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The 43 GHz SiO maser emission around the Mira variable TX Cam

62 epoch movie of the v=1, J=1→0 transition.

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Abstract. We have produced a new version of the movie of the v=1, J=1→0 43 GHz SiO maser around the Mira variable TX Cam. The new movie consists of 62 epochs, 18 more than the previous one. Observations of the masers were carried out using NRAO's Very Long Baseline Array⋆⋆ (VLBA) approximately every two weeks, from May 1997. The new movie covers about 1.64 stellar cycles. Gaussian fitting will give us the proper motions of the individual components and the determination of the percentage and position angle of polarisation will be used to produce the first polarisation movie.

1. Introduction

A stage in the evolutionary path of stars with main sequence mass less than 8 $M_\odot$ is the Asymptotic Giant Branch (AGB) which is located in the top right part of the H-R diagram. Stars at that point have a dense degenerate core and a large mantle with small density. During the early AGB (EAGB) phase stars slowly expel matter at a high rate (10^{-7} to $10^{-4} M_\odot$ yr^{-1}). The next stage is the TP-AGB where thermal pulses begin. The star becomes a variable and, according to its amplitude and light curve, can be classified in types. Of particular interest are the Mira variables, which have a fluctuation in their magnitude in V-band $\Delta V \geq 2.5^m$ and almost regular periodicity.

Miras are evolved red giants with a typical radius of >2 AU. Their temperature is quite low (about 2000 K) but because of their pulsation it can vary up to 30%, in tandem with their luminosity which can change by up to 8 magnitudes in visual light. They have already used their central hydrogen and helium and are left with a degenerated core of C and O. Above the core lies the He-shell and over that the H-mantle. The outer parts of it are cool enough to allow molecules to form. The development of shock waves takes place in the extended parts of the atmosphere. This is where the mass loss occurs in the form of stellar wind. Different molecules are deposited in different envelopes around the star, all together forming the stars circumstellar envelope (Habing, 1998). One of these molecules is SiO.

Silicon monoxide is a simple rotor, thus its rotational levels are completely characterised by its angular momentum J. Another important property is that it has no unfilled electron shells, hence it is non-paramagnetic. If the conditions of population inversion and stimulated emission are fulfilled, the molecule starts masing. The maser effect occurs in rotational transitions of excited vibrational states and the emission is highly linearly polarised, as a result of its para-magnetism. The first SiO maser was detected in December 1973 by Snyder and Bull in the star forming region of Orion A. This kind of emission is not common in these regions. However, Miras often exhibit SiO maser emission, located very close to their surfaces. Lines have been detected from several rotational transitions and from molecules with different isotopes of Si.

TX Cam is a Mira variable exhibiting strong SiO maser emission. As its name suggests, it is located in the constellation of Camelopardalis (the Giraffe) with coordinates RA:05h 00m 51.186" and DEC:56^o 10' 54.341". Its period is 557 days (Kholopov et al., 1985), its distance is estimated between 310-1200 pc (Olofson et al.,1991; Bujarrabal et al., 1987) and the mass loss rate $\sim 1.1 \times 10^{-6} M_\odot \cdot yr^{-1}$ (Knapp & Morris, 1985). TX Cam's spectral type can be classified as M8-M10. For a distance of 317 pc, its radius can be estimated, giving a range between 1.3 (Cahn & Elitzur, 1979) and 3.1 AU (Pegourie, 1987) and the dust formation radius obeys the relationship $R_{in} \sim (3.4 \pm 1.4) R_\star$. The first SiO maser around it was discovered by Spencer (1977). Since then emission from several transitions (Jewell et al.,1987) and isotopes (Barcia et al., 1989) has been detected. Several molecules have been found and the detection of C- and S- molecular species indicate that the star might be undergoing a transition from an O-rich to a C-rich star (Cho & Ukita, 1995). Usually Miras exhibit maser emission from other molecules, such as OH and H_2O, surprisingly though, no other masers are detectable in the region around TX Cam (Dickinson, 1976; Wilson & Barrett 1972).

