Part Id. Supernova Remnants

Cosmic MASERs: From Protostars to Blackholes
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Supernova Remnants and OH (1720 MHz) Masers

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Abstract. Anomalous OH masers were detected towards supernova remnants (SNRs) more than 30 years ago. The satellite line at 1720 MHz was detected in emission, while the main lines (1665 and 1667 MHz) and the other satellite line, at 1612 MHz, occurred only in absorption. Independently, 25 years ago, a theoretical model was proposed whereby 1720 MHz OH masers could be collisionally excited by the passage of a shock through a molecular cloud. For an efficient inversion of the 1720 MHz transition, the gas should have a narrow range of physical properties, namely a kinetic temperature $50 \leq T_K \leq 125$ K, a volume density $n_{H_2} \sim 10^5$ cm^{-3}, and a column density of OH gas $10^{16} - 10^{17}$ cm^{-2}. However, it was not until 1994, with interferometric observations, that the importance of studies of these masers, formed when an SNR is in direct interaction with a molecular cloud, was realised. This discovery triggered a series of surveys to search all known Galactic SNRs. I will review the outcomes of these surveys and discuss the consequences of using 1720 MHz masers as a diagnostic tool for calculating shocked gas conditions, for magnetic field determinations (from Zeeman splitting measurements) and for measuring the properties of SNRs.

1. Introduction

The first natural masers were detected from the hydroxyl (OH) molecule in 4 ground state ($^2\Pi_{3/2}(J = 3/2)$) transitions, the result of lambda doubling and hyperfine splitting of two rotational ladders (Weinreb et al. 1963). The main lines at 1665 MHZ and 1667 MHz are most often associated with massive star formation (Reid & Moran 1988) and the 1612 MHz satellite line has been used to probe the circumstellar shells of evolved stars (Cohen 1989). The other satellite line at 1720 MHz occurred less frequently and was usually weaker. Anomalous emission from this transition was observed towards supernova remnants (SNRs) as bright, narrow lines, detected simultaneously with broad absorption features for the other 3 transitions (Goss & Robinson 1968; Turner 1969; De Noyer 1979). The impact of these results was only recently realised and a new field of maser study was opened.

SNRs are extremely important for the dynamical and chemical composition and evolution of the Galaxy. They are the principal source of energy and heavy elements and have a major role in initiating shock-driven chemistry and the acceleration of cosmic rays. However, finding specific cases of SNRs interacting directly with the interstellar medium (ISM) has been difficult because the main

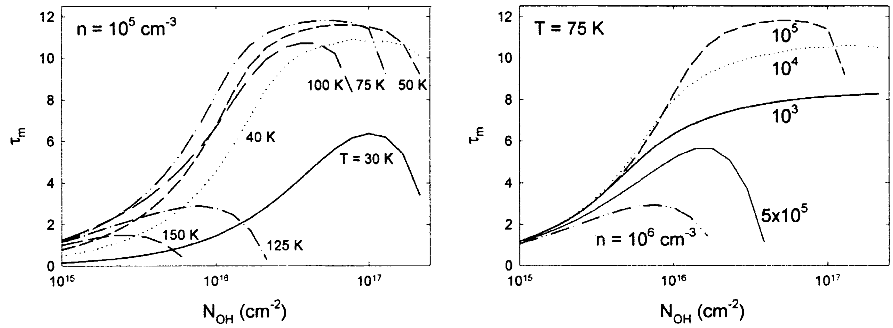

Figure 1. Maser optical depth as a function of OH column density for (*left*) various temperatures, at density $n_{H2} = 10^5$ cm^{-3}, (*right*) various densities, at temperature $T = 75$K. (Figure from Lockett et al. 1999)

observational measurements of these objects has been from their continuum synchrotron radiation. Associations have been established by indirect methods such as the absorption of atomic hydrogen (HI) against the SNR or by morphological matching of HI emission with the radio continuum source (e.g. Dubner et al. 1998).

Following the intial discovery of the 1720 MHz OH masers towards the SNRs, W28, W44 and IC443, a detailed study of W28 was made by Frail, Goss & Slysh (1994), who concluded that the lines were indeed produced as masers, consistent with a shock excitation model proposed by Elitzur (1976). The implication was that these masers could be a powerful new diagnostic tool for probing the interaction of SNR shocks with adjacent molecular clouds and global surveys of SNRs which were initiated as a consequence.

