

Circumstellar molecular line emission from S-type AGB stars: mass-loss rates and SiO abundances[★]

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Received 26 January 2009 / Accepted 16 March 2009

ABSTRACT

Aims. The main aim is to derive reliable mass-loss rates and circumstellar SiO abundances for a sample of 40 S-type AGB stars based on new multi-transitional CO and SiO radio line observations. In addition, the results are compared to previous results for M-type AGB stars and carbon stars to look for trends with chemical type.

Methods. The circumstellar envelopes are assumed to be spherically symmetric and formed by a constant mass-loss rate. The mass-loss rates are estimated from fitting the CO observations using a non-local, non-LTE radiative transfer code based on the Monte Carlo method. In the excitation analysis, the energy balance equation is solved self-consistently simultaneously as the radiative transfer and the temperature structure of the gas is derived. Effects of dust grains are also included in the molecular excitation analysis. Once the physical properties of the circumstellar envelopes are determined, the same radiative transfer code is used to model the observed SiO lines in order to derive circumstellar abundances and the sizes of the SiO line-emitting regions.

Results. We have estimated mass-loss rates of 40 S-type AGB stars and find that the derived mass-loss rates have a distribution that resembles those previously derived for similar samples of M-type AGB stars and carbon stars. The estimated mass-loss rates also correlate well with the corresponding expansion velocity of the envelope, in accordance with results for M-type AGB stars and carbon stars. In all, this indicates that the mass loss is driven by the same mechanism in all three chemical types of AGB stars. In addition, we have estimated the circumstellar fractional abundance of SiO relative to H₂ in 26 of the sample S-type AGB stars. The derived SiO abundances are, on average, about an order of magnitude higher than predicted by stellar atmosphere thermal equilibrium chemistry, indicating that non-equilibrium chemical processes determines the abundance of SiO in the circumstellar envelope. Moreover, a comparison with the results for M-type AGB stars and carbon stars show that for a certain mass-loss rate, the circumstellar SiO abundance seems independent (although with a large scatter) of the C/O-ratio.

Conclusions. In our comparison of S-type AGB stars with carbon stars and M-type AGB stars, we find no large differences in circumstellar physical properties or SiO abundances depending on the chemical type of the star.

Key words. stars: AGB and post-AGB – stars: abundances – stars: carbon – stars: late-type – stars: mass-loss

1. Introduction

The final evolutionary stage of low- to intermediate-mass stars, as they ascend the asymptotic giant branch (AGB), is characterized by an intense mass loss. The stellar wind builds up gradually and creates a circumstellar envelope (CSE), carrying gas and dust from the star into the interstellar medium. The molecular setup and grain types in CSEs are to a large extent determined by the C/O-ratio in the photosphere of the central star. The AGB stars are normally divided into two distinct spectral types: M-type stars, with C/O < 1 and carbon stars, with C/O > 1. Abundance analysis has also revealed stars with photospheric C/O-ratios close to unity (within approximately 5%), so called S-type AGB stars (Scalo & Ross 1976). The spectra of S-type AGB stars are dominated by ZrO bands (as opposed to spectra of M-type AGB stars which are dominated by TiO bands) indicating that the S-type AGB stars have an enhancement in elements formed through the slow neutron capture process.

Due to having a C/O-ratio close to unity, it is tempting to identify S-type AGB stars with a brief transitional phase as the

star evolves from an oxygen-rich M-type AGB star into a carbon star. Dredge-up of carbon from He-shell burning would change the spectral type of the star sequentially: M-MS-S-SC-C. As possible transition objects, S-type AGB stars might very well help to achieve a deeper understanding of the chemical evolution as a star ascends the AGB, as well as shed light on the mass-loss mechanism(s), which is (are) not yet fully understood in detail. Several surveys of CO emission from their CSEs have been performed (Bieging & Latter 1994; Sahai & Liechti 1995; Bieging et al. 1998; Groenewegen & de Jong 1998; Jorissen & Knapp 1998; Ramstedt et al. 2006). Circumstellar molecular line emission from molecules other than CO has previously been searched for, and detected, only in a handful of objects and only for HCN and SiO (Bieging & Latter 1994; Bieging et al. 1998).

The aim of this work is to thoroughly investigate the circumstellar physical and chemical properties of a sample of S-type AGB stars. The physical properties of the CSEs, in particular the mass-loss rates that produced them, are determined from the CO data using detailed, non-LTE, radiative transfer modelling which self-consistently calculates also the gas kinetic temperature. Detailed studies of the mass-loss properties of samples of carbon stars (Schöier & Olofsson 2001; Schöier et al. 2002),

[★] Appendices are only available in electronic form at <http://www.aanda.org>

M-type AGB stars (Olofsson et al. 2002; González Delgado et al. 2003), and S-type AGB stars (Ramstedt et al. 2006) have previously been performed.

Lately, the mechanisms driving mass loss in M-type AGB stars have been much debated (Woitke 2006; Höfner & Andersen 2007; Höfner 2008), and for the S-type AGB stars this is a matter of a long-standing debate (e.g., Willems & de Jong 1988; Sahai & Liechti 1995). The supposed lack of any free oxygen and/or free carbon to form dust (due to a C/O-ratio close to unity) has led to the suggestion that the S-type AGB stars would not be able to drive a wind as efficiently as the M-type AGB stars and the carbon stars. However, the results of Ramstedt et al. (2006) show no apparent differences between the mass-loss rate distribution of the S-type AGB stars and those found for carbon and M-type AGB stars.

Once the physical properties are known, from the CO analysis, they can be used to estimate abundances of other molecules in the CSE. The analysis of the S-type AGB stars in Ramstedt et al. (2006) was based on observations of CO($J = 3 \rightarrow 2$) data gathered at the APEX telescope supplemented with data collected from the literature. When examining the published data, Ramstedt et al. (2006) found a rather large scatter in the reported line intensities (especially for CO($J = 2 \rightarrow 1$) data) for individual objects, even when observed with same telescope. Since then, we have obtained more observational data, which warrants a re-analysis of the Ramstedt et al. (2006) work, and the results are reported here.

We have, as a first step after the CO observations, searched for circumstellar SiO radio line emission in several rotational transitions. Using the physical structure of the CSEs derived from the CO modelling, we estimate the abundance of SiO in the same sample of S-type AGB stars based on a detailed excitation analysis. There exists strong evidence that the circumstellar SiO emission carries information on the region where the mass loss is initiated and where the dust formation takes place (Reid & Moran 1981; Reid & Menten 1997; Schöier et al. 2006a) making it a particularly interesting molecule to study. Schöier et al. (2006b) modelled circumstellar SiO line observations from a sample of carbon stars and when comparing this to a similar analysis performed by González Delgado et al. (2003) for a large sample of M-type AGB stars, they found no apparent distinction between their circumstellar SiO abundance distributions. For the carbon stars, the derived abundances are several orders of magnitude higher than expected from thermal equilibrium stellar atmosphere chemistry. A possible explanation for the high SiO abundances derived for the carbon stars is the influence of a shock chemistry in the inner part of the wind (Cherchneff 2006). With the analysis performed in this work, the S-type AGB stars can be added to this comparison (see Sect. 6.3).

The sample of S-type AGB stars and the observational data are presented in Sects 2 and 3. The radiative transfer modelling is described in Sect. 4. The results are given and discussed in Sects 5 and 6, respectively. Finally, the conclusions are given in Sect. 7.

2. The sample

Jorissen & Knapp (1998) presents a sample of 124 S-type stars from the list of Chen et al. (1995) providing cross identifications between the *General Catalogue of Galactic S stars*, the *IRAS Point Source Catalogue* (PSC), and the *Guide Star Catalogue*. Only stars having flux densities of good quality in the 12, 25, and 60 μm bands in the IRAS PSC were retained in their sample. We have chosen the stars in the sample of Jorissen & Knapp

Table 1. The sample with variable types, periods P , luminosities L_\star , and distances D .

Source type	Var. [days]	P [L_\odot]	L_\star [pc]	D
R And	M	409	6000	300
W And	M	397	5800	280
Z Ant	SR	104	4000	470
VX Aql	M:	...	4000	790
W Aql	M	490	6800	230
AA Cam	Lb	...	4000	800
T Cam	M	374	5600	540
S Cas	M	611	8000	440
V365 Cas	SRb	136	4000	625
WY Cas	M	477	6700	600
AM Cen	Lb	...	4000	750
TT Cen	M	462	6500	880
UY Cen	SR	115	4000	590
V386 Cep	SR	...	4000	470
T Cet	SRb	159	4000	240
AA Cyg	SRb	213	4000	480
AD Cyg	Lb	...	4000	980
R Cyg	M	426	6100	440
χ Cyg	M	407	5900	110
TV Dra	Lb	...	4000	390
DY Gem	SRa	...	4000	680
R Gem	M	370	5500	710
ST Her	SRb	148	4000	300
RX Lac	SRb	174	4000	310
GI Lup	M	325	5000	690
R Lyn	M	379	5600	850
Y Lyn	SRc	110	4000	260
S Lyr	M	438	6300	1210
FU Mon	SR	310	4000	780
RZ Peg	M	439	6300	970
RT Sco	M	449	6400	270
ST Sco	SRa	195	4000	380
RZ Sgr	SRb	223	4000	730
ST Sgr	M	395	5800	540
T Sgr	M	392	5800	590
EP Vul	Lb	...	4000	510
DK Vul	SRa	370	4000	750
AFGL 2425	U	...	4000	610
CSS2 41	U	...	4000	880
IRC-10401	U	...	4000	430

that have previously been detected in circumstellar CO emission. Five stars have been added from the samples of Groenewegen & de Jong (1998) and Sahai & Liechti (1995) (selected from the S-type catalogs of Stephenson 1984, 1990), and one star was added from the sample of Biegging & Latter (1994) (selected from the list of Jura 1988). These six stars have also been detected previously in circumstellar CO emission. Only S-type stars with Tc lines detected in their spectra and with detectable infrared excess are safely identified as intrinsic thermally pulsing AGB stars. S-type stars with no Tc lines and no infrared excess are most likely extrinsic S-stars, i.e., they are part of binary systems and their chemical peculiarities are due to mass transfer across the system. Jorissen & Knapp investigate the extrinsic/intrinsic characteristics of their sample and we have only retained stars which they classify as intrinsic. The stars from the Groenewegen & de Jong and Sahai & Liechti samples have all been detected in Tc and/or show infrared excess. We therefore believe that our sample only consists of intrinsic S-type AGB stars. Our sample of 40 stars is listed in Table 1. Our selection criteria might introduce a bias in the sample toward S-type

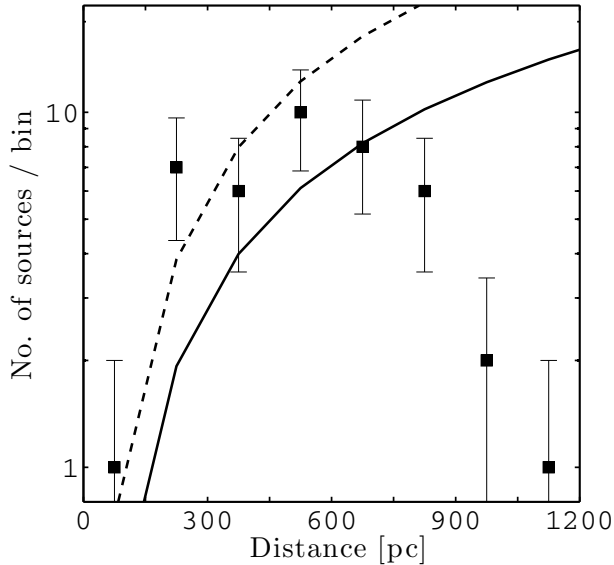


Fig. 1. The distance distribution of our sample of S-type AGB stars (squares) overlaid with the distribution found in Jura (1990) assuming a smooth surface distribution (solid line, see text in Sect. 2) of S-type AGB stars in the solar neighbourhood. The dashed line shows a fit to the observational results. The errors are based on Poisson statistics.

stars that have higher mass-loss rates, and S-type stars without or with very little mass loss will be missed. The reason for this selection is to be able to detect line emission from other molecules than CO.

For the Miras (M), bolometric luminosities are estimated using the period-luminosity relation of Whitelock et al. (1994), and periods are taken from the *General Catalogue of Variable Stars* (Kholopov et al. 1999). For the semiregular (SR, SRa, and SRb) and irregular variables (Lb), a luminosity of $4000 L_{\odot}$ was assumed in accordance with Olofsson et al. (2002). Corrections for the interstellar extinction, based on their galactic latitude, were applied for each star (Groenewegen et al. 1992). Distances are derived by fitting the spectral energy distribution (SED) calculated with DUSTY (Sect. 4.2), to observed fluxes (Sect. 3.4). The derived distances, and adopted periods and luminosities are presented in Table 1, together with the variability type. The derived distances from the SED modelling agree well with distances from Hipparcos parallaxes when available (for 7 stars).

Figure 1 shows the distance distribution of our sample in 150 pc bins. The distance distribution is overlaid with a distribution assuming that the stars are evenly distributed, that the surface density of carbon stars is 40 kpc^{-2} with a scale height of 200 pc, and that there are 1/3 as many S-type stars as carbon stars in the solar neighbourhood (Wing & Yorke 1977; Jura 1990). A direct fit to our sample within 600 pc, gives a surface density of 20 kpc^{-2} with a scale height of approximately 150 pc (dashed line, Fig. 1). Considering the uncertainties involved in the distance estimate, classification, etc., we find the results to be consistent and believe that our sample is representative of mass-losing S-type AGB stars and complete to about 600 pc. The sample of carbon stars studied by Schöier & Olofsson (2001) is representative of C-type AGB stars and complete to about 500 pc, while the completeness of the M-type AGB star samples of Olofsson et al. (2002) and González Delgado et al. (2003) have not been thoroughly investigated.

