Part IIa. SiO MASERs

https://doi.org/10.1017/S0074180900222511 Published online by Cambridge University Press

Cosmic MASERs: From Protostars to Blackholes
IAU Symposium, Vol. 206, 2002
V. Migenes and M. J. Reid, eds

SiO masers in red giants

E.M.L. Humphreys

Onsala Space Observatory, S-439 92 Onsala, Sweden

Abstract. In recent years, it has become possible to trace rapid structural changes occurring in the extended atmospheres of red giant stars through VLBI monitoring of SiO masers. The observations reveal a complex picture. Firstly, material is predominantly outflowing, but also infalls towards the star, in a pulsating inner envelope periodically disrupted by shocks. Secondly, circular polarization measurements may indicate that the inner circumstellar envelope is permeated by a magnetic field strong enough to be of dynamical importance. Finally, towards a few stars, observations also show evidence for rotation of the SiO maser region. Current SiO maser models can reproduce many of the key features of circumstellar SiO maser emission, and have successfully predicted e.g. the infall of SiO masing gas and the observed spatial separation of $v = 1$ and $v = 2$ 43 GHz masers. However, both stellar hydrodynamical and maser codes need to increase in complexity in order to model fully these regions. In this review I will discuss the current developments in circumstellar SiO maser observations and models.

1. Introduction

SiO masers are a feature of oxygen-rich, evolved stars. Some red supergiants and perhaps all large-amplitude red giant pulsators on the thermally-pulsing AGB - i.e. Miras, OH/IR stars and some Semi-Regular variables - are SiO emitters (Habing 1996). As markers of stellar radial velocity, SiO maser sources have been extensively surveyed for tracing galactic structure. At the last count, these surveys have revealed ~1200 stellar SiO sources (Deguchi et al. 2001).

SiO masers are intimately connected to stellar pulsation. Large-amplitude stellar pulsation in AGB stars (which shows up e.g. in the visual lightcurve as amplitudes of $\geq$ 2.5 mag) was linked to detectable SiO maser emission by Alcolea et al. (1990) and Hall et al. (1990). Further evidence associating SiO masers with stellar pulsational properties was provided by Heske (1989), who showed that SiO maser emission occurs simultaneously with time-dependent Hα emission, an indicator of the presence of strong shock waves. Finally, when the stellar pulsations cease, so do SiO masers (Nyman et al. 1998).

Peak SiO maser flux clearly correlates with the stellar IR continuum flux at 4 μm and 8 μm, corresponding to the SiO Δv=2 and 1 vibrational transitions respectively (Cho et al. 1996a; Bujarrabal 1987).

https://doi.org/10.1017/S0074180900222511 Published online by Cambridge University Press

2. Transitions & Isotopes

To date, ^{28}SiO maser emission has been detected in a range of rotational transitions, from $J = 1 - 0$ (43 GHz) up to $J = 10 - 9$ (430 GHz), within $v = 0$ to $v = 4$ (Pardo et al. 1998; Bieging et al. 2000). However, maser emission in the ground vibrational state is anomalously weak and these lines often appear to be thermally excited. The most highly excited maser is the $v = 4$ $J = 5 - 4$ detection in the supergiant VYCMa, which implies a significant SiO population in levels ~7000 K above ground state (Cernicharo et al. 1993), but this maser has not been detected towards giant stars. For surveys of low-frequency masers ($\leq J = 4 - 3$ at 172 GHz) in different vibrational states see Cho et al. (1996a,b;1998), for the high-frequency masers ($\geq J = 5 - 4$ at 215 GHz) see Humphreys et al. (1997) and Gray et al. (1999).

Maser emission has also been detected from the rare ^{29}SiO and ^{30}SiO isotopes, studied by Alcolea & Bujarrabal (1992). In this case maser emission is weaker, and also occurs from $v = 0$. Detections have been made for a range of rotational transitions in several v-states, see Cernicharo & Bujarrabal (1992) and González-Alfonso & Cernicharo (1997), including the ^{29}SiO $v = 3$ $J = 8 - 7$ transition (González-Alfonso et al. 1996). The remainder of this paper discusses emission from the main ^{28}SiO isotope.