2. Shock Excited Maser Emission

A model is required for the production of 1720 MHz (OH) masers, in isolation from the other ground-state masing transitions, which are located within the boundaries of SNRs. Additionally, there should be no obvious signs of star formation or infrared sources at the maser positions. Elitzur (1976) first proposed a model whereby only the 1720 MHz transition is strongly inverted by collisional excitation of the OH molecule following the passage of a non-dissociative shock through a molecular cloud. The principal mechanism for exciting OH masers is far-infrared (FIR) radiative pumping, hence, this differentiation of the 1720 MHz transition was a very promising hypothesis to test against observation.

The model was refined by Lockett & Elitzur (1989), Lockett et al. (1999) and Wardle (1999) among others, to predict that the 1720 MHz masers would be produced by optically thick radiative cascades, ending with a decay from the first excited state, $^2\Pi_{3/2}(J = 5/2)$, in the post-shock cooling molecular gas following the passage of a C-type shock from an SNR. Heated H_2 molecules excite the OH in the cooling tail of the shock. The physical conditions required to strongly pump the 1720 MHz transition are tightly constrained (Elitzur 1976; Lockett et al. 1999). The gas should have a kinetic temperature, T_K in the range 50 – 125

K and a density, $n_{H_2} \sim 10^5$ cm^{-3}. Figure 1, from Lockett et al. (1999), shows the gas conditions when the strongest masers are produced. Furthermore, the column density of OH, N_{OH}, should be in the range $10^{16} - 10^{17}$ cm^{-2}.

If the temperature or column density is larger than the figures given above, the inversion switches to the 1612 MHz satellite line. If the volume density is higher, quenching by collisions occurs and if it is lower, then detectable maser gains are not achieved. The presence of warm dust at 50K poses no threat to the 1720 MHz masers, but if the dust temperature rises to 100K, then IR reradiation preferentially pumps the main line masers (van Dishoeck, Jansen & Phillips 1993). Finally, if the shock speed is ≥ 45 km s^{-1}, then the H_2 molecules will be dissociated.

Lockett et al. (1999) found that the largest maser amplification occurs in the direction of greatest velocity coherence, which will be perpendicular to the motion of the shock front. This is similar to the conditions for forming water masers in star-forming regions (Elitzur, Hollenbach & McKee 1989). This geometric constraint does have the advantage that the maser velocity can be taken as a measure of the systemic velocity of the SNR in which it is located. Studies of molecular clouds by Wootten (1977, 1981) and Reach & Rho (1998) showed evidence of shocked gas with pre-shocked ambient properties, consistent with predictions from the shock excitation model for the 1720 MHz masers.

The conditions required to produce these masers mean that the shock must be continuous or C-type. However, a difficulty arises because too much water (H_2O) is generated via the oxygen chemistry cycle, relative to the abundance of OH needed. Wardle (1999) published a neat solution to this dilemma. X-rays associated with the SNR ionize the molecular cloud, exciting Lyman and Werner bands which decay radiatively to produce a weak flux of UV photons. These locally produced UV photons dissociate about 1% of the H_2O before the gas cools below 50K. H_2O is formed in the hotter part of the shock and this small dissociation will not affect the abundance of water. The masers form in a narrow region ($\sim 10^{15}$ cm) in the cooling tail of the C-shock. Externally produced UV photons would produce too much FIR radiation from heated dust, which would extinguish the 1720 MHz inversion.

The probability of a J-shock exciting the H_2 molecules has been considered, but such shocks require higher volume densities for propagation and have no intrinsic heating mechanism to moderate the fast cooling through OI lines. Insufficient OH would have accumulated before the gas was too cool to produce the 1720 MHz masers (Hollenbach & McKee 1989; Neufeld & Delgarno 1989).

The model for the formation of these OH (1720 MHz) masers and the conditions in the molecular cloud being impacted by an SNR shock are very closely constrained and there exists much confirming evidence from observations.

3. High Resolution Observations of W28

Early OH maser observations were of low angular resolution and unable to provide conclusive evidence for the nonthermal high brightness temperatures expected with maser emission. Frail et al. (1994) observed the SNR W28, known to be interacting with a molecular cloud of systemic velocity +7 km s^{-1}. They detected 26 unresolved spots of narrow emission lines with brightness tempera-

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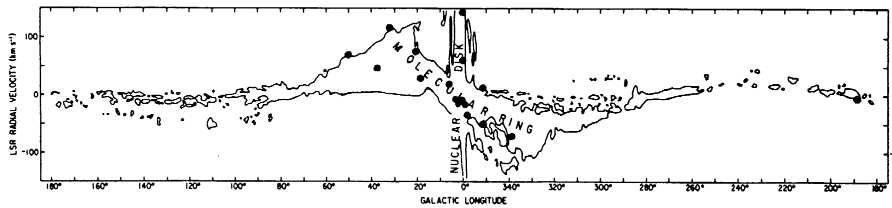

