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Stellar masers, circumstellar envelopes and supernova remnants

Athol J. Kemball
University of Illinois at Urbana-Champaign, USA

Abstract. This paper reviews recent advances in the study or circumstellar masers and masers found toward supernova remnants. The review is organized by science focus area, including the astrophysics of extended stellar atmospheres, stellar mass-loss processes and outflows, late-type evolved stellar evolution, stellar maser excitation and chemistry, and the use of stellar masers as independent distance estimators. Masers toward supernova remnants are covered separately. Recent advances and open future questions in this field are explored.

Keywords. masers, stars:AGB and post-AGB, stars:atmospheres, supergiants, planetary nebulae, supernova remnants

1. Introduction

This review concerns circumstellar masers and the masers associated with supernova remnants. The material covered focuses primarily on results published since the last maser symposium, IAU 206 (Migenes & Reid 2002), but avoids those areas covered separately by other papers in these proceedings.

In considering circumstellar masers, it is appropriate to start by first examining the host stars and the basic properties of the most common masers found in their circumstellar shells. The late-type evolved stars that host circumstellar masers are either red supergiants or large-amplitude long-period variables (LALPV), such as thermally-pulsing asymptotic giant branch (TP-AGB) stars. These stars are astrophysically important for well-known, but still important, reasons (Habing 1996):

(*a*) Through their mass-loss they enrich the chemical and dust composition of the interstellar medium from which new stars form.

(*b*) They are high-luminosity tracers of faint and obscured stellar populations and their main sequence progenitors; intermediate mass stars, for example, achieve their highest brightness at the tip of the AGB.

(*c*) They highlight an important short-lived stage of stellar evolution in the transition from the AGB to planetary nebulae.

The key properties of the most common circumstellar maser transitions are summarized in Table 1. Numerical values in this table are approximate only; representative temperatures and densities are drawn from Reid (2002). In the most basic model of circumstellar masers, the maser species enumerated in Table 1 are assumed concentrically distributed about the central star, at radii broadly correlated with the transition excitation temperature.

Given the late-type evolved stars and the basic properties of circumstellar masers they host, it is appropriate to ask the broader question of what larger astrophysical questions can be explored by stellar maser studies. We can answer this in part by noting first that masers are unique probes of obscured circumstellar astrophysics due to both their high brightness temperature and compact spatial structure. As such, they give us unique insights into the extended stellar atmosphere, the region between the photosphere and

Table 1. Common masers in late-type, evolved stars

	SiO	H_2O	OH
Transition	$v = 0, 1, 2, 3, ..; \triangle J = 1$	$6_{16} - 5_{23}$	$^2\Pi_{3/2}, J = 3/2, \triangle F = \{0, 1\}$
Radius (AU)	$\sim$ 3-6	$\sim$ 100	$\sim$ 1000
n_H (cm^{-3})	5.10^{10}	10^8	10^7
Temperature (K)	1500	750	450
Pumping mechanism	Radiative or collisional	Collisional	Radiative

dust formation point. They also allow the study of the mass-loss process both near the star and in the outflow at larger radii. The masers allow an exploration of circumstellar excitation and pumping conditions as well as circumstellar chemistry. They also allow independent methods of stellar astrometry and distance measurement. We consider each of these scientific areas in more detail below.

In addition to the topics listed here, stellar masers provide insights into stellar magnetic fields, basic maser theory, surveys for galactic population and dynamical studies, and are also used in specialized galactic center dynamics studies. Though each is extremely important, these issues are not included further in this review as they are covered by separate papers in these proceedings. Masers toward supernova remnants are covered in Section 7 below.

2. Extended atmosphere

The near-circumstellar environment is shown schematically in Figure 1, taken from Reid (2002). This region is dominated by mass-loss, shocks from the centrally-pulsating star, and is expected to have a complex kinematic and dynamical structure (Elitzur 1992). High-resolution imaging of this region is essentially only provided by SiO maser observations; a capability unmatched by contemporary telescopes in other wave-bands.