3. Line Profiles

Many maser transitions are simultaneously observable towards a single object, see Pardo et al. (1998). The line profiles tend to be composed of several narrow features spread over <10 kms^{-1}, up to several tens of kms^{-1} in the case of supergiant stars. They are usually centered near the stellar radial velocity to a few kms^{-1} accuracy. For a given source, the intensity ratio of the lineshapes varies during the stellar cycle, and 'typical' values also vary between source type (Nyman et al. 1993). See the AGB circumstellar envelope review by Habing (1996) for more details.

For some stars, unusally broad emission wings are also observed, which sometimes exceed the terminal velocity of the expanding circumstellar envelope as traced by thermal CO emission (Herpin et al. 1998 and references therein). There is a clear dependence of this wing emission, and of other lineshape properties discussed in Section 3.2, on stellar phase.

3.1. Polarization

SiO masers are generally linearly polarized, up to several tens of percent. As the degree of polarization varies for features peaking at different radial velocities in the lineshape, with polarization position angle almost constant across individual features, it was inferred before high resolution VLBI that emission originates from physically unrelated masing cells (e.g. Clark et al. 1985, see Section 4.3 for supporting VLBI data). Multi-frequency data suggest that $v = 1$ $J = 1 - 0$, $J = 2 - 1$ and $J = 3 - 2$ masers occur from the same masing clouds, and show that polarization increases with J value (McIntosh & Predmore 1991,1993). Polarimetry provides a method for measuring the lifetime and velocity dispersion of individual masing cells from single-dish monitoring. Using this technique, Fourre et al. (2000) find lifetimes of masing cells in the wide range 30 – 430 days, with average velocity dispersions of 0.33 – 0.67 kms^{-1}. Weaker circular polarization is also detected, not exceeding the several percent level.

3.2. Time Variations

Long-term monitoring observations show that SiO maser emission varies with the same period as the central star. The maximum of the SiO lightcurve usually lags that of the optical maximum, by a phase lag of ~ 0.2 on average (Alcolea et al. 1999), but varies in phase with near and mid-IR lightcurves. However the amplitude of the maser lightcurve does not appear to correlate with that in the IR (Nyman & Olofsson 1986). SiO line profiles do not reproduce between cycles.

More rapid variability was investigated by Pijpers et al. (1994), who observed the $v = 1$ $J = 1 - 0$ masers in R Cas and R Leo daily over 40 days. Variations in lineshape intensity were 20% in 10 – 20 days, accompanied by a displacement of 1 kms^{-1} in the velocity of the dominant maser peaks.

With respect to phase-dependent velocity effects, Cho et al. (1996a) find that the mean velocity of $v = 1$ & 2 $J = 1 - 0$ emission is red-shifted relative to the stellar velocity from ϕ 0.3 – 0.8; blue-shifted emission features appear from ϕ 0.85 and dominate from ϕ 0.0 – 0.2. This behaviour is similar to 1.6 μm CO velocity curves, which arise from a layer very close to the stellar photosphere (Hinkle, Lebzelter & Scharlach 1997 and references therein).

Whereas low frequency maser emission usually persists throughout the stellar cycle, Gray et al. (1998,1999) find that the variability of high-frequency SiO masers ($J = 7 - 6$ $v = 1$ & 2) is more dramatic. Emission appears to be exceptionally weak or absent in Mira variables over an optical phase range of approximately ϕ 0.4 – 0.7. Outside of this phase range, bright high frequency masers appear to be reasonably common. The velocity of high frequency emission is also a function of stellar phase.

4. VLBI Studies

VLBI data show that SiO masers are distributed in a ring-like structure of emitting spots surrounding the star, within a few stellar radii. In one of the the most significant, recent discoveries for SiO masers, Diamond et al. (1994) were the first to resolve such emission structure for the $v = 1$ $J = 1 - 0$ masers towards TX Cam and U Her using the VLBA, and show that *stellar SiO masers amplify tangentially*. Earlier European VLBI observations had already placed limits on the size of maser emission spots at $\sim 10^{12}$cm (Colomer et al. 1992). Some tens of percent of the single-dish maser flux are missing in these high resolution (<1 mas) observations. This suggests that more extended emission structure, resolved out on VLBA baselines, is also present.