3. Observational data

When modelling circumstellar molecular line emission it is essential to observe as many different transitions as possible of the molecule under study. The derived mass-loss rate (when assuming a spherically symmetric, smooth wind) should be considered as the average mass-loss rate that created the CSE probed by the observed line emission. Different transitions probe slightly different regions in the CSE depending on their excitation requirement and thus the average is taken over a larger part of the CSE if more transitions are obtained. The same is true when estimating the radial abundance distribution and, in particular, when estimating the size of the emitting region of a specific molecule. In this work, we have tried to obtain observations of at least three transitions of CO and SiO for as many of the sample sources as possible (Tables A.1–B.2).

3.1. Observations of circumstellar CO and SiO radio line emission

The first analysis of CO radio line emission from this sample was published in Ramstedt et al. (2006). There, data from the literature (mainly $J = 1 \rightarrow 0$ and $2 \rightarrow 1$) was analysed together with $J = 1 \rightarrow 0$ data collected with the Onsala Space Observatory (OSO) 20 m telescope¹ (January 2006), and $J = 3 \rightarrow 2$ data of 18 sources collected with the APEX 12 m telescope² (from August to October 2005).

The CO data base has since then been substantially extended. New observations of $J = 1 \rightarrow 0$ and $2 \rightarrow 1$ line emission were performed at the IRAM 30 m telescope³ using the AB SIS receiver combination observing both polarizations simultaneously in August 2006. Further observations of $J = 3 \rightarrow 2$ line emission were performed at APEX using APEX-2A during the autumn of 2006 and at the James Clerk Maxwell Telescope⁴ (JCMT) in April 2007. At the JCMT we used HARP due to problems with the B receiver. As spectrometers, the VESPA autocorrelator at IRAM, the FFTS at APEX, and the ACSIS digital autocorrelator at the JCMT were used.

New SiO observations of $J = 2 \rightarrow 1$ line emission were performed at OSO using an SIS receiver and the autocorrelator spectrometer in the low-resolution mode in January 2006. Observations of $J = 2 \rightarrow 1$ and $5 \rightarrow 4$ line emission were performed at the IRAM 30 m telescope in August 2006, and further observations of $J = 6 \rightarrow 5$ and $8 \rightarrow 7$ line emission were performed at JCMT during the autumn of 2006 and spring 2007. The observations at IRAM and the JCMT were obtained simultaneously as the CO observations using the same receiver and spectrometer setups. During 2006 and 2007 observations of $J = 8 \rightarrow 7$ line emission was performed at APEX using the same setup as for the CO observations (all these lines are in the $v = 0$ state). Simultaneously as the $J = 2 \rightarrow 1$, $v = 0$, observations at

¹ The Onsala 20 m telescope is operated by the Swedish National Facility for Radio Astronomy, Onsala Space Observatory at Chalmers University of Technology, with support from the Swedish Research Council.

² The Atacama Pathfinder Experiment (APEX) is a collaboration between the Max-Planck-Institute für Radioastronomie, the European Southern Observatory, and the Onsala Space Observatory.

³ IRAM is supported by CNRS/INSU (France), the MPG (Germany), and the IGN (Spain).

⁴ The James Clerk Maxwell Telescope is operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the United Kingdom, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada.

Table 2. Energies of the upper levels, E_{up} , main-beam efficiencies, η_{mb} , and main-beam FWHM:s, θ_{mb} , at the frequencies of the observed CO and SiO lines.

Transition	Frequency [GHz]	E_{up} [K]	η_{mb}	θ_{mb} ["]	Telescope
CO($J = 1 \rightarrow 0$)	115.271	5.5	0.43	33	OSO
CO($J = 1 \rightarrow 0$)	115.271	5.5	0.74	22	IRAM
CO($J = 2 \rightarrow 1$)	230.538	16.6	0.52	11	IRAM
CO($J = 3 \rightarrow 2$)	345.796	33.2	0.56	14	JCMT
CO($J = 3 \rightarrow 2$)	345.796	33.2	0.70	18	APEX
SiO($J = 2 \rightarrow 1$)	86.847	6.3	0.65	44	OSO
SiO($J = 2 \rightarrow 1$)	86.847	6.3	0.78	29	IRAM
SiO($J = 5 \rightarrow 4$)	217.105	31.3	0.57	12	IRAM
SiO($J = 6 \rightarrow 5$)	260.518	43.8	0.69	21	JCMT
SiO($J = 8 \rightarrow 7$)	347.331	75.0	0.63	14	JCMT
SiO($J = 8 \rightarrow 7$)	347.331	75.0	0.70	18	APEX

OSO, the $J = 2 \rightarrow 1$, $v = 1$ line (which is of maser origin) was observed. We observed SiO($J = 2 \rightarrow 1$, $v = 1$) line emission in 24 of our sample stars. For four of the stars, WY Cas, V386 Cep, TV Dra and R Gem, this is the first detection of SiO maser emission.

At OSO the observations were performed using the dual beam-switch mode. The observations at IRAM were performed using wobbler switching and a dual-polarization mode. At APEX position-switching was used with the reference position located at $+2'$ in azimuth. The JCMT observations were also performed using position-switching with a $2'$ throw. Regular pointing checks were performed during all observations and typically found to be consistent within $\approx 3''$ of the pointing model.

The data was reduced using CLASS, Starlink, and XS⁵ by subtracting a first order polynomial baseline fitted to the emission-free channels, and then binned to improve the signal-to-noise ratio. The typical spectral resolution of the reduced data is 1 km s^{-1} . The raw spectra are stored in the T_{A}^* scale, where T_{A}^* is the antenna temperature corrected for the atmospheric attenuation using the chopper-wheel method. The intensity scale is subsequently given in main-beam brightness temperature, $T_{\text{mb}} = T_{\text{A}}^*/\eta_{\text{mb}}$, where η_{mb} is the main-beam efficiency. The adopted main-beam efficiencies are given in Table 2 together with frequency, the energy of the upper level, and main beam FWHM for the respective transition. The uncertainty in the absolute intensity scale is estimated to be about $\pm 20\%$. Velocities are given with respect to the Local Standard of Rest (LSR).

3.2. CO line profiles

All new spectra are presented in Appendix A, and the integrated intensities and peak main-beam brightness temperatures are given in Tables A.1. Our previous analysis of CO emission lines from S-stars (Ramstedt et al. 2006) was based on new APEX observations in combination with data from the literature. When examining the previously published data, we found a large scatter in the reported CO($J = 2 \rightarrow 1$) intensities and consequently these data were not used in the final analysis. The new CO($J = 2 \rightarrow 1$) data is generally stronger than the data discarded in Ramstedt et al. (2006). As an example, the new CO($J = 2 \rightarrow 1$) line intensities obtained at IRAM are, on

⁵ XS is a package developed by Bergman to reduce and analyze a large number of single-dish spectra. It is publicly available from [ftp://yggdrasil.oso.chalmers.se](http://yggdrasil.oso.chalmers.se)

average, a factor of about three stronger than those reported in Sahai & Liechti (1995).

The observed line profiles are in general of good quality ($S/N \sim 5$ or larger) and can, to a first approximation, be reconciled with those expected from a smooth spherically symmetric outflow. There is no evidence for any “detached-shell” sources in the sample (see e.g. the carbon star sample results of Olofsson et al. 1993). A closer inspection shows that some of the stars (e.g., W And, W Aql, DY Gem, and R Gem) have line profiles with weak wings extending beyond the parabolic line profile. This might be indicative of recent mass-loss-rate modulations in these sources or of asymmetric outflows. The six observed lines toward T Cet all show an asymmetry with stronger emission on the red-shifted side, similar to what is observed due to strong self-absorption (Huggins & Healy 1986). However, the star has a derived mass-loss rate of only $4 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ and all lines are found to be optically thin in the model. Consequently, the model does not reproduce the observed line profiles since strong self-absorption requires optically thick lines. Most likely, this is an indication that T Cet has an asymmetric outflow.

3.3. SiO line profiles

A total of 26 stars were detected in circumstellar SiO line emission. All new spectra are presented in Appendix B, and the integrated intensities and peak main-beam brightness temperatures are given in Tables B.1 and B.2. The observed spectra are generally of good quality ($S/N \sim 3$ or larger). As previously discussed by González Delgado et al. (2003), the SiO line profiles are often found to be narrower than the CO line profiles. However, many of the SiO lines show weak wings extending beyond the main emission feature and the total velocity widths are similar to those of the CO lines. It should be kept in mind that for poorer quality data, the uncertainty in the line width can be several km s^{-1} .

3.4. Dust continuum emission

The SEDs were constructed using J , H , and K band data (2MASS) and IRAS fluxes.

4. Radiative transfer modelling

4.1. The circumstellar model

The CSE is assumed to be spherically symmetric and formed by a constant mass-loss rate. It is assumed to be expanding at a constant velocity, derived from fitting the CO line widths, and to have a micro-turbulent velocity distribution with a Doppler width of 1.0 km s^{-1} . In addition, a thermal contribution to the local line width is added, based on the derived kinetic temperature of the gas. The density structure is obtained from the conservation of mass.

4.2. Dust emission modelling

The dust radiative transfer was solved using the publicly available code DUSTY⁶. Amorphous carbon grains (Suh 2000) or amorphous silicate grains (Justanont & Tielens 1992) were assumed based on the IRAS low-resolution spectra (LRS) classification according to Volk & Cohen (1989). Three parameters are adjustable when fitting the model SEDs to the observed flux

⁶ <http://www.pa.uky.edu/~moshe/dusty/>

densities; the dust optical depth at $10\ \mu\text{m}$, τ_{10} , the dust temperature at the inner radius of the dust envelope, $T_d(r_i)$, and the stellar temperature, T_* . One large grid per dust type was calculated. The optical depth at $10\ \mu\text{m}$ ranges from 0.01 to 3.0 in steps of 10%, the inner dust temperature is varied from 500 to 1500 K, and the stellar temperature from 1800 to 2400 K, both in steps of 100 K. Once the grid is calculated, the solution can be scaled to the luminosity and distance of any star and a fit to the observed flux densities can be found (Ivezic & Elitzur 1997). For simplicity, the dust grains are assumed to be of the same size with a radius of $0.1\ \mu\text{m}$, and have a density of $2\ \text{g cm}^{-3}$ (carbon grains) or $3\ \text{g cm}^{-3}$ (silicate grains).

4.3. Physical properties of the gas content in the CSEs

The adopted method for the radiative transfer analysis of the circumstellar CO radio line emission has been described in detail in previous articles (Schöier & Olofsson 2001 for carbon stars, and Olofsson et al. 2002 for M-type stars) and therefore only a short description is given here.

The non-LTE radiative transfer code is based on the Monte Carlo method. The code has been benchmarked to high accuracy against a wide variety of molecular-line radiative transfer codes (van Zadelhoff et al. 2002; van der Tak et al. 2007). In the excitation analysis of the CO molecule, 41 rotational levels are included in each of the two lowest vibrational states ($v = 0$ and $v = 1$). Energy levels and radiative transition probabilities, as well as collisional rate coefficients for collisions between CO and H_2 , are taken from Schöier et al. (2005)⁷. When weighting together collisional rate coefficients for CO in collisions with ortho- and para- H_2 an ortho-to-para ratio of 3 is adopted. Radiation from the central source (assumed to be a blackbody) and the cosmic microwave background is included. When the dust optical depth could be constrained in the dust radiative transfer analysis (see Sect. 5.1), i.e., there is a significant amount of thermal dust grains present in the wind, the corresponding modification to the radiation field is also included in the molecular excitation analysis.

The energy balance equation for the gas is solved self-consistently. Cooling is due to line cooling from CO and H_2 and the adiabatic expansion of the gas. The dominant gas-heating mechanism is collisions between the H_2 molecules and the dust grains. Photoelectric heating is also included and it is mostly important in the outer parts of the CSE. The free parameters describing the dust; the dust-to-gas mass-loss-rate ratio, Ψ , the average density of an individual dust grain, ρ_g , and the dust grain radius, a_g , are combined in the parameter h (see Schöier & Olofsson 2001 for a definition). The h -parameter thus gives a measure of how efficiently the gas is heated due to collisions with dust grains. Following Schöier & Olofsson (2001), we have adopted an average efficiency factor for momentum transfer, which is constant throughout the CSE, $\langle Q_{\text{rp}} \rangle^\dagger = 3 \times 10^{-2}$.

The radial CO abundance distribution is estimated using the model presented in Mamon et al. (1988). The initial abundance of CO relative to H_2 , is assumed to be 6×10^{-4} . The inner radius of the CSE was taken from the SED fitting when the model could be constrained, and is otherwise assumed to be $5\ r_*$. A change in the inner radius with a factor of two will affect the resulting line intensities by less than 15% (Schöier & Olofsson 2001).

The mass-loss rate and the h -parameter are the remaining free parameters in the CO line modelling.

4.4. SiO line radiative transfer modelling

The same non-LTE Monte Carlo radiative transfer code is used for the analysis of the SiO radio line emission, where 41 rotational levels are included in each of the two lowest vibrational states ($v = 0$ and $v = 1$). Energy levels and radiative transition probabilities, as well as collisional rate coefficients for collisions between SiO and H_2 , are taken from Schöier et al. (2005). The physical properties of the CSEs (mass-loss rates and radial gas temperature distributions) are taken from the results of the CO modelling. All other assumptions are the same. Also here, a decrease in the inner radius by a factor of two will result in a small change ($\leq 10\%$) of the model line intensities. The only free parameters when fitting the SiO line emission is the SiO abundance at the inner radius, and, when several lines were observed, the outer radius of the SiO emitting region (Sect. 4.5). These two parameters can be used to test chemical models of the inner CSE and photodissociation models for the outer envelope, respectively.

4.5. The radial SiO abundance distribution

The radial SiO abundance distribution, i.e., the ratio of the number densities of SiO molecules to H_2 molecules, $f = n(\text{SiO})/n(\text{H}_2)$, is assumed to be described by a Gaussian

$$f(r) = f_0 \exp\left[-\left(\frac{r}{r_e}\right)^2\right]. \quad (1)$$

For 18 out of 26 detected stars, too few transitions are observed in order to constrain both the abundance and the size of the emitting region. For these stars the extent of the SiO envelope is assumed to scale with the density of the CSE according to the scaling law found by González Delgado et al. (2003),

$$\log r_e = 19.2 + 0.48 \log\left(\frac{\dot{M}}{v_e}\right), \quad (2)$$

where \dot{M} is the mass-loss rate and v_e the gas expansion velocity of the wind, both found from the CO line modelling. For a discussion about the validity of Eq. (2) see González Delgado et al. (2003), Schöier et al. (2006b), and Sect. 5.3.

