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The distribution of carbonaceous molecules and SiN around the S-type AGB star W Aquilae

T. Danilovich[1]†, M. Van de Sande[2], A. M. S. Richards[3] and the ATOMIUM Consortium

[1]Institute of Astronomy, KU Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium
email: taissa.danilovich@kuleuven.be

[2]School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK

[3]JBCA, Dept Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK

Abstract. S-type AGB stars, with C/O ratios close to 1, are expected to have a mixed circumstellar chemistry as they transition from being oxygen-rich stars to carbon-rich stars. Recently, several different carbonaceous molecules, thought to be more characteristic of carbon stars, have been found in the circumstellar envelope of the S-type AGB star W Aql. We have obtained new high spatial resolution ALMA images of some of these molecules, specifically HC_3N, SiC_2 and SiC, and SiN, which we present here. We report diverse behaviour for these molecules, with SiC_2 being seen with a symmetric spatial distribution around the star, SiN and SiC being asymmetrically distributed to the north-east of the star, and HC_3N being seen in a broken shell to the south-west. These differing distributions point to complex dynamics in the circumstellar envelope of W Aql.

Keywords. stars: AGB, circumstellar matter, stars: individual: W Aql

1. Introduction

W Aquilae (W Aql) is an S-type AGB star, meaning that it has a C/O ratio close to 1. S-type AGB stars are expected to have a mixed circumstellar chemistry as they transition from being oxygen-rich stars to carbon-rich stars. Such mixed chemistry was indeed reported by Danilovich et al. (2014), based on *Herschel*/HIFI observations. Recently, a spectral scan of W Aql with the APEX telescope by De Beck & Olofsson (2020) identified several different carbonaceous molecules, previously thought to be more characteristic of carbon stars, in the circumstellar envelope of W Aql, including C_2H, SiC_2, SiN and, tentatively, HC_3N.

Here we present high spatial resolution ALMA observations of W Aql with a focus on carbonaceous molecules and SiN. Our spatially resolved observations allow us to identify in which regions of the circumstellar envelope the various molecules are present.

2. Observational results

W Aql was observed as part of the ATOMIUM ALMA Large Programme (2018.1.00659.L) over bands across the frequency range $\sim$214–270 GHz. For medium resolution observations, the approximate synthetic beam size was $0.4 \times 0.3''$ with a maximum recoverable scale of $3.9''$, and for low resolution observations the approximate

†Senior Postdoctoral Fellow of the Fund for Scientific Research (FWO), Flanders, Belgium.

Table 1. Emission lines of carbon-bearing molecules and SiN detected towards W Aql.

Molecule	Frequency [GHz]	Transition J_{K_a,K_c}	→	$J'_{K'_a,K'_c}$	E_{up} [K]	Molecule	Frequency [GHz]	Transition $J \rightarrow J'$	E_{up} [K]
SiC_2	220.774	$10_{0,10}$	→	$9_{0,9}$	59.8	HC_3N	227.419	$25 \rightarrow 24$	142.0
SiC_2	222.009	$9_{2,7}$	→	$8_{2,6}$	60.3	HC_3N	236.513	$26 \rightarrow 25$	153.4
SiC_2	235.713*	$10_{6,5}$	→	$9_{6,4}$	132.6	HC_3N	245.606	$27 \rightarrow 26$	165.2
SiC_2	235.713*	$10_{6,4}$	→	$9_{6,3}$	132.6	HC_3N	254.700	$28 \rightarrow 27$	177.4
SiC_2	237.150‡	$10_{4,7}$	→	$9_{4,6}$	93.7	SiC	236.288	$6 \rightarrow 5$ ($\Omega = 2$)	22.7
SiC_2	237.331	$10_{4,6}$	→	$9_{4,5}$	93.8				
SiC_2	254.982	$11_{2,10}$	→	$10_{2,9}$	81.9	SiN	262.156†	$13/2 \rightarrow 11/2$ ($N = 6 \rightarrow 5$)	31.5
SiC_2	259.433*	$11_{6,5}$	→	$10_{6,4}$	145.0				
SiC_2	259.433*	$11_{6,6}$	→	$10_{6,5}$	145.0				

Notes:
(*) indicates blended lines; (†) indicates a line with hyperfine components. (‡) indicates a line partially truncated by the edge of the observed band. **References:** Line frequencies from Müller et al. (2012) for SiC_2, from Creswell et al. (1977); de Zafra (1971); Mallinson & de Zafra (1978); Chen et al. (1991); Yamada et al. (1995) and Thorwirth et al. (2000) for HC_3N, from Cernicharo et al. (1989) for SiC, and from Saito et al. (1983) for SiN, all via CDMS (Müller et al. 2001, 2005).

synthetic beam size was $1.0 \times 0.7''$ with a maximum recoverable scale of $8.9''$. Full details of the observations are given in Decin *et al.* (2020) and Gottlieb et al. (2021). Plots of zeroth moment maps presented here are of combined datasets, with synthetic beam sizes ranging from $0.05''$ to $0.2''$.

