VLA survey of the 22 GHz H$_2$O masers toward 10 silicate carbon stars \textsuperscript{1,2,3,4,5}

(Research Note)

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Abstract

Context. Despite their carbon-rich photospheres, silicate carbon stars show evidence of oxygen-rich circumstellar material, which is considered to exist in disks. Silicate carbon stars represent interesting cases that allow us to study the possible effects of binarity on stellar evolution and the mass loss accompanied by the formation of disks.

Aims. We present a small survey of the 22 GHz H$_2$O masers toward 10 silicate carbon stars with much better sensitivity than the previous observations.

Methods. We observed our sample with the Karl G. Jansky Very Large Array (VLA) using the most expanded configuration (A-configuration) with a maximum baseline of 36 km. For some of our program stars with noisy IRAS Low Resolution Spectra (LRS), we present new mid-IR spectra obtained with the Very Large Telescope Interferometer and the Spitzer Space Telescope.

Results. We detected the H$_2$O masers toward 5 out of 10 silicate carbon stars (EU And, V778 Cyg, IRAS06017+1011, V1415 Cyg, and NC83=V1945 Cyg), with NC83 being new detection. No H$_2$O masers were detected toward BM Gem, IRAS07221-0431, IRAS08002-3803, IRAS18006-3213, and HD189605. The velocity separation between the most blue- and red-shifted maser features is 10–14 km s$^{-1}$. If we assume that the masers originate in circum-companion disks, the measured velocity separations translate into a lower limit of the rotational velocity of 5–7 km s$^{-1}$, and the upper limit of the radius of the maser emitting region is estimated to be 10–68 AU for a companion mass of 0.5–1.7 $M_{\odot}$. The new mid-IR spectra of NC83, IRAS06017+1011, and HD189605 confirm the 10$\mu$m silicate emission. The latter two stars show a bump at $\sim 11.5\mu$m, which is presumably due to SiC originating in the ongoing mass loss from the carbon-rich primary star, not due to crystalline silicate. We also report on the detection of the UV flux at 2271 Å toward HD189605.

Key words. radio lines: stars – techniques: interferometric – stars: circumstellar matter – stars: carbon – stars: chemically peculiar – stars: AGB and post-AGB

1. Introduction

Silicate carbon stars are characterized by oxygen-rich circumstellar material in spite of their carbon-rich photospheres (Little-Marenin 1986; Willems & de Jong 1989). As summarized in Ohnaka et al. (2006 and references therein), a currently believed hypothesis suggests that silicate carbon stars have a low-luminosity companion (a main-sequence star or a white dwarf) and that oxygen-rich material shed by the mass loss in the past, when the primary star was an oxygen-rich giant, is stored in a circumbinary disk or in a circumstellar disk around the unseen companion until the primary star becomes a carbon star (Morris 1987; Lloyd-Evans 1990; Yamamura et al. 2000). However, the formation mechanisms of such circumbinary or circum-companion disks and their relation to binary parameters are unknown. Moreover, this scenario does not explain the following peculiar chemical composition of the photosphere of silicate carbon stars: highly enriched in $^{13}$C with $^{12}$C/$^{13}$C$\approx 4-5$, in marked contrast to $^{12}$C/$^{13}$C $\geq 20$ in normal carbon stars (Ohnaka & Tsuji 1999). This anomalous chemical composition is difficult to explain by standard stellar evolution theory and may be related to binarity (e.g., Zhang & Jeffery 2013; Sengupta et al. 2013). Thus, silicate carbon stars represent interesting cases that allow us to study the possible effects of binarity on stellar evolution and the mass loss accompanied by the formation of disks.