Since then, maser rings have been imaged at 43 and 86 GHz towards several stars (for example: Greenhill et al. 1995 for $v = 1$ $J = 1 - 0$ masers in VX Sgr; Boboltz et al. 1997 for $v = 1$ $J = 1 - 0$ masers in R Aqr; Doeleman et al. 1998 for $v = 1$ $J = 2 - 1$ masers in VX Sgr; Desmurs et al. 2000 for $v = 1$ & 2 $J = 1 - 0$ masers in TX Cam & IRC+10011; Yi et al. th. pr. for $v = 1$ & 2 $J = 1 - 0$ masers in TX Cam & R Cas), firmly placing SiO masers in the extended atmosphere

https://doi.org/10.1017/S0074180900222511 Published online by Cambridge University Press

between the stellar photosphere and the inner radius of the circumstellar dust shell (Greenhill et al. 1995). Thus energy and chemical requirements for SiO masers are fulfilled: close to the star in warm, dense regions for populating energy levels >1800 K above ground state, and placing them in regions of high gas phase SiO abundance, within the radius at which dust condensation takes place. SiO masers are believed to lie just beyond the stellar "radio photosphere", at around $2R_*$ (Reid & Menten 1997).

These data point to the inhomogeneity of the extended atmosphere, the cause of which is unknown. A proposed mechanism for the formation of maser clumps is through thermal instabilities resulting from infrared band cooling by SiO and CO (Cuntz & Muchmore 1994). Runaway cooling of this type results in a bifurcated envelope structure with two phases which differ in kinetic temperature and in molecular abundance. One phase would form the maser clumps, and the other a hotter, less dense background medium. Gray et al. (1998) find that this mechanism is consistent with SiO maser observations. Another route to clump formation is the magnetohydrodynamical Parker instability (Hartquist & Dyson 1997), if the magnetic field is sufficiently strong.

4.1. Time Variations

The maser ring is not static, its diameter changes with stellar phase. The first proper motion measurements showed the maser ring in the symbiotic Mira R Aqr in *contraction* as its intensity faded, with an average velocity of $\sim$ 4 kms^{-1}. These observations covered around a quarter of the stellar cycle ($\cong$ 100 days) and were consistent with infall under gravity (Boboltz et al. 1997).

The most complete multi-epoch data is the monitoring of the $v = 1$ $J = 1-0$ masers in TX Cam over >1.5 cycles by Diamond & Kemball, see Diamond (these proceedings; hereafter th. pr.). Both infalling and outflowing gas is observed, but *expansion dominates the dynamics.* Over a nine month period in 1998, the ring had expanded by >10% in some directions (Diamond & Kemball 1999). Some of the maser components move outwards with a constant velocity of $\sim$ 10 kms^{-1}.

Disruption to the maser ring appears to occur at minimum maser light (Yi et al. th. pr.). Around this time, a new maser ring is observed to form within the inner radius of the previous ring.

4.2. Multi-Transition Observations

Miyoshi et al. (1994) made the first simultaneous observations of $v = 1$ & 2 $J = 1 - 0$ masers towards the supergiant μ Cep using KNIFE, and concluded that they were spatially coincident. This may still hold for supergiant stars. However, towards several red giants, there is a clear average spatial separation between the $v = 1$ $J = 1 - 0$ and the $v = 2$ $J = 1 - 0$ maser rings, when observed at resolutions which are higher by an order of magnitude ($\sim$0.5 mas). The separation is $\leq$0.6 AU, the $v = 2$ masers lying inside the corresponding $v = 1$ features (Desmurs et al. 2000; Yi et al. th. pr.). The significance for SiO maser pump schemes is discussed in Section 5.1. Also important for constraining models is the phase-dependent separation of the rings. Studies underway include Gardner et al. (2000) for *o* Cet and Yi et al. (th. pr.) for TX Cam and R Cas.

4.3. Polarization Structure

In the VLBA data there is a highly ordered polarization pattern. Most SiO maser spots are linearly polarized in a direction which is tangential to the maser ring (Kemball & Diamond 1997; Desmurs et al. 2000), see Kemball (th. pr.). The degree of linear and circular polarization varies substantially between components. When averaged over the shell, linear polarization is at around the 30 % level and circular polarization is $\sim 3\%$.

