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rmaa@astroscu.unam.mx
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Reynoso, Estela M.
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RADIO OBSERVATIONS OF SNR ENVIRONMENTS

Estela M. Reynoso[1,2]

RESUMEN

Se calcula que la mayoría de los remanentes de supernovas (RSNs) en nuestra galaxia se encuentran muy cerca o dentro de las nubes moleculares en las que nacieron sus estrellas progenitoras. Cuando un RSN interactúa con nubes interestelares, no sólo se altera la morfología y la evolución del RSN sino que también las nubes se calientan, se comprimen, se disocian, o sufren modificaciones en su química. La turbulencia que se genera en las nubes moleculares puede desencadenar formación estelar. El estudio de la emisión en radio en líneas atómicas y moleculares proveniente de RSNs aporta información fundamental para describir el ambiente en el cual evoluciona un RSN y determinar posibles sitios de interacción RSN-nube interestelar. La detección de máseres de OH en la línea satélite de 1720 MHz permite acotar tanto las características del medio ambiente chocado como de la dinámica del frente de choque del RSN. En este artículo presento una recopilación de distintos resultados obtenidos a partir de observaciones en radio en diferentes líneas espectrales y bajo distintas condiciones en dirección a algunos RSNs y sus entornos.

ABSTRACT

Most supernova remnants (SNRs) in our Galaxy are expected to be close to their parent molecular clouds. The interaction between SNRs and interstellar clouds not only alter the morphology and evolution of a SNR but also heat, compress, disrupt or modify the chemistry of the cloud. The turbulence generated in molecular clouds can trigger star formation. Radio emission from atomic and molecular lines toward SNRs provide unvaluable information to describe the ambient in which a SNR is evolving and determine possible sites of SNR-interstellar cloud interaction. The detection of OH masers in the satellite line at 1720 MHz can set strong constraints in the characteristics of the shocked ambient medium as well as on the dynamics of the SNR shock front. In this article I review some relevant results derived from radio observations in different spectral lines and under a variety of conditions towards SNRs and their environments.

Key Words: **ISM: ATOMS — ISM: CLOUDS — ISM: MOLECULES — RADIO LINES: ISM — SUPERNOVA REMNANTS**

1. INTRODUCTION

The rate of supernova (SN) explosions arising from massive progenitors has been estimated to be $\sim 85\%$ based on a combination of evidence from external galaxies and from historical SNe in our own Galaxy (e.g. Tammann et al. 1994; Samland 1998). A massive star evolves fast enough so that when it explodes, it is not expected to have moved too far away from its parental molecular cloud. As an example, Huang & Thaddeus (1986) surveyed 26 SNRs in the outer Galaxy in the 2.6 mm CO line and found that half of them depict spatial coincidences with large molecular complexes.

Massive stars are characterized by strong mass outflows or winds which are enhanced in the later stages of stellar evolution. These winds modify the circumstellar medium creating *interstellar bubbles* (Castor et al. 1975; Weaver et al. 1977), hot evacuated cavities surrounded by thin expanding shells. Anisotropies in the winds as well as stars with high spatial velocities (Weaver et al. 1977; García Segura & Mac Low 1995) lead to a variety of structures. Moreover, the confluence of hot plasma bubbles may lead to the formation of hot tunnels in the Galaxy (Cox & Smith 1974). Several wind blown bubbles have been detected through H I observations around WR and OB stars (e.g. Cappa & Niemela 1984; Arnal 1992; Cichowolski et al. 2001; Cappa et al. 2002; Cichowolski & Arnal 2004; Vasquez et al. 2005). Therefore, a supernova will in most cases explode inside a medium previously disturbed by a stellar wind. The morphology of the remnant of a SN explosion is determined by the history of mass loss from the progenitor, the explosion itself and by preexisting inhomogenities in the interstellar medium

[1]Instituto de Astronomía y Física del Espacio, C. C. 67, Sucursal 28, 1428 Buenos Aires, Argentina (ereynoso@iafe.uba.ar).

[2]Departamento de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Argentina.

(ISM). Understanding which is the influence of each of these factors on the observational characteristics of a SNR is essential for a correct interpretation. A starting point to discriminate between them is to probe the ISM through atomic and molecular lines in radio wavelengths.