A number of astrophysical sub-themes are of interest and importance in studies of the extended atmosphere. These can be broadly categorized as issues of kinematics, dynamics, and the physical conditions supporting individual maser transitions. In kinematics, there are open questions concerning localized flows, their connection to the central star and convective envelope, the nature and extent of any global asymmetry established at the base of the mass-loss process, and the matching of gas kinematics in this region to pulsation hydrodynamic models. The dynamical issues concern the nature of any shaping forces, and the magnitude and dynamical influence of local or global stellar magnetic fields. Physical conditions cover issues of excitation and chemistry.

Knowledge of the convective stellar envelope is limited primarily to numerical simulation studies (Freytag Steffen & Dorch 2002; Porter, Anderson & Woodward 1997). In the 3-D heat convection study of a red-giant atmosphere by Porter, Anderson & Woodward (1997), in which heat was supplied steadily to the central core to drive the convection, two unexpected behaviors arose, namely pulsation and large-scale convective flows. Complex convective structures and phenomena in the stellar envelope are likely to have a significant impact on the extended atmosphere.

The extended atmosphere can be studied uniquely using VLBI observations of SiO masers, which act as ultra-compact astrophysical probes of this region. Their importance as probes of this inner CSE was realized soon after their first detection in the 1970s but early imaging studies faced difficult technical challenges (Moran *et al.* 1979; Genzel *et al.* 1979), primarily due to the low sensitivity of millimeter-wavelength VLBI arrays. The advent of improved VLBI sensitivity enabled new observations (Colomer *et al.* 1992; Miyoshi *et al.* 1994); in particular, the commissioning of the VLBA†, a little over ten years ago, provided dramatically-improved imaging capabilities compared to the challenges faces by the earliest observations (Diamond *et al.* 1994; Greenhill *et al.* 1995).

A particularly important result in the last several years has been the conduct of simultaneous near-infrared (NIR) interferometry and radio interferometry imaging campaigns of stellar SiO maser sources using the VLBA both in conjunction with the VLTI‡ (Boboltz & Wittkowski 2005; Wittkowski *et al.* 2005) and with IOTA/FLUOR¶ (Cotton *et al.* 2004, 2006). These observations have allowed the unambiguous co-location of photospheric and SiO radii at $\frac{R_{SiO}}{R_*} \sim 1.5-3.0$, without having to rely on model-based photospheric diameter estimates. The monitoring campaign reported by Cotton *et al.* (2004) also hints at a possible relationship between the relative location of the 3.6 μm photosphere and a dependence of the SiO maser radius on the relative 3.6 to 2.2 μm photospheric radii. Those stars in this monitoring sample with higher 3.6 μm opacity in the molecular photosphere also appear to have large dust condensation radii.

At longer IR wavelengths, the ISI|| has recently reported an important direct measurement of radial pulsation in the diameter of Mira at 11 μm, showing a fluctuation in the continuum photosphere of +11% between stellar pulsation phase $\phi = -0.08$ to 0.15 (Weiner, Hale & Townes 2003), in good agreement with theoretical models for Mira-class pulsation.

Pulsation affects the extended atmosphere directly, driving periodic shocks into the near-circumstellar environment (NCSE) (Bertshinger & Chevalier 1985). The shock

† http://www.vlba.nrao.edu
‡ http://www.eso.org/projects/vlti
¶ http://tdc-www.harvard.edu/IOTA
|| http://isi.ssl.berkeley.edu/index.htm

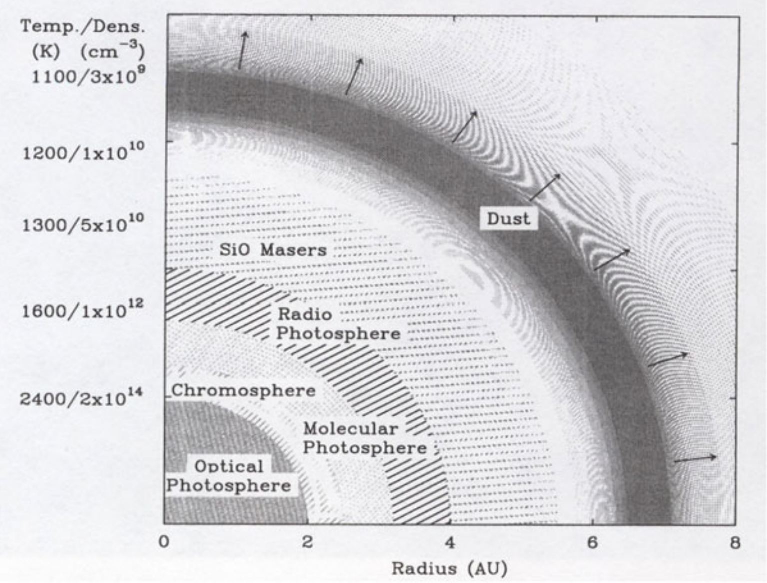

Figure 1. Schematic representation of the circumstellar envelope of a stellar maser from the inner envelope out to the dust formation zone; Figure 3 from Reid (2002)