A total of 110 lines have been identified towards W Aql (Wallström et al, *in prep*), including lines from common molecules such as CO, HCN, SiO, SiS and CS, less-studied molecules such as the metal halides AlCl and AlF (Danilovich et al. 2021), SiN and the carbon-bearing molecules SiC, SiC_2 and HC_3N. Emission from the latter four molecules is presented and discussed below. Table 1 includes frequencies and upper energy levels of all the detected lines from these four molecules. Selected line spectra for these molecules are plotted in Fig 1.

2.1. *SiC_2*

Seven individual lines of SiC_2 were detected in the ATOMIUM observations towards W Aql. This includes two lines that are blends of two transitions, as indicated by the asterisks in Table 1, and one line that was partially truncated when falling on the edge of a band in our observations. Although there are additional SiC_2 lines that fall in the observed frequency ranges, these other lines are all predicted to be more than an order of magnitude fainter than our detected lines. Hence we did not expect to detect them at our observational sensitivity. We also checked our data for the brightest vibrationally excited SiC_2 lines in the $\nu_3 = 1$ state, but found no detections.

The line shapes across the different transitions are consistently double-peaked with the red peak generally brighter than the blue (see Fig 1). This asymmetry in velocity space is most likely owing to non-spherical dynamics in the circumstellar envelope. The spatial distribution of the SiC_2 emission in the plane of the sky is relatively symmetric, with minor asymmetries most likely attributable to noise. Three zeroth moment maps of selected lines are plotted in Fig 2 and show that the emission is approximately centred on the continuum peak.

2.2. *HC_3N*

Four lines of HC_3N were detected towards W Aql in the ATOMIUM observations. Although HC_3N is known to exhibit hyperfine splitting, this is negligible and not detectable at the spectral resolution of our observations, and hence neglected here. The

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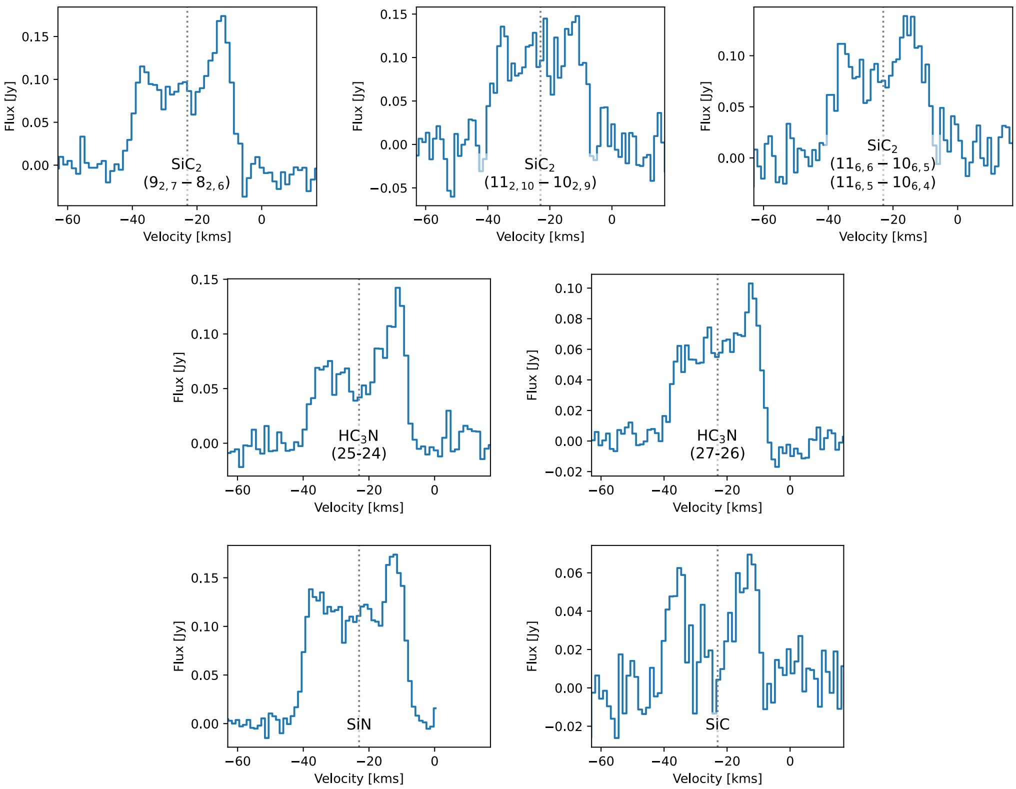