2. INTERACTION BETWEEN SNRS AND THE ISM

One major problem in studying the interaction of a supernova remnant (SNR) with an inhomogeneous ISM is the determination of distances to discard projection effects. A method widely used to estimate the distance to a SNR is to identify its systemic velocity and derive the corresponding distance applying a Galactic rotation model (e.g. Fich et al. 1989). The most reliable method to set constraints to the systemic velocity is the study of H I absorption against the background emission from the remnant.

Morphological coincidences between the radio continuum emission from a SNR and the surrounding H I emission at a given spectral velocity are often invoked as an argument to assign a systemic velocity to the SNR, assuming that the morphology is revealing a physical interaction between them (e.g. Puppis A, Dubner & Arnal 1988; VRO 42.05.01, Landecker et al. 1989; CTA1, Pineault et al. 1993; 3C400.2, Giacani et al. 1998; G18.8+0.3, Dubner et al. 1999; G114.3+0.3, G116.5+1.1, and G116.9+0.2, Yar-Uyanıker et al. 2004). However, such coincidences could be incidental, as shown by Paron et al. (2006) for RCW 103. An H I absorption study towards this SNR using the Australia Telescope Compact Array (ATCA) interferometer (Reynoso et al. 2004) showed an absorption-like feature at +34 km s^{-1}. At that velocity, the H I distribution depicts a remarkable morphological correspondence with RCW 103. However, after a further filtering in the Fourier plane was applied, the absorption-like feature at +34 km s^{-1} was removed (Reynoso et al. 2004), revealing that it was not produced by neutral gas foreground to the remnant. The SNR's systemic velocity was found to be ~ -43 km s^{-1}, as previously measured by Caswell et al. (1975). Furthermore, Paron et al. (2006) observed the J:1–0 transition of two molecules, CO and HCO^+, and confirmed a systemic velocity of –45 km s^{-1}. They also show that at such velocity, there is no apparent association between the SNR and the H I distribution.

Rather than morphology, more reliable indications of SNR-ISM interaction are given by spectral line broadenings of the order of 20 km s^{-1} or greater, as detected for example in W28, W44 (Frail & Mitchell 1998), HB21 (Koo et al. 2001) or 3C 391 (Reach & Rho 1999); high ratios between transitions from higher to lower excitation states ($R_{u'-u,l'-l}$), like in W44, IC 443 (Seta et al. 1998), G18.8+0.3 or G349.7+0.2 (Dubner et al. 2004); and by the presence of OH masers in the satellite line of 1720 MHz. Because of its relevance in the study of interactions between SNRs and molecular clouds, this latter topic will be discussed in more detail in the next section.

3. OH (1720 MHZ) MASERS AS TRACERS OF MOLECULAR SHOCKS

The first OH masers at the satellite line of 1720 MHz were detected towards W28 and W44 (Goss & Robinson 1968). Since then, a number of surveys (Frail et al. 1996; Green et al. 1997; Koralesky et al. 1998; Yusef-Zadeh et al. 1999) revealed that nearly 20 SNRs (or $\sim$ 10% of the known Galactic SNRs) have at least one OH maser at 1720 MHz. Images of the CO J:1–0 emission towards some of these SNRs (3C 391, Wilner et al. 1993; G16.7+0.1, G349.7+0.2, Reynoso & Mangum 2000, 2001) support the association of the OH (1720 MHz) masers with sites of interaction between SNRs and molecular clouds.

The origin of this maser emission is explained by the passage of a shock front through molecular gas (Elitzur 1976), where the population inversion is produced by collisions with H_2 behind a C-type shock. The physical conditions necessary for OH (1720 MHz) maser emission to occur impose very tight constraints to the physical properties of the shocked gas: temperatures between 50 and 125 K, densities of the order of 10^5 cm^{-3}, and shock velocities $\lesssim 45$ km s^{-1}, where the shock must be viewed edge-on (Lockett et al. 1999). Therefore, the presence of OH (1720 MHz) masers not only constitutes a powerful tool to diagnose SNR-molecular cloud interactions, but also provide information on the physical conditions of the shocked cloud and the characteristics of the shock itself. Furthermore, the velocity of the OH (1720 MHz) masers can be identified with the systemic velocity of an SNR.

