Mem. S.A.It. Vol. 82, 703

Memorie della

Supernova remnant shock - Molecular cloud interactions

Masers as tracers of hadronic particle acceleration

Dale A. Frail

National Radio Astronomy Observatory, Array Operations Center, P.O. Box O, 1003 Lopezville Road, Socorro, NM 87801-0387, USA, e-mail: dfrail@nrao.edu

Abstract. We review the class of galactic supernova remnants which show strong interactions with molecular clouds, revealed through shock-excited hydroxyl masers. These remnants are preferentially found among the known GeV and TeV detections of supernova remnants. It has been argued that the masers trace out the sites of hadronic particle acceleration. We discuss what is known about the physical conditions of these shocked regions and we introduce a potential new maser tracer for identifying the sites of cosmic ray acceleration. This review includes a reasonably complete bibliography for researchers new to the topic of shock-excited masers and supernova remnants.

Key words. ISM: molecules – masers – shock waves – cosmic rays – supernova remnants

1. Introduction

Cosmic rays were discovered nearly 100 years ago, yet we still do not know with any certainty the identity of the cosmic accelerators. It has long been argued that supernova remnant (SNR) shocks are the primary sites for accelerating galactic cosmic rays (e.g. Blandford & Eichler 1987). Observations of non-thermal radio and X-rays from SNRs have established that *electrons* are accelerated in these shocks (up to 100 TeV) (Koyama et al. 1995), but the bulk of galactic cosmic rays (99%) are *hadrons* and here solid evidence has been lacking.

The most promising method of searching for evidence of hadronic cosmic rays has been to look for GeV and TeV emission from SNRs. The cosmic ray protons and other hadrons, accelerated in SNR shocks, collide with the ambient gas producing high-energy particles called neutral pions which decay quickly into γ-rays ($\pi^\circ \rightarrow \gamma\gamma$). EGRET provided some early detections of SNR-γ-ray associations but with only crude localizations (Esposito et al. 1996). Interest in this topic has been reinvigorated in recent years with a new generation of atmospheric Cerenkov imaging telescopes (e.g. HESS, MAGIC, VERITAS) and the launch of NASA's *Fermi* satellite with greatly increased sensitivity and angular resolution over past experiments.

Simply finding GeV/TeV emission spatially coincident with an SNR is not sufficient to demonstrate that hadrons are undergoing diffusive shock acceleration in the SNR. There are other potentially confusing sources

Send offprint requests to: D. A. Frail of γ-ray emission originating primarily from leptonic (i.e. electron) processes (Aharonian et al. 2008a). Most of the identified galactic TeV sources have turned out to be pulsar wind nebulae (PWN) where the γ-rays originate from the pulsar termination wind shock. Young SNRs ($\sim 10^3$ yrs) can also produce γ-rays by Bremsstrahlung emission and inverse Compton scattering of the ambient radiation field. Distinguishing between these alternatives is not straightforward.

SNRs whose cosmic rays are interacting with dense molecular clouds (MCs) are expected to be bright γ-ray sources. In these cases it is necessary to rule out leptonic processes and to show quantitative agreement with the predictions of the model in order to build a strong case for the acceleration of hadronic cosmic rays. The γ-ray flux from neutral pion decay depends on the ratio n/d^2 where d is the SNR distance and n is the ambient gas density. Fortunately radio astronomy provides one simple method to obtain both of these hard-to-measure parameters. In this review we show that the OH(1720 MHz) maser transition has become one of the more important *in situ* tracers of molecular shocks in SNRs (see the excellent review by Wardle & Yusef-Zadeh 2002). Through extensive observations and theory, the OH(1720 MHz) masers have been recognized as a key signpost for the interaction of SNRs with MCs (Jiang et al. 2010).

2. Observational properties of OH(1720 MHz) masers

Anomalous emission from the OH satellite line at 1720 MHz was first noted toward the SNR W 44 and W 28 in the late 1960s (Goss & Robinson 1968). This result was largely forgotten until 25 years later when high sensitivity, high resolution Very Large Array (VLA) observations showed 26 compact, narrow line features tracing the interaction zone between the SNR and the MC (Frail et al. 1994). The high brightness temperature ($T_b > 4 \times 10^5$ K) and narrow line widths ($\Delta V \simeq 1 \mathrm{kms}^{-1}$) argued convincingly for a non-thermal, i.e. maser origin for the OH(1720 MHz) emission.