Ambiguity in the interpretation of SiO maser polarization arises as SiO is non-paramagnetic. Zeeman splitting is smaller than the SiO linewidth (say 0.6 kms^{-1}) unless the magnetic field is of the order $\sim 10^3$ G. Taking a Zeeman interpretation, the linear polarization pattern provides an indication of the magnetic field structure and the observed circular polarization implies a magnetic field strength of 5 – 10 G (Kemball & Diamond 1997; Elitzur 1996). For a field of this strength, the magnetic pressure will greatly exceed the gas thermal pressure for the conditions expected in the SiO maser zone (see Barvainis, McIntosh & Predmore 1987). In this case the magnetic field would be the governing force in determining the kinematics of maser cells.

Under the non-Zeeman interpretation, the observed linear polarization is due to anisotropy in the radiative pumping of SiO masers by stellar photons (Western & Watson 1983). Here the quantization axis is provided by the pumping process itself, the radial direction of the stellar IR pump photons, rather than by a magnetic field. Tangential polarization then arises as molecules rotating in the tangential plane preferentially absorb the stellar photons. This is clearly described by Desmurs et al. (2000). Given the observed linear polarization, Wiebe & Watson (1998) show that the circular polarization can be produced if the direction of a magnetic field, of only 30 mG, changes in orientation along the line of sight.

4.4. Rotation in the SiO Maser Zone

Evidence for rotation in the SiO maser zone has been observed for several stars - NML Cyg (Boboltz & Marvel 2000); IK Tau (Boboltz & Diamond 2000); R Aqr (Hollis et al. 2000) and VX Sgr (Doeleman et al. 1998), see Diamond (th. pr.).

5. SiO Maser Models

Kwan & Scoville (1974) showed how SiO maser inversions can result when vibrational transitions become optically thick. Vibrational de-excitation rates are then modified such that they decrease for increasing J. This mechanism yields the systematic overpopulation of higher J, and so can lead to masers, as long as the population transfer to higher vibrational levels (the maser pump) is via collisions or an indirect radiative route.

Whether the maser pump acting in red giant stars is primarily radiative (e.g. Bujarrabal 1994,a,b) or collisional (e.g. Lockett & Elitzur 1992; Doel et al. 1995) remains a matter of debate. This is complicated for the SiO maser in a region where both radiation and collisions are important in transferring molecules into higher vibrational levels. Given that collisional and radiative pump rates are a function of distance from the star, temperature and density, masing cells at different radii from the star may be pumped differently, and observed features could arise from a combination of schemes. The major requirement for SiO maser models is that they include an accurate description of both the radiative and collisional processes in the maser zone.

Observationally the pump mechanism has proved hard to constrain, with the correlation between SiO maser intensity and the IR continuum naturally explained by radiative pumping, and the dependence on stellar pulsation explained by collisional pumping. Earlier observations suggesting the spatial coincidence of $v = 1$ & 2 $J = 1 - 0$ masers (Miyoshi et al. 1994) were used as evidence of a collisional pump mechanism. However, recent high resolution observations show that components in the $v = 1$ & 2 $J = 1 - 0$ are spatially separated on average. These observations indicate that radiative pump mechanisms should not be be discounted, but are not evidence in favour of radiative pumping *per se*. Both Gray & Humphreys (2000) and Bujarrabal (1994a,b) predict this separation, in addition to tangentially-amplifying emission rings which form close to the star.

In order to investigate the effect of stellar pulsation on SiO masers, Humphreys et al. (1996) and Gray & Humphreys (2000) couple a SiO maser model to a M-Mira hydrodynamic pulsation model. In calculations performed around every two weeks during the cycle of the model star, VLBI and single-dish data can be well-reproduced qualitatively. Masers form in a tangentially amplifying ring within a few stellar radii. Lineshapes, of extent around 10 km^{-1}, form a single dominant peak near the stellar velocity and maser emission from the range $v = 1 - v = 3$ up to $J = 10 - 9$ is found. Masing material is infalling for around a third of the stellar cycle, but a shock-driven expansion of the maser ring occurs during the remainder of the cycle. Bright maser emission originates from the post-shock gas. Gray & Humphreys (2000) predict that the spatial separation between the $v = 1$ & 2 $J = 1 - 0$ maser rings is a stellar phase-dependent quantity, varying between 0.1 – 0.3 AU during the stellar cycle for an o-Cet type star.

