Circumstellar Masers in the Galactic center

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Abstract Blind and targeted surveys for maser emission (OH, H_2O, and SiO) in the central degree ($\leq$ 150 pc) of the Galactic center will be discussed, with the emphasis on masers in OH/IR stars. Using the masers, some recent clues about the kinematics and evolution of the central part of the Milky Way galaxy will be given. An outlook toward measuring proper motions and individual stellar orbits in the nucleus of the Galaxy with, for example, the new VERA array will be presented.

Keywords: Masers, Galactic center, AGB stars, Circumstellar matter, Astrometry

Introduction

Of the different types of masers found in the Galactic center (GC), here I will try to give a summary of the masers found in the circumstellar environment (CSE) of late-type stars, mostly Asymptotic Giant Branch (AGB) stars of the OH/IR type. I will not further mention maser emission related to massive star formation, nor mention maser emission generated by shocks between molecular clouds.

First, I will shortly recall the results of studies of OH/IR stars in the Galaxy that are relevant to this contribution in Sect. 1. In Sect. 2, a compilation of different surveys for maser emission in the GC is given. Section 3 describes three different samples of OH/IR stars in the GC, of which one population points to a starburst episode of the nucleus of our Galaxy some few Gyr ago. Finally, in Sect. 4, I will look forward to prospects for astrometry with AGB stars in the GC, which makes it possible to obtain e.g. a geometric distance to the GC and reveal the shape of stellar orbits and the central gravitational potential.

1. Circumstellar masers

After the mission of the Infrared Astronomical Satellite (IRAS) in the mid 1980-ies, it became clear that the IRAS color-color diagram was an efficient tool to find circumstellar masers, in particular OH/IR stars (Olnon et al. 1984; van der Veen & Habing 1988). The dust particles in the circumstellar environments (envelopes, and/or shells) obscure the central star, and re-radiate the stellar emission in the infrared (IR). The radiation pressure on the dust, and the collisions with the gas molecules, causes the star to loose it mass and form this expanding circumstellar environment, with expansion velocities ($v_{\rm exp}$) ranging between a few, to about 30 $\rm km\,s^{-1}$, depending on physical properties of the star and its environment (such as the dust-to-gas ratio δ, which I will use as synonym for metallicity). The circumstellar environments of the variable, oxygen-rich stars may provide the physical conditions to form and sustain maser emission from, in particular, SiO, H_2O, and OH molecules.

Most of these circumstellar masers are found in AGB stars, low and intermediate-mass stars with a degenerate C/O core that have evolved away from the main sequence toward the asymptotic giant branch of the color-magnitude or Hertzsprung-Russel diagram. These masers are also found in massive supergiant stars that have non-degenerate cores, but their number density is very small compared to the AGB stars.

By targeting IR sources with IRAS colors characteristic of CSE's, many double peaked 1612 MHz OH masers, the so-called OH/IR stars, have been found over the Galaxy (e.g. te Lintel Hekkert et al. 1991). The OH/IR stars are AGB stars with the highest mass-loss rates, and with denser obscuring shells compared to optically visible Mira-type and Red Giant Branch stars. The 1612 MHz OH maser originates in the outer part of the CSE, typically 1000 AU away from the star, where one observes a blue shifted and a red shifted maser from the expanding shell. The centroid of the blue and red shifted OH maser velocity reveals the line-of-sight velocity of the central star; half the difference defines the shell expansion velocity, $v_{\rm exp}$. As the OH masers are generally strong, OH/IR stars can be found all over the Galaxy and even in the Large Magellanic Cloud (LMC; e.g. Baud et al. 1979; Wood et al. 1992).

In the studies involving physical properties and Galactic distribution it is evident that there is a statistical correlation. Of course there is a blend of different OH/IR stars 'polluting' the samples, so the correlations should be considered in statistical sense and not be applied to individual objects. However, in general the more luminous, more massive, higher mass-loss rate, higher $v_{\rm exp}$, higher metallicity (δ, dust-to-gas ratio), and younger objects with a smaller stellar velocity dispersion are found in the Galactic plane, following Galactic rotation more closely. In short, there is a statistical (anti-)correlation of $v_{\rm exp}$ with age, in the sense that low luminosity, lower mass, low mass-loss rate Mira-type variables correlate with lower $v_{\rm exp}$ sources, and high luminosity, higher mass, high