This initial discovery prompted several targeted surveys toward the known sample of SNRs in our galaxy. The strategy was to carry out a single dish survey on the NRAO 140-ft, Parkes 64-m, and Green Bank Telescopes. Candidates were followed up with interferometric imaging with the Australia Telescope Compact Array and the VLA. The advantage of this particular approach was that the known galactic SNR population could be surveyed quickly and efficiently. The major disadvantage was the relatively high flux density threshold, suggesting that these surveys are not complete (Hewitt & Yusef-Zadeh 2009). Future OH maser observations should be carried out as deep interferometry surveys ($S_{lim} \leq 50$ mJy) where there will be less confusion from diffuse, thermal OH emission.

We list the current sample of 23 SNRs with OH(1720 MHz) maser detections in Table 1. Successful searches toward the Large Magellanic Cloud have also been conducted but they are not listed in this table (Brogan et al. 2004; Roberts & Yusef-Zadeh 2005). Considering the detections as a whole, about 10% of all SNRs have OH(1720 MHz) masers (Green et al. 1997; Hewitt & Yusef-Zadeh 2009). The SNRs with OH(1720 MHz) masers appear to trace the broad scale distribution of molecular gas in our galaxy. The detections are not found randomly throughout the galaxy but rather are found in the inner galaxy, in particular within the molecular ring and nuclear disk. The luminosity distribution of the OH(1720 MHz) masers (defined as $S \times d^2$, where S is the peak flux density in mJy and d is the distance in kpc) is broad, covering 10^2 to 10^6 mJy kpc^2, with a median $\sim 10^4$ mJy kpc^2.

The OH(1720 MHz) masers are located on or near the peaks of the radio synchrotron emission which is generated by electron acceleration along the expanding SNR shock. OH(1720 MHz) masers are preferentially located along the edges of thin filaments or clumps of molecular gas with broad lines widths seen ($\Delta V \simeq 30$ kms^{-1}), indicative of post-shock gas (Frail & Mitchell 1998; Reach & Rho 1999; Lazendic et al. 2002; Seta et al. 2004; Reach et al. 2005; Lazendic et al. 2010; Zhou & Chen 2011).

Table 1. A distance-ordered list of OH(1720 MHz) supernova remnants

(l,b)	RA (J2000)	Dec. (J2000)	d_{kpc} (kpc)	# masers	γ-rays?	Name	Reference
189.1, +3.0	06 17 00	+22 34	1.5	6	Y	IC443	Claussen et al. (1997)
6.4,−0.1	18 00 30	-23 26	2.0	41	Y	W28	Claussen et al. (1997)
34.7,−0.4	18 56 00	+01 22	2.5	25	Y	W44	Claussen et al. (1997)
5.7,−0.0	17 59 02	−24 04	3.2	1	P		Hewitt & Yusef-Zadeh (2009)
8.7,−0.1	18 05 30	−21 26	3.9	1	Y	W30	Hewitt & Yusef-Zadeh (2009)
9.7,−0.0	18 07 22	−20 35	4.7	1	N		Hewitt & Yusef-Zadeh (2009)
359.1,−0.5	17 45 30	−29 57	5.0	6	P		Yusef-Zadeh et al. (1995)
5.4,−1.2	18 02 10	−24 54	5.2	2	N	Milne 56	Hewitt & Yusef-Zadeh (2009)
49.2,−0.7	19 23 50	+14 06	6.0	2	Y	W51C	Green et al. (1997)
357.7,+0.3	17 38 35	−30 44	6.4	5	N		Yusef-Zadeh et al. (1999)
357.7,−0.1	17 40 29	−30 58	>6	2	N	MSH 17-39	Frail et al. (1996)
348.5,+0.1	17 14 06	−38 32	8	10	Y	CTB 37A	Frail et al. (1996)
32.8,−0.1	18 51 25	−00 08	5.5/8.5	1	P	Kes 78	Koralesky et al. (1998)
0.0,+0.0	17 45 44	−29 00	8.5	28	Y	SgrAEast	Pihlström et al. (2011b)
1.0,−0.1	17 48 30	−28 09	8.5	1	N		Yusef-Zadeh et al. (1999)
1.4,−0.1	17 49 39	−27 46	8.5	2	N		Yusef-Zadeh et al. (1999)
31.9,+0.0	18 49 25	−00 55	9.0	2	N	3C 391	Frail et al. (1996)
337.0,−0.1	16 35 57	−47 36	11	3	N	CTB 33	Frail et al. (1996)
21.8,−0.6	18 32 45	−10 08	5.2/11	1	N	Kes 69	Green et al. (1997)
346.6,−0.2	17 10 19	−40 11	5.5/11	5	N		Koralesky et al. (1998)
349.7,+0.2	17 17 59	−37 26	>11	5	N		Frail et al. (1996)
16.7,+0.1	18 20 56	−14 20	2.2/14	1	N		Green et al. (1997)
337.8,−0.1	16 39 01	−46 59	12.3	1	P	Kes 41	Koralesky et al. (1998)

The masers in a given SNR all have similar radial velocities with small scatter. There is close agreement between the velocity of the masers and the systemic velocity of molecular gas in the vicinity. This velocity matching has been interpreted to mean that the masers originate in a shock transverse to the line of sight (Frail et al. 1996; Claussen et al. 1997).

