A search for symbiotic behaviour amongst OH/IR colour mimics

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ABSTRACT
Recent maser surveys have shown that many potential OH/IR stars have no OH masers in their circumstellar envelopes, despite the modest requirements which should be implicitly met by IRAS colour-selected candidates. It has been suggested that these OH/IR colour mimics must have a degenerate companion which dissociates OH molecules and disrupts the masing action, ie. that they are related to symbiotic Miras. Coincidentally, there is a paucity of long-period symbiotic Miras and symbiotic OH/IR stars. Phenomenologically, those that are known seem to cluster in the zone where field Miras transform into OH/IR stars. If it could be proven that OH/IR colour mimics contain a degenerate star, that observable evidence of this star is hidden from view by circumstellar dust whilst it slowly accretes from the wind of its Mira companion, then we have an excellent explanation for not only the existence of OH/IR colour mimics, but also for the low observed frequency of symbiotic OH/IR stars and the common occurrence of very slow novae in long-period symbiotic Miras. Here, we employ radio continuum radiation (which should escape unhindered from within the dust shells) as a simple probe of the postulated hot degenerate companions which would inevitably ionize a region of their surrounding gas. We compare the radio and infrared properties of the colour mimics with those of normal symbiotic Miras, using the strong correlation between radio and mid-IR emission in symbiotic stars. We show that if a hot companion exists then, unlike their symbiotic counterparts, they must produce radiation-bounded nebulae. Our observations provide no support for the above scenario for the lack of observed masers, but neither do they permit a rejection of this scenario.

Key words: binaries: symbiotic – radio continuum: stars – stars: AGB, post-AGB.

1 INTRODUCTION
As a Mira evolves from short to longer pulsational periods, its mass-loss rate increases dramatically (Schild 1989). The object evolves from a classical Mira into a variable OH/IR source, a label which denotes the simultaneous presence of copious far-infrared emission and a 1,612-MHz OH maser. Circumstellar (CS) dust, formed in the wind of these pulsating giants, protects their molecules against photodissociation by interstellar UV. Its associated infrared (IR) emission also pumps the OH molecules for their stimulated emission. Stars without dust have no masers – there is no defensive shield. We therefore expect 1,612-MHz masers to be associated with strong, stellar far-IR sources and vica versa (particularly those that are oxygen-rich as a surplus of oxygen is required for the OH masers).

Potential OH/IR stars can be identified in the Infrared Astronomical Satellite (IRAS) Point Source Catalog (PSC) by searching for the signature of a dust shell – ie. its colour (eg. Engels et al. 1984; Gaylard et al. 1989). This approach has added over 1,000 new examples of the OH/IR phenomenon to the literature by successfully finding their 1,612 MHz OH masers (Eder, Lewis & Terzian 1988; Lewis, Eder & Terzian 1990; Lintel-Hekkert et al. 1991).

Despite the apparent success of colour selection techniques, recent maser surveys (eg. Lewis 1992a) have demonstrated that many potential OH/IR stars have no 1,612-MHz OH masers despite the modest requirements of a flux of 35- and 53-micron pump photons and a suitable column density of OH molecules (which should be implicitly met by IRAS PSC colour-selected candidates). Many also lack mainline (1,665 and 1,667 MHz) OH and 22-GHz water masers. For these objects the absence of a detectable OH maser has been shown to be independent of telescope sensitivity and it is not attributable to IR variability (less than 2 percent are detected when observed for the second time). Furthermore, many of the candidate stars are O-rich (LRS types 2n–3n, ie. the 9.7-micron silicate feature is present in either emission...
or absorption). Lewis (1992a) and Lewis & Engels (1993) demonstrated that 17% of LRS type 2n–3n sources with colours suggestive of CS dust shells have no OH or H₂O masers.

It has been suggested (Lewis 1992b) that the natural explanation for the “OH/IR colour mimics” is that they are systems with a degenerate companion – a local source of UV which disrupts the CS shell and prevents the masing action, ie. that the colour mimics are closely related to symbiotic Miras.

According to the conventional picture of the symbiotic Miras (which are probably represented exclusively by the D(nusty)-type sub-class of symbiotic stars), a hot, degenerate star ionizes the Mira wind giving rise to a forest of emission lines in the optical/UV (together with the normal far-IR dust emission and semi-regular pulsations expected from the cooler star). The hot companion exhibits unusually slow nova-like outbursts (eg. RR Tel), possibly the consequence of shell flashes resulting from accretion from the Mira wind (see eg. Allen & Wright 1988). The symbiotic Miras are less numerous than the S(tellar)-type sub-class which contain a first-ascent red giant whose stellar atmosphere is the dominant contributor to the observed IR emission.