emerges at pre-maximum, accelerating gas outwards, which subsequently falls back under the influence of gravity (Hinkle, Hall & Ridgway 1982; Hinkle, Lebzelter & Scharlach 1997; Alvarez *et al.* 2000). This produces a double-lined S-shaped velocity profile in photospheric infrared lines such as 1.6 μm CO $\triangle\nu = 3$ absorption (Hinkle, Hall & Ridgway 1982). The shocks levitate material above the the hydrostatic atmosphere and subsequent radiation pressure on dust couples to the gas and carries it further outwards. Shock formation in the NCSE is studied in a number of spherically-symmetric, piston-driven hydrodynamic models of the stellar atmosphere (Bowen 1988; Bessel, Scholz & Wood 1996; Humphreys *et al.* 2002). Shock propagation through the NCSE in these models leads to a saw-tooth velocity profile with radius. The models also accurately predict a net mass-loss of material to the outer circumstellar environment over time and a complex interaction between accelerating and decelerating gas from successive pulsation cycles.

In the time since the last maser conference in 2001, the number of synoptic imaging campaigns of stellar SiO masers has increased significantly and yielded new results. These imaging campaigns are enabled by the technical advances in VLBI imaging at this wavelength, as noted above. Cotton and collaborators are monitoring a small LALPV sample in a snapshot imaging campaign (Cotton *et al.* 2004, 2006). Synoptic imaging of the Mira variable TX Cam has also continued both at short-spacing in pulsation phase (Diamond & Kemball 2003; Gonidakis 2005), and over longer phase increments (Yi *et al.* 2005). Gonidakis (2005) has shown that the median SiO maser component lifetime in TX Cam is approximately 150-200 days, a substantial fraction of the 557 day stellar pulsation period. This permits detailed proper motion studies, as reported by Diamond & Kemball (2003); Gonidakis (2005). A global proper motion analysis shows outer components falling back from earlier pulsation cycles simultaneously with outflow during the current pulsation cycle. This is consistent with the saw-tooth velocity profile discussed above; however, there are significant local departures from a globally ordered flow in the measured proper motions in NSEW quadrants of the projected shell (Diamond & Kemball 2003). The mean velocities are broadly consistent with shock damping in the radio photosphere however, as deduced from upper limits to radio continuum stellar variability by Reid & Menten (1997).

An important astrophysical question in this area is the degree of agreement between measured mean global radial motions and the predictions of pulsation hydrodynamic models of the type discussed above. Recent reported mean global motions are summarized in Table 2 against the pulsation phase interval $\triangle\phi$, and whether the outflow was generally contracting, expanding, or neither. This table show that there are disagreements between individual stars in the same pulsation phase range (e.g. R Aqr, TX Cam, and VX Sgr), where both expansion and contraction are variously reported. However, note that this is comparing a known binary, a Mira variable, and a supergiant. Some authors (Cotton *et al.* 2004, 2006) have also reported no systematic motions with pulsation phase for their sample. However, it is clear that this picture is likely more complex. If we examine TX Cam over multiple pulsation periods we can argue for inter-cycle variability and possible interaction between two competing time-scales, the pulsation period and the free-fall gravitational time-scale, possibly causing a non-strictly repeating pattern of global motions. We also note that there are systematic measurement effects that need to be carefully addressed. The inner shell is not circular and robust estimators are needed to determine the mean inner radius (Diamond & Kemball 2003). For at least one pulsation phase interval of TX Cam, there is clear evidence for ballistic deceleration with physically reasonable parameter values (Diamond & Kemball 2003). It is not true for all pulsation phase cycles however.