OH(1720 MHz) masers also provide a unique way to directly measure the strength and orientation of the magnetic fields in SNR shocks using Zeeman splitting of the line (Yusef-Zadeh et al. 1996; Claussen et al. 1997; Koralesky et al. 1998; Brogan et al. 2000; Hoffman et al. 2005a,b). These observations have yielded values for the magnetic field of order 1 mG, giving derived magnetic pressures comparable to the thermal pressure of the hot gas interior to the SNR. These same observations give measurements for the size of the maser spots of order 10^{15} cm or ~100 AU (Claussen et al. 1999b; Hoffman et al. 2003).

Two interesting correlations exist for those SNRs with OH(1720 MHz) masers. Claussen et al. (1997) first noted that the SNRs detected at GeV energies by EGRET were among the best examples of SNR-MC interactions (IC 443, W 28 and W 44) and they suggested that OH(1720 MHz) SNRs would make important candidates for future GeV and TeV surveys. The new generation of instruments supports this initial supposition, with several new claims of associations between SNRs and γ-ray sources (Hewitt et al. 2009; Castro & Slane 2010; Kosack et al. 2010). We list these associations in Table 1 (Y=yes, N=no, P=possible).

Frail et al. (1996) and Green et al. (1997) first noted that the OH(1720 MHz) SNRs belonged predominantely to a particular class of so-called "mixed morphology" SNRs (25% of

X-ray SNRs) which have center-filled thermal X-ray emission. This hypothesis was put on a firmer statistical footing by Yusef-Zadeh et al. (2003), and while there is no agreement on how this interior X-ray gas is produced (Cox et al. 1999; White & Long 1991), the strong correlation argues that SNR-MC interactions play an important role.

3. The origin and excitation of OH(1720 MHz) masers

The hydroxyl (OH) molecule is abundant in the interstellar medium. In its ground state it has four ground state transitions: two main lines at 1665.4 MHz and 1667.4 MHz, and two satellite lines at 1612.2 MHz and 1720.5 MHz (Elitzur 1992). The 1665 and 1667 MHz lines are typically associated with star-forming regions while 1612 MHz are associated with evolved stars, but all of these lines are inverted through pumping of far-infrared photons. OH(1720 MHz) masers, in contrast, are pumped through collisions; far-infrared radiation effectively acts to destroys the inversion of the 1720 MHz line.

Theoretical modeling suggests that the OH is formed downstream of a slow, compression-type shock (20-30 kms^{-1}) that has propagated into an adjacent MC. A strong OH(1720 MHz) maser inversion is collisional excited at temperatures of 30-120 K and densities of order $n = 10^4$-10^5 cm^{-3} (Lockett et al. 1999; Wardle 1999). Maser amplification needs large column densities of OH molecules ($10^{16} - 10^{17}$ cm^{-2}) with *small* velocity gradients. Thus masers will occur preferentially where the observer's line-of-sight velocity gradient is small. OH(1720 MHz) masers therefore favor edge-on geometries (i.e. transverse shocks). This immediately explains why the observed velocity of the masers, SNR and MC agree. Thus the detection of an OH(1720 MHz) maser is not just unambiguous proof that an SNR-MC interaction is taking place, it also provides both a kinematic distance d and the gas density n. The ratio n/d^2 is a key parameter for testing the hadronic acceleration models (Aharonian et al. 2008a).

The ionization of the OH remains an interesting area for future research. Most of the gaseous oxygen in the dense, post-shock gas is taken up in H_2O formation and therefore it must be dissociated to get the required columns of OH. Wardle (1999) produced a self-consistent physical model in which the thermal ($T < 1$ keV) X-rays in the interior provide the necessary ionization, conveniently explaining the association between OH(1720 MHz) SNRs and mixed morphology SNRs (Yusef-Zadeh et al. 2003). More recently Hewitt et al. (2009) have suggested that the H_2O could be dissociating instead from the local cosmic rays accelerated in the shock. If true, OH(1720 MHz) masers are not merely a signpost of hadronic particle acceleration; rather, the locally enhanced cosmic ray density is necessary to produce the OH(1720 MHz) masers. This hypothesis can be tested directly with observations of the cosmic ray ionization rate ζ_{CR} using the abundance ratio of $[DCO^+]/[HCO^+]$ (Ceccarelli et al. 2011) in dense clouds or measuring H_3^+ columns (Indriolo et al. 2010) in diffuse clouds.

