EVIDENCE OF A HADRONIC ORIGIN FOR THE TeV SOURCE J1834−087

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ABSTRACT

We report on the discovery of compact, narrow OH line emission from the hydroxyl molecule at 1720 MHz toward the extended TeV source J1834−087. The origin of this high energy emission is unknown; it could be powered by one or more candidate neutron stars (leptonic) or by cosmic rays interacting with dense gas (hadronic). The OH emission is detected near the center of J1834−087, coincident with the radio continuum of the supernova remnant W41, and the radial velocity of the line is the same velocity as a giant molecular cloud along the line of sight. We argue that the OH is maser emission stimulated by the interaction of the W41 shock with the molecular cloud. The known correlation between γ-ray bright supernova remnants and OH masers favors a hadronic interpretation for this high energy emission.

Key words: cosmic rays – gamma rays: ISM – ISM: supernova remnants

1. INTRODUCTION

The pace of discovery in very high energy (VHE; >100 GeV) astronomy has quickened in recent years due to a new generation of atmospheric Cerenkov imaging telescopes (e.g., H.E.S.S., MAGIC, VERITAS). These instruments are characterized by a large field of view (~5°), sensitivities of 1% of the Crab Nebula, and angular resolutions of a few arcminutes. Surveys with these instruments have led to the discovery of nearly 100 VHE galactic and extragalactic sources, which is an order of magnitude increase in VHE sources in only a decade (Weekes 2008; Rieger et al. 2013).

VHE astronomy finds itself in a golden period, not unlike radio astronomy after World War II, with large catalogs of unidentified sources. Much effort, therefore, has been going into making correlated, multi-wavelength observations in order to identify the sources of VHE emission. Many astrophysical processes are known to accelerate particles that produce accompanying high energy radiation and the VHE emission often provides the most stringent tests of theoretical models. The sources which have been identified to date have fallen into several different populations, including pulsar wind nebulae (PWNe), shell-type supernova remnants (SNRs), binary stars, Wolf–Rayet stars, giant molecular clouds (GMCs), the Galactic Center, nearby star-forming galaxies, and active galactic nuclei.

Despite this progress, more than 25% of all VHE sources remain unidentified. One of the more intriguing of these sources is J1834−087. Discovered by the H.E.S.S. telescope (Aharonian et al. 2006), and confirmed by the MAGIC telescope (Albert et al. 2006), J1834−087 is an extended TeV source 11′ diameter (see Figure 1). There is a likely GeV counterpart 2FGL J1834.3−0848 detected by the Fermi satellite (Nolan et al. 2012). The extended VHE emission is localized to near the center of the large diameter (27′) shell-type SNR W41 or G23.3−0.3 (Helfand et al. 2006). These basic properties are confirmed with a deeper H.E.S.S. integration (52 hr) and a reanalysis of 4 yr of Fermi data (Méhault 2011). The distance to W41 has been determined to be approximately 4.2 kpc (Leahy & Tian 2008).

There is no consensus on the origin of the high energy emission from J1834−087. The gamma-rays could be produced from a leptonic process, whereby the relativistic electrons accelerated at the termination shock of the PWNe up-scatter low energy photons via inverse Compton scattering. There are no fewer than three candidate neutron stars that might be responsible. Bartko & Bednarek (2008) suggest that the Vela-like PSR J1833−0827, 24′ from W41, is responsible for the VHE emission. XMM observations toward J1834−087 detect a bright, hard X-ray source and faint, diffuse emission offset from the point source (Mukherjee et al. 2009). The authors argue that the X-ray emission originates from a young pulsar and its accompanying PWN. Follow-up observations made with the Chandra satellite found no evidence for a physical association between the point source and the extended emission (Misanovic et al. 2011). Instead, the compact XMM source is resolved into a point source CXOU J183434.9−084434 surrounded by diffuse emission 20′′ in diameter, whose spectrum is more suggestive of dust scattering than a PWN. No X-ray pulsations have been detected from the point source. Finally, there is the magnetar Swift J1834.9−0846, seen in projection toward J1834−087 (Kargaltsev et al. 2012), but no claims have been made that this magnetized neutron star could be powering the extended TeV emission.

Alternatively, the TeV emission from J1834−087 may have a hadronic origin. Cosmic rays, accelerated by a SNR, collide with the ambient gas producing neutral pions which decay into gamma-rays (π0 → γγ). Strong evidence in favor of the hadronic origin has recently been found in a number of galactic SNRs (Giuliani et al. 2011; Ackermann et al. 2013). Albert et al. (2006) suggested a hadronic origin for J1834−087, noting the spatial coincidence of a GMC toward the center of W41. A similar morphological argument was put forth by Tian et al. (2007), based on CO and H I spectra. Neither of these studies, however, provide any direct evidence that the SNR shock of W41 is interacting with a molecular cloud. In this Letter, we undertake observations of the hydroxyl molecule (OH) in its ground state at 1720.530 MHz (Section 2). Through repeated studies, OH (1720 MHz) masers have emerged as an important tracer of molecular shocks, and their detection (Section 4) can be taken to be strong evidence in favor of gamma-rays from hadronic particle acceleration.

2. OBSERVATIONS

The Karl G. Jansky Very Large Array (VLA) observed toward J1834−087 on 2011 October 25 under program 11B-009.
Three pointings were made, each with a 30 arcmin diameter field of view. The first pointing was at the center of W41 ($l, b = 23^\circ.3, -0^\circ.3$). The second pointing was toward the SNR G22.7$-$0.2 ($l, b = 22^\circ.5, -0^\circ.1$), which is adjacent to W41 and may be co-located. The third pointing was made between the two SNRs ($l, b = 23^\circ.0, -0^\circ.2$). The VLA was used in its D configuration, giving a synthesized beam of approximately 45 arcsec.