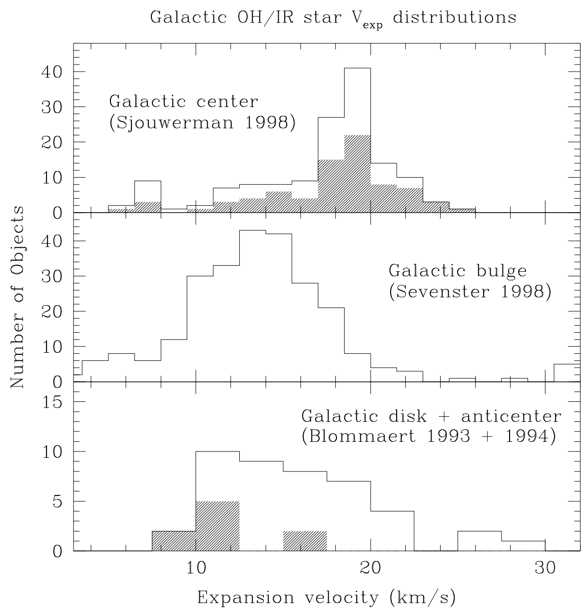

Figure 1 Distribution of v_{exp} for different samples. The bottom panel shows the combined distribution for OH/IR stars in the Galactic disk and anti-center (shaded), the center panel shows the distribution for the Galactic bulge. They are characteristic overall wide distributions due to a mixture of stars with e.g. different luminosities, ages and metallicity (δ). The Galactic center distribution (top) is different in the sense that *next to a wide* distribution, it also shows a *peaked* distribution - see Sect. 3 for an interpretation.

mass-loss rate visibly obscured OH/IR stars correlate with higher v_{exp} objects. However, it is also found that in the Galactic anti-center, and in the LMC, high mass OH/IR stars have low v_{exp}, and low mass Galactic bulge stars have higher mass-loss rates than low mass field stars.

Clearly, not only the bolometric luminosity (L_*), but also the metallicity (δ) of the stellar material influences the individual values of v_{exp}. It can be summarized as (Habing et al. 1994; Elitzur, these proceedings)

$$v_{\mathrm{exp}}^2 \propto \delta \cdot \sqrt{\mathrm{L}_*}$$

This explains why the correlation of v_{exp} with age only holds in statistical sense, as the observed samples generally consist of a mixture of stars with different chemical abundances and different mass and luminosities. A histogram of the distribution of v_{exp} for these samples is usually broadened due to this effect (Fig. 1).

A good review of current knowledge of AGB stars and their circumstellar environment is from Habing (1996). Elsewhere in these proceedings, sub-topics on Galactic distribution issues of AGB stars e.g. the period-luminosity relation (Groenewegen, Whitelock), astrometry (van Langevelde) and stellar kinematics and Galactic dynamics (Feast, Habing, Messineo, Winnberg) can be found.

2. Masing AGB stars in the GC

The onset of AGB studies in the GC started when Baud et al. (1979) and Olnon et al. (1981) surveyed for OH/IR stars toward the GC. However, the largest increase in newly found OH/IR stars came with a survey by Lindqvist et al. (1992b; also Winnberg et al. 1985), who used an interferometer to deal with source confusion as noted by Habing et al. (1983). Since then several other surveys in the 1612 MHz OH line have been performed, with different telescopes, sensitivity limits and sky and velocity coverages (van Langevelde et al. 1992a; Sevenster et al. 1997; Sjouwerman et al. 1998b). Note that all these OH surveys toward the GC were blind; IRAS was confused in the GC and the IRAS color-color diagram could not readily be used to find the OH/IR sources.

Because of this, the IR colors, luminosities and periods for the GC OH/IR stars were determined by classical photometry, which was difficult because of crowding, extinction, and the variable nature of the sources (e.g. Jones et al. 1994; Blommaert et al. 1998). A blind 2.2 μm IR monitoring survey by Glass et al. (2001) for long-period variables, and the color-color diagrams of the ISOGAL and MSX satellites revealed other AGB stars, i.e. evolved stars without OH masers.

As AGB stars are also known to exhibit H_2O and SiO masers, blind and targeted IR (and OH) surveys were initiated. Many H_2O masers were found, but they were not as numerous as the OH masers and fairly often also connected to star forming regions instead of AGB stars (Guesten & Downes 1983; Lindqvist et al. 1990; Taylor et al. 1993; Levine 1995; and also Nakada et al. 1993; Menten et al. 1997; Sjouwerman et al. 2002). The conclusion was that the H_2O masers in AGB stars were too few and also too variable to warrant a detailed study.