The known symbiotic Miras appear to be generally devoid of maser emission, according to a number of recent searches, and the hypothesis is that the hot companion is responsible for either the dissociation of the relevant molecules or for disruption of the maser emission mechanism (eg. Norris et al. 1984). In support of this picture, Lewis, Hajian & Terzian (1992) searched the International Ultraviolet Explorer (IUE) data archive for a small, colour-selected sample of stars without OH or H₂O masers (many, in fact, were bona fide symbiotic stars) and found that most exhibited a strong UV continuum. Thus it is reasonable to suspect that the absence of maser emission may be associated with the presence of a hot companion.

Phenomenologically, symbiotic Miras cluster in the zone where field Miras transform into OH/IR stars (Schöier 1989). The correspondingly high mass-loss rate of D-type symbiotic Miras is generally thought to lead to stronger optical/UV line emission than is seen from the S-types. This effect enhances a symbiotic Mira’s chance of discovery in objective prism surveys. However, it is possible that these symbiotics spend many years prior to outburst in hibernation (resembling solitary Miras in most respects) as the hidden companion accretes slowly from the Mira’s wind. In this case the hot companion and associated emission lines would be totally obscured optically by the dusty CS shell of the Mira. Schöier (1989) has suggested that the obscuration of the hot component by the dusty CS shell produces a selection against the detection of symbiotic binaries with Mira or OH/IR stars cool components and may therefore be responsible for their paucity. The suggestion by Lewis (1992b) is that the hot companion may never-the-less be effective in destroying any maser action, even though it is not optically visible. Recently, Lewis et al. (in preparation) obtained new IUE data for an unbiased sample of colour mimics (our sample – see later) they failed to detect UV continuum emission, presumably because of obscuration by CS dust. Lewis suggests with resignation that ‘D-type symbiotic stars can be identified among sources with thick, opaque dust shells by a persistent absence of appropriate masers.’

Thus these colour-mimics have implications for a proper understanding of the evolution of OH/IR stars and for the behaviour of symbiotic binaries. To properly test the hypothesis of Lewis (and thereby address some of the questions posed above) it is necessary to somehow probe through the CS dust shells of OH/IR colour mimics. Here, we describe a search for free-free continuum at cm wavelengths from gas ionized by the hot, stellar component. Radio continuum radiation should easily escape from within a CS dust shell.

Observations of radio continuum emission have long been exploited to acquire knowledge of processes in symbiotics (eg. Seaquist & Taylor 1990) and it is worth noting that all of the symbiotic Miras accessible from the VLA have been detected at 3.6 cm. Our method of determining whether the degenerate companions truly exist is therefore to compare the continuum flux densities of the OH/IR colour mimics with continuum measurements of symbiotic stars from the northern- and southern-sky surveys by Seaquist, Krogulec and Taylor (1993, hereafter SKT93) and Ivison & Seaquist (in preparation).

In what follows we describe our continuum measurements of 15 IRAS FSC OH/IR colour mimics (massive, oxygen-rich, LRS types 2n–3n) using the NRAO Very Large Array (VLA).

2 OBSERVATIONS AND RESULTS

Observations of 15 OH/IR colour mimics at 3.6 cm were carried out during 1993 September 03–04 using the VLA in a hybrid of the C and D configurations with the northern arm of the array longer than the eastern and western arms. The total bandwidth for our observations was 100 MHz, centred at 8.44 GHz (3.6 cm). Two separate IF pairs were employed, each containing right and left circular polarizations, thus four measurements were recorded at 15-s intervals for each antenna. Later, during mapping, the four measurements were averaged for each time interval. The FWHM of the synthesized beam (averaged between major and minor axes) was about 7 arcsec.

The observing procedure was standard in most respects. Observations (four 10-min snapshots centred on a position 10 arcsec north of each target star) were sandwiched and interspersed with brief measurements of bright, unresolved calibrators. The flux densities of the targets were tied to those of their nearby calibrators which, in turn, were tied to the flux density of 3C 286 (5.27 Jy at 3.6 cm).