Table 2. Measured pulsation kinematics

Reference	Sources	$\triangle\phi$	Projected velocity (kms^{-1})	Outflow or infall
Boboltz *et al.* (1997)	R Aqr	0.78-1.04	-4.2	Contraction
Diamond & Kemball (2003)	TX Cam	0.7-1.5	+7	Expansion
Cotton *et al.* (2004)	See below[1]	Various		No pattern
Yi *et al.* (2005)	TX Cam	0.60-1.05		Slowing expansion
Gonidakis (2005)	TX Cam	1.5-2.7		Both
Cotton *et al.* (2006)	See below[2]	Various		No pattern
Chen *et al.* (2006)	VX Sgr	0.75-0.80	-4	Contraction

1: R And, Mira, U Ori, R Leo, W Hya, S Crb, U Her, R Aqr, R Cas.
2: Mira, U Ori, R Aqr.

The issue of rotation in the extended atmosphere is also important from a kinematic and evolutionary perspective. Two detections of SiO maser shell rotation, including differential rotation, have been reported since the last maser meeting, namely for R Aqr (Hollis *et al.* 2001) and Mira (Cotton *et al.* 2006), both known binaries. This is, however, not common for other sources, as evident in the sector-averaged velocity plots reported by Cotton *et al.* (2006) for their LALPV sample. Substantial rotation is difficult to explain in evolved late-type stars that are not part of multiple star systems.

The expanded range of SiO imaging studies, such as those enumerated in Table 2, continue to reveal clear evidence for spatially-coherent arcs and filaments in the SiO maser region (Kemball & Diamond 1997). These local features have recently been argued by Yi *et al.* (2005) to be from spokes of SiO flows with line-of-sight velocities either slightly red- or blue-shifted with respect to the systemic stellar velocity. This kinematic structure maximizes the line-of-sight velocity coherence. The radial spokes are especially visible in several TX Cam image epochs reported by Yi *et al.* (2005), one of which is reproduced here as Figure 2.

3. Outflows

The water and hydroxyl masers probe intermediate and outer circumstellar radii (Chapman & Cohen 1986; Booth *et al.* 1981). These masers trace the mass-loss process beyond the dust formation point; in this region, the flow is driven by radiation pressure on dust. The astrophysical sub-themes that are relevant to this region of the outflow include the kinematic structure of the mass-loss, including the degree of asymmetry on local and global scales, and the connection of this kinematic pattern to the inner NCSE. For cases where a dominant kinematic pattern is clear, the science issue becomes that of identifying any shaping processes. This is also a particularly important area of the outflow in which to explore the evolutionary onset of more extreme asymmetry related to post-AGB evolution, including stellar jets.

Some of these science questions have been explored in recent MERLIN† observations of stellar water masers; Bains *et al.* (2003) report the first connected-element resolution of individual maser spots, and derive important parameters relating to the water maser region surrounding four LALPV stars: IK Tau, U Ori, RT Vir, and U Her. They report significant departures from spherical symmetry in tori that have an inner radius of 6-16 AU and an outer radius of 24-54 AU. Individual maser components are resolved out at 2-4 AU, and are found to be density-bounded ($\sim 10^{1-2}$ times ambient), with

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† http://www.merlin.ac.uk

a volume filling factor $< 0.5\%$. In related MERLIN observations of the red-supergiant, VX Sgr, Murakawa *et al.* (2003) have performed a proper motion study of the water maser emission toward this source over a five year interval. A bi-conical outflow is used to describe the water maser kinematics. A similar over-density of maser components and a comparable extrapolated cloud size at the stellar surface of $\sim 0.07R_*$ is reported, relative to that given by Bains *et al.* (2003) for the sample of low-mass AGB stars. Both observations confirm an accelerating flow across the water maser region, with a logarithmic velocity gradient of $0.5 \leqslant \epsilon \leqslant 1$.

Concerning the role of water maser studies as a probe of early-onset post-AGB asymmetry, a particularly important result in recent years has been the discovery and exploration of a rare sub-class of AGB stars showing highly-collimated stellar jets (Imai *et al.* 2004; Vlemmings, Diamond & Imai 2006). The dynamical age of the jets is very young ($< 35 - 100$ years) and only a handful of such sources are known, consistent with this dynamical age. This rare class of "water fountain" sources is described in separate review papers in these proceedings by Imai and Vlemmings.

