPN or an OH/IR star en route to repeating its history of mass loss at the beginning of its next thermal pulse cycle. We are led by its small V_e for its red IR colors to believe that it comes from a low-mass (∼1 $M_\odot$) progenitor, since this combination is very uncommon among OH/IR stars with (25−12) μm > -0.4, although quite usual for high-latitude ($|b| > 10°$) OH/IR stars, in which case its IR colors and V_e match those of the high-latitude PPN candidate IRAS 20531+2909 (Lewis, Eder, & Terzian 1990, hereafter LET). Its identification as a PPN then explains the red colors. On the other hand, an about-to-be reborn, low-mass, OH/IR star intrinsically has a modest luminosity, although modeled trajectories for its evolution in IR color-color plots suggest that it probably would not achieve such a red (25−12) μm color for very long (Steffen, Szczerba, & Schönberner 1998). However, these objects, unlike PPNs, should have Mira-like periods. The constancy of the IR flux and the lack of any periodicity in the main line fluxes of 18455+0448 lead us to consider it a PPN.

This is the first time that an erstwhile strong 1612 MHz maser has been observed to decay systematically by such a large factor. On the other hand, there is an instance of comparable brevity for the converse process, where masers have grown from nothing on a decadal timescale: the 1612 and 1665 MHz masers of 19566+3423 currently exhibit a factor of 3 increase in both intensity and velocity range since 1988 (Lewis 1999). However, no one anticipated the brevity of any of these changes, which was perhaps an oversight. OH/IR stars become O-rich PPNs while still exhibiting masers, which are usually lost before a PPN evolves into a planetary nebula. Thus, the 70 mJy masers of the PPN IRAS 18095+2704 (LET) point to the likely presence of much stronger masers in its past, whose maximum peak intensity was presumptively ∼30 Jy when this is inferred from $S(25)$. As the expansion age of the inner edge of the dust shell in 18095+2704 is ∼103 yr (Hrivnak, Kwok, & Volk 1988; LET) and masers will usually decline only after the decrease in mass-loss rate has begun to move into the masing zone itself, which must require much of the wind travel time to occur, the decline of its masers from past glory presumptively occurs in much less than 103 yr; indeed, our experience with 18455+0448 suggests that it may have happened in less than 10 yr. Thus, 1612 MHz masers may perhaps always be extinguished rather abruptly.

The brevity of the timescale for the decline in the masers of 18455+0448 contrasts sharply with that for gross physical changes implied by the size of its masing shell. This is estimated from equation (12) of Netzer & Knapp (1987), which summarizes the results of their simulation of the circumstellar OH distribution generated by the photodegradation of water by interstellar UV, with R_{OH} the radius of the peak in the OH distribution, as

$$R_{OH}(10^{16}\ \mathrm{cm}) = A(\dot{M}/10^{-5}\ M_\odot\ \mathrm{yr}^{-1})^{0.7}(V_e/\mathrm{km\ s}^{-1})^{-0.4}, \quad (3)$$

where $A = 5.4$ is the Habing mean UV flux and $V_e = 6.35$ km s^{-1}. A plausible $\dot{M}$ is obtained from the relation of Baud & Habing (1983),

$$\dot{M}(M_\odot\ \mathrm{yr}^{-1}) = 1.8 \times 10^{-7} V_e(\mathrm{km\ s}^{-1}) S_{1612}^{0.5}(\mathrm{Jy}) D(\mathrm{kpc}), \quad (4)$$

where $S_{1612} = 1.16$ Jy is the geometric mean of the two peak 1612 MHz fluxes in 1988. Then for $D = 12$ kpc, $\dot{M} = 1.5 \times 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$, which on substitution into equation (3) gives 18455+0448 an $R_{OH} = 3.4 \times 10^{16}$ cm. The expansion timescale for moving gas from the photosphere to R_{OH} is $\tau = R_{OH}/V_e \sim 1700$ yr, while the radial thickness of the OH distribution (assuming a steady state $\dot{M}$) is ∼$3R_{OH}$. The consequent ∼0.2% (10/5100 yr) shortening of the OH column highlights the near irrelevance of the "kinematic" timescale to explaining the decline of the mildly saturated ($N_{OH} \sim 0.8 \times 10^{17}$ cm^{-2}) masers.