Figure 1. Spectra of selected SiC_2 (top row) and HC_3N (middle row) lines, and spectra of the only detected SiN and SiC lines (bottom row) towards W Aql. Spectra were extracted for a circular aperture centred on the continuum peak with a radius of 1.8″ from the medium spatial resolution ALMA data cubes for SiC_2 and HC_3N and for the low spatial resolution data cubes for SiC and SiN. The dotted vertical lines represent the $\upsilon_{\rm LSR} = -23$ of W Aql and the spectral resolution is ~ 1 km s^{-1}.

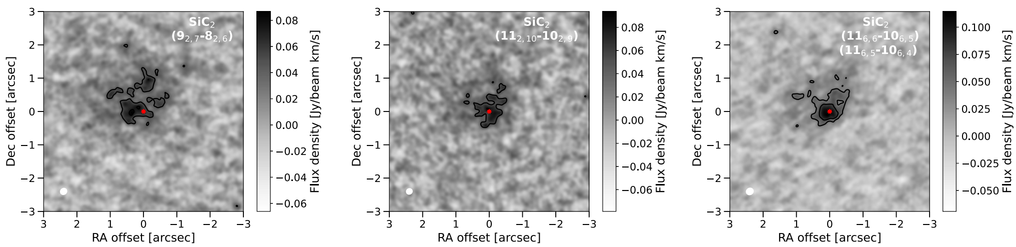

Figure 2. Selected zeroth moment maps of SiC_2 towards W Aql. Shown are maps for the $(9_{2,7} \rightarrow 8_{2,6})$ line (left), the $(11_{2,10} \rightarrow 10_{2,9})$ line (centre), and the blended $(11_{6,6} \rightarrow 10_{6,5})$ and $(11_{6,5} \rightarrow 10_{6,4})$ lines (right). North is up and east is left. The synthetic beam sizes are given by the white ellipses in the bottom left of each plot, the stellar position based on the continuum peak is indicated at (0,0) and the contours indicate levels of 3 and 5σ flux.

observed HC_3N lines are listed in Table 1 and consist of all four lines covered in our frequency settings. We also checked for lines from the singly-substituted ^{13}C isotopologues of HC_3N, but all covered lines were undetected.

The spectra of the detected HC_3N lines are similar in shape to SiC_2 (see Fig 1), with two-peaked profiles showing a brighter peak on the red side. Zeroth moment maps of two example HC_3N lines are given in Fig 3 and show a clearly asymmetric flux distribution

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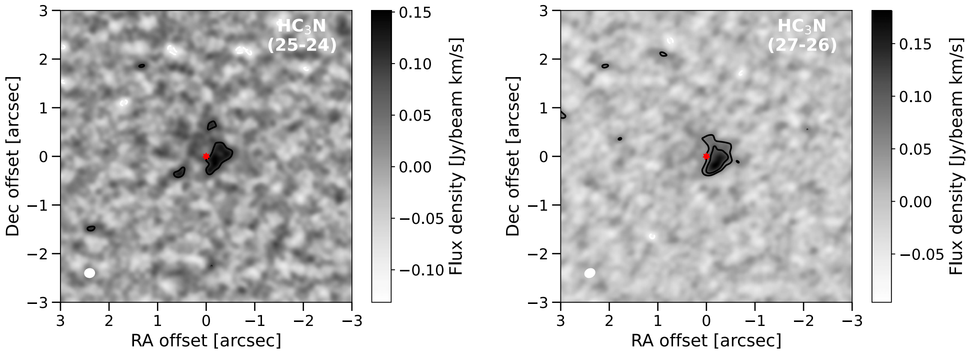

Figure 3. Selected zeroth moment maps of HC_3N towards W Aql. Shown are maps for the ($25 \rightarrow 24$) and ($27 \rightarrow 26$) lines in the left and right panels respectively. North is up and east is left. The synthetic beam sizes are given by the white ellipses in the bottom left of each plot, the stellar position based on the continuum peak is indicated at (0,0) and the contours indicate levels of 3 and 5σ flux.

that is not centred on the continuum peak. This asymmetric distribution resembles a partly broken (or partly undetected) shell structure surrounding the star. The emission peaks around $0.3''$ from the continuum peak, when measuring for the ($27 \rightarrow 26$) line.