Figure 2. Distribution of SNRs containing OH (1720 MHz) masers on a longitude-velocity diagram of CO emission. (Figure from Green et al. 1997)

tures $> 4 \times 10^5$K and velocities mostly in the range 6 – 8 km s^{-1}, in agreement with the molecular cloud velocity and the systemic velocity of the SNR (from HI absorption). Frail et al. (1994) interpreted the Stokes V profiles measured as due to Zeeman splitting, implying a line-of-sight magnetic field of $\sim$ 5 mG. Linear polarization of a few percent was also detected. These results initiated a series of surveys to determine how many SNRs had these OH masers.

4. Surveys of Supernova Remnants

Two kinds of survey were conducted: (1) global searches to find new maser SNRs (Frail et al. 1996; Green et al. 1997; Koralesky et al. 1998; Yusef-Zadeh et al. 1995, 1996, 1999) and (2) deep, high resolution studies of well-known SNRs (W28, W44, IC443) to confirm maser brightness temperatures, estimate magnetic field strengths and calculate linear sizes of the masing regions (Claussen et al. 1997).

A particular strategy was adopted for most of the global surveys. Initially, a single dish search using the Parkes and Greenbank telescopes was made of SNRs taken from Green's (1996) catalogue. There were $\sim$ 35% positive detections, but most would be non-masing thermal emission from warm gas. Follow-up measurements were made with high resolution interferometers - the Very Large Array (VLA) and the Australia Telescope Compact Array (ATCA) - using comparable angular ($6'' - 15''$) and spectral ($\sim$ 1 km s^{-1}) resolution and sensitivity (5 – 15 mJy bm^{-1}). The Galactic Center region was surveyed as a grid of 88 pointings with the VLA, and then higher resolution measurements were made of selected positions. Table 1 summarises the results. The single dish surveys are complete to about 100 mJy. Since the interferometer follow-ups did not produce a large number of weak masers, we can be reasonably confident that the results are largely complete.

Typically, the SNR maser sources are bright, narrow lines with small central velocity variation, even over several parsecs. The spots are always found within the synchrotron shell and all the SNRs for which X-ray observations have been made, have centrally peaked thermal X-ray counterparts. This is consistent with the environment expected for masing. The maser velocities are in good

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No. SNRS searched	172 (>75% of total known)
No. maser sources found	20 ($\sim$ 10% sample searched)
No. outside Molecular Ring ($\lvert l \rvert \leq 40°$)	1 (IC443)
Fraction SNRs searched in Molecular Ring	50%
No. maser SNRs in Molecular Ring	19 (20% sample searched)
No. maser SNRs in Nuclear Ring ($\lvert l \rvert \leq 5°$)	7 (35% sample searched)
Flux density range of masers	30mJy (3C391) - 79 Jy (W28)
Luminosity range	5 orders of magnitude

Table 1. Statistics from SNR Surveys.

agreement with other measures of the systemic velocity of the SNR and the interacting molecular cloud. This is true even for Sgr A East in the complex region near the Galactic Center (Yusef-Zadeh et al. 1996 and this proceedings).

The indepth studies by Claussen et al. (1997) found brightness temperatures in the range $10^4 - 10^8$K. Some masers were spatially resolved with random orientations. It is not clear if the features are intrinsically extended, scatter broadened or most likely, a blending of several features. Zeeman splitting was measured in $\sim$ 50% spots. It seems probable the masers are saturated, but there is some disagreement on this question and what effect this may have on estimates for the line-of-sight magnetic fields. Nevertheless, significant magnetic fields have been detected, often showing ordering over several parsecs. Claussen et al. (1997) conclude that their results are consistent with the collisional excitation model. To give an example of the distribution of masers within the SNR synchrotron shell, Figure 3 (Brogan et al. 2000) shows the masers detected in CTB 37A.

5. Related Results

5.1. Shocked molecular Gas

Frail & Mitchell (1998) made CO observations towards maser spots in 3 SNRs. They found broadened CO emission lines, indicative of shocked gas, near the continuum ridges and narrow/unshocked lines away from the ridges. Estimates of gas densities confirm early measurements for molecular clouds (Wootten 1977, 1981) and the likelihood of a C-type shock.