4. A new maser tracer for molecular shocks

OH(1720 MHz) masers are not infallible tracers of SNR-MC interactions. Only 10% of the known SNRs in our galaxy have OH masers and GeV/TeV emission is not seen in about half of the OH(1720 MHz) SNRs. Due the narrow physical conditions needed to excite the OH(1720 MHz), the *absence* of masers tells us nothing about whether hadronic cosmic rays could be responsible for the observed γ-rays from an SNR.

OH(1720 MHz) is not the only shock-excited maser. Theoretical predictions suggest that excited-state OH may be present under similar physical conditions. However, searches for these lines near 6 GHz have not yielded any detections (Fish et al. 2007; Pihlström et al. 2008; McDonnell et al. 2008) nor have any 22 GHz water masers been found near SNRs (Claussen et al. 1999a; Woodall & Gray 2007). Additionally, the widespread methanol molecule (CH_3OH) can be collisionally pumped, resulting in not just one line but several dozen bright maser transitions at radio wavelengths. Theoretical modeling shows that the brightest shock-excited masers are expected for the transitions at 36.169 GHz and at 44.070 GHz, with slightly weaker masers for the 84.521 GHz and 95.169 GHz transitions (Morimoto et al. 1985; Cragg et al. 1992). These CH_3OH masers are excited over a much larger range of densities and temperatures than OH(1720 MHz).

The first detection of a CH_3OH maser toward an SNR was reported by Zubrin & Shulga (2008) toward Kes 79 at 95 GHz. Observations at 95 GHz with the Arizona Radio Observatory 12-m and VLA observations at 44 GHz failed to confirm this detection (Claussen and Frail, unpublished). Methanol masers have been detected at 36 and 44 GHz toward the galactic center (Haschick et al. 1990; Szczepanski et al. 1989), while recent VLA observations have localized them to where the SNR Sgr A East is seen interacting with a molecular ridge (Sjouwerman et al. 2010; Pihlström et al. 2011a). There is evidence that the CH_3OH masers are offset from the known OH(1720 MHz) masers in this region and that the CH_3OH may be excited in hotter and denser gas than the OH (i.e. closer to the molecular shock front). Motivated by this intriguing result, we have recently undertaken a VLA CH_3OH survey (36 and 44 GHz) of 21 OH(1720 MHz) SNRs (Pihlström et al. in preparation). Owing to the small field-of view (1-arcmin at 44 GHz vs 27-arcmin at 1720 MHz) the survey is strongly biased. We have focused our VLA observations mainly toward OH(1720 MHz) masers sites and toward some GeV/TeV peaks.

In our partial reduction of the survey data we have detected a 44 GHz CH_3OH maser in the SNR W 28. The maser is found in region OH-D, well away from the bulk of the known OH(1720 MHz) masers. More intriguingly, the CH_3OH maser lies near the peak in the TeV emission of W 28 (Aharonian et al. 2008b) where no OH(1720 MHz) had been seen previously. Pumping models predict that this transition is excited at temperatures of T=80-200 K and densities $n = 10^5 - 10^6$ cm^{-3}, conditions both hotter and more dense than that needed to excite the OH(1720 MHz) line. This preliminary result potentially makes methanol a new and important signpost for SNR-MC interactions, giving us a more robust and ubiquitous tracer to help us pinpoint SNR-MC interactions and measure their physical properties over a wider range.

Acknowledgements. I thank my collaborators Ylva Pihlström, Mark Claussen and Loránt Sjouwerman for allowing me to discuss our preliminary methanol results. The Very Large Array is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

