Molecular Line Observations of the Tornado Nebula and its Eye

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We present millimetre and NIR molecular-line observations of the Tornado nebula and its Eye. The observations were motivated by the presence of OH(1720 MHz) maser emission towards the nebula, believed to be an indicator of interaction between a supernova remnant and a molecular cloud. We found that the distribution of molecular gas around the Tornado complements its radio morphology, implying that the nebula’s appearance has been influenced by the structure of the surrounding molecular gas. Our NIR H2 observations revealed the presence of shocked molecular gas at the location where the nebula is expanding into the surrounding molecular cloud.

It has been suggested that the Eye of the Tornado is related to the nebula on the basis of their apparent proximity. Our NIR and millimetre-line observations show that the two objects are not spatially related. Br γ line emission, in conjunction with IR data at longer wavelengths and high-resolution radio continuum observations, suggests that the Eye is a massive protostellar source deeply embedded within a dense molecular core.

1 Introduction

The Tornado nebula (G357.7–0.1) is a peculiar radio source located towards the Galactic Centre region. It has been classified as a supernova remnant (SNR) due to its steep radio spectrum and linear polarization (e.g., Kundu et al. 1974, Caswell et al. 1980, Shaver et al. 1985a), but its unique morphology has led to other interpretations (e.g., an accretion powered nebula, Becker & Helfand 1985). The Eye of the Tornado (G357.63–0.06) is a compact radio source located 30″ from the emission peak of the nebula. It was initially thought to be responsible for the formation of the nebula (e.g., through mass ejection from a pulsar or accreting binary system), but was instead found to have a flat radio spectrum and was suggested to be an HII region (Shaver et al. 1985b).

2 Tornado

Frail et al. (1996) found a single OH(1720 MHz) maser at the northwestern tip of the Tornado (see Figure 1). When not accompanied by maser emission from the other three OH ground–state transitions at 1612, 1665 and 1667 MHz, the detection of this maser has been recognized as a signature of SNR/molecular
cloud interactions (see Koralesky et al. 1998 and references therein). Its presence may support the classification of the nebula as an SNR. The maser has a velocity of \(-12.4 \text{ km s}^{-1}\), implying a distance of 11.8 kpc to the nebula and placing the Tornado behind the Galactic Centre.

Using the University of New South Wales Fabry-Perot narrow-band tunable filter (UNSWIRF), we detected 2.12 \(\mu\text{m}\) H\(_2\) 1–0 S(1) emission towards the OH(1720 MHz) maser in the Tornado nebula (see Figure 1). The correlation of the emission peaks in the radio continuum and H\(_2\) images suggest that the H\(_2\) emission originates from an expansion of a shock wave and is most probably shock excited, as found in other SNRs associated with the OH(1720 MHz) maser (e.g., Lazendic et al. 2002a,b). The OH(1720 MHz) maser is located at the western edge of the H\(_2\) emission, which is more sharply defined than the rest of the ring, probably delineating the leading edge of the shock front.

Molecular transitions at millimetre wavelengths were also detected at the maser velocity of \(-12 \text{ km s}^{-1}\) using the 15-m Swedish-ESO Submillimeter Telescope (SEST). Emission from molecular species other than \(^{12}\text{CO}\) and \(^{13}\text{CO}\), e.g., HCO\(^+\), HCN and H\(_2\)CO, was found to be very weak (see Lazendic et al. 2003 for more details). Molecular gas associated with the OH(1720 MHz) maser and H\(_2\) emission is optically thick, cold (\(\sim 7 \text{ K}\)) and dense (\(\sim 10^5 \text{ cm}^{-3}\)). This density is in agreement with the requirements for the OH(1720 MHz) maser production in the post-shock gas behind the SNR shock front (Lockett et al. 1999), but the temperature is much lower than that expected in the post-shock gas in which the maser is created (50 – 125 K). However, since the cloud is optically thick, our CO observations are probing only the envelope of the cloud. Observations of more optically thin transitions of \(^{12}\text{CO}\) and \(^{13}\text{CO}\) are needed to examine the whole cloud temperature.

The structure of the associated molecular gas complements the radio morphology of the Tornado nebula (see Figure 2), implying that the distribution of the surrounding medium has influenced the nebula’s unusual appearance. In particular, two minima in the molecular gas distribution, located symmetrically on each side of the nebula, coincide with large arc-like filaments in the nebula and point to locations where the shock could perhaps expand more readily than in the other regions.
Fig. 2 An image of $^{13}$CO 1–0 emission (shown in greyscale and black contours) integrated between $-16$ and $-9$ km s$^{-1}$, overlaid with contours of the 20 cm radio continuum emission. The $^{13}$CO contour levels are: 3.8, 5.7, 7.6, 9.5, 11.4, 13.3, 15.2 and 17.1 K km s$^{-1}$. The lightest colours represent the weakest emission. The 20 cm contour levels are: 2.7, 8.1, 13.5, 18.9, $2.43 \times 10^{-2}$ Jy beam$^{-1}$. The cross marks the location of the OH(1720 MHz) maser.

3 Eye of Tornado

Fig. 3 NIR and radio images of the Eye. (left) 2.16μm continuum image of the field centred on the Eye, overlaid with the Brγ line image. Contours are at 3, 5, 7, 9, 12, 15 and $1.6 \times 10^{-19}$ W m$^{-2}$ arcsec$^{-2}$. (right) 6 cm VLA image overlaid with contours of 20 cm VLA image. Contours are at 8, 26, 52, 104, 156, 208 and $2.58 \times 10^{-3}$ Jy beam$^{-1}$. 
Using the 3.8-m UK Infrared Telescope in conjunction with the CGS4 spectrometer we found 2.16 µm Brγ emission towards the Eye. The emission peaks at a velocity of \( \sim -200 \text{ km s}^{-1} \), which drastically differs from the velocity of the molecular gas associated with the Tornado. The velocity of the Brγ emission indicates the distance to the Eye is 8.5 kpc, which makes the Eye foreground to the Tornado nebula. A similar velocity towards the Eye has also been measured using the H92α radio recombination line (Brogan 

The Eye is resolved by the NIR and radio measurements (see Figure 3) as a compact HII region, and therefore must be undergoing massive star formation. It consists of four knots of emission, each about 1.5′′ across and of similar brightness, placed symmetrically about the perimeter of a circle 6′′ across. There are faint extensions extending \( \sim 2′′ \) to the south and to the west in the Brγ image, but no emission from its centre.

A fit to flux measurements from our NIR and other IR data obtained from Midcourse Space Explorer (MSX) and Infrared Astronomy Satellite (IRAS) is consistent with the Eye being a warm (\( \sim 190 \text{ K} \)), unresolved (\( \sim 0.05′′ \)) blackbody source at the core of an extended (\( \sim 5.5′′ \)), cold (\( \sim 35 \text{ K} \)) greybody. The best fit value of this two-component greybody gives an angular size for the Eye which is similar to the size derived from the NIR and radio images. The Eye’s integrated infrared luminosity of \( \sim 2 \times 10^4 L_{\odot} \) suggests it harbors a massive (\( \sim 12 M_{\odot} \)) protostellar source, perhaps a B0 star (see Burton et al. 2003 for more details).

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