High spatial resolution mid-IR (8–13 $\mu$m) observations with the mid-IR interferometric instrument MIDI at the ESO’s Very Large Telescope Interferometer (VLTI) have spatially resolved the dusty environment of silicate carbon stars and suggest the presence of circumbinary disks (Ohnaka et al. 2006; Deroo et al. 2007). On the other hand, our MIDI observations of the sil-
Our 22 GHz water maser mapping of the silicate carbon star EU And with the Very Long Baseline Array (VLBA) shows that the masers are aligned with a slightly S-shaped structure along a straight line (Ohnaka & Boboltz 2008). This is similar to what is found in the silicate carbon star V778 Cyg by Szczerba et al. (2006) suggest that the masers likely originate in warped circum-companion disks viewed almost edge-on.

The masering of more silicate carbon stars is indispensable for understanding the spatial structure of the oxygen-rich circumstellar material. In order to select objects appropriate for the detailed imaging with VLBA, we carried out a small survey of the H$_2$O masers at 22 GHz toward 10 silicate carbon stars with the Karl Jansky Very Large Array (VLAA). Our goal is to detect potential targets for future VLBA imaging with much better sensitivity than the previous observations in the literature.

### 2. Observations and data reduction

Table [1](#) gives a list of our 10 program stars, which were selected from the list of the confirmed silicate carbon stars in Engels (1994). From Table 3 of his paper, which consists of 13 stars, we excluded two stars, MC79-11 and CGCS3922. MC79-11 is too southern to observe from VLA. The identification of CGCS3922 as a silicate carbon star is not entirely established, as Lloyd-Evans (1991) notes. Besides, the star is included in a list of Li-rich “K giants” in De la Reza et al. (1997). We observed the remaining 11 stars, but the results of IRAS07204-1032 (CGCS1682) will be presented in a separate paper together with VLBA imaging observations (Boboltz et al., in prep). The H$_2$O masers were previously detected toward five objects, as summarized in Table [1](#).

| Name             | CGCS$^1$ | RA (J2000) | DEC (J2000) | Date 2007 | Det. | Previous H$_2$O maser detection (references) |
|------------------|----------|------------|-------------|-----------|------|------------------------------------------|
| IRAS06017+1011   | 1158     | 06:04:31.4 | +10:10:55   | Aug 19    | Y    | Y (E94)                                  |
| BM Gem           | 1653     | 07:20:59.0 | +24:59:58   | Aug 19    | N    | N (N87, LM88, EL94, BLM96, L97)          |
| IRAS07221-0431   | 1698     | 07:24:39.2 | +04:37:55   | Aug 19    | Y    | Y (E94)                                  |
| IRAS08002-3803   | 2011     | 08:02:05.1 | +38:11:52   | Aug 19    | N    | N (N88, D89)                             |
| IRAS18006-3213   | 3935     | 18:03:53.0 | +32:13:00   | Aug 20    | Y    | Y (LM88, EL94, BLM96)                    |
| N83              | 4222     | 19:15:01.3 | +54:17:26   | Aug 20    | Y    | Y (LM88, EL94, BLM96)                    |
| HD189605         | 4595     | 20:01:05.2 | +07:21:51   | Aug 20    | Y    | N (N84, E94)                             |
| V778 Cyg         | 4923     | 23:36:07.4 | +60:05:26   | Aug 20    | Y    | Y (N87, D88, LM88, LM93, EL94, C00, SH08, K13, EPC) |
| V1415 Cyg        | 5548     | 22:01:17.6 | +54:32:34   | Aug 20    | Y    | Y (E94)                                  |
| EU And           | 5848     | 23:19:58.2 | +47:14:28   | Aug 20    | Y    | Y (BLM87, LM88, LM93, EL94, BLM96, C00, O808, SH08, K13) |