How to explain the timescale for the decay of the masers? Let us suppose that something, like the UV flux that occurs when a shell is subjected to a symbiotic nova's outburst, changes the physical conditions giving rise to OH through much of a shell. This thought leads us to search for an ongoing change in the ability of interstellar UV to penetrate the circumstellar dust shell, which in turn reminds us that dust grains have a drift velocity through circumstellar gas that decreases with $\dot{M}$ (Steffen et al. 1997).

Our working model assumes that 18455+0448 has a fossil circumstellar shell with a growing central "vacuole" or empty zone within an expanding spherical shell. Every column density of gas then decreases with time, while dust grains within the column are impelled outward by radiation pressure with a larger expansion velocity, V_e(dust), than the gas. And, since $\dot{M} \sim 0$, no new dust forms within the shell, so the column density of dust decreases slightly faster than that of the gas. The final element of our model postulates a gradual decline toward zero in $\dot{M}$ over a time Δt, rather than an abrupt decline where $\Delta t \rightarrow 0$. This feature introduces a declining dust-to-gas ratio with time over the innermost range of radii, $\Delta r \sim V_e(\mathrm{dust})\Delta t$, as the dust drift velocity moves dust differentially outward, as illustrated by Figure 3. Moreover, this differential process is enhanced further by the increase in the dust drift velocity as $\dot{M}$ decreases. At a time $\tau \times [V_e(\mathrm{gas})/V_e(\mathrm{dust})]$ after $\dot{M} \sim 0$, the dust-dilution process results in a progressive reduction in the column density of dust protecting OH from interstellar UV. The exponential attenuation of the incoming UV flux by the dust is thus reduced, which allows UV to destroy more molecules thereafter and so reduces the OH number density at an accelerating rate. This in turn lowers the (exponential) gain available to masers.

4. CONCLUSIONS

The 1612 MHz spectrum of IRAS 18455+0448 has changed drastically since the first observation of it in 1988. Its 40 km s^{-1} feature had disappeared entirely when it was first reobserved in 1998 July, while its 27 km s^{-1} peak had decreased in intensity by a factor of 20. This feature has decayed exponentially since by a further factor of ~10 when estimated from spectra with a constant 0.57 km s^{-1} resolution, or by a factor of 3 under the increasing deployed resolution. It will soon fade below the threshold for easy detection at Arecibo. We believe this is the first time that such a large systematic change has been monitored in a maser. By contrast, the main line masers of 18455+0448 as yet exhibit only modest secular changes in peak intensity and do not differ markedly from their first-epoch intensities. The exponential decline in the 1612 MHz maser, the lack of Mira-like periodicity in all of the OH masers, together with the mid-IR flux stability and IR colors of 18455+0448, are consistent with it being a young proto–planetary nebula. We surmise that the rapid weakening of its 1612 MHz maser is then explicable provided the $\dot{M}$ of the OH/IR star declined gradually toward zero, as this feature introduces an ever more pronounced decline in the dust-to-gas ratio with time over the innermost range of radii in a circumstellar shell. Interstellar UV then leaks more easily into the shell to destroy remaining molecules.

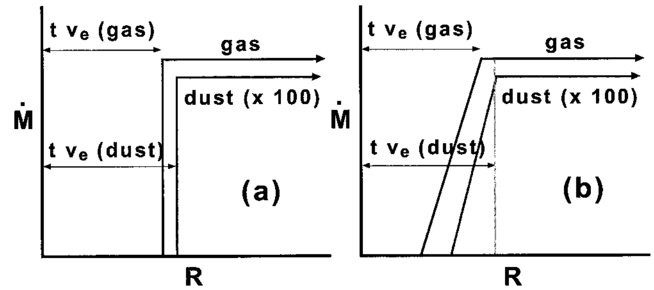

FIG. 3.—Schematic representation of the evolution of the dust-to-gas ratio in a fossil shell at time t after mass loss stops: (a) for abrupt termination of mass loss, where the ratio is effectively constant; and (b) for a gradual cessation of mass loss over Δt, where differential migration of dust generates an ongoing temporal change in the dust-to-gas ratio over a radial range $\Delta r = \Delta t V_e(\mathrm{dust})$.

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