Shell-like structures are expected for HC_3N based on chemical models (Van de Sande & Millar 2021). Indeed, Agúndez *et al.* (2017) found HC_3N emission present in a shell around the nearby carbon star CW Leo, as part of a detailed ALMA study. We ran some preliminary radiative transfer models assuming 1D spherical symmetry and comparing our results to azimuthally averaged observations. Based on these results, if we assume that the HC_3N emission towards W Aql is part of a shell-like structure, then the distance of this shell from the star is comparable to that of CW Leo if we also assume that the size of the shell scales linearly with mass-loss rate.

2.3. *SiN*

A single line of SiN (composed of three unresolved hyperfine components) was covered by the ATOMIUM observations and was clearly detected towards W Aql. The spectrum of SiN (see Fig 1) is again a two-peaked profile, with the red peak brighter than the blue peak. A comparison with the same SiN line as observed with APEX by De Beck & Olofsson (2020) tells us that all the flux is recovered by our ALMA observations and that no large scaled structure is resolved out. A clear asymmetry is seen in the zeroth moment map, plotted in Fig. 4, where the bulk of the emission comes from an apparent wedge in the north to north-east, and includes some emission overlapping with the continuum peak.

Prior to the current study, the only evolved star for which SiN has been detected is CW Leo (Turner 1992). The observations of Turner (1992) were performed with the NRAO 12 m telescope and hence were not spatially resolved. No interferometric observations of SiN have been published until now. This means that we are unable to compare the asymmetric distribution of SiN in the CSE of W Aql with any other stars.

2.4. *SiC*

Only one line of SiC was covered by the ATOMIUM observations and was detected with a lower signal to noise than the other lines presented here. Similar to the other lines, the spectrum is two-peaked, as can be seen in Fig 1, but the signal to noise is not adequate to judge whether the red peak is brighter than the blue peak. The zeroth moment map,

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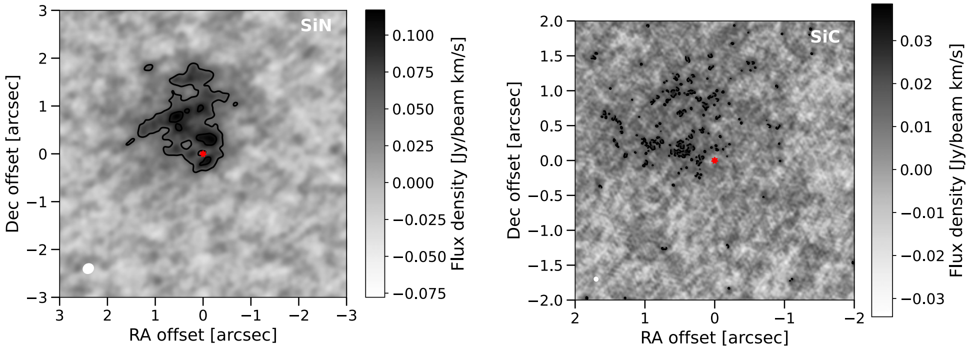

Figure 4. Zeroth moment maps of (left) SiN ($N = 6 \rightarrow 5$, $J = 13/2 \rightarrow 11/2$) and (right) SiC ($J = 6 \rightarrow 5$) towards W Aql. North is up and east is left. The synthetic beam sizes are given by the white ellipses in the bottom left of each plot, the stellar position based on the continuum peak is indicated at (0,0) and the contours indicate levels of 3 and 5σ flux.

shown in Fig 4 and centred on the continuum peak, shows emission coming mainly from the north-east quadrant of the map. Overall, the distribution of SiC is similar to that of SiN, although the lower signal to noise makes a more detailed analysis difficult.

Massalkhi et al. (2018) surveyed a sample of 25 carbon stars and and detected (clearly or tentatively) a line of SiC towards 12 of their sources. In contrast, SiC_2 was more frequently detected, seen towards 22 of their sources. They also found a correlation between the intensities of their detected SiC line and a chosen SiC_2 line for the same stars, which they interpret as a correlation between the abundances of the two species. We cannot rule out a correlation between the abundances of SiC and SiC_2 for W Aql, however the fact that they are not co-located suggests a more complex relationship between the two species.

