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AGB maser stars as tracers of stellar populations

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Abstract. Masers are known to occur in circumstellar envelopes of AGB stars that are long-period variables and have entered the TP-AGB phase. The maser radiation is intrinsically weak and detection limits prevent us from seeing maser stars much beyond the Galactic Center. Very deep searches have led to the detection of a handful of maser stars in the Large Magellanic Cloud. Some 1000 stellar masers are known. They trace a population of stars with main sequence masses between 1 and 6 $M_\odot$ and ages between 2 and 8 Gyr, the same population that is traced by Cepheids. Their distribution in our Galaxy is the same as that of the red giants, and therefore the stars trace the galactic bar. An outstanding feature is a small disk of radius 150 pc around the galactic center. The disk is in rapid, solid body rotation and leads to a good measurement of the mass density within that distance for Sgr A.

1. The question

The organizers of this colloquium asked me to discuss maser stars as tracers of stellar populations. Because only a handful maser stars are known *outside* of the Milky Way Galaxy (MWG) – these few happen to be all in the Large Magellanic Cloud – only our MWG will de discussed. Detectable maser stars may exist in the Sagittarius Dwarf Galaxy, but I am not aware of any detection. A second limitation is that stellar masers are found only in the circumstellar envelopes of red giants with a high rate of mass-loss (more than 10^{-7} $\dot{M}_\odot$ per year). Such stars are probably all on the AGB; I will limit myself here to AGB stars. I will skip over masers associated with star formation and masers found in the dense rings of molecular gas around the nucleus of AGNs.

By definition masers amplify microwave and mm line radiation non-linearly. There are masers known at sub-mm and mid-IR wavelengths but they are few, have hardly been studied and will be ignored here. I will discuss first radio astronomical studies, then move to infrared studies and then I will describe a ongoing study in which I am involved.

Masers are often studied for their own sake – one wants to determine the astrophysical properties of the associated stars. Maser stars, however, also help to answer questions about the structure and the history of our MWG. How significant these answers will be depends on the sample of maser stars at our disposal: what do we know about the distance and velocity of each star, of its age and its atomic abundances? And how large is the sample and how complete? One part of an answer is that maser stars have a main-sequence mass between

1 and, say, 6 $M_\odot$: they trace about the same population as the Cepheids, stars with ages between those of the OB stars, 10 to 100 Myr, and very old stars such as RR Lyrae variables, 10 Gyr or more.

2. The radio astronomical view

By definition masers are the product of non-linear amplification of thermal radiation. The amplification occurs in circumstellar envelopes at temperatures (a few hundred K) and densities (1 molecule per cm^3) that are lower than in the stellar atmosphere and much higher than in the interstellar medium. Amplification occurs most easily when the spontaneous emission coefficient, Einstein's A, is small relative to the induced transition rate coefficient, Einstein's B, with the consequence that the first detected, strongest and best studied examples are the OH, H_2O and SiO masers that appear at centimeter and millimeter wavelengths.

Relevant here are the masers found in expanding circumstellar envelopes of AGB and post-AGB stars. The SiO, H_2O and OH are found exclusively around M-type giants, nowadays also called oxygen-rich AGB stars. In the other type of AGB stars, the carbon stars, HCN masers are found but the maser is faint and not well studied.

Radio astronomical spectroscopy is mainly done with heterodyne techniques and that leads to a very high spectral resolution ($\lambda/\Delta\lambda \sim 10^6$). In addition, radio astronomy offers interferometry as a standard technique with the advantage of milliarcsec position measurements and an angular resolution of the same order. This is superior by about one order of magnitude to what is offered in infrared and optical astronomy. To set the balance right one should realize that maser stars are rare and intrinsically weak emitters: we know very few stellar masers significantly beyond the center of our MWG.

More than 1000 stellar masers are known in our MWG. I will discuss some relevant surveys in more detail in section 4.

Very promising is a Japanese project called "VERA", in which proper motions and accurate positions will be measured of SiO masers at mm wavelengths using a dedicated interferometer. First fringes have already been seen (Honma et al. 2003).