5. Results

5.1. Dust optical depth and radial dust temperature distribution

As known since previous studies of S-stars on the AGB (e.g., Sahai & Liechti 1995; Jorissen & Knapp 1998), the dust content of S-star CSEs is low. The dust radiative transfer analysis performed here show that the dust optical depth can be constrained for only 12 out of 40 sample stars. For the other stars the SED is dominated by the emission from the central star and DUSTY has been used to determine only the stellar effective temperature (in addition to the distance/luminosity of the source). The best-fit model is found by minimizing

$$\chi^2 = \sum_{i=1}^N \frac{(F_{\text{mod},\lambda} - F_{\text{obs},\lambda})^2}{\sigma_\lambda^2}, \quad (3)$$

where F_λ is the flux density and σ_λ the uncertainty in the measured flux density at wavelength λ . The summation is done over

⁷ <http://www.strw.leidenuniv.nl/~moldata>

Table 3. LRS classification, adopted dust type (amorphous silicate, AMS, or amorphous carbon, AMC), stellar radius, r_* , inner radius of the CSE, r_i , stellar temperature, T_* , temperature at the inner boundary, $T_d(r_i)$, dust optical depth at $10 \mu\text{m}$, τ_{10} , drift velocity, v_{dr} , dust mass-loss rate, \dot{M}_d , and dust-to-gas mass-loss-rate ratio, Ψ .

Source	LRS class	Dust type	r_* [10^{13} cm]	r_i [10^{14} cm]	T_* [K]	$T_d(r_i)$ [K]	τ_{10}	v_{dr} [km s^{-1}]	\dot{M}_d [$10^{-9} M_\odot \text{ yr}^{-1}$]	Ψ [10^{-3}]
R And	E	AMS	5.6	4.9	1800	500	0.02	6.8	0.4	0.6
W And	E	AMS	3.1	1.5	2400	...	...	...	...	...
Z Ant	E	AMS	1.6	8.2	2400	...	...	...	...	...
VX Aql	...	AMC	2.6	1.3	2400	...	...	...	...	...
W Aql	E	AMS	6.0	3.7	1800	600	0.10	5.7	2.4	1.1
AA Cam	...	AMC	2.6	1.3	2400	...	...	...	...	...
T Cam	S	AMC	3.0	1.5	2400	...	...	...	...	...
S Cas	E	AMS	6.5	3.0	1800	700	0.10	5.3	2.2	0.6
V365 Cas	F	AMC	2.6	1.3	2400	...	...	...	...	...
WY Cas	E	AMS	4.0	2.0	2200	...	...	...	...	...
AM Cen	...	AMC	2.6	1.3	2400	...	...	...	...	...
TT Cen	...	AMS	3.3	1.7	2400	...	...	...	...	...
UY Cen	C	AMC	2.6	0.5	2400	1500	0.03	15	0.4	2.9
V386 Cep	...	AMS	4.6	11	1800	300	0.04	14	3.8	19
T Cet	...	AMC	2.6	1.3	2400	...	...	...	...	...
AA Cyg	S	AMC	2.6	1.3	2400	...	...	...	...	...
AD Cyg	E	AMC	4.6	2.3	1800	...	...	...	...	...
R Cyg	E	AMS	3.8	1.9	2200	...	...	...	...	...
χ Cyg	E	AMS	3.1	0.6	2400	1400	0.03	9.0	0.1	0.2
TV Dra	...	AMS	2.6	1.3	2400	...	...	...	...	...
DY Gem	F	AMS	2.6	1.3	2400	...	...	...	...	...
R Gem	F	AMC	3.0	1.5	2400	...	...	...	...	...
ST Her	...	AMS	3.1	3.1	2200	600	0.03	13	0.6	4.4
RX Lac	S	AMC	2.6	1.3	2400	...	...	...	...	...
GI Lup	F	AMC	2.9	1.5	2400	...	...	...	...	...
R Lyn	F	AMC	3.0	1.5	2400	...	...	...	...	...
Y Lyn	...	AMS	1.9	1.0	2400	...	...	...	...	...
S Lyr	...	AMS	5.7	5.1	1800	500	0.09	5.0	2.4	1.2
FU Mon	S	AMC	2.6	1.3	2400	...	...	...	...	...
RZ Peg	C	AMC	2.6	1.3	2400	...	...	...	...	...
RT Sco	E	AMS	3.3	1.7	2400	...	...	...	...	...
ST Sco	E	AMS	2.6	1.3	2400	...	...	...	...	...
RZ Sgr	F	AMC	2.6	1.3	2400	...	...	...	...	...
ST Sgr	E	AMS	3.1	1.6	2400	...	...	...	...	...
T Sgr	F	AMC	3.1	1.6	2400	...	...	...	...	...
EP Vul	F	AMC	2.6	1.3	2400	...	...	...	...	...
DK Vul	F	AMC	2.6	1.3	2400	...	...	...	...	...
AFGL 2425	...	AMS	4.6	2.9	1800	600	0.10	8.4	1.4	4.8
CSS2 41	...	AMS	4.6	4.1	1800	500	0.10	8.5	3.0	5.2
IRC-10401	...	AMS	4.6	4.1	1800	500	0.07	11	2.3	6.6

all N independent observations. The reduced χ^2 for the best-fit model is given by

$$\chi_{\text{red}}^2 = \frac{\chi_{\text{min}}^2}{N - p}, \quad (4)$$

where p (the number of adjustable parameters) is 3 in our case.

Table 3 shows the LRS classification, the assumed dust type, the stellar radius, r_* , the inner radius of the CSE, r_i , and the stellar temperature, T_* . The inner radius is assumed to be $5 r_*$ for all stars where the dust optical depth could not be constrained. Table 3 also gives the temperature at the inner radius of the dust shell, $T_d(r_i)$, the dust optical depth at $10 \mu\text{m}$, τ_{10} , the dust-to-gas mass-loss-rate ratio, Ψ , and the dust mass-loss rate, \dot{M}_d , for the stars where this could be calculated. The dust mass-loss rate is given by

$$\dot{M}_d = \frac{2\pi}{\chi_{\text{gr},\nu}} v_{d,\infty} r_i \tau_{d\nu}, \quad (5)$$

where $\chi_{\text{gr},\nu}$ is the grain cross section per unit mass at a given frequency ν , $v_{d,\infty}$ is the dust expansion velocity, and $\tau_{d\nu}$ is the dust optical depth at a given frequency. A $\chi_{\text{gr},10\mu\text{m}}$ of 1.1×10^3 and 3.5×10^3 has been used for the stars with carbon and silicate dust, respectively. The dust expansion velocity is calculated from the gas expansion velocity derived in the CO line modelling and the drift velocity between the dust and gas particles, v_{dr} , given by

$$v_{\text{dr}} = \left(\frac{L_* v_e \langle Q_{\text{TP}} \rangle^\dagger}{\dot{M} c} \right)^{1/2} \quad (6)$$

(Kwok 1975).

5.2. Mass-loss rates, radial gas temperature distribution and kinematics

All results from the CO radiative transfer analysis, mass-loss rates, h -parameters, gas expansion velocities, stellar velocities,

v_{LSR} , χ_{red}^2 for the best-fit models, and the number of observational constraints, N , are given in Table 4.

For slightly more than half of the stars, enough data ($N \geq 3$) is available to constrain both h and \dot{M} . Models are calculated for a large number of mass-loss rates and h -parameters and the best-fit model is found by minimizing

$$\chi^2 = \sum_{i=1}^N \frac{(I_{\text{mod},i} - I_{\text{obs},i})^2}{\sigma_i^2}, \quad (7)$$

where I_{mod} and I_{obs} are the integrated intensities of the modelled and observed lines, respectively. σ is in most cases dominated by the calibration uncertainties assumed to be 20%. For observations with poorer S/N , σ is set higher according to the quality of the data (although never above 30%). The reduced χ^2 is given by Eq. (4), where $p = 2$.

For the remaining stars, we have assumed the value of h depending on the stellar luminosity; $h = 0.2$ for $L_{\star} < 5000 L_{\odot}$ and $h = 0.5$ for $L_{\star} \geq 5000 L_{\odot}$ (in accordance with Schöier & Olofsson 2001 and Olofsson et al. 2002). This is indicated by a colon in Table 4 and the reduced χ^2 is given by Eq. (4) with $p = 1$.

Generally, the mass-loss rates are well constrained, and the observed CO lines are well-reproduced by the model. For many of the stars, it is not possible to find an upper limit to the h -parameter. This is not surprising, since the excitation in these low-mass-loss-rate stars is dominated by the radiation from the central star and is not very sensitive to the temperature structure of the gas and the adopted dust parameters. For some stars the χ_{red}^2 of the best-fit model is rather large. The derived χ^2 is very sensitive to the line ratios, and any calibration errors in one line (larger than our estimated uncertainties) might result in a large χ_{red}^2 (see Fig. 2, CO($J = 2 \rightarrow 1$)). Therefore it is difficult to determine whether inadequacies in the model or calibration errors are responsible for the poor fit in some cases. We find no systematic trends with particular lines or telescopes. Figure 2 shows the best-fit model from the radiative transfer analysis overlaid on the observed line profiles for χ Cyg. The χ^2 -map is also shown with the innermost contour representing the 1σ -level. This fit is good, but not perfect, e.g., in the details of the line shapes, and the main reason for this is not easily identified.

Compared to the mass-loss rates found in Ramstedt et al. (2006), the larger quantity of data makes the new mass-loss-rate estimates more reliable. In particular, it is possible to determine the h -parameter for a larger number of stars. A comparison shows that the inclusion of the new data in the analysis has changed the estimated mass-loss rates by less than a factor of two. For seven stars the change is slightly larger. There is no systematic change upwards or downwards.

5.3. SiO abundances and radial distribution

All results from the SiO radiative transfer analysis, SiO fractional abundances, f_0 , the size of the SiO emitting regions (as derived from Eq. (2)), r_e , SiO gas expansion velocities, $v_e(\text{SiO})$, χ_{red}^2 for the best-fit models, and the number of observational constraints, N , are given in Table 5. Again, the best-fit model is found by minimizing Eq. (7) and χ_{red}^2 is defined by Eq. (4), where $p = 1$ when r_e is given by Eq. (2). The derived abundances range from 4×10^{-7} to 1.4×10^{-4} . The median value is 6×10^{-6} . Figure 3 shows a histogram of the circumstellar SiO abundances for the S-type stars compared to those found for M-type stars (González Delgado et al. 2003) and carbon stars (Schöier et al. 2006b). The spread of the SiO abundance distribution for the S-type stars

Table 4. Mass-loss rates, h -parameters, and terminal gas expansion velocities, v_e , derived from fitting the radiative transfer model to the CO line observations.

Source	\dot{M} [$10^{-7} M_{\odot} \text{ yr}^{-1}$]	h	v_e [km s^{-1}]	v_{LSR} [km s^{-1}]	χ_{red}^2	N
R And	6.6	0.4	8.3	-16.5	1.3	5
W And	1.7	0.5	6.0	-35.0	1.1	5
Z Ant	0.9	0.2:	6.0	-16.0	0.4	2
VX Aql	1.0	0.2:	7.0	6.7	...	1
W Aql	22	1.0	17.2	-26.0	0.6	5
AA Cam	0.4	0.2:	3.4	-46.8	2.8	2
T Cam	1.0	0.2:	3.8	-11.7	0.1	2
S Cas	35	0.2	20.5	-31.0	3.6	4
V365 Cas	0.3	0.2:	6.2	-2.1	...	1
WY Cas	11	0.5	13.5	7.0	6.6	3
AM Cen	1.5	0.2:	3.2	-27.0	2.0	2
TT Cen	25	0.5:	20.0	4.0	7.4	2
UY Cen	1.3	0.2:	12.0	-26.0	0.2	2
V386 Cep	2.0	0.2:	16.0	-51.8	...	1
T Cet	0.4	0.2	5.5	22.0	1.2	6
AA Cyg	2.9	0.2	4.5	27.5	2.1	3
AD Cyg	2.1	0.2:	8.0	21.0	0.1	2
R Cyg	6.3	0.5	9.0	-18.5	5.0	5
χ Cyg	3.8	0.2	8.5	9.0	2.0	6
TV Dra	0.5	0.2	4.7	22.0	7.8	3
DY Gem	7.0	0.2	8.0	-16.7	2.0	3
R Gem	4.4	0.8	4.5	-60.0	3.7	4
ST Her	1.3	0.2	8.5	-4.5	1.4	4
RX Lac	0.8	0.2:	6.5	-15.4	...	1
GI Lup	5.5	0.5:	10.0	6.0	...	1
R Lyn	3.3	0.2	7.5	16.0	0.5	5
Y Lyn	2.3	1.0	7.5	-0.5	3.9	3
S Lyr	20	0.5:	13.0	49.0	7.6	2
FU Mon	2.7	0.2	2.8	-42.0	0.6	3
RZ Peg	4.6	0.2:	12.6	-23.4	...	1
RT Sco	4.5	0.5:	11.0	-47.0	3.2	2
ST Sco	1.5	0.2	5.5	-4.5	2.0	3
RZ Sgr	30	0.6	9.0	-31.0	1.4	3
ST Sgr	2.0	0.5:	6.0	55.7	0.1	2
T Sgr	1.4	0.2	7.5	9.0	3.8	3
EP Vul	2.0	0.2	5.7	0.0	8.9	3
DK Vul	2.5	0.6	4.5	-15.0	5.7	4
AFGL 2425	3.0	0.2	8.7	57.0	0.2	3
CSS2 41	5.8	0.2	17.0	21.5	2.4	3
IRC-10401	3.5	0.2:	17.0	19.0	13.4	2

(as measured by the ratio between the 90th percentile and the 10th percentile) is about a factor of 25.