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IRAS06017+1011, IRAS07221-0431, NC83, HD189605, and V1415 Cyg, the quality of the IRAS LRS is too poor to detect the 10 μm silicate emission definitively or study its spectral shape in detail. Therefore, we searched for newer mid-IR spectra for these objects. IRAS06017+1011 was observed with VLTI/MIDI on 2005 December 22 (Program ID: 076.D-0250, P.I.: K. Ohnaka). The data were reduced with the MIA+EWS ver2.4\(^{1}\), and the spectra were calibrated using HD39400 (K1.5IIb) as a spectroscopic standard star, using the method described in Ohnaka et al. (2006). NC83 and HD189605 were observed with the InfraRed Spectrometer (IRS, Houck et al. 2004) onboard the Spitzer Space Telescope (Werner et al. 2004) on 2004 December 9 and 2005 October 11, respectively, using the Short-High and Long-High modes with a spectral resolution of ~600 (Program ID: P03325, P.I.: C. Waelkens). We downloaded the Post Basic Calibrated Data (PBCD) from the Spitzer Heritage Archive. As presented in Sect. 2, the new mid-IR spectra confirm the silicate emission in these stars.

3. Results and discussion

We detected the H\(_2\)O maser emission from 5 out of 10 sources: EU And, IRAS06017+1011, NC83, V778 Cyg, and V1415 Cyg, with NC83 being the first maser detection. Figure 1 shows the H\(_2\)O maser spectra of these five stars. The velocity range of the detected maser peaks, the velocity and intensity of each peak, and the integrated flux are given in Table 2. For the non-detection sources, we give the upper limit of the maser intensity set by the 3σ RMS noise estimated as described in Sect. 2.

For NC83, Little-Marenin et al. (1988), Engels & Leinert (1994), and Benson & Little-Marenin (1996) searched for H\(_2\)O masers at more than 10 epochs in total in the 1980s and 1990s but detected no H\(_2\)O masers. In 2007 we detected a strong single-peaked H\(_2\)O maser (20 Jy) at \(V_{\text{LSR}} = 79 \ \text{km s}^{-1}\) in 1992 (Engels 1994), but we detected no H\(_2\)O masers, despite the detection limit (3σ RMS) of 0.02 Jy. This means that the maser intensity has decreased by more than a factor of 38. While significant time variations in the H\(_2\)O masers toward silicate carbon stars are not unusual, the drastic variation by a factor of ~40 seen in NC83 and IRAS07221-0431 is unique. This might be caused by some mechanism different from the usual erratic variations in the masers in stars such as V778 Cyg and IRAS06017+1011 (as described below). NC83 and IRAS07221-0431 are worth long-term monitoring.

In addition to this "on/off" variation, we also detected noticeable time variations in the maser intensity and spectral shape in IRAS06017+1011 and V778 Cyg. Engels (1994) detected a strong single-peaked H\(_2\)O maser (20 Jy) at ~13 km s\(^{-1}\) toward IRAS06017+1011 in 1992, while our VLA spectrum obtained 15 years later is very different, showing a peak (4.2 Jy) at ~24 km s\(^{-1}\) and much weaker peaks of 150 and 140 mJy at ~18 and ~15 km s\(^{-1}\), respectively. Our VLA spectrum of V778 Cyg is also remarkably different from the MERLIN spectrum taken in 2001 (Szczerba et al. 2006), which shows the strongest peak at ~15 km s\(^{-1}\) and a much weaker peak at ~17 km s\(^{-1}\).

The VLA H\(_2\)O maser spectra of EU And, IRAS06017+1011, and NC83 are characterized by blue- and red-peaks separated by 8.9, and 14 km s\(^{-1}\), respectively, and weaker peaks in between. The VLA spectrum of V778 Cyg is dominated by a single peak at ~17 km s\(^{-1}\), but there are weaker peaks of 0.22 Jy at ~19.5 km s\(^{-1}\) and 0.21 Jy at ~14.2 km s\(^{-1}\) on each side of the primary peak (Fig. 1 bottom right). In addition, there is some low-level emission from ~24.0 to ~20.1 km s\(^{-1}\) that is 3-4σ above the RMS noise of 0.02 Jy. This means a velocity separation of ~10 km s\(^{-1}\) between the most blue- and red-shifted features. The H\(_2\)O maser spectrum of V1415 Cyg is also dom-

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\(^{1}\) http://home.strw.leidenuniv.nl/~affe/ews/index.html

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Fig. 1. VLA spectra (vector-averaged cross-power spectra over all baselines) of five silicate carbon stars with the detection of the H\(_2\)O masers.
inated by a single peak. This spectral feature is much broader (~10 km s\(^{-1}\)) than the features in our other spectra, but the spectrum of V1415 Cyg was recorded with a much wider channel spacing of ~2.64 km s\(^{-1}\). Therefore, this single peak is likely a blend of several narrower features. In this case, the velocity width of this single peak of ~10 km s\(^{-1}\) would approximately correspond to the velocity separation between the most blue- and red-shifted peaks.