Let me go briefly over two results of maser studies that are relevant for this colloquium; both are from a recent Leiden thesis by Vlemmings (2002). The high angular resolution and the high positional accuracy make it possible to measure proper motions and parallaxes out to about a few hundred pc, a factor 2 to 3 beyond the reach of the Hipparcos satellite. Vlemmings studied four long-period variables with OH masers at 18 cm with the VLBA, the US interferometer that extends from Hawaii to the Virgin Island of St Croix over the full North-American continent. Vlemmings found a parallax and a proper motion for each; the parallaxes range from 12 ± 4 to 2.3 ± 0.5 milliarcsec and the proper motions from -8.9 ± 0.4 to 80.5 ± 2.4 milliarcsec per year. This work is now extended to a few more Miras; 500 pc is the estimated distance limit for this technique. The results agree with those of Hipparcos but reach a higher accuracy. Variations in the ionosphere of the Earth limit the accuracy of the measurements and thus the solar cycle has some effect on the measurement.

The second result concerns circular polarization by Zeeman splitting of water maser lines at 22 GHz by a magnetic field of 270 ± 30 mG in the circumstellar envelope of the Mira variable S Per. This work has been extended to other maser stars leading to a mapping of their magnetic fields and clear indications that the magnetic fields are dipolar (Vlemmings, private communication).

As is the case in most astronomical studies, it is the distance to a source that is most difficult to measure. There is a proven method to combine radio interferometry together with the "light" curve of the variation of the 1612-MHz (18-cm) OH line flux and to derive a geometric distance to a maser star. But the measurements are difficult and take a long time; it is very hard to reach high precision. A more appropriate way is to study the variability in the infrared.

3. The infrared view

The non-linear amplification of mm and cm radiation often takes place in cool circumstellar envelopes where the temperature of the stellar photons has been lowered by absorption and subsequent re-emission by dust particles. AGB stars share a high luminosity with a high rate of outflow of cool matter, and these are essential factors in the production of dust particles. Maser stars are therefore strong emitters at mid-infrared wavelengths and usually also at near-infrared wavelengths. There is a minority of maser stars where the circumstellar envelope is so thick that even radiation at near-infrared wavelengths is absorbed by the envelope.

The completion of several IR surveys in recent years (see the next section) has enlarged enormously our data base of point sources emitting strongly in photometric bands from 1 to 25 μm. What is the link between maser stars and infrared stars? The answer is complex. On the one hand all maser stars coincide with an infrared source with specific characteristics: a broad spectral energy distribution peaking between 2 and 12 μm, often with the "9.7 mum" feature in absorption or in emission (e.g. Ortiz et al. 2002). The reverse, however, is not true: there may be two infrared sources with the same spectral energy distribution, of equal strength and yet only one contains a maser, the other does not. This fact, first noticed by Murray Lewis is not yet explained; all we can say is that there is an unknown factor at work that decides whether a star shall have a maser or not.

An interesting result obtained by Messineo (private communication) is that when one compares the infrared radiation integrated over near and infrared wavelengths from a maser star with those of the surrounding RGB stars, the maser star is by far the brightest. Because this is always so, the maser star is not only apparently the brightest, but is also intrinsically the brightest and this strengthens the conclusion that a maser star is the one AGB star in a sea of RGB stars. Another result by Messineo is that by comparing the DENIS survey measurement for each star with that of the 2MASS survey, the near IR-fluxes of the many RGB stars are the same in both surveys, whereas the fluxes of the AGB stars differ significantly. The conclusion is that the AGB star is always a long-period variable and the RGB stars are not.

Concerning more detailed observations, spectroscopy and mapping, the possibilities of the infrared observer have been behind those of the radio astronomers. Luckily, the IR and optical possibilities are improving rapidly and may catch up in a few years: interferometry is becoming a mature technique not only at all infrared wavelengths but also down to visual wavelengths. Already infrared photometry is now good enough to measure accurately the apparent bolometric magnitude ($m_{\rm bol}$) and the variability of the stars (period, amplitude) and these are clearly parameters of fundamental significance. The future looks bright.

Thanks to the large monitoring programmes in search of gravitational microlensing effects by Machos, thousands of new long-period variables have been found in the bulge of the MWG and in the Magellanic Clouds. These have provided the spectacular insight that several period-luminosity relations exist (Wood 1999). These relations offer the best means to derive the distances to the AGB stars, including those with masers.