A particularly unusual and rare source studied by Babkovskaia *et al.* (2006); Szczerba *et al.* (2006) presents water masers in a warped disk around a companion to the SiC star V778 Cyg.

OH observations of the supergiant NML Cyg are also reported by Etoka & Diamond (2004). In this source, they present evidence for two shells, an older spherical shell, presumed from an earlier mass-loss phase, and a younger asymmetric flow.

4. Late-type stellar evolution

In this section, we consider the issue of post-AGB evolution, and how stellar masers can inform our understanding of this phase of stellar evolution. Planetary nebulae (PNe) show a rich diversity of point- and axi-symmetric structure (Balick & Frank 2002).

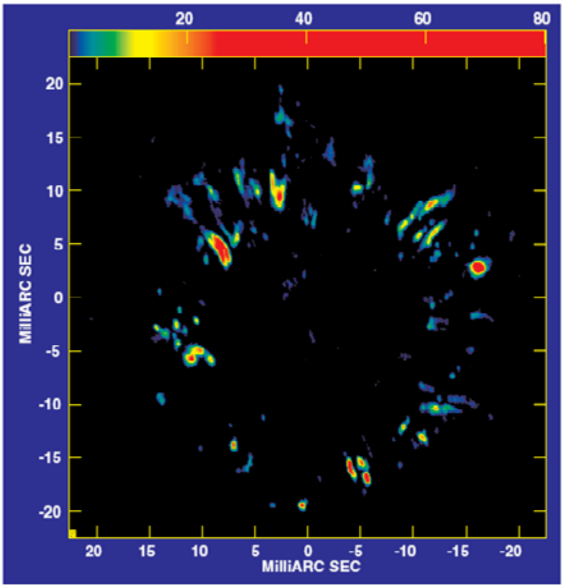

Figure 2. VLBI maps of $v = 1, J = 1-0$ SiO maser emission toward TX Cam, summed over all channels of emission. The bar shows the flux scale in Jy/beam (Figure 3 from Yi *et al.* (2005)).

The immediate post-AGB (PAGB) evolution is heavily shrouded and masers provide a powerful method to study this transition phase, complementary to imaging studies in other wave-bands, such as infrared.

The astrophysical sub-themes that are important in this area concern how to explain the prevalence of point- and axi-symmetry in PNe. Four major shaping mechanisms have been proposed including binarity, equatorial density enhancement, a globally-acting magnetic field and sculpting by highly-collimated stellar jets (Morris, Sahai & Claussen 2003). It is of significant interest to determine when the shaping mechanism is activated on the AGB.

An over-arching issue in this area is also how to identify and select post-AGB objects in samples of OH-IR stars, such as the complete 1612 MHz OH survey conducted by Sevenster *et al.* (1997a,b, 2001). PAGB identification in such surveys is considered by Sevenster (2002) based on clustering in color-color IR plots, using both IRAS and MSX data. Follow-up observations of candidate PAGB stars in the Sevenster survey are presented by Deacon, Chapman & Green (2004); their observations show a significantly higher incidence of asphericity in the candidate PAGB sample and further strengthen the IR color-color selection analysis by Sevenster (2002).

Kinematic models for OH outflow sources are presented by Zijlstra *et al.* (2001) using a two component model, consisting of a shell/torus (20-25 kms^{-1}) and higher-velocity linear outflow (10-80 kms^{-1}).

Masers are particularly rare in young PNe, and only a handful of such sources are known although they are very important. These sources are discussed by Gómez (these proceedings).

5. Excitation and chemistry

The question of maser excitation, pumping, and circumstellar chemistry cuts across both theory and observation. It is needed to understand physical conditions in the masering regions and most importantly to properly interpret observations. In addition, these issues are central to predicting new masering transitions that may be accessible using future telescopes.