3. Discussion and conclusions

The molecules presented here all exhibit similar spectral profiles, with two peaks and a tendency for the red peak to be brighter than the blue peak. However, the spatial distribution of these molecules can be divided into three categories: SiC_2 emission is seen centrally and coinciding with the continuum peak; HC_3N emission is seen mainly to the west of the continuum peak and could represent part of a broken or not fully-detected shell structure; and SiN and SiC emission mainly originates in the north-east quadrant relative to continuum peak. The AlF emission presented in Danilovich et al. (2021) is also asymmetric with a qualitatively similar distribution to SiN and SiC. Taken together, these asymmetries suggest complex dynamics and chemistry in the circumstellar envelope of W Aql.

The CO ($2 \rightarrow 1$) emission of W Aql, observed as part of ATOMIUM, can be seen in Decin *et al.* (2020) and the accompanying supplementary materials, and shows a spiral-like structure with many arcs. Despite the somewhat chaotic nature of this emission, the overall circumstellar envelope of W Aql appears roughly circular on the scale of the CO emission. Note, however, that the ATOMIUM CO emission suffers from resolved out flux and hence smooth large scale structure is not recovered. Lower resolution ALMA observations of the CO ($3 \rightarrow 2$) emission is presented by Ramstedt *et al.* (2017). In those data, for which all the flux is recovered, individual arcs are not resolved but the larger scale structure is asymmetric on scales $\sim 5 - 10''$, with some extended CO emission visible to the south east of the continuum peak. This represents a fourth category of asymmetry

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not exhibited by the molecules studied here and further enforces the need for a detailed analysis of the dynamics in the circumstellar envelope of W Aql.

There are several other molecular species detected towards W Aql, some of which may also exhibit spatial asymmetries. We plan to carefully catalogue and study these in future work, with the goal of presenting a more complete understanding of the dynamics of the circumstellar envelope of W Aql.

References

Agúndez, M., Cernicharo, J., Quintana-Lacaci, G., et al. 2017, *A&A* 601, A4

Cernicharo, J., Gottlieb, C. A., Guelin, M., Thaddeus, P., & Vrtilek, J. M. 1989, *ApJL* 341, L25

Chen, W., Bocquet, R., Wlodarczak, G., & Boucher, D. 1991, *International Journal of Infrared and Millimeter Waves* 12(9), 987

Creswell, R. A., Winnewisser, G., & Gerry, M. C. L. 1977, *Journal of Molecular Spectroscopy* 65, 420

Danilovich, T., Bergman, P., Justtanont, K., et al. 2014, *A&A* 569, A76

Danilovich, T., Van de Sande, M., Plane, J. M. C., et al. 2021, *A&A* 655, A80

De Beck, E. & Olofsson, H. 2020, *A&A* 642, A20

de Zafra, R. L. 1971, *ApJ* 170, 165

Decin, L., Montargès, M., Richards, A. M. S., et al. 2020, *Science* 369(6510), 1497

Gottlieb, C. A., Decin, L., Richards, A. M. S., et al. 2021, *A&A* Forthcoming

Mallinson, P. D. & de Zafra, R. L. 1978, *Molecular Physics* 36(3), 827

Massalkhi, S., Agúndez, M., Cernicharo, J., et al. 2018, *A&A* 611, A29

Müller, H. S. P., Cernicharo, J., Agúndez, M., et al. 2012, *Journal of Molecular Spectroscopy* 271(1), 50

Müller, H. S. P., Schlöder, F., Stutzki, J., & Winnewisser, G. 2005, *Journal of Molecular Structure* 742, 215

Müller, H. S. P., Thorwirth, S., Roth, D. A., & Winnewisser, G. 2001, *A&A* 370, L49

Ramstedt, S., Mohamed, S., Vlemmings, W. H. T., et al. 2017, *A&A* 605, A126

Saito, S., Endo, Y., & Hirota, E. 1983, *J. Chem. Phys.* 78(11), 6447

Thorwirth, S., Müller, H. S. P., & Winnewisser, G. 2000, *Journal of Molecular Spectroscopy* 204, 133

Turner, B. E. 1992, *ApJL* 388, L35

Van de Sande, M. & Millar, T. J. 2021, *MNRAS*

Yamada, K. M. T., Moravec, A., & Winnewisser, G. 1995, *Zeitschrift Naturforschung Teil A* 50(12), 1179