Frail & Mitchell (1998) mapped the CO J:3-2 emission towards OH (1720 MHz) masers in 3C 391, W28 and W44 and found that in many cases, the masers were coincident with CO clumps and were preferentially distributed along a narrow region at the edge of the CO peaks. Moreover, they detected clear spectral broadenings in the CO J:3-2 line towards the masers (see also Reach & Rho 1999). Based on different transitions of H_2CO towards a CO peak in W28, they find temperatures of about 80 K and densities of 2×10^6 cm^{-3}, in very good agreement with theoretical models. Reach et al. (2002) observed the H_2 emission towards one of the CO J:3-2 clumps in 3C 391 and found a number of "prestellar" cores (gravitationally bound), with the maser projected onto one of them. However, they found that the H_2 lump containing the maser accounts only for 3% of the total H_2 luminosity, implying that OH masers are not one-to-one tracers of molecular shocks.

CO observations in different transitions have also been performed towards G349.7+0.2 (Dubner et al. 2004), another SNR with OH (1720 MHz) masers associated. In all of them, a cloud enclosing the OH (1720 MHz) masers was detected. The authors found high line ratios $R_{2-1/1-0}$, $R_{3-2/2-1}$ and $R_{3-2/1-0}$, typical of shocked gas. Lazendic et al. (2004) observed several molecular species towards this remnant: ^{12}CO, ^{13}CO, CS, HCN, H_2CO (not enhanced by the shock in this case), HCO^+ and SO (enhanced with respect to dark clouds), and SiO (not detected). They also observed extended OH emission, with an abundance greater than in cold clouds. Theoretical models predict enhanced OH in SNRs due to the dissociation of H_2O by far UV photons self-generated in the shock front through radiative de-excitation of collisionally excited H_2 (Wardle 1999). No line broadenings have been detected towards this SNR.

4. RADIO OBSERVATIONS OF THE ENVIRONS OF HISTORICAL SNRS

The SN explosions most recently witnessed by humankind occurred about 300 to 400 years ago. The remnants of these explosions are young enough that the blast wave should not have been affected by inhomogenities in the ISM. However, in some cases, signatures of SNR-ISM interaction are already observed. In other cases, the SNR has been clearly influenced by a circumstellar environment product of stellar mass losses prior to the outburst. In what follows, I will briefly describe the results of surveying the environs of the three youngest historical Galactic SNRs: Tycho's, Kepler's and Cassiopeia A (Cas A).

4.1. *Tycho's SNR*

Tycho's SNR is the remnant of a type Ia SN that exploded in 1572. Non-circular motions in the Perseus arm, where this SNR appears to be located, make H I absorption studies useless for distance determinations. Based on the "two armed spiral shock" (TASS) model, Schwarz et al. (1995) derive a distance of 2.2 kpc at –50 km s^{-1} or 2.8 kpc at –40 km s^{-1}. A VLA H I absorption study (Reynoso et al. 1999) revealed a density enhancement on the eastern region over the face of the remnant, towards the direction where the lower expansion velocities were measured (Reynoso et al. 1997a). In particular, a small knot at v~ -52 km s^{-1} was detected in absorption at the position where the expansion velocity is lowest. The deceleration of the shock front due to the high density of this knot is also supported by a broadened Hα component at the same position (Ghavamian et al. 2000), indicative of interaction between the SNR and the ISM.

In emission, there are H I structures apparently associated with the remnant between ~ -51.5 and –57 km s^{-1} (Reynoso et al. 1999). Surprisingly, there is a decrement in the emission next to the eastern border of the SNR shell, where higher densities are observed in the absorption study. The authors attribute this behavior to self-absorption processes, where a warmer H I component is self-absorbing a cooler component. This scenario is compatible with an excess of diffuse Hα emission outside of the eastern edge of the shell which would be due to collisional excitation in mostly neutral gas heated by a precursor to a temperature of $\sim$ 12,000 K (Ghavamian et al. 2000). The recent detection of a CO cloud adjacent to the radio shell (Lee et al. 2004) gives further support to the presence of a dense cloud to the East of Tycho's SNR. There is, however, a $\sim$ 10 km s^{-1} shift between the atomic and molecular components. Lee et al. (2004) explain this discrepancy as a possible acceleration of the neighboring gas before excitation by the shock wave.