These simulations have some quantitative drawbacks e.g. the contrast between minimum and maximum maser intensity during the stellar cycle is over-predicted by these simulations. However, these problems can largely be attributed to the use of a spherically symmetric model which does not include time-dependent chemistry or rapid radiative cooling by molecular components, such as CO and SiO. The lack of magnetic field (and rotation) in the model star is a likely contributing factor to why the complexity of maser kinematics observed in TX Cam is not fully reproduced in the simulations. Indeed, observational data (e.g. Reid & Menten 1997) indicate that the nature of the extended atmosphere can differ markedly from this model.

Finally, overlaps of infrared pumping lines between the SiO isotopes (^{28}SiO, ^{29}SiO and ^{30}SiO) are likely to be responsible for several masers in the higher SiO vibrational states ($>v = 3$) (Herpin & Baudry 2000).

6. Conclusions & Prospects

Significant progress has been made with respect to the observation, and to the modelling, of SiO maser emission over the past decade. With the regular observation of SiO masers on sub-milliarcsecond scales, we have better prospects than ever before for understanding the processes governing the complex extended atmosphere region.

The challenge is to interpret these observations in terms of the temperature, number density, velocity and magnetic field structure of the extended atmosphere. Models have not yet incorporated the effects of stellar magnetic fields and rotation, and SiO maser polarization radiation transport codes need to be produced. However, it is encouraging that several theoretical predictions have been fulfilled (e.g. high frequency maser emission, tangentially-amplifying maser rings), and that models are now able to reproduce many of the observed features of stellar SiO masers.

New generation maser codes, which calculate radiative transfer accurately (e.g. using Accelerated Lambda Iteration) for many level systems, are under development and hydrodynamical models which incorporate time-dependent dust formation and chemistry are being produced for O-rich stars. In addition, the *ab intitio* data for SiO collisions with atomic and molecular hydrogen have recently been calculated (Jimeno et al. 1999). These developments will yield increasingly accurate model predictions for stellar SiO masers.

Acknowledgments. This work has been supported by the Swedish Foundation for International Cooperation in Research and Higher Education (STINT), and by a grant from the IAU Symposium No. 206 Local Organizing Committee. I am grateful to M. Gray for the critical reading of this contribution.

References

Alcolea, J., & Bujarrabal, V. 1992, A&A, 257, 701
Alcolea, J., Bujarrabal, V., & Gomez-Gonzalez, J. 1990, A&A, 231, 431
Alcolea, J., Pardo, J.R., Bujarrabal, V., et al. 1999, A&AS 139, 461
Barvainis, R., McIntosh, G., & Predmore, C. R. 1987, Nature, 329, 613
Bieging, J.H., Shaked, S., & Gensheimer, P. D. 2000, ApJ, 543, 897
Boboltz, D., Diamond, P.J., & Kemball, A.J. 1997, ApJ, 487, L147
Boboltz, D.A., & Diamond P.J. 2000, AAS, 197, 4507
Boboltz, D.A., & Marvel, K.B. 2000, ApJ, 545, L149
Bowen, G. 1988, ApJ, 329, 299
Bujarrabal, V. 1994a, A&A, 285, 953
Bujarrabal, V. 1994b, A&A, 285, 971
Bujarrabal, V., Planesas, P., & del Romero, A. 1987, A&A, 175, 164
Cernicharo, J., & Bujarrabal, V. 1992, ApJ, 401, L109
Cernicharo, J., Bujarrabal, V., & Santaren, J. L. 1993, ApJ, 407, L33
Cho, S.-H., Chung, H.-S., Kim, H.-R., et al. 1998, ApJS, 115, 277
Cho, S.-H., Kaifu, N., & Ukita, N. 1996a, AJ, 111, 1987
Cho, S.-H., Kaifu, N., & Ukita, N. 1996b, A&AS, 115, 117
Clark, F. O., Troland, T. H., & Miller, J. S. 1985, ApJ, 289, 756
Colomer, F., Graham, D. A., Krichbaum, T. P., et al. 1992, A&A, 254, L17