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2. Previous Observations of TX Cam

The ring structure of the SiO masers around TX Cam was first revealed in 1994 by Diamond and Kemball. The transition studied was the v=1, J=1→0 at 43 GHz and the ring seemed to form at a distance of 2-4 $R_\star$ away from the star (12.6 AU for a distance of 450 pc). This distance indicates that the ring lies between the photosphere and the dust forming region, in the extended atmosphere. There is no evident emission inside the ring, an indication that the amplification must be tangential rather than radial. The average width of the ring was estimated to be about 1.2 AU and the outflow seemed to be ordered and not chaotic.

The polarisation properties of the masers around TX Cam were studied in 1997 (Kemball and Diamond). As expected, linear polarisation was predominant, for most of the components around 25% but for some of them as high as 100%. In contrast, circular polarisation was quite absent and no more than 3-5% for some components. For these values of polarisation the magnetic field was estimated ≈3-5 G. Global order and direction transverse to the radial flow were the main characteristics of its morphology.

The first movie of the 43 GHz emission consisting of 21 epochs was presented in the 191st Symposium of the International Astronomical Union in Montpellier, France in August 1998. The phase covered ranged from $\phi \sim 0.6$ to $\phi \sim 1.2$. Observations started on May 1997 and for every 2 weeks using NRAO's VLBA (Diamond and Kemball, 1999). The most important result was that the ring was expanding and the velocities of individual components were constant throughout their lives at $\sim$3.65 km s^{-1}.

The morphology of the magnetic field and the pumping mechanism is possibly related (Desmurs et al., 2000), showing that tangential polarisation through collisional pumping can occur if the magnetic field is strong in specific directions. Since in TX Cam it is ordered, the pumping is most probably radiative.

3. Observation and Data Reduction

The original movie consisted of 44 epochs. The new observations have added another 18 epochs, raising the number to 62. After August 1999 observing occurred every month

The transition observed is the v=1, J=1→0 at 43 GHz, using the 10 VLBA antennas and one of the VLA. The bandwidth is 4 MHz for 128 channels, thus 31.25 kHz spectral resolution and rest frequency 43.11499 GHz, centred at 22.9039 km s^{-1}. The phase range covered is from $\phi \sim 1.2$ to $\phi \sim 2.2$. For all the epochs the right polarisation system temperature was around 93 K, the left 104 K and the antenna point source sensitivities around 10.5 Jy K^{-1}. The synthesised beam used was 0.54 × 0.42 mas with major axis position angle 20°. Images 100 ×100 mas were made for each epoch.

For each epoch approximately 2.5 hours of data were obtained on TX Cam itself. Apart from TX Cam, 3 other sources were observed, 0359+509 as a calibrator and 3C454.3 and 0609-157 as fringe finders. The data were correlated at the VLBA correlator in Socorro giving all 4 Stokes parameters.

Because of the huge amount of data, we used an automated procedure which includes all amplitude, phase and polarisation calibration and imaging. Self-calibration was performed with another procedure, all of them within the AIPS package.

4. The Movie

Some of the new frames of the movie can be seen in figure 2. Each image is the total intensity image (Stokes I), integrated for all velocities using the AIPS task SQASH. Because there is not enough accuracy in the absolute position, the creation of the movie was not that straightforward. In order to align the images in such a way to have the desired result, tasks and procedures performing specific operations have been used. First a rough estimate of the centre of the image is made and then we extract a 680×680 image from the initial 1024×1024 containing the ring. Then at first, pixel level, correction of the ring's position is made comparing, by blinking, every new frame with the previous one. A second, more accurate, correction of the order of 0.0001 of the pixel is performed with a software created for the needs of the movie, and then applied with LGEOM. The final image then is extracted and, after some editing if necessary, is converted to animated gif and .avi files with commercial software. For some epochs the quality of the data resulted in poor quality image. Also, after the 24^{th} of August, observations occurred every month instead of 15 days. In order to fill the gaps created in the movie by the above factors, the interpolation task COMB in AIPS was used