The SiO gas expansion velocity is found to be, on average, 20% smaller than the CO gas expansion velocity (for 19 out of 26 stars). González Delgado et al. (2003) discuss the possibility that the SiO emission probes the very outer parts of the gas acceleration zone and that this would explain the discrepancy in the line width. SiO typically probes regions closer to the star by about a factor of 5–10 compared to CO. A trend of narrowing of the SiO lines with higher frequency might then also be expected, since rotational transitions involving higher energy levels (Table 2) tend to probe warmer and denser regions closer to the star. In addition, the line width can be reduced due to strong self-absorption on the blue-shifted side of the SiO lines that are optically thick. We do not find a trend with narrowing of higher frequency lines nor with the mass-loss rate (as would be expected if self-absorption was the predominant effect) and can therefore not firmly conclude that the SiO emission probes the acceleration zone.

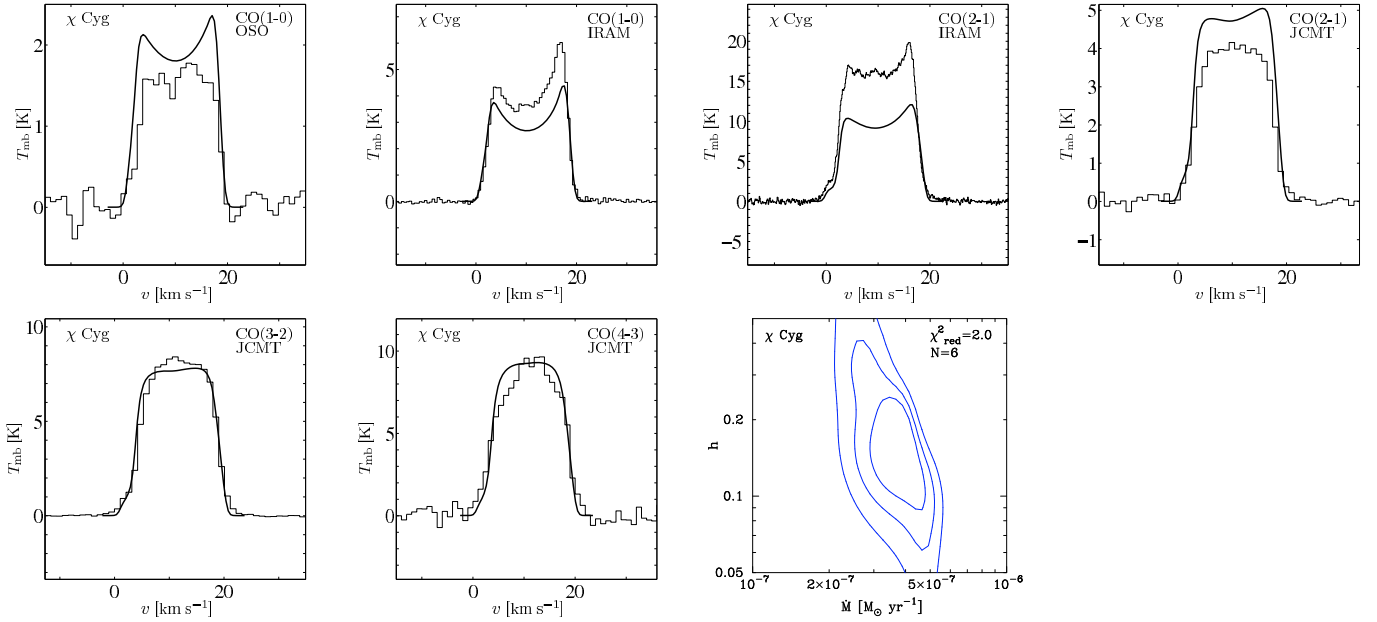


Fig. 2. The observed CO line profiles toward χ Cyg (histogram) overlaid with the results from the radiative transfer model (solid line) for the best-fit model with $\chi^2_{\text{red}} = 2.0$. The χ^2 -map of the full analysis of χ Cyg is also shown. LSR velocity scales are used.

Table 5. Circumstellar SiO fractional abundance, f_0 , radius of the SiO line-emitting region from Eq. (2), r_e , and gas expansion velocities derived from fitting the SiO line radiative transfer model to the observations, $v_e(\text{SiO})$. The reduced χ^2 for the best-fit model and the number of observational constraints, N , are also given.

Source	f_0 [10^{-6}]	r_e [10^{15} cm]	$v_e(\text{SiO})$ [km s^{-1}]	χ^2_{red}	N
R And	4.0	6.2	8.3	1.0	5
W And	12	3.8	4.8	0.8	2
W Aql	2.0	7.8	17.0	0.6	4
S Cas	6.0	8.9	20.5	4.2	3
WY Cas	1.5	6.3	10.0	2.2	3
V386 Cep	140	2.5	13.5	0.3	3
T Cet	12	2.0	5.5:	...	1
AA Cyg	1.9	5.6	4.0	3.7	2
R Cyg	4.0	5.8	9.0	1.3	4
χ Cyg	10	4.7	7.0	4.7	4
TV Dra	26	2.4	4.5	5.7	2
DY Gem	1.8	6.5	6.5	0.5	2
R Gem	1.4	6.8	4.0	2.1	3
RX Lac	3.0	2.5	3.0	2.0	3
Y Lyn	1.0	3.9	5.0	0.5	3
S Lyr	10	8.5	11.5	3.0	2
RT Sco	1.5	4.5	9.5	0.4	2
ST Sco	1.0	3.7	5.5	7.9	2
RZ Sgr	0.4	12	7.0	0.2	2
ST Sgr	10	4.1	6.0	...	1
T Sgr	22	3.1	5.0	...	1
EP Vul	10	4.2	5.0	1.3	3
DK Vul	3.8	5.9	3.5	0.4	2
AFGL 2425	16	4.2	8.7	3.3	3
CSS2 41	68	4.1	16.0	0.3	2
IRC-10401	14	3.2	17.0	22.8	3

Table 6 shows the results (with 1σ -errors) of the best-fit models when r_e is left as a free parameter. In this case, the modelling generally gives a good fit to the observed SiO lines (see Fig. 4) with χ^2_{red} on the order of unity. From the χ^2 -analysis we

find that the derived SiO abundances are generally determined within a factor of ≈ 4 (except for R And, Fig. 4). S Cas has a large χ^2_{red} -value and the same can be observed for the result from the CO model (Table 4). This might indicate that S Cas is not well reproduced by a spherically symmetric wind model. The same can be noted for the SiO model of χ Cyg. However, both models are based on rather noisy SiO($J = 2 \rightarrow 1$) lines from OSO, and the line ratios between this line and the other available lines are not reproduced. Thus, we can not decide whether the bad fit is due to the model being incorrect for these stars, or observational uncertainties. For T Cet, only the SiO($J = 8 \rightarrow 7$) line was observed (at APEX). A fit to the width of the line gives $v_e(\text{SiO}) = 16.0 \text{ km s}^{-1}$. Since only one line is available and the data is rather noisy (see Fig B.1), we have chosen to model the star with the expansion velocity derived from the CO model ($N = 6$), $v_e = 5.5 \text{ km s}^{-1}$. For IRC-10401 enough lines are available to try to fit the size of the SiO envelope and the abundance simultaneously. However, we are not able to constrain r_e for this object and have chosen to use r_e from Eq. (2).

To be able to compare our results to what has previously been found for M-type stars (González Delgado et al. 2003) and carbon stars (Schöier et al. 2006b) we have decided to derive all SiO abundances using Eq. (2) for the size of the SiO emitting region in order to be consistent. Figure 5 shows a comparison between the radii derived when r_e is left as a free parameter and those using Eq. (2). The error bars correspond to the 1σ limits. Only results from models with a $\chi^2_{\text{red}} < 2.5$ and where the SiO($J = 8 \rightarrow 7$) line was available are shown in Fig. 5. We conclude that our results are consistent with Eq. (2) and that the size of the SiO emitting region does not differ significantly between the different chemical types. This is in agreement with the results of Schöier et al. (2006b).

6. Discussion

6.1. Mass loss of S-type AGB stars

Figure 6a shows our mass-loss-rate results for the S-type AGB star sample compared with previous results for carbon stars

Table 6. Circumstellar SiO fractional abundance, f_0 , and the radius of the SiO line-emitting region, r_e , with 1σ -errors, from the best-fit model. The reduced χ^2 for the best-fit model and the number of observational constraints, N , are also given.

Source	f_0	r_e	χ^2_{red}	N
R And	$5.1 \pm 4.9 \times 10^{-5}$	$4.0 \pm 3.0 \times 10^{15}$	0.6	5
W Aql	$3.0 \pm 1.0 \times 10^{-6}$	$6.5 \pm 2.5 \times 10^{15}$	0.2	4
S Cas	$9.0 \pm 6.0 \times 10^{-6}$	$9.0 \pm 4.0 \times 10^{15}$	7.2	3
WY Cas	$1.2 \pm 0.3 \times 10^{-6}$	$1.3 \pm 0.7 \times 10^{16}$	2.2	3
V386 Cep	$7.5 \pm 2.5 \times 10^{-5}$	$3.0 \pm 2.0 \times 10^{15}$	0.7	3
R Cyg	$3.0 \pm 1.0 \times 10^{-6}$	$8.5 \pm 3.5 \times 10^{15}$	1.2	4
χ Cyg	$1.3 \pm 0.7 \times 10^{-5}$	$5.0 \pm 3.0 \times 10^{15}$	5.2	4
R Gem	$1.3 \pm 1.1 \times 10^{-5}$	$3.0 \pm 2.0 \times 10^{15}$	1.1	3
RX Lac	$1.8 \pm 0.8 \times 10^{-6}$	$3.6 \pm 2.4 \times 10^{15}$	1.0	3
Y Lyn	$1.9 \pm 1.1 \times 10^{-6}$	$3.5 \pm 1.5 \times 10^{15}$	0.9	3
EP Vul	$2.3 \pm 1.7 \times 10^{-5}$	$3.1 \pm 2.0 \times 10^{15}$	0.7	3
AFGL 2425	$6.5 \pm 2.5 \times 10^{-6}$	$4.3 \pm 3.5 \times 10^{16}$	1.2	3

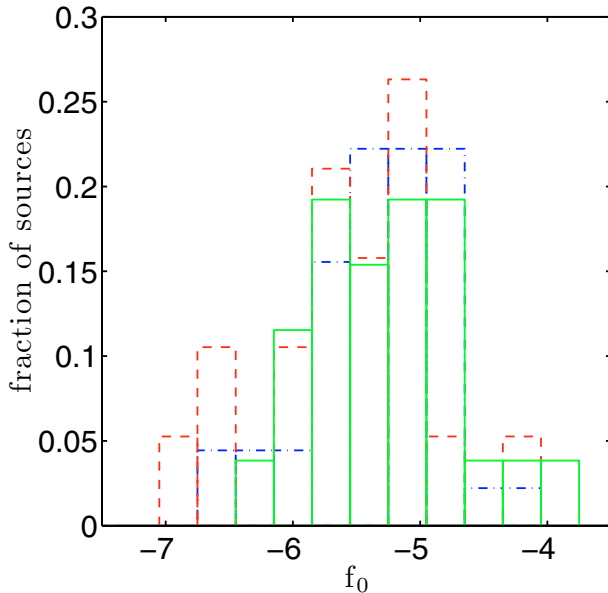


Fig. 3. Circumstellar SiO fractional abundances (f_0) for the S-type (solid, green line; 26 stars), M-type (dashed-dotted, blue line; 45 stars; González Delgado et al. 2003), and carbon star (dashed, red line; 19 stars; Schöier et al. 2006b) samples.

(Schöier & Olofsson 2001) and M-type AGB stars (Olofsson et al. 2002; González Delgado et al. 2003). We confirm here the result of Ramstedt et al. (2006) that the mass-loss-rate distributions for the three different samples are very similar. The median value for the S-type stars using the new data is $2.7 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, and the M-type and carbon stars both have a median of $3.0 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. There are possibly fewer S-type stars with high mass-loss rates and due to our sample selection criteria (see Sect. 2) S-type stars with no or very little mass loss will be missed. The derived mass-loss rates depend on the adopted CO fractional abundance, which differs for the three chemical types in accordance with stellar atmosphere models. Figure 6b shows the gas expansion velocity distribution derived from the CO line widths for the three samples. The median gas expansion velocity for the S-type stars is 8 km s^{-1} , and 7.5 and 11 km s^{-1} for the M-type and carbon stars, respectively, indicating that the carbon stars have CSEs with higher gas expansion velocities. Finally, Fig. 6c shows the relation between the mass-loss rates and the

expansion velocities for the three samples. We find no apparent difference depending on chemistry (apart from the higher gas expansion velocities in the carbon star sample) and suggest that this points to a mass loss that is driven by the same mechanism(s) in the S-type, M-type and carbon AGB stars.

Another indication of this can be seen in Fig. 7 where the mass-loss rate (a and b) and expansion velocity (c and d) are plotted against the stellar variability period. As already discussed by Schöier & Olofsson (2001) for the carbon star sample, the mass-loss rate increases with the period of the star for all chemistries. The same trend can be observed for the expansion velocity. If the efficiency for driving a wind by radiation pressure on dust was weaker in the S-type stars, due to, e.g., a low dust-to-gas ratio or a dust type incapable of driving a wind, the S-type stars would occupy a different parameter space than the M-type stars and the carbon stars in these plots. However, it is not possible to distinguish between the three different types.

6.2. Dust-to-gas ratio

The average of the derived dust-to-gas mass-loss-rate ratios is about 2.8×10^{-3} for the S-type AGB stars in Table 3 (V386 Cep excluded; this is likely the same type as GX Mon discussed in Ramstedt et al. 2008). Groenewegen et al. (1999) derived dust-to-gas ratios of 48 M-type stars and found an average of 5.8×10^{-3} , and Ramstedt et al. (2008) derived dust-to-gas ratios of four high-mass-loss-rate M-type stars resulting in, on average, 2.8×10^{-3} . For the carbon stars the average dust-to-gas ratios might be slightly lower (2.5×10^{-3} , Groenewegen et al. 1998, 2×10^{-3} , Ramstedt et al. 2008). We conclude that the apparently low dust content in S-type AGB stars reflects the fact that they, for the most part, are low mass-loss rate objects. Their dust-to-gas ratios seem to be in agreement with what is derived for AGB stars of other chemical types, implying that the dust formation efficiency is similar in all three chemical types.