Much more successful and, as I'll show later, much more useful were the blind and targeted searches for SiO masers in AGB stars, especially close to Sgr A*, the black hole in the dynamical center of the Galaxy (e.g. Lindqvist et al. 1987, 1991; Izumiura et al. 1998; Nakada et al. 1993; Jiang et al. 1995; Menten et al. 1997; Deguchi et al. 2000, 2002; Miyazaki et al. 2001; Imai et al. 2002; Sjouwerman et al. 2002). Compared to the H_2O masers in AGB stars, the 43 GHz SiO masers are less variable. Also, the SiO masers are located very close to the star, within a few $\mathrm{km\,s^{-1}}$ of the stellar line-of-sight velocity and at this high frequency their image will be less broadened by interstellar scattering than for the low frequency OH masers. This makes the 43 GHz SiO masers ideal dynamical probes for the central part of the Galaxy. Pilot projects to detect 86 GHz with the 15m SEST (Winnberg 1987; Sjouwerman 1998, pers. comm.) were not successful because of sensitivity. Recently however, Messineo et al. (2002) successfully used the 30m IRAM telescope on an IR selected sample to obtain a detection rate in the 86 GHz SiO line of $\sim$60 %. Almost all of the $\sim$40 strongest 86 GHz SiO masers also show 43 GHz SiO masers, and because VLBI at 43 GHz is easier than at

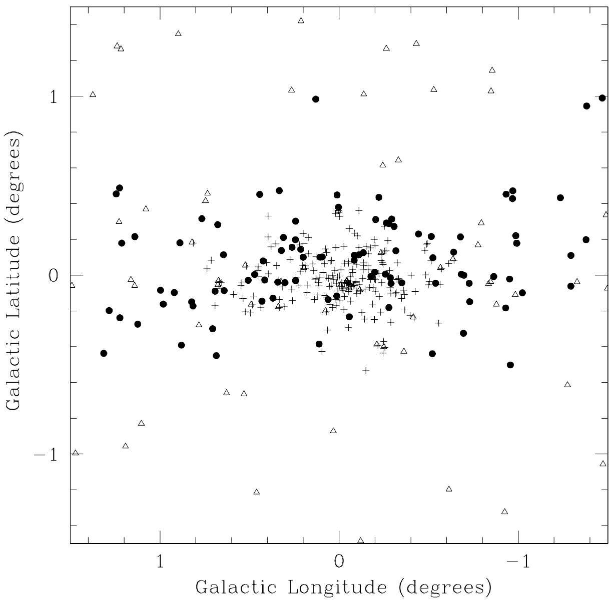

Figure 2 OH (crosses, triangles) and 86 GHz SiO (dots) maser detections in the GC. The 43 GHz SiO maser detections can be found in Sjouwerman et al, these proc. The OH masers were found in deep, blind, and limited sky coverage surveys (crosses: Lindqvist et al. 1992b; Sjouwerman et al. 1998b) - hence partly the concentration to the center (also number density) - and a shallow all-sky survey (triangles: Sevenster et al. 1997). The IR targeted 86 GHz SiO masers (Messineo et al. 2002, also these proc.) fill the area between the two OH surveys.

86 GHz, the 43 GHz SiO masers will be very important for dynamical studies (Sect. 5), e.g. with VERA (Sjouwerman et al., these proc.).

Most of our current knowledge of the AGB stars in the GC (Fig. 2) comes from the earlier OH maser studies in combination with the classical IR photometry and period determinations (also in the OH line; van Langevelde et al. 1993). The H_2O masers are too variable, and not many have been found to allow a detailed study. However, at the moment the 43 (and 86) GHz SiO masers are promising probes to further extend our knowledge about AGB stars in the GC (periods, luminosity, composition, evolution and structure of the GC, etc.).

3. Populations in the GC

Figure 1 displays the $v_{\rm exp}$ distribution for the OH/IR stars in the GC (top panel). Compared to the distribution for the Galactic bulge and Galactic disk plus anticenter, the distribution for the GC is much more peaked. All distributions show a broad histogram that can be explained by a general mixture of stars with different composition and luminosities. In the GC case, not only is the mean $v_{\rm exp}$ high, but in view of the overall distribution there is a clear excess of stars with almost the same $v_{\rm exp}$ (17 $< v_{\rm exp} < 20\ {\rm km\,s^{-1}}$). As the overall luminosities of the GC stars do not differ much from the OH/IR star luminosities in the bulge (van der Veen & Habing 1990; Blommaert et al. 1998; Wood et al. 1998), the relation

$v_{\rm exp}^2 \propto \delta \cdot \sqrt{\rm L_*}$ gives away the overall high mean metallicity in the center of about 1.8 times the mean metallicity in the bulge.