Calibration closely followed the recipes laid down in the NRAO AIPS Cookbook. The phase and amplitude solutions were extremely stable throughout the 15-hr observing period. Maps of each target were then made using the MX routine within AIPS. The maps had dimensions 256 x 256 pixels, usually with 1.00 or 2.25 arcsec pixels, and we employed up to 5,000 CLEAN iterations. The resulting noise level was very close to the theoretical limit, usually between 15 and 25 μJy.

Larger maps were made for targets with bright, confusing objects nearby. For example, a planetary nebula (He

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Table 1. The sample of OH/IR colour mimics and results of the VLA observations

| Source name(s) | IRAS LRS type | Coordinates (B1950) | Flux Density at 3.6 cm/8.44 GHz |
|----------------|---------------|---------------------|-------------------------------|
| 06181+0406     | 23            | 06 18 07.3          | +04 06 36                     | 3σ < 59                      |
| 06582+1507     | 22            | 06 58 17.3          | +15 07 58                     | 3σ < 81                      |
| 18281+2149     | 25            | 18 28 08.8          | +21 49 50                     | 3σ < 67                      |
| 18586+0106     | 35            | 18 58 38.1          | +01 06 57                     | 3σ < 229                     |
| 19135+0931     | 24            | 19 13 30.6          | +09 31 32                     | 3σ < 56                      |
| 19282+2253     | 26            | 19 28 12.1          | +22 53 39                     | 3σ < 60                      |
| 19310+1745     | 39            | 19 31 02.8          | +17 45 31                     | 3σ < 73                      |
| 19420+3318     | 24            | 19 42 01.5          | +33 18 08                     | 3σ < 67                      |
| 19548+3035     | 21            | 19 54 48.8          | +30 35 53                     | 3σ < 61                      |
| 19558+3333     | 31            | 19 55 53.3          | +33 33 11                     | 440 ± 90*                    |
| 19573+3143     | 29            | 19 57 18.0          | +31 43 55                     | 3σ < 69                      |
| 19584+2652     | 32            | 19 58 26.7          | +26 52 18                     | 3σ < 55                      |
| 19586+3637     | 31            | 19 58 39.1          | +36 37 50                     | 3σ < 46                      |
| 20217+3330     | 24            | 20 21 42.7          | +33 30 53                     | 3σ < 69                      |
| 20220+3404     | 34            | 20 22 04.2          | +34 04 53                     | 3σ < 69                      |

* R.A. = 19h 58m 39.4s; dec = 36° 37′ 50″ (B1950)

1–4, PK 68 +12°2) was visible ∼3 arcmin to the NNE of the colour mimic 19573+3143 (at R.A. (B1950) = 19h 57m 20.5s; dec = 31° 46′ 23″) and so a 17′ × 17′ map was created.

Our search list began as the sample of O-rich colour mimics (IRAS PSC LRS types 2n–3n) listed in Table 7 of Lewis (1992a). Lewis & Engels (1993) later pruned the list from 26 to 15 objects by obtaining very high sensitivity OH mainline and H2 22-GHz line data with the Arecibo and Effelsberg antennas, respectively. The list of remaining targets (together with IRAS coordinates and alternative names) is given in Table 1 together with the 3.6-cm flux density for the one detected and upper limits for the remaining 14 objects. We accepted a detection if the radio position was within the 95 percent significance level error ellipse of the IRAS coordinates. The upper limits are three times the rms noise on the map.

3 DISCUSSION

3.1 IRAS colours

Figure 1(a) shows an IRAS two-colour diagram of the OH/IR colour mimics in our sample, superimposed upon the colour distribution of typical OH/IR stars. The data were taken directly from the IRAS PSC. For comparison, the colour distribution of 53 symbiotics (those detected in two or more of the 12-, 25- and 60-micron bands) is shown in Figure 1(b). Of the ∼165 known symbiotic stars, 68 were detected in at least one band by IRAS (Munari & Ivison, in preparation).

The (25–12) and (60–25) colours are defined in the νSν formalism, for an assumed blackbody temperature of 300 K, as

\[(25 – 12) = \log_{10} \left( \frac{S_{25} \times 12 \times 0.89}{S_{12} \times 25 \times 1.09} \right) \quad (1)\]

and

\[(60 – 25) = \log_{10} \left( \frac{S_{60} \times 25 \times 0.82}{S_{25} \times 60 \times 0.89} \right) \quad (2)\]

where \(S_{12}, S_{25}\) and \(S_{60}\) are the IRAS PSC flux densities at 12, 25 and 60 microns.