6.3. Circumstellar SiO abundances and constraints on chemical models

The SiO abundances derived for the sample of S-type AGB stars range between 4×10^{-7} and 1.4×10^{-4} . All stars (except RZ Sgr, which has the highest wind density) have abundances above or well above the expected thermal equilibrium value for $C/O = 1$ (6.4×10^{-7} , Cherchneff 2006). The median value of 6×10^{-6} is almost an order of magnitude larger than the equilibrium value. Cherchneff (2006) derives an SiO abundance at $5 r_{\star}$ of 3.3×10^{-5} for $C/O = 1$ in a non-equilibrium shock-chemistry model. The SiO abundance derived in a shock-chemistry model is sensitive to the specific parameters of the star, such as the pulsational period and the shock velocity. The periods of the S-type AGB stars in our sample range between about 100–600 days but we find no obvious correlation with the derived SiO abundance. However, in a real, dynamic stellar atmosphere the chemistry is most likely much more complicated than in the present chemical models, and simple dependencies on single parameters, like the period, may not exist. We find no correlation between the LRS class and the derived SiO abundance for the S-type stars.

The derived circumstellar SiO abundances for the sample of S-type AGB stars are compared to those obtained for carbon stars (Schöier et al. 2006b) and M-type AGB stars (González Delgado et al. 2003) in Fig. 3. The three distributions are very similar suggesting that the abundance of SiO in a circumstellar chemistry is not very sensitive to the C/O ratio. In Fig. 8 the

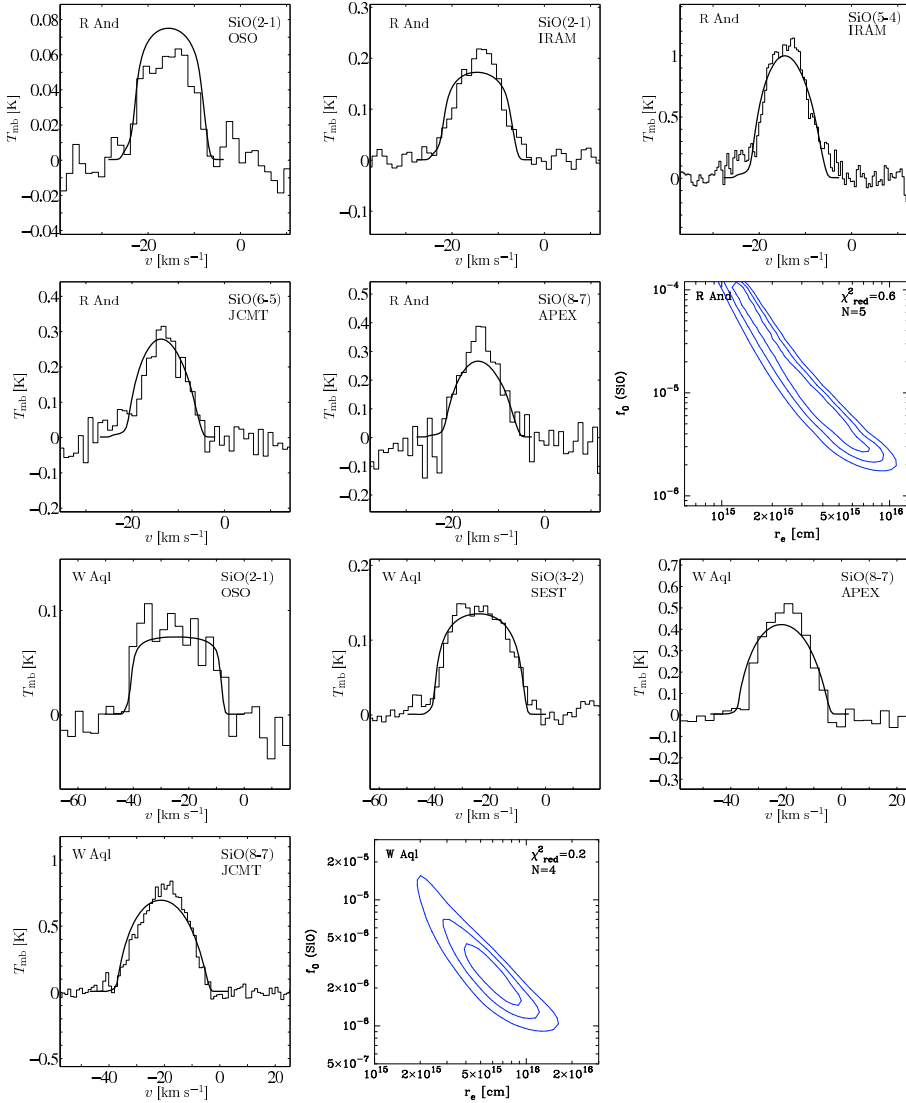


Fig. 4. The observed SiO line profiles toward R And and W Aql (histogram) overlaid with the results from the radiative transfer model (solid line) for the best-fit models with $\chi^2_{\text{red}} = 0.6$ and 0.2 , respectively. LSR velocity scales are used. The χ^2 -maps of the full analysis for the two stars are also shown.

estimated abundances are plotted against a measure of the density of the wind (\dot{M}/v_e). For a specific density the SiO abundance can vary by up to two orders of magnitude. From the χ^2 -analysis we find that the abundances derived when also the size of the emitting region is a free parameter, are determined within a factor of ≈ 4 . Equation (2) is derived using a relatively large number of stars with a large range in mass-loss rates and might give a statistically more accurate abundance. Similar investigations of abundances of circumstellar molecules, for which the results are more in line with what would be expected in equilibrium chemistry (e.g., SiS and HCN), show a smaller range in the derived abundances for different stars (Schöier et al. 2007; Schöier & Olofsson 2008).

For AGB stars with low density envelopes, such as the majority of the stars discussed here, condensation of SiO molecules onto dust grains is not very effective and most probably not the cause for the observed scatter in the derived SiO abundances (see Sect. 6.5). At chemical equilibrium a spread in the abundances is also to be expected depending on the C/O ratio and the temperature of the star. Around C/O = 1, the change in the amount of SiO formed is rather drastic, and between 0.95 and 1.05 the amount of SiO can change with up to two orders of magnitude (Markwick 2000). If the temperature is varied between 2200 and 2600 K for a given C/O-ratio, the SiO abundance will change

less than an order of magnitude⁸. For the S-type stars alone it is not possible to conclude whether the spread in the derived abundances is indicative of a non-equilibrium chemistry or due to a spread in the C/O-ratio around 1. However, given the results for all three chemical types, we conclude that the spread in the derived circumstellar SiO abundances most probably is real and indicative of a shock-chemistry in the formation zone of SiO.

The derived SiO envelope sizes (see Table 6 and Fig. 5) can be used to test photochemical models of the circumstellar envelope. Using a simple photochemical model (Lindqvist et al. 2000; González Delgado et al. 2003, and references therein) with typical stellar, circumstellar and dust parameters for our sample of S-type AGB stars, and adopting an unshielded photodissociation rate of $2.5 \times 10^{-10} \text{ s}^{-1}$ (González Delgado et al. 2003), we obtain the relation between SiO envelope size (r_e) and density measure (\dot{M}/v_e) shown in Fig. 5 (dashed line). These predictions agree well with the observed values and the relation described by Eq. (2) (solid line in Fig. 5) used in the abundance estimates.

6.4. SiO maser emission

There are several indications that SiO maser emission originates from close to the stellar photosphere (Reid & Moran 1981). The

⁸ Astrochemistry.net-SiO, H2, 19 Jan. 2009.

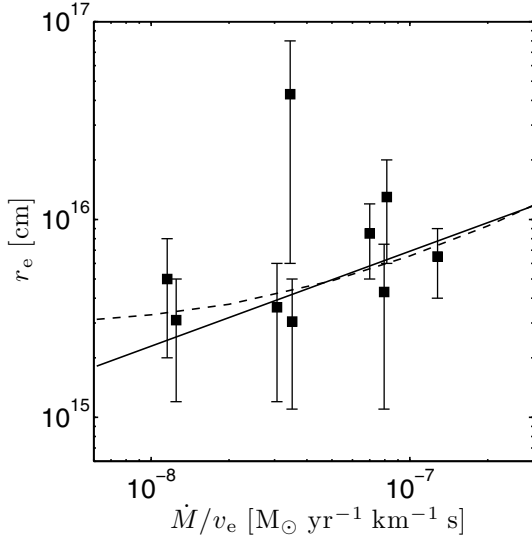


Fig. 5. Circumstellar SiO envelope sizes (r_e) estimated from the best-fit models plotted against the wind density (\dot{M}/v_e). The solid line is derived from Eq. (2), which is based on a fit to SiO envelope estimates for a sample of M-type AGB stars (González Delgado et al. 2003). The dashed line shows the prediction using a simple photochemical model (see Sect. 6.3).

energy of the masing state is about 1800 K ($v = 1$) or higher, and VLBA observations confirm that the masers are formed within a few stellar radii of the star (see for instance Cotton et al. 2006, and references therein). This corresponds to the region where the dust is formed (Salpeter 1974; Danchi et al. 1994; Reid & Menten 1997). Observations of SiO masers can therefore provide information on whether there is SiO present in the dust formation region, and hence whether it can be one of the constituents of the dust formed. The non-detection of SiO maser emission toward carbon stars is thought to be indicating that the SiO molecules are formed further out in the wind than in M-type AGB stars.

SiO maser emission has been searched for in 30 of our sample stars, and has previously been detected in nine (Jorissen & Knapp 1998). The results of our SiO($J = 2 \rightarrow 1$, $v = 1$) observations are given in Table B.2, and the detected lines are shown in Fig. B.3. In four stars the SiO maser has previously not been detected, and in another four stars we can not confirm previous detections (R Cyg, R Lyn, Y Lyn and EP Vul), most likely a result of time variability. In Table B.2 we give distance independent upper limits for the sources observed. Unfortunately the reason for the non-detections is not possible to identify but time variability may play a role.

Out of the 12 S-type stars in our sample classified as showing silicate emission in their LRS spectra, eight were observed and six were detected. Nine stars are classified as being featureless and out of these, six were observed and one was detected. Out of the three stars classified as not showing any IR excess, two were observed and none was detected, and finally, out of the 13 unclassified stars, seven were observed and two were detected in the SiO($J = 2 \rightarrow 1$, $v = 1$) maser line. These results are in line with a situation where the silicate stars have a C/O-ratio slightly less than one, and hence have enough SiO in their photospheres to produce SiO masers, while the others, in general, have C/O-ratios slightly larger than one, and hence too low photospheric SiO abundances to produce SiO masers.

6.5. SiO chemistry and implications for dust formation

The formation of SiO in AGB winds with shocks is discussed by Cherchneff (2006) for different C/O-ratios. It is described how the formation of SiO is linked to the presence of OH and how the lack of OH in the inner wind of carbon stars explain their inability to form silicate dust despite their high SiO abundances further out in the CSE.

For the S-type AGB stars, the situation is more complicated. The exact C/O-ratio is not known for the stars in our sample, but it is most likely a spread around 1. The C/O-ratio of course has implications for both the chemistry and the dust formed. Cherchneff (2006) finds that the chemistry of the inner winds of stars with C/O = 0.98 is very similar to the M-type chemistry, while the chemistry of stars with C/O = 1.01 is very similar to that of carbon stars. In our comparison (Figs. 3 and 8) it is not possible to distinguish between the different chemical types in terms of their circumstellar SiO abundances. Given also the similarity of the mass-loss-rate distributions for the different chemical types, the most likely explanation is that the S-type stars in our sample have a spread in their C/O-ratio where some stars are more M-type like (forming silicate dust) and some are more carbon-star like (forming carbon dust). However, we are not able to exclude a scenario where two components of dust have formed in stars with a C/O-ratio close to unity.

For M-type AGB stars (González Delgado et al. 2003) and carbon stars (Schöier et al. 2006b) there is a clear trend that the circumstellar SiO abundance gets lower as the density of the wind increases (Fig. 8), indicative of adsorption of SiO onto dust grains. For the sample of S-type AGB stars only an indication of such a trend may be seen, possibly due to the lack of high mass-loss rate objects. The dashed line in Fig. 8 shows a depletion curve based on a simple model presented in González Delgado et al. (2003). A relatively large scatter around the curve is expected since the condensation is sensitive to stellar, circumstellar, and dust characteristics. Further support for a depletion scenario comes from recent interferometric observations. Schöier et al. (2006a) modelled interferometric observations of SiO($J = 5 \rightarrow 4$) emission and infrared observations of rovibrational transitions of the extreme carbon star IRC+10216, and found that a two-component radial abundance distribution (a compact high abundance, pre-condensation, component combined with a more extended low abundance, post-condensation, component) is needed in order to explain the observations. Models of interferometric observations of M-type AGB stars (Schöier et al. 2004) also show that a two-component radial abundance distribution gives a better fit to the observed data. The observations at hand for the S-type AGB stars do not allow a proper investigation of a scenario in which SiO molecules are incorporated into grains (see discussion in Schöier et al. 2007). Instead, the abundances derived here should be considered as post-condensation abundances.