References

Aharonian, F., Buckley, J., Kifune, T., & Sinnis, G. 2008a, Reports on Progress in Physics, 71, 096901
Aharonian, F., et al. 2008b, A&A, 481, 401
Blandford, R., & Eichler, D. 1987, Phys. Rep., 154, 1
Brogan, C. L., Frail, D. A., Goss, W. M., & Troland, T. H. 2000, ApJ, 537, 875
Brogan, C. L., Goss, W. M., Lazendic, J. S., & Green, A. J. 2004, AJ, 128, 700
Castro, D., & Slane, P. 2010, ApJ, 717, 372
Ceccarelli, C., et al. 2011, ApJ, in press.
Claussen, M. J., Frail, D. A., Goss, W. M., & Gaume, R. A. 1997, ApJ, 489, 143
Claussen, M. J., Goss, W. M., Frail, D. A., & Seta, M. 1999a, AJ, 117, 1387
Claussen, M. J., Goss, W. M., Frail, D. A., & Desai, K. 1999b, ApJ, 522, 349
Cox, D. P., et al. 1999, ApJ, 524, 179
Cragg, D. M., Johns, K. P., Godfrey, P. D., & Brown, R. D. 1992, MNRAS, 259, 203
Elitzur, M. 1992, ARA&A, 30, 75
Esposito, J. A., Hunter, S. D., Kanbach, G., & Sreekumar, P. 1996, ApJ, 461, 820
Fish, V. L., Sjouwerman, L. O., & Pihlström, Y. M. 2007, ApJ, 670, L117
Frail, D. A., Goss, W. M., & Slysh, V. I. 1994, ApJ, 424, L111
Frail, D. A., Goss, W. M., Reynoso, E. M., Giacani, E. B., Green, A. J., & Otrupcek, R. 1996, AJ, 111, 1651
Frail, D. A., & Mitchell, G. F. 1998, ApJ, 508, 690

Goss, W. M., & Robinson, B. J. 1968, Astrophys. Lett., 2, 81
Green, A. J., et al. 1997, AJ, 114, 2058
Haschick, A. D., Menten, K. M., & Baan, W. A. 1990, ApJ, 354, 556
Hewitt, J. W., Yusef-Zadeh, F., & Wardle, M. 2008, ApJ, 683, 189
Hewitt, J. W., Yusef-Zadeh, F., & Wardle, M. 2009, ApJ, 706, L270
Hewitt, J. W., & Yusef-Zadeh, F. 2009, ApJ, 694, L16
Hoffman, I. M., et al . 2003, ApJ, 583, 272
Hoffman, I. M., Goss, W. M., Brogan, C. L., & Claussen, M. J. 2005a, ApJ, 627, 803
Hoffman, I. M., Goss, W. M., Brogan, C. L., & Claussen, M. J. 2005b, ApJ, 620, 257
Indriolo, N., et al. 2010, ApJ, 724, 1357
Jiang, B., et al. 2010, ApJ, 712, 1147
Koralesky, B., et al. 1998, AJ, 116, 1323
Kosack, K. 2010, Poster paper at 25th Texas Symposium on Relativistic Astrophysics, Heidelberg, Germany
Koyama, K., et al. 1995, Nature, 378, 255
Lazendic, J. S. et al. 2002, MNRAS, 331, 537
Lazendic, J. S., et al. 2010, MNRAS, 409, 371
Lockett, P., Gauthier, E., & Elitzur, M. 1999, ApJ, 511, 235
McDonnell, K. E., Wardle, M., & Vaughan, A. E. 2008, MNRAS, 390, 49
Morimoto, M., Kanzawa, T., & Ohishi, M. 1985, ApJ, 288, L11
Pihlström, Y. M., et al. 2008, ApJ, 676, 371
Pihlström, Y. M., Sjouwerman, L. O., & Fish, V. L. 2011a, arXiv:1105.4377
Pihlström, Y. M., Sjouwerman, L. O., & Mesler, R. A. 2011b, arXiv:1107.4341
Reach, W. T., & Rho, J. 1999, ApJ, 511, 836
Reach, W. T., Rho, J., & Jarrett, T. H. 2005, ApJ, 618, 297
Roberts, D. A., & Yusef-Zadeh, F. 2005, AJ, 129, 805
Seta, M., et al. 2004, AJ, 127, 1098
Sjouwerman, L. O., Pihlström, Y. M., & Fish, V. L. 2010, ApJ, 710, L111
Szczepanski, J. C., Ho, P. T. P., Haschick, A. D., & Baan, W. A. 1989, The Center of the Galaxy, 136, 383
Yusef-Zadeh, F., Uchida, K. I., & Roberts, D. 1995, Science, 270, 1801
Yusef-Zadeh, F., et al. 1996, ApJ, 466, L25
Yusef-Zadeh, F.,et al. 1999, ApJ, 527, 172
Yusef-Zadeh, F., Wardle, M., Rho, J., & Sakano, M. 2003, ApJ, 585, 319
Wardle, M. 1999, ApJ, 525, L101
Wardle, M., & Yusef-Zadeh, F. 2002, Science, 296, 2350
White, R. L., & Long, K. S. 1991, ApJ, 373, 543
Woodall, J. M., & Gray, M. D. 2007, MNRAS, 378, L20
Zhou, P., & Chen, Y. 2011, ApJ submitted, arXiv:1103.2527
Zubrin, S. Y., & Shulga, V. M. 2008, Young Scientists 15th Proceedings, 41