In the GC, there is a clear distinction in mean Galactic rotation between low $v_{\rm exp}$ sources (no net rotation) and the high $v_{\rm exp}$ sources (strong rotation). The distinction appears at $v_{\rm exp} \approx$ 16.5-17 km s^{-1}, at the rise of the peak in the $v_{\rm exp}$ distribution, in contrast to the 18 km s^{-1} used on statistical grounds by Lindqvist et al. (1992a). The sources that make up the excess in the $v_{\rm exp}$ distribution, are strong Galactic rotators, as the high $v_{\rm exp}$ sources beyond the fall in the peak in the distribution (at 20 km s^{-1}). To investigate the statistical difference between the low and high $v_{\rm exp}$ groups, this means that *in addition*, one has to investigate the $17 < v_{\rm exp} < 20$ km s^{-1} sources separately (and not divide them up almost equally in the two earlier groups of $v_{\rm exp} < 18$ km s^{-1}, and $v_{\rm exp} > 18$ km s^{-1}). In Sjouwerman et al. (1999) it is shown that the low and high $v_{\rm exp}$ groups have a wide range of physical properties, whereas the properties for the $17 < v_{\rm exp} < 20$ km s^{-1} group are also more peaked, leading to the suggestion that most of these stars have the *same* physical properties. Because the AGB phase is short compared to the total lifetime, most of the stars in this group should therefore have the same age - and have been formed at the same time. It is difficult to estimate an exact age because of many uncertainties, but between about 1 and 4 Gyr ago, the Galactic nucleus would have resembled a starburst galaxy.

Note that the general conclusion of Lindqvist et al. (1992a) is not altered, but next to a relatively old population of low $v_{\rm exp}$ stars that show no net Galactic rotation and a relatively young population of high $v_{\rm exp}$ stars that follow Galactic rotation closely, there also is a diminishing population of stars that follow Galactic rotation, has $v_{\rm exp}$ between 17 and 20 km s^{-1}, was formed in an isolated era about 2 Gyr ago, and of which the observed high metallicity OH/IR stars (of M = 1.5-2 $\rm M_\odot$), are the most massive remaining representatives (Sjouwerman et al. 1999).

4. Astrometry in the GC

The best demonstration of astrometry with masers in the GC so far is by Menten et al. (1997). In an effort to find an IR position for Sgr A*, which is a radio source for which no unambiguous IR counterpart has been found, they identified several H_2O and SiO masers with IR point sources, thus linking the IR to the accurate radio reference frame, placing an upper limit to the (non-detected) IR emission from Sgr A*.

Because of interstellar scattering, and in lesser extent the intrinsic size of the masing region, the 1612 MHz OH masers are not suited for astrometry in the GC (van Langevelde et al. 1992b; Frail et al. 1994).

The intrinsic, as well as the scatter sizes for the 43 GHz masers measure about 1 mas at the GC, which means that in principle relative positions of the SiO masers, and thus the underlying stars, with respect to Sgr A* can be made with this precision. In the IR, the best accuracy is 50 mas (e.g. Ghez et al. 1998), which makes the 43 GHz masers (next to the IR work of Ghez and co-workers) very useful to measure the individual stellar orbits around the black hole, Sgr A*, also because the line-of-sight velocity of the star will be known instantaneously (in contrast to spectroscopic IR measurements, which are difficult to perform).

A star in a circular orbit around a 2.6×10^6 $M_\odot$ black hole would show a circular velocity of 106 $\mathrm{km\,s^{-1}}$ over the orbital radius in pc. For a distance of the GC of 8 kpc and a typical stellar velocity of 100 $\mathrm{km\,s^{-1}}$, this would mean a proper motion of 2.6 mas $\mathrm{yr^{-1}}$. This is measurable with VLBI instruments like the VLBA and VERA. In the VLBA case the feasibility of obtaining mas accurate positions with respect to Sgr A* was (Sjouwerman et al. 1998a) and will (Reid et al., in preparation) be demonstrated. However, because of the rapid phase fluctuations at 43 GHz, VLBI at these frequencies requires the phase to be tracked from a nearby calibrator (e.g. Sgr A* itself!) to the targeted SiO maser, for example with the VLBA in a 20/20 sec calibrator/target cycle (Sjouwerman et al. 1998a) and wasting observing time. The dual beam VERA does not have this disadvantage, because one beam can be pointed at a maser while the other can be observing simultaneously while being pointed at a calibrator source 0.5-2 degrees away.

With VLBI it is possible to measure individual stellar proper motions using the 43 GHz SiO masers as accurate to about 50 $\mathrm{km\,s^{-1}}$ within 5 years, and possibly individual stellar orbits within the next decade. The ultimate test will be to compare the proper motions and orbits for the sources which could be measured both in the 43 GHz SiO maser as well as in the IR.

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