7. Conclusions

We have modelled multi-transitional CO radio line data from 40 S-type AGB stars. We have also modelled multi-transitional SiO data of 26 stars from the same sample. The results are compared to similar samples of M-type AGB stars (Olofsson et al. 2002) and carbon stars (Schöier & Olofsson 2001). We arrive at the following conclusions:

- We find that the mass-loss rate distributions are very similar for the three chemical types (Fig. 6a), and so are the relations

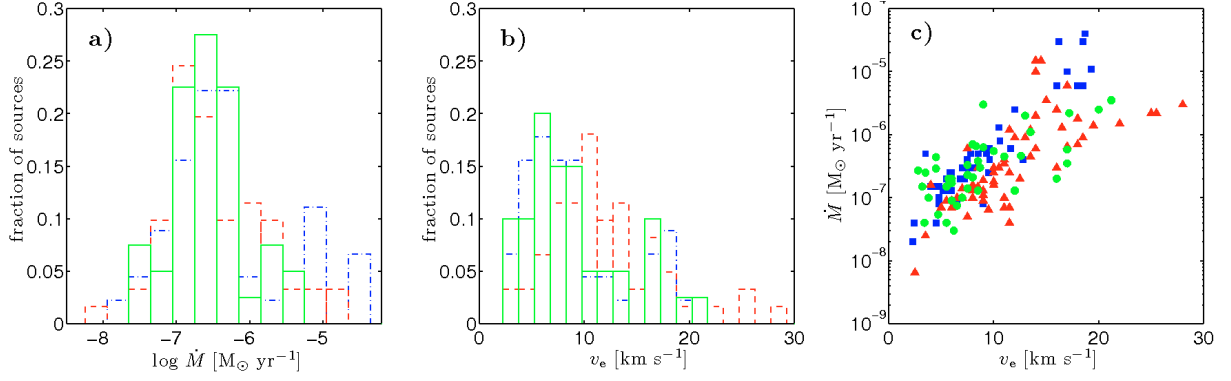


Fig. 6. **a)** Mass-loss-rate distributions for S-type stars (solid, green line; 40 stars), M-type stars (dashed-dotted, blue line), and carbon AGB stars (dashed, red line) samples. **b)** Gas expansion velocity distributions derived from fitting the CO line widths for the S-type (solid, green line), M-type (dotted, blue line) and carbon AGB star (dashed, red line) samples. **c)** Mass-loss rates plotted against the gas expansion velocities for S-type stars (green dots), M-type stars (blue squares), and carbon AGB stars (red triangles) samples.

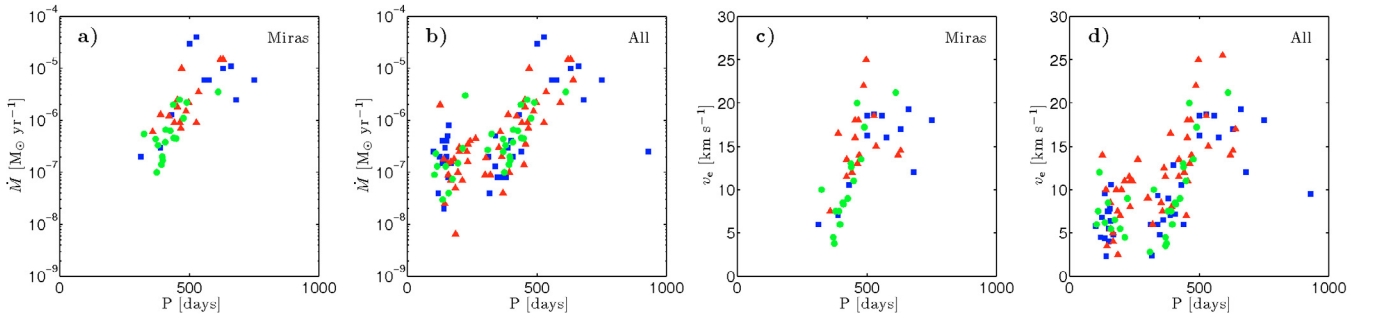


Fig. 7. Mass-loss rates plotted against the periods of the Miras (**a**) and all variable types (**b**) for S-type stars (green dots), M-type stars (blue squares), and carbon AGB stars (red triangles) samples. Gas expansion velocities plotted against the periods of the Miras (**c**) and all variable types (**d**) for S-type stars (green dots), M-type stars (blue squares), and carbon AGB stars (red triangles) samples.

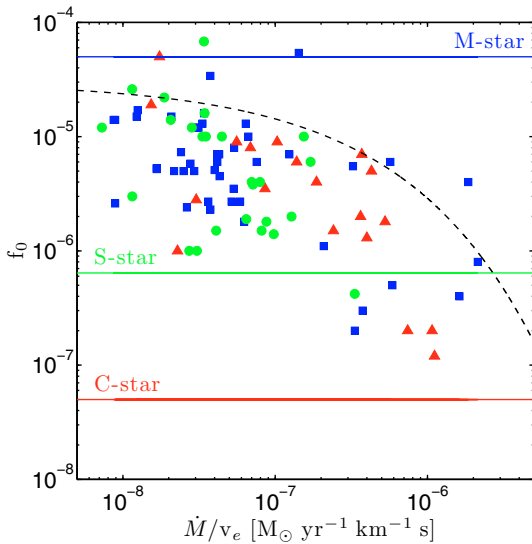


Fig. 8. Circumstellar SiO fractional abundances (f_0) as a function of wind density (\dot{M}/v_e) for S-type (green dots), M-type (blue squares) (González Delgado et al. 2003), and carbon stars (red triangles) (Schöier et al. 2006b). The horizontal lines mark the abundances predicted from equilibrium chemistries (Cherchneff 2006). The dashed line shows the expected post-condensation abundance, $f(\infty)$, (scaled to 3.0×10^{-5} , roughly the expected fractional abundance at $5 r_{\star}$ for low mass-loss rates when $C/O = 1$) from a model including adsorption of SiO onto dust grains (see González Delgado et al. 2003, for details).

between mass-loss rate and expansion velocity of the stellar wind (Fig. 6c). Further, it is not possible to distinguish between the different chemical types when examining how the mass-loss rate correlates with the pulsation period of the star (Fig. 7). The most likely explanation for the observed trends is a mass loss that is driven by the same mechanism(s) in all three chemical types. The only apparent difference is that the carbon star CSEs have higher gas expansion velocities (on average), most likely an effect of a higher acceleration efficiency of the carbon grains.

- The derived dust-to-gas mass-loss-rate ratios for 11 of the sample stars show an agreement with what has previously been found for M-type AGB stars and carbon stars, implying that the dust formation efficiency is similar in all three chemical types.
- The median value of the estimated circumstellar SiO fractional abundances in S-type AGB stars is almost more than an order of magnitude higher than predicted by thermal equilibrium chemistry, suggesting that shock-induced non-equilibrium chemical processes are important in regulating the chemistry in the inner wind.
- The derived circumstellar SiO abundances for the S-type AGB stars range from 4×10^{-7} to 1.4×10^{-4} . For a specific wind density (\dot{M}/v_e) there is a scatter of almost two orders of magnitudes, in accordance with what has previously been found for the other chemical types. In terms of their distribution of SiO circumstellar abundances, it is not possible to

distinguish between the three different chemical types, and we propose that, although there is a large scatter, the circumstellar SiO abundance is independent of the C/O-ratio for a given mass-loss rate and expansion velocity. The formation efficiency of SiO in a shock chemistry will be sensitive to other specific parameters of the star, like pulsational period and shock velocity. We believe that the scatter obtained in the SiO abundance estimates is real and indicative of a shock chemistry in the outer atmosphere.

- Previous analysis of M-type AGB stars (González Delgado et al. 2003) and carbon stars (Schöier et al. 2006b) show a clear trend in that the circumstellar SiO abundance decreases as the density of the stellar wind increases. The trend is indicative of adsorption of SiO onto dust grains. The same trend can be suspected for the sample of S-type AGB stars, however, the number of high-mass-loss-rate S-type AGB stars is low and no firm conclusion can be drawn.

Despite the limitations due to the selection criteria of the samples compared, we believe that our conclusions apply to AGB stars in general.

Acknowledgements. The authors acknowledge support from the Swedish Research Council. This work has benefited from research funding from the European Community's Sixth Framework Programme under RadioNet contract R113CT 2003 5158187 and R113CT 2003 5058187. This article made use of data obtained through the JCMT archive as Guest User at the Canadian Astronomy Data Center, which is operated by the Dominion Astrophysical Observatory for the National Research Council of Canada's Herzberg Institute of Astrophysics.

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Appendix A: New CO spectra**Table A.1.** Observational results of circumstellar CO radio line emission.

Source	Transition	I_{mb} [K km s ⁻¹]	T_{mb} [K]	Telescope or reference
R And	CO(1-0)	5.7	0.44	BL94
	CO(1-0)	34.9	2.4	I
	CO(2-1)	135.5	9.6	I
	CO(2-1)	32.0	2.5	J ^a
	CO(3-2)	43.0	3.3	J ^a
W And	CO(1-0)	1.4	0.12	BL94
	CO(1-0)	3.8	0.4	O
	CO(1-0)	9.5	0.9	I
	CO(2-1)	55.3	4.7	I
	CO(3-2)	7.0	0.6	Y95
Z Ant	CO(2-1)	0.7	0.07	JK98
	CO(3-2)	2.0	0.6	A ^a
VX Aql	CO(1-0)	0.7	0.05	SL95
W Aql	CO(1-0)	28.4	1.3	N92
	CO(2-1)	54.8	2.1	K98
	CO(3-2)	93.2	3.5	K98
	CO(3-2)	136.2	5.0	A ^a
	CO(4-3)	199.5	7.4	J ^a
AA Cam	CO(2-1)	1.8	0.06	SL95
	CO(3-2)	0.8	0.17	J
T Cam	CO(1-0)	2.0	0.3	I
	CO(2-1)	8.1	1.2	I
S Cas	CO(1-0)	13.8	0.4	O ^a
	CO(1-0)	38.2	1.1	I ^a
	CO(2-1)	157.3	4.8	I ^a
	CO(3-2)	31.0	1.1	J ^a
V365 Cas	CO(2-1)	0.7	0.07	SL95
WY Cas	CO(1-0)	3.5	0.12	O ^a
	CO(1-0)	12.8	0.6	I
	CO(2-1)	64.4	2.9	I
AM Cen	CO(1-0)	0.6	0.08	SL95
	CO(3-2)	1.1	0.24	A ^a
TT Cen	CO(1-0)	1.9	0.05	SL95
	CO(3-2)	13.9	0.5	A
UY Cen	CO(2-1)	1.0	0.07	SL95
	CO(3-2)	1.6	0.1	A ^a
V386 Cep	CO(2-1)	8.4	0.3	I
T Cet	CO(2-1)	2.0	0.28	S ^a
	CO(2-1)	3.7	0.4	J ^a
	CO(3-2)	6.1	0.7	A ^a
	CO(3-2)	7.2	0.8	J ^a
	CO(4-3)	9.5	0.97	J ^a
	CO(6-5)	10.0	1.1	J ^a
AA Cyg	CO(1-0)	1.5	0.11	BL94
	CO(1-0)	5.7	0.7	I ^a
	CO(2-1)	17.4	2.3	I ^a
AD Cyg	CO(1-0)	0.9	0.08	I ^a
	CO(2-1)	3.8	0.31	I
R Cyg	CO(1-0)	2.5	0.15	BL94
	CO(1-0)	4.4	0.3	O ^a
	CO(1-0)	16.4	1.0	I ^a
	CO(2-1)	70.2	4.2	I ^a
	CO(3-2)	14.6	2.3	S95
χ Cyg	CO(1-0)	27.2	1.8	O ^a
	CO(1-0)	70.9	6.0	I ^a
	CO(2-1)	60.2	4.2	J ^a
	CO(2-1)	265.8	19.8	I
	CO(3-2)	119.5	8.3	J ^a
	CO(4-3)	134.6	9.6	J ^a
TV Dra	CO(1-0)	0.6	0.02	O ^a
	CO(1-0)	1.5	0.16	I ^a
	CO(2-1)	4.1	0.6	I ^a

Table A.1. continued.

Source	Transition	I_{mb} [K km s ⁻¹]	T_{mb} [K]	Telescope or reference
DY Gem	CO(1-0)	4.4	0.3	I ^a
	CO(2-1)	17.1	1.3	I ^a
	CO(3-2)	2.6	0.35	A ^a
R Gem	CO(1-0)	2.4	0.3	O ^a
	CO(1-0)	9.7	1.3	I ^a
	CO(2-1)	34.1	5.2	I ^a
	CO(3-2)	6.5	0.97	A ^a
ST Her	CO(1-0)	1.5	0.2	O ^a
	CO(1-0)	4.9	0.24	KJ94
	CO(2-1)	17.4	1.05	KJ94
	CO(3-2)	5.1	0.34	K98
RX Lac	CO(1-0)	2.0	0.3	GJ98
GI Lup	CO(3-2)	4.6	0.3	A ^a
R Lyn	CO(1-0)	0.3	0.03	BL94
	CO(1-0)	0.8	0.1	O ^a
	CO(1-0)	2.0	0.18	I ^a
	CO(2-1)	5.8	0.5	I ^a
	CO(2-1)	0.9	0.08	JK98
Y Lyn	CO(1-0)	4.1	0.3	O ^a
	CO(1-0)	14.3	1.1	I ^a
	CO(2-1)	56.4	4.4	I ^a
S Lyr	CO(1-0)	1.9	0.1	O ^a
	CO(3-2)	6.9	0.32	A
FU Mon	CO(1-0)	3.3	0.7	I ^a
	CO(2-1)	7.0	2.0	I ^a
	CO(3-2)	1.3	0.3	A ^a
RZ Peg	CO(2-1)	3.5	0.21	SL95
RT Sco	CO(1-0)	3.8	0.20	SL95
	CO(3-2)	32.6	1.8	A
ST Sco	CO(1-0)	0.6	0.06	BL94
	CO(1-0)	1.4	0.14	SL95
	CO(3-2)	4.5	0.5	A
RZ Sgr	CO(1-0)	6.4	0.38	S
	CO(2-1)	10.7	0.87	S
	CO(3-2)	11.7	1.0	A
ST Sgr	CO(1-0)	0.8	0.66	SL95
	CO(3-2)	4.9	1.0	A
T Sgr	CO(1-0)	1.5	0.17	I
	CO(2-1)	5.2	0.4	I
	CO(3-2)	2.5	0.2	A
EP Vul	CO(1-0)	0.9	0.12	BL94
	CO(1-0)	0.6	0.08	SL95
	CO(3-2)	3.1	0.35	A
DK Vul	CO(1-0)	1.3	0.04	BL94
	CO(1-0)	2.9	0.6	I
	CO(2-1)	9.6	1.7	I
	CO(3-2)	3.6	0.7	A
AFGL 2425	CO(1-0)	3.3	0.2	I
	CO(2-1)	10.5	0.75	I
	CO(3-2)	2.8	0.25	A
CSS2 41	CO(1-0)	2.6:	0.15:	I
	CO(2-1)	4.7:	0.3:	I
	CO(3-2)	2.5:	0.1:	J
IRC-10401	CO(1-0)	2.9	0.12	GJ98
	CO(3-2)	9.5	0.45	A

A; APEX, I; IRAM, J; JCMT, J^a; JCMT archival data, O; OSO; BL94; Bieging & Latter (1994), Y95; Young (1995), JK98; Jorissen & Knapp (1998), SL95; Sahai & Liechti (1995), N92; Nyman et al. (1992), K98; Knapp et al. (1998), S95; Stanek et al. (1995), KJ94; Kahane & Jura (1994), GJ98; Groenewegen & de Jong (1998).