The measured velocity separations can be used to estimate the projected rotational velocity of the maser emitting region in circumbinary or circum-companion disks. We suggest that the masers in IRAS06017+1011, NC83, and V1415 Cyg originate in circumbinary disks similar to EU And and V778 Cyg (Ohnaka & Boboltz 2008; Szczepanik et al. 2006) for the following reason. The amount of the IR excesses toward these stars is similar and modest (see Table 3 of Engels 1994) and, therefore, implies that the oxygen-rich circumstellar material is optically thin. As Yamamura et al. (2000) argue, such material cannot exist stably in a circumbinary or circum-primary disk because the oxygen-rich material would be blown away by the intense radiation pressure from the primary carbon star.

It should be noted that the velocity separation measured at a given epoch can be narrower than the true velocity separation due to significant time variations in the maser intensity and the spectral shape as described above. Therefore, we checked the H\(_2\)O maser spectra previously presented in the literature (references listed in Table 1) to estimate the true velocity separation for the sources with the positive maser detection with VLA except for NC83 (our VLA observation is the first maser detection for this source). The maximum maser velocity range obtained from the past and present maser spectra is ~42.6...-29.5 km s\(^{-1}\), -24.0...-13.0 km s\(^{-1}\), -24.0...-14.2 km s\(^{-1}\), for EU And, IRAS06017+1011, and V778 Cyg, respectively. Therefore, the velocity separation in EU And, IRAS06017+1011, V778 Cyg, and NC83, are 13.1, 11.0, 9.8, 13.8 km s\(^{-1}\), respectively. In the case of V1415 Cyg, the only previous detection is reported by Engels (1994), who detected a narrow, single peak at ~28.2 km s\(^{-1}\). As mentioned above, the single peak in our VLA spectrum, which appears at roughly the same velocity, is much broader. Therefore, we took the width of this broad feature (~10 km s\(^{-1}\)) as the velocity separation.

A half of measured velocity separations corresponds to the projected rotational velocity of the putative circumbinary disks. Therefore, the observed velocity separations of 10–14 km s\(^{-1}\) translate into the projected rotational velocities of 5–7 km s\(^{-1}\) for five stars shown in Fig. 1. If we adopt 0.5–0.8 \(M_\odot\) for the companion mass as in EU And (Ohnaka & Boboltz 2008) and assume the Keplerian rotation, the radius of the maser emitting region is estimated to be 10–32 AU. Adopting a higher mass of 1.7 \(M_\odot\) derived for V778 Cyg by Babkovskaia et al. (2006) leads to a radius of 68 AU for the rotational velocity of 5 km s\(^{-1}\). Because the velocity separations estimated from the past and present maser spectra are still a lower limit, the estimated projected rotational velocities are a lower limit. The projected rotational velocities themselves give a lower limit on the (de-projected) rotational velocities. Therefore, the radius of the maser emitting region estimated above is an upper limit.

If the masers originate in circumbinary disks, the velocity range of the maser spectra is expected to systematically drift due to the orbital motion of the companion around the primary star if observed long enough. However, this is difficult to detect for two reasons. Firstly, the orbital period is expected to be as long as a few hundred years. For example, the modeling of the masers toward V778 Cyg by Babkovskaia et al. (2006) suggests a mass of 1 \(M_\odot\) and 1.7 \(M_\odot\) for the primary star and the companion, respectively, with a separation of 80 AU. This translates into an orbital velocity of ~2 km s\(^{-1}\) and a period of ~440 years. Secondly, the small systematic drift in the velocity range caused by the orbital motion is masked by the erratic time variation of the masers as mentioned above. We searched for possible systematic drifts in the velocity range of the masers in the spectra of V778 Cyg and EU And, which are the best tar-