It is clear from Figure 1 that, in terms of their IRAS colours, the OH/IR colour mimics are more closely related to the (D-type) symbiotic Miras than to the S-type symbiotics. We also note a strong similarity between the colours of the ‘yellow’ (D-type) symbiotic stars, specifically V741 Persei, Wray 157 and AS 201, and those of normal OH/IR stars (cf. Kenyon, Fernández-Castro & Stencel 1988).

3.2 OH and H2O masers in symbiotic Miras

The recent maser-line survey of symbiotic Miras by Seaqquist & Ivison (in preparation) resulted in the detection of 1,612-MHz OH and 22-GHz H2O masers in H1–36 and R Aqr (see also Ivison, Seaqquist & Hall 1994). The level of maser emission from H1–36 (∼250 mJy) would certainly have ensured its detection had it been a target in the search for OH and H2O emission from OH/IR colour mimics by Lewis & Engels (1993). The detection of H1–36 at 1,612 MHz is ironic because the work presented by Lewis (1992a) was inspired by the association of H1–36 with IRAS source 17463–3700 and its supposed lack of a detectable OH maser. R Aqr is the nearest known symbiotic star (d = 200 pc), and detection of its masers would not have been possible at the distance of H1–36 (d > 5 kpc).

Both R Aqr and H1–36 are sources of intense radio continuum and optical line emission. It is generally thought that 10^4–10^6 K degenerate stars orbit the Mira components, probably with binary separations in the range 10–1,000 AU. In the case of H1–36, it is possible that the hot companion lies outside the dusty CS envelope as the reddening to-
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Figure 1. IRAS two-colour diagrams of (a) the 15 OH/IR colour mimics observed by the VLA and (b) the 53 symbiotic stars detected in two or more of the 12-, 25- or 60-micron IRAS bands. Both sets of data are superimposed upon the colour distribution of normal OH/IR stars (Lewis & Engels 1993). Four-pointed stars: OH/IR colour mimics; filled circles: D-type symbiotics; empty circles: S-type symbiotics; filled diamonds: D'-type symbiotics.

Towards the Mira exceeds that towards the ionized nebula by \( \sim 18 \) mag (Allen 1983).

Thus recent maser-line observations have unequivocally shown that dust can shield some CS hydroxyl and water molecules from dissociation, even in systems which possess intense local sources of UV. If degenerate companions are responsible for the lack of masers in OH/IR colour mimics then it is probably reasonable to assume that the UV luminosity of these hot stars cannot be much less than that of the degenerate companion in H1–36.

3.3 Radio continuum studies of symbiotic stars and the colour mimics

Radio continuum observations of \( \sim 75 \) percent of the known symbiotic stars have been obtained during recent years by SKT93 and Ivison & Seaquist (in preparation) using the

Figure 2. The continuum flux density at 3.6 cm versus that at 12 \( \mu m \) for the symbiotic stars observed by SKT93 and Ivison & Seaquist (in preparation) and the OH/IR colour mimics. Stars referred to explicitly in the text are labelled. Four-pointed stars: OH/IR colour mimics; filled circles: D-type symbiotics; empty circles: S-type symbiotics; filled diamonds: D'-type symbiotics.

Figure 3. The continuum flux density at 3.6 cm versus that at 25 \( \mu m \) for symbiotic stars and OH/IR colour mimics. Four-pointed stars: OH/IR colour mimics; filled circles: D-type symbiotics; empty circles: S-type symbiotics; filled diamonds: D'-type symbiotics.

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VLA and Australia Telescope Compact Array. Both of these surveys concentrated at a wavelength of 3.6 cm.

SKT93 investigated the dependence of the radio–IR correlation on IR waveband, using both flux densities and luminosities for this purpose. Their work confirmed that a radio–IR correlation exists, and that it is strongest in the mid-IR (Spearman–Rank correlation coefficients: 0.73 at 12 μm; 0.64 at 25 μm, both with significance > 99.9 percent). This causes no surprise as both the dust and the ionized gas are thought to form part of the CS envelope in symbiotic binary systems.