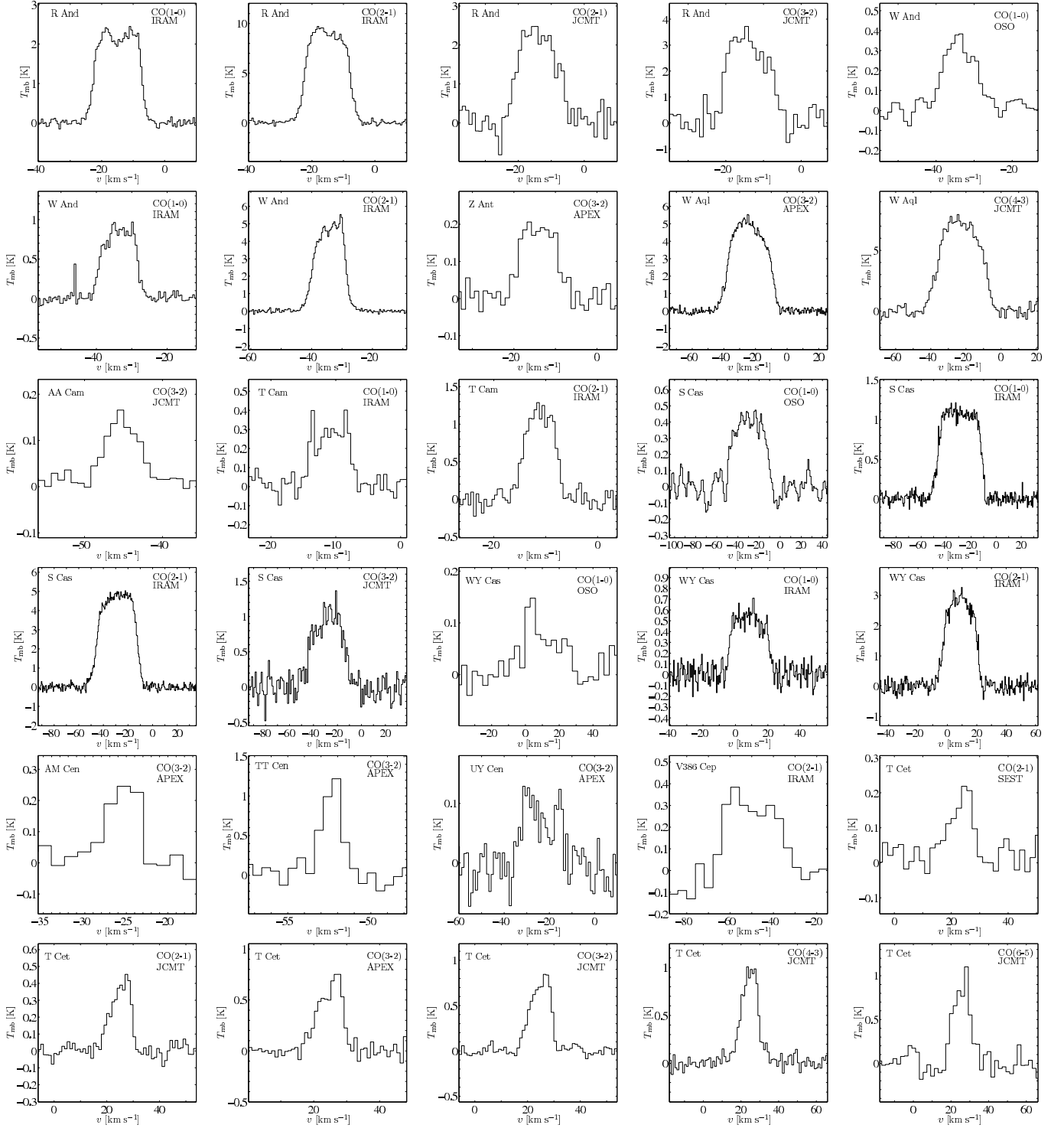


Fig. A.1. New observations of circumstellar CO line emission. The source name is shown to the *upper left*, and the transition observed and the telescope used is shown to the *upper right* of each frame. LSR velocity scales are used.

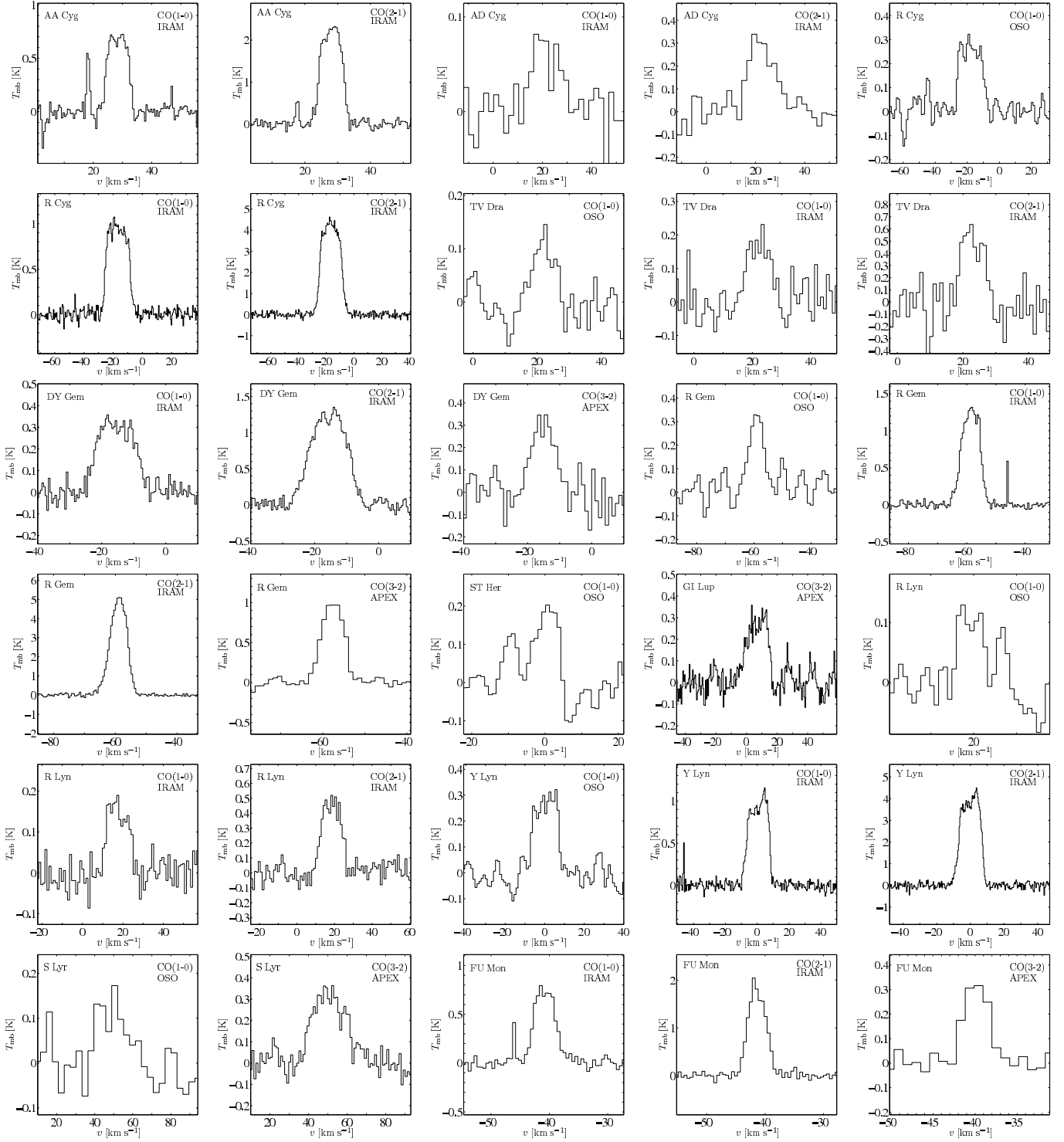


Fig. A.1. continued.

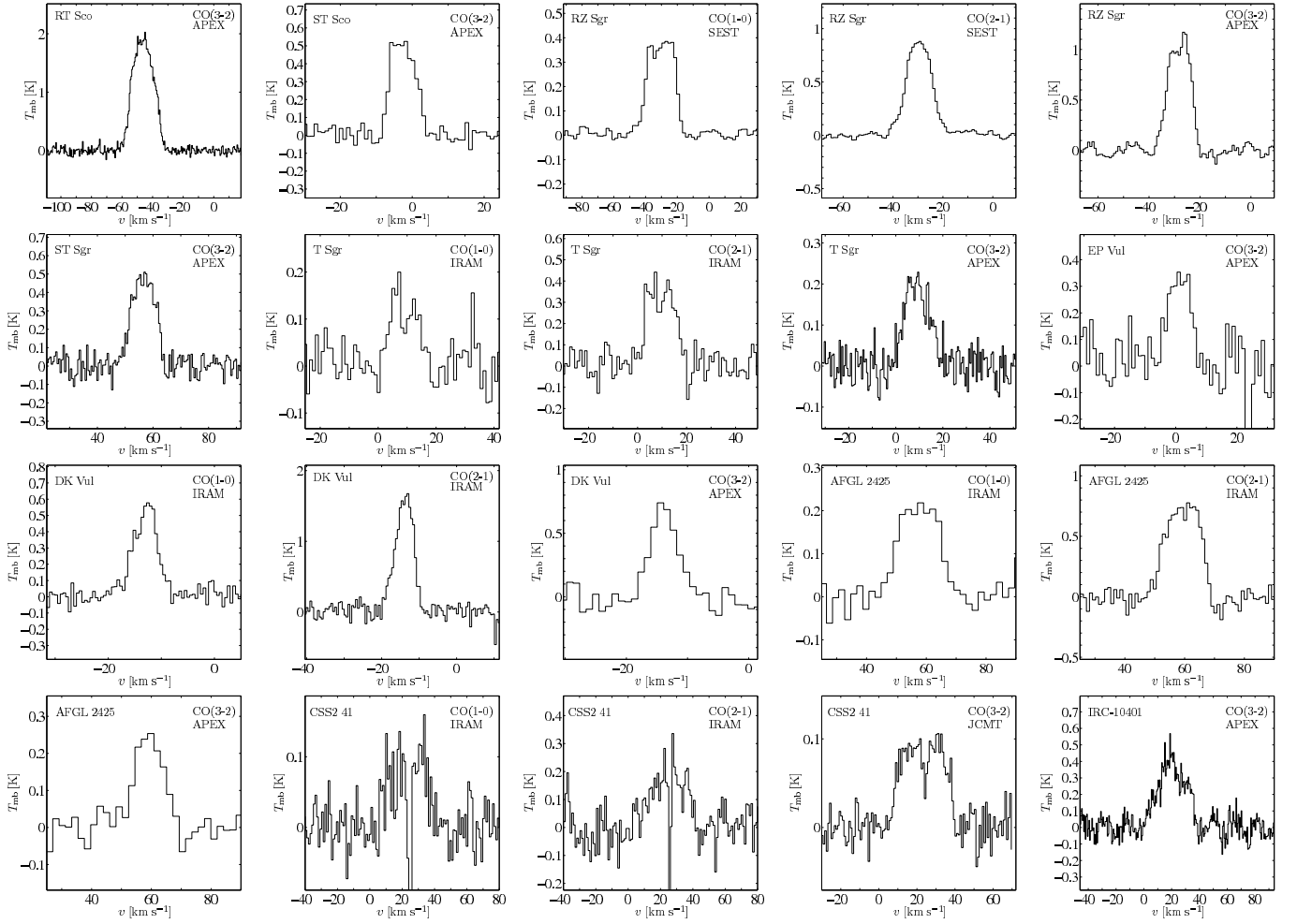


Fig. A.1. continued.

Appendix B: New SiO spectra**Table B.1.** Observational results of circumstellar SiO radio line emission.