5.2. Absence of H_2O Masers in SNRs

In HII regions, strong H_2O masers are produced by shock excitation for kinetic temperatures $300 \leq T_K \leq 600$K and densities $n_{H_2} \sim 10^9$ cm^{-3} (Hollenbach 1997), and they often occur together with OH masers. Claussen, Goss & Frail (1999a) searched selected areas of the three well-studied SNRs (W28, W44, IC 443) and made no detections (except for an unrelated stellar H_2O maser in W44, previously known). The conclusion is that the column density of H_2O is probably too low to produce detectable water masers, but is sufficient to produce enough post-shock OH for a strong 1720 MHz maser to form, which is consistent with the model proposed (Elitzur 1976).

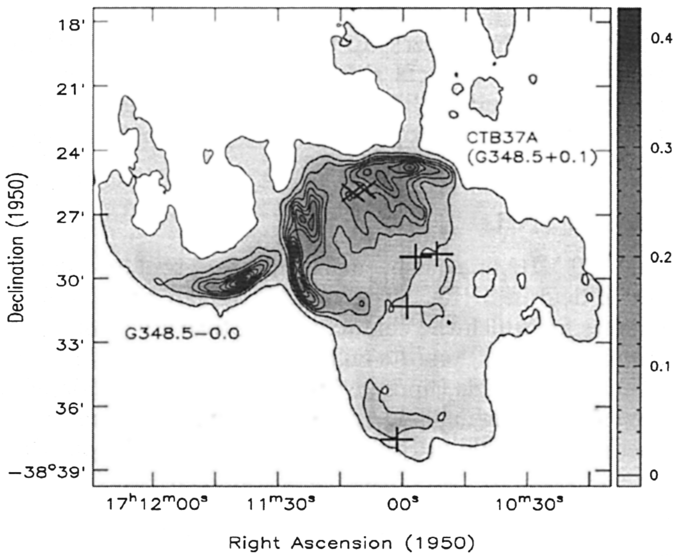

Figure 3. VLA 20 cm continuum image with OH (1720 MHz) maser positions marked: plus symbols show features with velocities about −65 km s^{-1} and crosses show masers with velocities about −22 km s^{-1}. (Figure from Brogan et al. 2000)

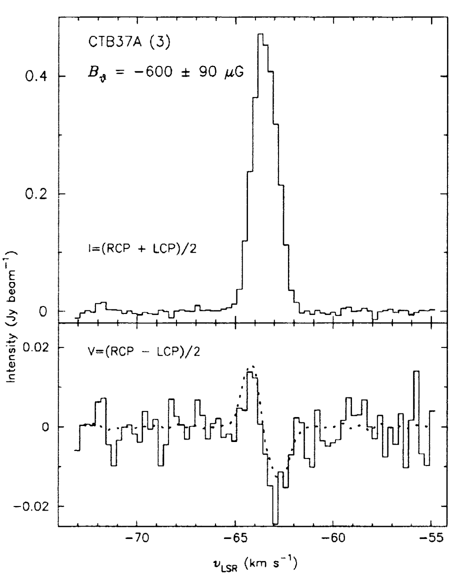

Figure 4. One of the maser features from SNR CTB 37A. The upper panel shows the Stokes I profile and the lower panel shows the Stokes V profile. The estimated line-of-sight magnetic field is $1500 \pm 200\mu$G. (Figure from Brogan et al. 2000)

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5.3. Maser Sizes

Claussen et al. (1999b) found linear sizes up to 3 times the expected maser diameters, if the masing region is 10^{15} cm thick, as predicted. It is unclear if the features are intrinsically extended (like the 1612 MHz masers) or scatter broadened. If a scattering screen is the explanation, the location would vary for each SNR.

5.4. Magnetic Fields in SNRs

Zeeman splitting of the 1720 MHz line has been an important tool for calculating the line-of-sight magnetic field in SNRs. Brogan et al. (2000) have doubled to 10 the number of remnants for which the characteristic Stoke's V profile can be measured. Brogan (this proceedings) reports on more recent results. Most of the SNRs show significant magnetic fields (up to a few mG) often well-ordered over several parsecs, and sometimes showing field reversals. A spectrum, showing the corresponding characteristic S-profile in Stoke's V, is reproduced from Brogan et al. (2000) in Figure 4.