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Table 2. Result of the VLA H\(_2\)O maser observations of our program stars. The central velocity and the searched velocity range, as well as the RMS noise level are listed. For positive detections, the velocity (\(V_{peak}\)) and intensity (\(S_{peak}\)) of each peak are given, together with the integrated flux (\(S_1\)). For non-detection sources, the upper limit (3\(\sigma\) RMS noise) is given.

| Name          | CGCS\(^1\) | \(V_{LSR}\) range (km s\(^{-1}\)) | \(S_1\) (10\(^{-21}\) W m\(^{-2}\)) | \(V_{peak}\) (km s\(^{-1}\)) | \(S_{peak}\) (Jy) | \(S_1\) (mJy) |
|---------------|-------------|-----------------------------------|-----------------------------------|---------------------------|--------------|-------------|
| IRAS06017+1011| 1158        | -13.0...-54.6...+28.3...-24.0...-15.1 | -24.0...-4.2...6.5...5.3          | 18.4...0.15...0.14       | 4.2          | 6.5         |
| BM Gem        | 1653        | +76.1...+34.0...+118.2...-9...-15.1 | -15.1...0.14...<0.015...5.1     | -18.4...0.15...0.14      | 4.2          | 6.5         |
| IRAS07221-0431| 1698        | +79.0...+36.9...+121.1...-7...-11.1 | -11.0...0.0...0.023...7.8       | -18.4...0.15...0.14      | 4.2          | 6.5         |
| IRAS08002-3803| 2011        | 0.0...-42.1...+42.1...-4.5      | 15.0...0.0...0.023...7.8       | -18.4...0.15...0.14      | 4.2          | 6.5         |
| IRAS18006-3213| 3935        | +176.7...+134.6...+218.8...-4.5        | 11.0...0.0...0.023...7.8       | -18.4...0.15...0.14      | 4.2          | 6.5         |
| NC83          | 4222        | -6.7...-48.3...+34.6...-8.2...+5.6 | 7.3...0.0...0.06...0.13        | -18.4...0.15...0.14      | 4.2          | 6.5         |
| HD189605      | 4595        | +58.2...+16.1...+100.3...-18.4...+13.9 | -13.9...0.0...0.024...9.7     | -18.4...0.15...0.14      | 4.2          | 6.5         |
| V778 Cyg      | 4923        | -17.0...-58.3...+24.6...-25.0...-14.2 | 22.0...0.0...0.05...0.07       | -18.4...0.15...0.14      | 4.2          | 6.5         |
| V1415 Cyg     | 5548        | 0.0...-81.7...+81.6...-34.3...-21.1 | 3.5...0.0...2.1...0.21        | -18.4...0.15...0.14      | 4.2          | 6.5         |
| EU And        | 5848        | -36.0...-77.5...+5.4...-42.0...-34.1 | 5.2...0.0...16...0.21         | -18.4...0.15...0.14      | 4.2          | 6.5         |

\(^3\) Little-Marenin et al. (1988) report a possible detection of a peak at ~12.4 km s\(^{-1}\) toward EU And. However, it is not a definitive detection, we did not include this peak.
gets for this purpose, thanks to the ample maser observations in the past (see references in Table 1), but could find no definitive systematic drift.