Cuntz, M., & Muchmore, D.O. 1994, ApJ, 433, 303
Deguchi, S. Nakashima, J.I., & Balasubramanyam, R., 2001, PASJ, 53, 305
Desmurs, J.F., Bujarrabal, V., Colomer, F., & Alcolea, J. 2000, A&A, 360, 189
Diamond, P. J., & Kemball, A. J. 1999, in IAU 191, 195
Diamond, P.J., Kemball, A.J, Junor, W., et al. 1994, ApJ, 430, L61
Doel, R.C., Gray, M.D., Humphreys, E.M.L., et al. 1995, A&A 302, 797
Doeleman, S.S., Lonsdale, C.J., & Greenhill, L.J. 1998, ApJ, 494, 400
Elitzur, M. 1996, ApJ, 457, 415
Fourre, R., Jewell, P. R., & Glenn, J. 2000, AAS, 197, 4404
Gardner, J.M., Phillips, R.B., & Boboltz, D. A. 2000, AAS, 197, 4506
González-Alfonso, E., Alcolea, J., & Cernicharo, J. 1996, A&A, 313, L13
González-Alfonso, E., & Cernicharo, J. 1997, A&A, 322, 938
Gray, M.D. & Humphreys, E.M.L. 2000, New Ast., 5, 155
Gray, M. D., Humphreys, E. M. L., & Yates, J. A. 1999, MNRAS, 304, 906
Gray, M. D., Ivison, R. J., Humphreys, E. M. L., et al. 1998, MNRAS, 295, 970
Greenhill, L.J., Colomer, F., Moran, J.M., et al. 1995, ApJ, 449, 365
Habing, H. J. 1996, A&AR, 7, 97
Hall, P.J., Allen, D.A., Troup, E.R., et al. 1990, MNRAS, 243, 480
Hartquist, T.W., & Dyson, J.E. 1997, A&A, 319, 589
Herpin, F., & Baudry, A. 2000, A&A, 359, 1117
Herpin, F., Baudry, A., Alcolea, J., Cernicharo, J. 1998, A&A, 334, 1037
Heske, A., 1989, A&A, 208, 77
Hinkle, K.H., Lebzelter, T., & Scharlach, W.W.G., 1997, AJ, 114, 2686
Hollis, J. M., Pedelty, J. A., Forster, J. R., et al. 2000, ApJ, 543, L81
Humphreys, E.M.L., Gray, M.D., Yates, J.A., et al. 1996, MNRAS, 282, 1359
Humphreys, E.M.L., Gray, M.D., Yates, J.A., et al. 1997, MNRAS, 287, 663
Jimeno, P., Gray, M.D., & Balint-Kurti, G.G. 1999, JChemPhys, 111, 4966
Kemball, A.J., & Diamond, P. J. 1997, ApJ, 481, L111
Kwan, J., & Scoville, N. 1974, 1974, ApJ, 194, L97
Lockett, P., & Elitzur M. 1992, ApJ, 399, 704
McIntosh, A. C., & Predmore, C. R. 1991, in ASP Conference Series, 16, 83
McIntosh, A. C., & Predmore, C. R. 1993, ApJ, 404, L71
Miyoshi, M., Matsumoto, K., Kameno, S., et al. 1994, Nature, 371, 395
Nyman, L.-A., Hall, P.J., & Le Bertre, T. 1993, A&A, 280, 551
Nyman, L.-A. Hall, P. J., & Olofsson, H. 1998, A&AS, 127, 185
Nyman, L.-A., & Olofsson, H. 1986, A&A, 158, 67
Pardo, J. R., Cernicharo, J., González-Alfonso, E., et al. 1998, A&A, 329, 219
Pijpers, F.P., Pardo, J.R., & Bujarrabal, V. 1994, A&A, 286, 501
Reid, M.J., & Menten, K.M., 1997, ApJ, 476, 327
Western, L. R., & Watson, W. D. 1983, ApJ, 275, 195
Wiebe, D. S., & Watson, W. D. 1998, ApJ, 503, L71