4.2. *Kepler's SNR*

This is the remnant of a SN explosion occurred in 1604. At present, there is no agreement in the SN type. Both in radio and in X-rays, this SNR appears as a circular shell with the northern arc much brighter than the rest of the shell. At a distance of about 5 kpc, as inferred from different estimates including H I absorption, this SNR lies far away from the Galactic plane, hence the influence of the ISM on its evolution should be negligible.

Reynoso & Goss (1999) observed the H I 21 cm line towards Kepler's SNR using the VLA. The absorption spectrum confirmed a systemic velocity of +21.3 km s^{-1}, while in emission there appeared no external gradients at this velocity or beyond that could explain the observed brightness asymmetry. Therefore, radio observations rule out that the morphology of this remnant obeys to factors external to the progenitor star. Jura et al. (2001) compared the morphology of Kepler's SNR with the incomplete circumstellar CO shell created around the evolved, massive star HD 179821 by a magnetized wind. The authors suggest that when HD 179821 explodes as a SN, it may resemble Kepler's SNR.

The preferred model to explain Kepler's SNR asymmetry, however, is a bow shock created by a runaway star ($V_* = 280$ km s^{-1}) that was overun by the blast wave after the explosion (e.g. Bandiera & van den Bergh 1991). This model accounts for the departure of Kepler's SNR from the Galactic plane. In a recent paper, Velázquez et al. (2006) computed a two-dimensional simulation of an explosion inside a cavity previously blown by a high velocity progenitor. They could reproduce the morphology, size and X-ray luminosity of the remnant using parameters typical of a type Ia SN.

4.3. *Cassiopeia A*

This is the remnant of a type II SN, with an uncertain age (probably $\sim$ 330 yrs). In optical wavelengths, Cas A is characterized by a population of fast moving knots (FMK) and quasi-stationary floculi (QSF), identified respectively with SN ejecta and stellar mass loss prior to the explosion. Based on proper motion of the optical knots, the distance is estimated to be $\sim$ 3.4 kpc.

In radio wavelengths, Cas A is one of the brightest sources in the sky. Therefore, its strong radio continuum emission was often used as background for several Galactic absorption studies. Different molecules have been observed in absorption in this direction (NH_3, HCN, H_2CO, OH, ^{13}CO; see Reynoso & Goss 2002, and references therein), as well as recombination atomic lines (e.g. Anantharamaiah et al. 1994; Payne et al. 1994). Absorption studies provide information on the gas foreground to Cas A, however very little is known about the gas directly related with the SNR.

In H I, Cas A appears to lie behind a "curtain" of strong absorption from –45 to –54$\tilde{k}$ (Bieging et al. 1991). Several H I clumps have been detected at anomalous velocities, between –60 and –70 km s^{-1}, that lie mainly over the southern and eastern regions of the shell (Reynoso et al. 1997b). The positions and velocities of these clumps can be fitted by a $\sim$ 2.5 pc radius shell associated with Cas A expanding at about 23 km s^{-1}. Reynoso et al. (1997b) propose a scenario in which recombined wind driven clumps were ejected by a WN-type progenitor and are still moving ahead of the shock front.

The strong emissivity from Cas A makes H I emission studies extremely difficult because of the dynamic range involved. However, at higher frequencies the brightness of Cas A decreases and therefore it is possible to observe molecular lines in emission in millimetric wavelengths. Low resolution CO observations (Troland et al. 1985) show that the molecular clumps detected in absorption are part of larger molecular clouds. Based on several anomalies on the western edge of Cas A, Keohane et al. (1996) propose that the remnant is interacting with a molecular clous in this direction. Liszt & Lucas (1999) made higher resolution maps of the ^{12}CO and ^{13}CO emission, and took absorption and emission spectra of HCO^+ and $C^{18}O$. They found no evidence of the interaction suggested by Keohane et al. (1996). High resolution H_2CO observations towards Cas A (Reynoso & Goss 2002) give marginal but hardly conclusive evidence of interaction.

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