The new mid-IR spectra of IRAS06017+1011, NC83, and HD189605, shown in Fig. 2 reveal the silicate emission, confirming that these stars are silicate carbon stars. While the Spitzer/IRS spectra of NC83 and HD189605 are available only longward of 10 μm, the combination with the 22 μm flux measured by AKARI (Ishihara et al. 2010) indicates the 10 μm silicate feature. The spectra of IRAS06017+1011 and HD189605 exhibit a bump centered at 11–11.5 μm, which is clear when compared with BM Gem in Fig. 2. This bump is also seen in the silicate carbon stars IRAS08002-3803 (Ohnaka et al. 2006) also plotted in Fig. 2) and IRAS18006-3213 (Deroo et al. 2007). A comparison with the spectrum of the carbon-rich Mira SS Vir obtained with the Infrared Space Observatory (ISO), shown in Fig. 2, suggests that the bump centered at 11 μm resembles the SiC feature often observed in usual carbon stars. Therefore, we suggest that the bump at 11–11.5 μm is due to SiC, which originates in the ongoing mass loss from the carbon-rich primary star.

It is noteworthy that the Spitzer/IRS spectrum of HD189605 shows no signatures of crystalline silicate, although the spectral resolution of 600 is sufficient to resolve its sharp features. In Fig. 2, the ISO spectrum of the post-AGB star AC Her obtained with a spectral resolution of 750 is plotted. AC Her, one of the best examples, shows fine, sharp crystalline silicate features, which can be seen, for example, at 11.4, 16, and 18 μm (Molster et al. 2002). None of these features are seen in HD189605.

Furthermore, HD189605 was detected in the near-UV with the Galaxy Evolution Explorer (GALEX) with a flux of 5.1–7.7 μJy at 2271 Å. The offset of the object detected with GALEX (GALEX J200105.1-072151) from the position of HD189605 measured in the optical and IR is 0′′.2–0′′.9, which is within the positional error of the GALEX data. This means that the near-UV emission is likely associated with HD189605. The UV emission may originate from an accretion disk around the putative companion as in BM Gem (Izumiura et al. 2008). Therefore, HD189605 is a good candidate for studying the accretion process in silicate carbon stars.

There seems to be no clear correlation between the maser detection and the amount of the IR excess. For example, IRAS06017+1011 and BM Gem show approximately the same amount of the IR excess (see their SEDs in Figs. 3b and 3c in Kwok & Chan 1993). However, IRAS06017+1011 shows masers, while BM Gem has not shown any masers so far.

The detection of the masers does not show a clear correlation with the shape of the silicate feature, either. For example, IRAS06017+1011 shows a broad silicate feature with a 11.5 μm bump, while EU And shows a narrow silicate feature. Nevertheless, both objects show maser emission. This can be understood if SiC in the ongoing mass loss from the carbon-rich primary star is responsible for the 11.5 μm bump. In this case, the shape of the 10 μm feature is not related to the oxygen-rich material.

4. Conclusions
We presented the result of a survey of the 22 GHz H2O masers toward 10 silicate carbon stars using the VLA. H2O masers were detected in five stars, including NC83, for which masers have been detected for the first time. The H2O maser spectra show a velocity separation of 10–14 km s−1 between the most blue- and red-shifted peaks. This suggests a lower limit of the rotation velocity of the circum-companion disks of 5–7 km s−1 and an upper limit of the radius of the maser emitting region of 10–68 AU for a companion mass of 0.5–1.7 M⊙.

We confirmed the 10 μm silicate feature in IRAS06017+1011, NC83, and HD189605 using newer mid-IR spectra obtained with VLTI/MIDI and the Spitzer Space Telescope. The silicate feature in IRAS06017+1011 and HD189605 shows a broad bump centered at 11–11.5 μm. We suggest that SiC in the ongoing mass loss from the carbon-rich primary star, not crystalline silicate, may be responsible for this bump. We also detected near-UV emission toward HD189605 with GALEX.

The radius of the maser emitting region of 10–68 AU translates into 5–68 mas for distances of 1–2 kpc. This is resolvable with VLBA. High spatial resolution imaging of more silicate carbon stars with VLBA is feasible and necessary to reveal the spatial distribution of oxygen-rich material.

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Fig. 2. New mid-IR spectra of IRAS06017+1011 obtained with VLTI/MIDI (a), NC83 (b), and HD189605 (c), both obtained with Spitzer/IRS. Also plotted are the scaled spectra of IRAS08002-3803, BM Gem, AC Her, and SS Vir.
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