6. OH Absorption

As an independent check on the shock excitation model for 1720 MHZ maser formation, OH absorption measurements were made against the bright SNR W28 (Wardle et al. 2001, in preparation). Broad main line absorption features were detected. Measurements of integrated optical depth, assuming a reasonable cloud temperature, give an estimate of the column density of OH of $\sim 4.5 \times 10^{16}$ cm^{-2}, consistent with expectations. Furthermore, the OH absorption is well aligned with the shocked molecular gas (Arikawa et al. 1999).

7. Conclusions

The 1720 MHz (OH) masers found within the rim of a selected number of shell SNRs are a powerful probe of conditions existing when an SNR shock wave overruns a molecular cloud. The result of being able to determine systemic velocities and hence, distances and linear sizes for the SNRs, is a major boost to understanding their evolution. The Zeeman effect has allowed estimates of the compressed magnetic fields associated with these sources. All the observations confirm the model for production of these masers, in which the the gas and shock parameters are tightly constrained. Work is in progress on studies of some southern maser SNRs (Lazendic et al. 2001, in preparation) and searches for these objects in the Magellanic Clouds have started (Brogan et al. 2001, in preparation).

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References

Arikawa, Y., Tatematsu, K., Sekimoto, Y. & Takehashi, T. 1999, PASJ, 51, L7

Brogan, C. L., Frail, D. A., Goss, W. M., & Troland, T. H. 2000, ApJ, 537, 875
Claussen, M. J., Goss, W. M. & Frail, D. A. 1999a, AJ, 117, 1387
Claussen, M. J., Frail, D. A., Goss, W. M., & Desai, K. 1999b, ApJ, 522, 349
Cohen, R. J. 1989, Rep Prog Phys, 52, 881
De Noyer, L. K. 1979, ApJ, 232, L165
Dubner, G. M., Green, A. J., Goss, W. M., Bock, D. C.-J. & Giacani, E. B. 1998, AJ, 116, 1842
Elitzur, M. 1976, ApJ, 203, 124
Elitzur, M., Hollenbach, D. J., & McKee, C. F. 1989, ApJ, 346, 983
Frail, D. A. & Mitchell, G. F. 1998, ApJ, 508, 690
Frail, D. A., Goss, W. M., & Slysh, V. I. 1994, ApJ, 424, L111
Frail, D. A., Goss, W. M., Reynoso, E. M., Giacini, E. B., Green, A. J., & Otrupcek, R. 1996, AJ, 111, 1651
Goss, W. M., & Robinson, B. J. 1968, Astrophys. Lett., 2, 81
Green, A. J., Frail, D. A., Goss, W. M. & Otrupcek, R. 1997, AJ, 114, 2058
Green, D. A. 1996, *A Catalogue of Galactic Supernova Remnants (1996 August version)*, Mullard Radio Astronomy Observatory, Cambridge, U.K. (available on the Web at "http://www.mrao.cam.ac.uk/surveys/snrs/")
Hollenbach, D. J. 1997, in IAU Symp. 182, Herbig-Haro Flows and the Birth of Low Mass Stars, eds. B. Reipurth & C. Bertout, 181
Hollenbach, D. J. & McKee, C. F. 1989, ApJ, 342, 306
Koralesky, B., Frail, D. A., Goss, W. M., Claussen, M. J. & Green, A. J. 1998, AJ, 116, 1323
Lockett, P. & Elitzur, M. 1989, ApJ, 344, 525
Lockett, P., Gauthier, E. & Elitzur, M. 1999, ApJ, 511, 235
Neufeld, D. A. & Delgarno, A. 1989, ApJ, 340, 869
Reach, W. T. & Rho, J. 1998, ApJ, 507, L93
Reid, M. J. & Moran, J. M. 1988, Galactic & Extragalactic Radio Astronomy, eds. G. L. Verschuur & K. I. Kellermann (New York: Springer), 255
Turner, B. E. 1969, ApJ, 157, 103
van Dishoeck, E. F., Jansen, D. J., & Phillips, T. G. 1993, A&A, 279, 541
Wardle, M. 1999, ApJ, 527, L109
Weinreb, S., Barrett, A. H., Meeks, M. L. & Henry, J. C. 1963, Nature, 200, 829
Wootten, A. 1977, ApJ, 216, 440
Wootten, A. 1981, ApJ, 245, 105
Yusef-Zadeh, F., Uchida, K. I. & Roberts, D. 1995, Science, 270, 1801
Yusef-Zadeh, F., Roberts, D. A., Goss, W. M., Frail, D. A., & Green, A. J. 1996, ApJ, 466, L25
Yusef-Zadeh, F., Goss, W. M., Roberts, D. A., Robinson, B. & Frail, D. A. 1999, ApJ, 527, 172