Source	Transition	I_{mb} [K km s ⁻¹]	T_{mb} [K]	Telescope or reference
R And	SiO(2-1)	0.9	0.06	O
	SiO(2-1)	2.5	0.22	I
	SiO(5-4)	13.4	1.12	I
	SiO(6-5)	3.2	0.31	J
	SiO(8-7)	3.5	0.39	A
W And	SiO(2-1)	1.7	0.25	I
	SiO(5-4)	6.8	1.1	I
W Aql	SiO(2-1)	2.6	0.08	O
	SiO(3-2)	3.9	0.15	S/B98
	SiO(8-7)	10.1	0.52	A
	SiO(8-7)	16.9	0.84	J
S Cas	SiO(2-1)	1.7	0.06	O
	SiO(2-1)	6.1	0.22	I
	SiO(5-4)	35.8	1.5	I
WY Cas	SiO(2-1)	0.6	0.04	I
	SiO(5-4)	3.3	0.2	I
	SiO(8-7)	0.9	0.11	J
V386 Cep	SiO(2-1)	1.2	0.07	I
	SiO(5-4)	4.3	0.26	I
	SiO(8-7)	2.1	0.13	J
T Cet	SiO(8-7)	0.7	0.03	A
AA Cyg	SiO(2-1)	0.3	0.05	I
	SiO(5-4)	2.0	0.3	I
R Cyg	SiO(2-1)	0.3	0.03	O
	SiO(2-1)	1.3	0.14	I
	SiO(5-4)	6.3	0.65	I
	SiO(8-7)	2.0	0.20	J
χ Cyg	SiO(2-1)	4.5	0.47	O
	SiO(2-1)	23.1	1.94	I
	SiO(5-4)	72.3	6.7	I
	SiO(8-7)	38.1	3.56	J
TV Dra	SiO(2-1)	0.6	0.08	I
	SiO(5-4)	1.3	0.21	I
DY Gem	SiO(5-4)	1.1	0.09	I
R Gem	SiO(2-1)	0.2	0.06	I
	SiO(3-2)	0.1	0.03	S/B98
	SiO(5-4)	1.7	0.30	I
RX Lac	SiO(2-1)	0.3	0.05	I
	SiO(5-4)	1.7	0.30	I
	SiO(8-7)	0.6	0.07	J
Y Lyn	SiO(2-1)	0.4	0.07	I
	SiO(5-4)	2.6	0.33	I
	SiO(8-7)	1.8	0.14	J
S Lyr	SiO(2-1)	0.5	0.04	I
	SiO(5-4)	3.0	0.19	I
RT Sco	SiO(3-2)	0.5	0.04	S/B98
	SiO(8-7)	1.5	0.19	A
ST Sco	SiO(3-2)	0.1	0.02	S/B98
	SiO(8-7)	0.5	0.07	A
RZ Sgr	SiO(3-2)	0.3	0.03	S/B98
	SiO(8-7)	0.5	0.10	A
ST Sgr	SiO(8-7)	0.6	0.08	A
T Sgr	SiO(8-7)	0.5	0.09	A
EP Vul	SiO(2-1)	0.4	0.07	I
	SiO(5-4)	1.8	0.27	I
	SiO(8-7)	0.7	0.12	A
DK Vul	SiO(2-1)	0.2	0.03	I
	SiO(5-4)	1.0	0.14	I
AFGL 2425	SiO(2-1)	0.9	0.07	I
	SiO(5-4)	2.0	0.20	I
	SiO(8-7)	0.5	0.08	A

Table B.1. continued.

Source	Transition	I_{mb} [K km s ⁻¹]	T_{mb} [K]	Telescope or reference
CSS2 41	SiO(2-1)	1.0	0.05	I
	SiO(5-4)	2.4	0.16	I
IRC-10401	SiO(2-1)	2.9	0.14	I
	SiO(5-4)	2.2	0.20	I
	SiO(8-7)	1.4	0.12	A

A; APEX, I; IRAM, J; JCMT, O; OSO, S; SEST; B98; [Bieging et al. \(1998\)](#)**Table B.2.** Observational results of circumstellar SiO($J = 2-1, v = 1$) emission.

Source	T_{mb} [K]	σ [K]	$T_{\text{mb}} \times D^2$ [K pc ²] ^a	prev. det. ^b
R And	0.52	0.016	4.7×10^4	Y
W And	0.72	0.027	5.7×10^4	Y
VX Aql	...	0.047	8.8×10^4	...
W Aql	0.17	0.022	9.0×10^3	Y
AA Cam	...	0.022	4.2×10^4	...
S Cas	1.9	0.025	3.7×10^5	Y
V365 Cas	...	0.026	3.0×10^4	...
WY Cas	0.15	0.014	5.4×10^4	...
V386 Cep	0.70	0.019	1.5×10^5	...
AA Cyg	...	0.023	1.6×10^4	N
AD Cyg	...	0.053	1.5×10^5	...
R Cyg	...	0.008	4.5×10^3	Y
χ Cyg	8.1	0.082	9.8×10^4	Y
TV Dra	0.08	0.012	1.2×10^4	N
DY Gem	...	0.030	4.2×10^4	...
R Gem	0.19	0.015	9.3×10^4	N
ST Her	...	0.022	6.0×10^3	...
RX Lac	...	0.032	9.3×10^3	...
R Lyn	...	0.027	6.0×10^4	Y
Y Lyn	...	0.012	2.4×10^3	Y
S Lyr	...	0.037	1.6×10^5	...
FU Mon	...	0.038	6.9×10^4	N
EP Vul	...	0.050	3.9×10^4	Y
DK Vul	...	0.043	7.2×10^4	...

^a For the non-detections we use $3\sigma \times D^2$; ^b from [Jorissen & Knapp \(1998\)](#) and references therein.

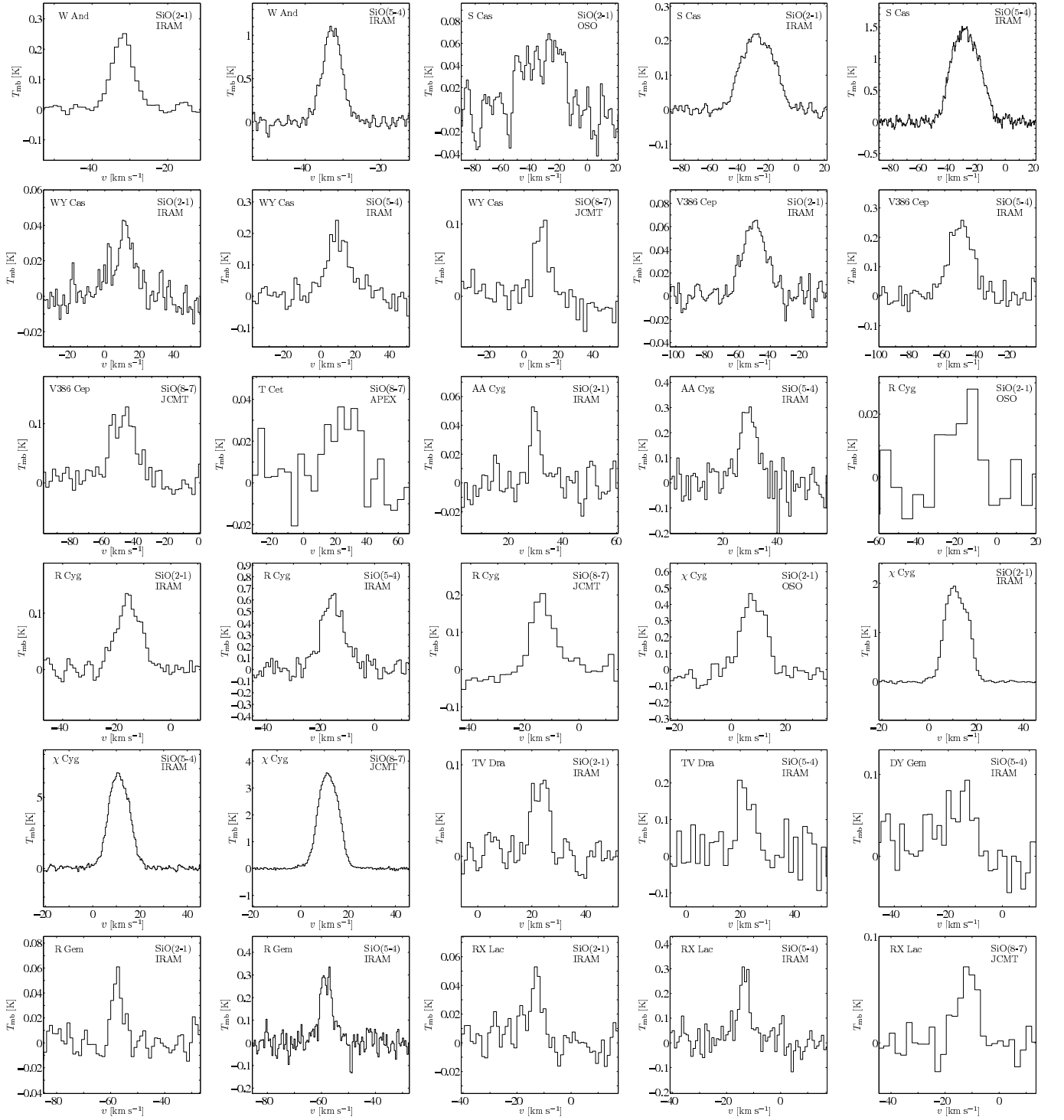


Fig. B.1. New observations of circumstellar SiO line emission ($v = 0$). The source name is shown to the *upper left*, and the transition observed and the telescope used is shown to the *upper right* of each frame. LSR velocity scales are used.

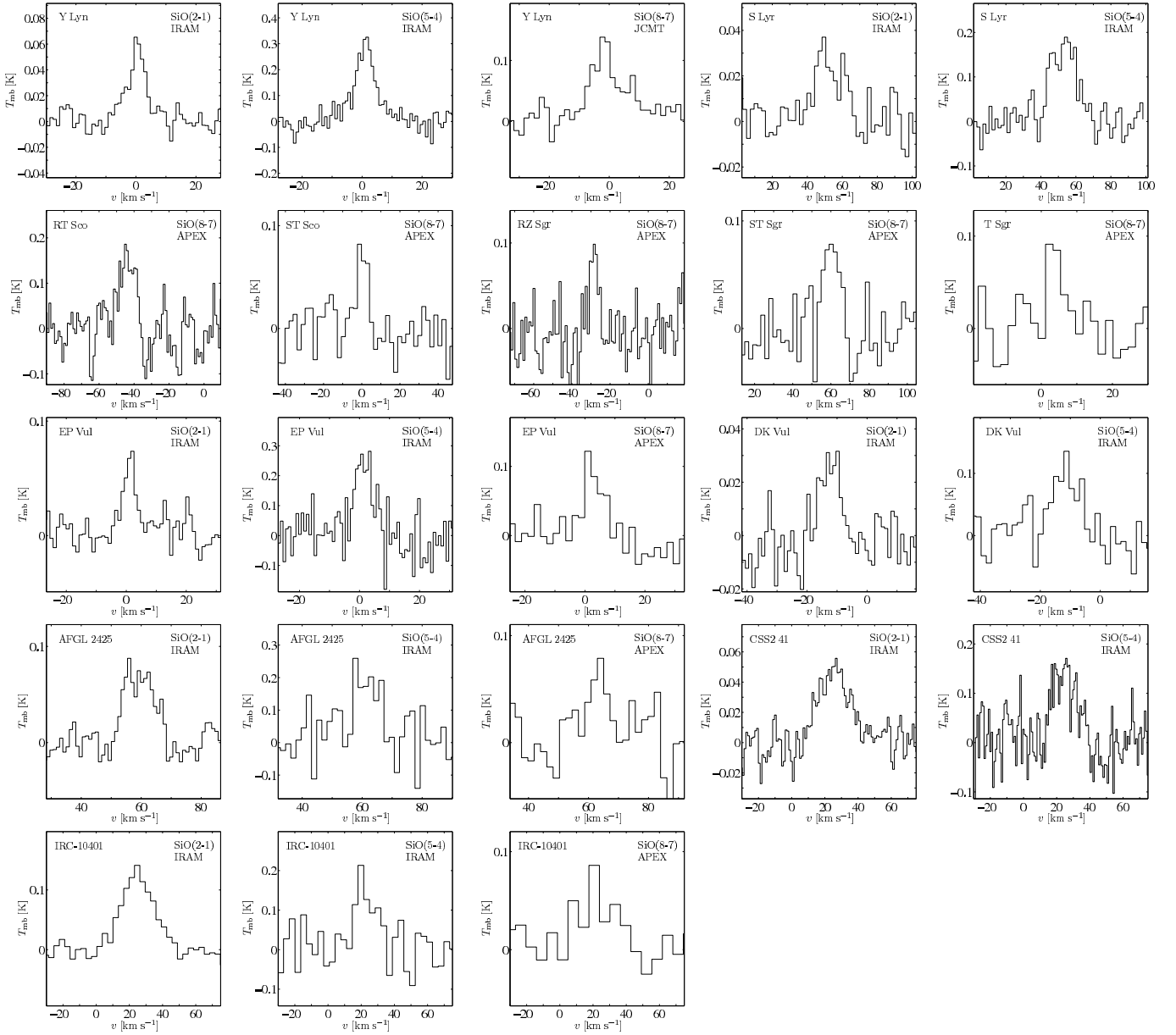


Fig. B.2. continued.

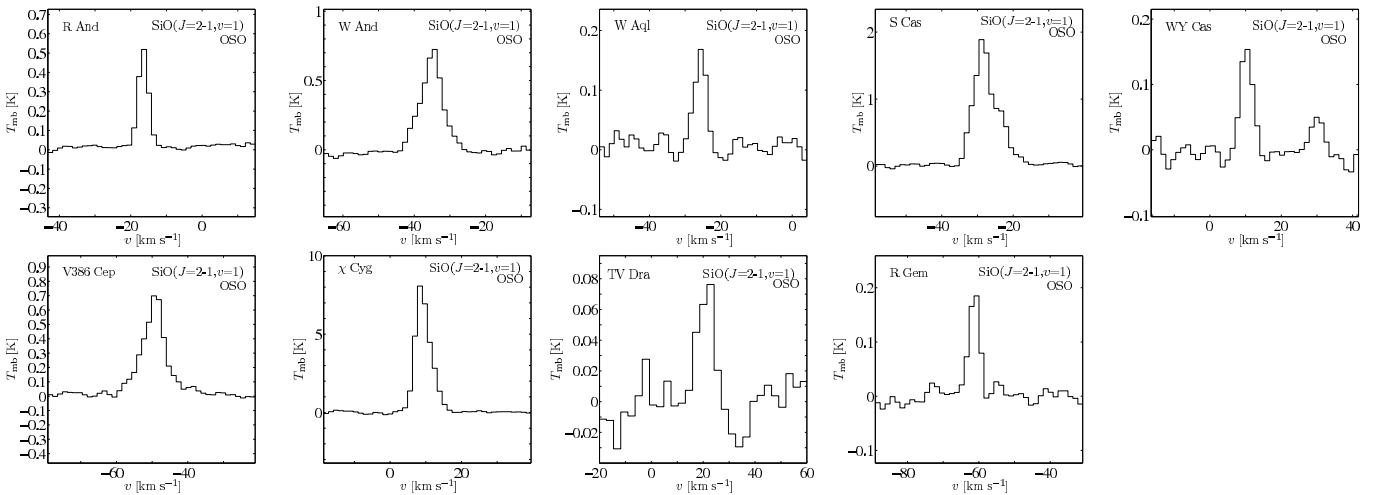


Fig. B.3. New observations of circumstellar SiO line emission ($v = 1$). The source name is shown to the *upper left*, and the transition observed and the telescope used is shown to the *upper right* of each frame. LSR velocity scales are used.