Figures 2 and 3 show the most complete sample of radio and IR measurements of symbiotic stars to date, a total of 60 sources for which both IRAS and 3.6 cm data exist, together with the measurements of the colour mimics. IRAS flux densities for the symbiotics were drawn from Munari & Ivson (in preparation) and Kenyon et al. (1988). For the symbiotics, the correlation between both 12 and 25 μm flux densities and the 3.6 cm flux density is clear to the eye, especially for the D-types. The correlation improves further if the very slow novae, V1016 Cyg, HM Sge and RR Tel, are ignored. We note that the position of H1–36 on this diagram offers some credence to the idea, propounded by Allen (1983), that this system has also experienced a very slow nova-like event.

It is immediately clear even without recourse to statistical tests that there is virtually no similarity between our sample of OH/IR colour mimics and the radio-luminous D-type symbiotic Miras. Nor is there any similarity between S- or D′-type symbiotics and the colour mimics. This impression is confirmed by a 2-D Kolmogorov-Smirnov test (ignoring upper limits for the symbiotics whilst treating upper limits for the colour mimics as detections) which yields a probability \( p < 10^{-7} \) that the two samples are drawn from the same population. A 1-D test using survival analysis methods (Feigelson & Nelson 1985; Isobe, Feigelson & Nelson 1986) on a sample restricted to the range of IR flux densities occupied by the color mimics yields \( p < 10^{-4} \). All upper limits are included in the latter test. In only one case, that of 19558+3333, is there any possibility of an ionized nebula approaching the scale of those found in symbiotic Miras. Even for 19558+3333, the 3.6-cm flux density is more than an order of magnitude lower than symbiotic Miras with equivalent levels of mid-IR emission.

Thus it is clear that if the colour mimics possess hot companions, then the size of the ionized zone is relatively small. The radio detected symbiotics are nearly all density bounded (SKT93), and it is therefore likely that the colour mimics are radiation bounded. In terms of the binary model considered by Taylor & Seaquist (1984) this is equivalent to stating that the ionization parameter \( X < 1/3 \), where \( X \) measures essentially the ratio of the UV luminosity to the available mass in the envelope. It is possible to estimate the upper limit on the radio continuum flux density for such a system if the distance and binary separation are assumed. A rough estimate of the distance for the colour mimics may be obtained by comparing them with the group of D-type symbiotics in Figures 2 and 3 occupying the same range in IR flux density and a broadly similar range in colour. The median distance for symbiotics in this group for which there are available distance estimates (eg. SKT93) is about 2 kpc. Then for an assumed binary separation of \( 5 \times 10^{14} \) cm, the binary model yields a 3.6-cm flux density less than 100 μJy, not very different from the observed limits for the colour mimics. Note also that if R Aqr, a probable radiation-bounded system (SKT93), were placed at 2 kpc, then its continuum flux density would be near our detectable limit, and its \( \text{H}_2\text{O} \) maser emission would also be undetectable, though its SiO maser emission might be detectable. Furthermore, a line of slope unity through R Aqr in Figures 2 and 3 passes close to the one detection in our sample, thus if R Aqr were displaced in distance so that its IR flux matched that of the detected object, its radio flux would be comparable to our detected source, suggesting perhaps that most of the colour mimics are strongly radiation bounded if they contain a hot component at all. This may be due either to an underluminous hot companion, excessive mass-loss rate or small binary separation when compared to the D-type symbiotics of similar colour.

4 CONCLUSIONS

The search for 3.6 cm free-free emission from a sample of OH/IR colour mimics with no OH masers yielded negative results with possibly one exception. The conclusion is that for all but one of these objects the suspected hot companion does not ionize sufficient gas to reveal its presence as a radio source. A comparison with radio-luminous D-type symbiotics shows that the colour mimics do not belong to the D-type sub-class with density-bounded envelopes. It is possible however that they are radiation-bounded D-type symbiotics similar to R Aqr, whose continuum emission would be only marginally detectable, and whose \( \text{H}_2\text{O} \) maser would be undetectable at the distances of the known D-type systems.

Thus our results do not exclude the possibility that the colour mimics possess hot companions provided they produce radiation-bounded nebulae under these circumstances. Our results therefore provide no support for the hypothesis that molecular masers are inhibited by UV radiation from a hot companion. Neither do they contradict the hypothesis since radiation-bounded nebulae trap only UV emission shortward of the Lyman continuum. It is noteworthy, however, that a 1,612-MHz OH maser has now been detected in the distant and radio-luminous symbiotic Mira, H1–36, indicating in this case that UV does not inhibit the maser in this object. Perhaps the only means to determine whether these OH/IR colour mimics are “closest D-type symbiotics” is to monitor them for the slow nova-type outbursts which characterize these systems.

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