5. Discussion

So far we have mainly concentrated on the production of the new frames and the new version of the movie. It is obvious that the gas in which the maser spots are embedded undergoes expansion. The ring starts as an almost perfect circle, but with time it changes, looking more like an ellipse. Emission from the north-eastern part of the ring starts weakening, while the western side remains particularly bright. At $\phi \sim 1.1$ matter starts to infall and the ring is gradually losing its luminosity. For $\phi \sim 1.5$ only some spots are bright enough to be obvious. At that time the matter that was infalling bounces back. At $\phi \sim 1.8$ the ring has gained its brightness and some very bright spots are appearing in the eastern part of it. A double structure appears for $\phi \sim 2.2$ and matter starts to infall again (almost a cycle after the first one), this time at the eastern part of the ring.

We haven't performed any Gaussian fitting until now, so this is going to be our main task from now on. The fitting will be made with AIPS++ using a new task called image.decompose in the Imager tool. The innovation in this task is that the fitting is 3 dimensional, using the

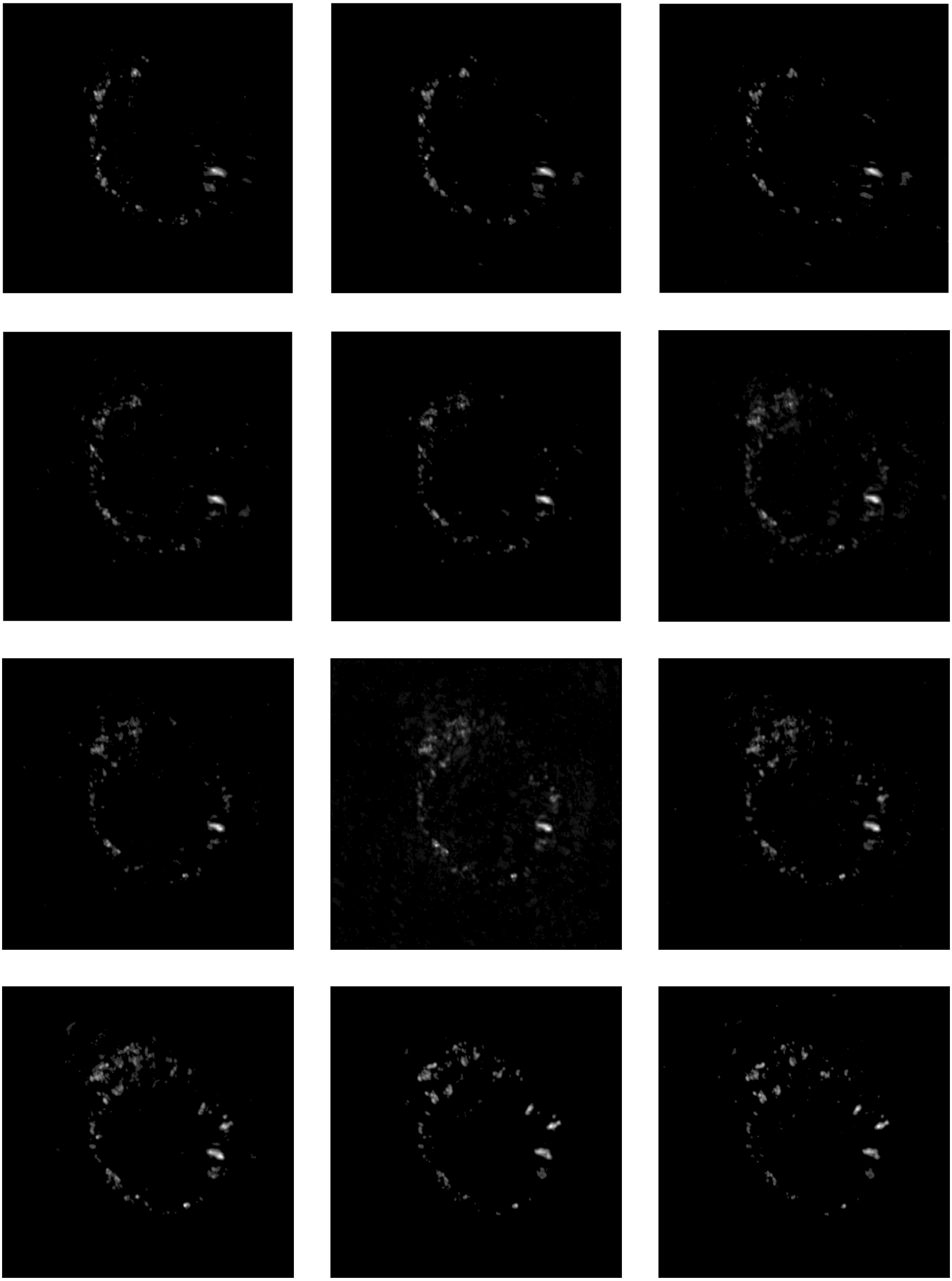

Fig. 1. 12 of the new frames, representing epochs 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 57 ,58. The change in the structure with time is obvious

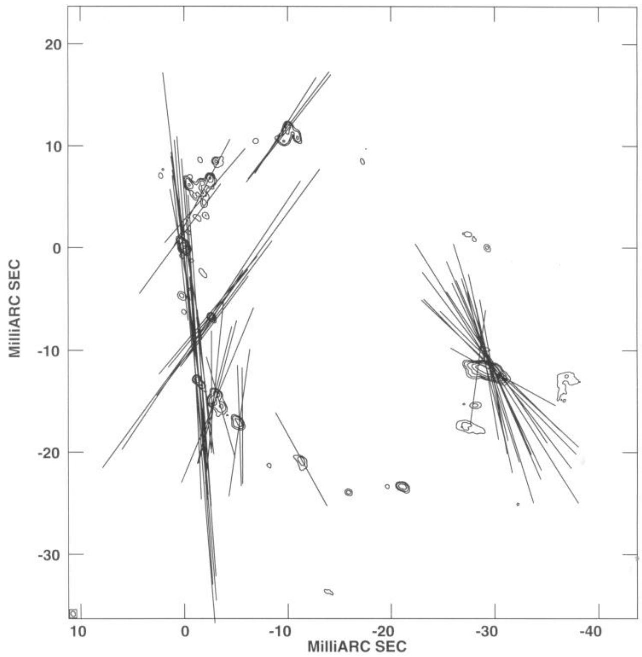

Fig. 2. Linear polarisation image for epoch 47. Vectors are plotted over the total intensity map and they indicate the direction of the magnetic field, with lengths proportional to the linear polarised intensity

cubes created during the data reduction. Thus, we will locate the individual components and determine their kinematics. We will be able then to compare the results with the ones obtained earlier from the movie (constant outflow velocity), but also with other observations that are in favour of matter inflow in other Miras (Hinkle et al.,1982).

Linear polarisation is prominent in all epochs reduced. After the fitting the determination of the percentage and position angle of polarisation for each feature in all epochs will be made. The next aim is to create a polarisation movie which will demonstrate the properties and how they change with the stellar phase. Shock waves are significant in Miras and are believed to cause extreme phenomena in polarisation and the magnetic field once per stellar cycle. Although so far the individual polarisation maps don't reveal any disruptions, maybe this movie give some insight. A more accurate estimation of the magnetic field intensity and morphology will be obtained and possible variability with time will be studied.

It is suggested that a passage of a shock wave should cause contraction and flux increase at around $\phi \sim 0.7$. The latter has already been observed, the former though not yet. If the outflow is continuous, a mechanism should be found that will be able to account for this behaviour.

Finally an answer to the pumping mechanism will be sought and comparisons with the latest results in favour of the radiative pumping will be made.

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