4. Results from recent surveys

4.1. Maser surveys

An unbiased way to find the maser stars is by scanning the sky with a radio telescope. The success rate depends on the number of masers detected per pointing. Because the beam of a radio telescope is proportionally larger for longer wavelengths, such unbiased surveys have been made only in the 18-cm (1612-MHz) OH maser line. The largest and most systematic survey is by Sevenster et al. (1997a,b) and co-workers who covered the galactic plane from $l = -30°$ to $l = +30°$ and found more than 750 masers with the characteristic double peak profile of OH/IR stars (the third and last paper is Sevenster et al. 2001); see below for a relevant website). SiO masers are all at mm and sub-mm wavelengths and unbiased surveys similar to those for OH have been carried out only in very small areas, e.g. around the galactic center (Miyazaki et al. 2001). Most SiO maser surveys start with known infrared point sources and will be discussed in the next subsection.

4.2. IR surveys

Several infrared surveys have been made over the last ten years and these complement nicely the IRAS survey of 1983: (i) the DENIS survey, a survey of the southern sky in the IJK_s-bands and from the ground; (ii) 2MASS, a survey of the full sky in the JHK_s-bands and from the ground; (iii) ISOGAL, a survey with the ISO satellite at 7 and at 15 μm in selected fields in the inner MWG ($-30° < l < +30°$, $-1° < b < +1°$); and (iv) MSX, a survey with a US military satellite in several bands between 4 and 26 μm covering the whole galactic plane between $b = \pm 2°$. The DENIS and 2MASS surveys reach about the same limiting magnitudes. ISOGAL is a factor of ten more sensitive than MSX but the surveyed region is much smaller.

The websites to the surveys are:

- the survey for OH/IR stars: http://www.strw.leidenuniv.nl/~sevenste
- the DENIS survey: http://www-denis.iap.fr
- the 2MASS survey: http://www.ipac.caltech.edu/2mass

- the ISOGAL survey: http://www-isogal.iap.fr
- and the MSX survey: http://www.ipac.caltech.edu/ipac/msx/msx.html

4.3. Preliminary results from an ongoing survey of 86 GHz SiO masers

An ongoing survey for 86-GHz SiO masers is being conducted by M. Messineo and friends. First results can be read in Messineo et al. (2002). The candidate maser stars have been selected from the ISOGAL and MSX mid-infrared surveys and the maser search is being carried out with the 30-m IRAM telescope in the Sierras Nevada mountains near Granada, Spain. This telescope is limited to the Milky Way above $l = -5°$ and an extension to the Australian array is therefore planned. About 530 SiO targets selected from the ISOGAL and MSX surveys have been observed and about 300 masers have been detected.

For each SiO target there is photometry available between 1 and 20 μm and thus one derives $m_{\rm bol}$; measurements are made at one epoch only and as the star is variable, its variability is the main source of uncertainty about the value of $m_{\rm bol}$. As mentioned above, each SiO target turns out to be a long-period variable and to have the highest $m_{\rm bol}$ in the field. A discussion of the interstellar extinction of the RGB stars and the SiO target AGB star leads to the conclusion that the average extinction of the surrounding RGB stars equals more or less that of the SiO target AGB star; this suggests that the SiO target is at the same distance as the majority of the RGB stars (Messineo et al., in preparation). This has an important implication that the distribution of the SiO targets equals that of the RGB stars, a distribution that has been modelled based on COBE results – for a recent study and references to previous work see Robin et al. (2003).

For the approximately 300 maser detections the radial velocity of the AGB star is known. We will soon compare the distribution of these velocities with those expected for the galactic bar. Here I single out one prominent feature in our observations: a thin disk of stars around the galactic center with a diameter of about 300 pc – a confirmation of the disk found by Lindqvist et al. (1992) in OH/IR stars. The stars show solid body rotation with a speed of $2\,{\rm km\,s^{-1}\,pc^{-1}}$ also found by Lindqvist et al. All SiO targets have an extinction of more than 3 mag at 2.2 μm, or 30 mag in the V band. Sevenster et al. (1995) have shown that the kinematics of this disk is a discrete feature well-distinguished from the orbits of the other maser stars in the inner MWG. This suggest at least a different origin. Over the years one and the same scenario has come up: an interstellar (intergalactic?) cloud with a mass of some million solar masses has fallen into the center of the MWG and has taken the velocity pattern corresponding to a large, but uniform, distribution of other (stellar?) matter that produces the gravity. Stars formed and the maser stars that we now see are the decaying remnants of the stars that formed there. This event must have happened at least 1 Gyr ago.

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Discussion

Romaniello: Why do the stars line up in the IR-F/R color-color diagram?

Habing: It's probably a cut off in distance.