Both collisional (Lockett & Elitzur 1991) and radiative (Deguchi & Iguchi 1976) mechanisms have been proposed for SiO maser pumping. There are observational discriminants between the two pumping mechanisms, primarily the relative spatial location of v=1 and v=2 masers, variability studies, and linear polarization morphology. There have been important recent observational results in this area, but conclusions drawn in the literature remain mixed. Based on the location of the v=1 and v=2 J=1-0 masers toward TX Cam, Yi *et al.* (2005) cite evidence for collisional pumping. However, Soria-Ruiz *et al.* (2004) draw the opposite conclusion from v=1 and v=2 J=1-0 imaging of the SiO masers toward IRC+10011 and χ Cyg. In recent variability studies, Pardo *et al.* (2004) reports finding a zero phase lag between IR and SiO flux density over an 11-year short time-spacing monitoring campaign, and McIntosh (2006) finds no time-lag between several vibrationally-excited J=1-0 transitions toward Mira. Both authors argue for radiative SiO pumping as a result. Asensio Ramos, Landi Degl'Innocenti & Trujillo Bueno (2005) consider the effect of anisotropic radiative pumping and the Hanle effect on the linear polarization morphology of SiO stellar masers.

Studies of the relative location of different rotational transitions in the same vibrational state, primarily J=2-1 relative to J=1-0, have shown perplexing results (Soria-Ruiz *et al.* 2004; Phillips *et al.* 2003). In the handful of sources imaged so far, the morphology is significantly different, contrary to basic theoretical expectations. Line overlaps may strongly influence the theoretical predictions about spatial location however, as discussed by Soria-Ruiz *et al.* (2004).

Another important recent result in SiO maser excitation has been the imaging of v=0, J=1-0 SiO maser emission towards a sample of late-type, evolved stars by Boboltz & Claussen (2004). A predominance of weak masers is confirmed and one source was found to have thermal emission. Although their spatial resolution is limited, they propose that v=0 is found at twice the radius of the v=1 emission.

Several new possible masers have been reported toward C-stars since our last meeting, including new HCN lines toward a sample of carbon stars (Bieging 2001), and a possible weak OH maser detection toward IRC+10216 (Ford *et al.* 2003).

Menten *et al.* (2006) also report the possible new detection of maser action in the H_2O $v_2 = 1, 6_{61} - 7_{52}$ line at 294 GHz toward VY CMa. In addition, Thorwirth *et al.* (2003) report weak maser emission in the J=9 l-type HCN transition toward CRL 618.

6. Independent distance estimates

Stellar masers can also be used to provide independent stellar distances. This technique, demonstrated by van Langevelde *et al.* (2000), is based on the assumption that the compact, blue-shifted maser emission is assumed coincident with the central star. The technique was applied to further AGB stars by Vlemmings *et al.* (2003).

OH stellar astrometry is likely limited to distances less than 1 kpc (Vlemmings *et al.* 2003); astrometry using H_2O and SiO masers can reach larger distances. Recently, Kurayama, Sasao & Kobayashi (2005) demonstrated stellar water maser astrometry in observations of UX Cyg. Vlemmings, van Langevelde & Diamond (2003) also showed positional coincidence between the brightest water maser feature toward U Her and the stellar Hipparcos position.

7. 1720 MHz OH masers toward supernova remnants

OH 1720 MHz masers, shock-excited toward supernova remnants (SNR), were first detected by Goss & Robinson (1968). Their phenomenology is now well-known and a sound theoretical basis has been established for their modeling and pumping (Green 2002).

They are an important probe of SNR shock interactions with molecular clouds, and are also found in the galactic center circumnuclear disk. They are considered in more detail in separate invited papers in these proceedings by Brogan, Yusef-Zadeh, and Hewitt.

8. The future

There remain important open astrophysical problems in the area of circumstellar and SNR masers, requiring advances in both observation and theory. An integrated model for the kinematics and dynamics of the mass-loss process from the convective stellar envelope, through the extended atmosphere to the outer circumstellar shell will require further detailed observations, and more complex numerical hydrodynamic models in order to explain the observed local and global asymmetries and to identify the underlying shaping forces. This is particularly important in so far as it concerns stellar magnetic fields of late-type, evolved stars. Recent detections of stellar jets in water maser emission also open new windows on post-AGB evolution. The theory of astrophysical masers continues to remain central to this field, and recent observations have posed new theoretical questions, particularly in the area of SiO excitation, that are vital to proper interpretation of observations. We are also on the cusp of major new observational advances in this field, driven by the commissioning of VERA†, ALMA‡, and the eVLA¶ and look forward to significant future results from these instruments.

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‡ http://www.alma.nrao.edu
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