The VLA WIDAR correlator was configured to collect data in dual polarization, with 256 channels each of width 3.906 kHz (0.7 km s$^{-1}$). We observed the ground state OH line at a rest frequency of 1720.530 MHz, shifting the center of the observing band to an LSR velocity of 70 km s$^{-1}$. The experiment is sensitive to OH lines with velocities from $-15$ km s$^{-1}$ to $+155$ km s$^{-1}$.

The data was calibrated in the Astronomical Image Processing System package following standard practice. The radio continuum was subtracted in the visibility plane before making spectral line data cubes. Neither deconvolution nor self-calibration were performed on these images. The rms noise in the final three images varied between 10 and 11 mJy beam$^{-1}$.

3. RESULTS

We searched for lines in the Stokes $I$ image cubes using the Common Astronomy Software Applications package. No OH lines were detected toward the second or third pointings, i.e., toward the SNR G22.7$-$0.2 or at the interface between W41 and G22.7$-$0.2. However, there is at least one compact OH emission feature in the W41 pointing at R.A.(J2000) = $18^h34^m47^s.4$, decl.(J2000) = $-8^\circ.4'48''77$ (±335), with a peak flux density of $S_p = 64$ mJy, a velocity $V_{LSR} = 74.2$ km s$^{-1}$, and a line width $\Delta V = 1.3$ km s$^{-1}$. There is a second weaker feature with $S_p = 59$ mJy, a velocity $V_{LSR} = 74.9$ km s$^{-1}$ and a line width $\Delta V = 2.6$ km s$^{-1}$. At R.A.(J2000) = $18^h34^m46^s.0$, decl.(J2000) = $-8^\circ.43'58''.6$ (±30) or $l, b = (23^\circ.27, -0^\circ.30)$, this feature is only 29″ away from the brighter line. Formally these fit as two separate lines but the synthesized beam is rather large 51″ x 37″ (15″), and higher angular resolution is needed to clearly separate them. In addition to these emission spots, we detect diffuse emission and absorption. Two arcminutes due north of the brightest line there is a 90″ long ridge of faint emission at $V_{LSR} = 71$ km s$^{-1}$ and corresponding absorption at $V_{LSR} = 76$ km s$^{-1}$. The velocity width of the absorption features is approximately twice that of the emission. There is no OH emission or absorption detected elsewhere in the 30 arcmin field centered on W41.

Diffuse OH emission (and absorption) at 1720 MHz has been detected toward a number of SNRs (Yusef-Zadeh et al. 1995, 1999), while compact, narrow-line OH emission has been seen now toward 24 galactic SNRs (Frail 2011). These compact features have been identified as simulated emission from a maser process based on their narrow lines and high brightness temperatures. Establishing a maser origin is important, for, as we show in Section 4, the excitation of OH (1720 MHz) masers requires a collisional pump not a radiative pump. This distinguishes OH (1720 MHz) masers from the other satellite line at 1612 MHz and the mainline OH masers at 1665 and 1667 MHz, which all can be radiatively pumped. Unfortunately, we cannot unambiguously identify the compact OH line toward W41 as maser emission. While the narrow linewidth is indicative of OH masers, the low angular resolution of our VLA observations only allows us to put a lower limit on the brightness temperature of $T_b \gtrsim 20$ K. Existing observations have shown the OH (1720 MHz) masers to be $\sim 200$ AU in size with $T_b \approx 10^4$ K, with a central core of $T_b \approx 10^3$ K (Hoffman et al. 2003). Some of the diffuse OH emission may also be due to masers. Hewitt et al. (2008) showed that there exists widespread, low-gain maser emission $T_b \lesssim 2500$ K toward these SNRs that had been resolved out by interferometer surveys. Future high angular resolution observations can easily confirm whether or not the OH emission toward W41 is due to masers.

If the compact, narrow-line features are masers, then they lie at the faint end of the flux density distribution of known OH (1720 MHz) masers where Hewitt & Yusef-Zadeh (2009) previously noted that existing surveys are incomplete. The W41 maser luminosity, defined as $S_p \times d^2$ (where $S_p$ is the peak flux density in mJy and $d$ is the distance in kpc), is $10^3$ mJy kpc$^2$. This value is fainter than the median of $10^4$ mJy kpc$^2$ but this distribution spans some four orders of magnitude (Green et al. 1997).

The putative masers are detected near the center of J1834$-$087, coincident with the radio continuum of W41, which is interior to the outer shell of the SNR (see Figure 1). The maser positions are also coincident within the errors (±0.01) of the centroid of the newly revised extended H.E.S.S. position of $l, b = (23^\circ.26, -0^\circ.31)$, implying a direct relation between the VHE emission and the masers (Méhault 2011). The radial velocity of the OH emission ($V_{LSR} = 74$ km s$^{-1}$) coincides with velocity centroid of a GMC noted by Albert et al. (2006) and Leahy & Tian (2008). This velocity agreement establishes that the OH emission originates from the GMC. There is some additional kinematic support for the SNR interacting with the GMC. The radio continuum of W41 is seen in absorption against OH has at $V_{LSR} = 76$ km s$^{-1}$, and thus the SNR lies...
behind the GMC at least. In Section 4 we show more directly that the detection of OH requires that the SNR is interacting with the molecular cloud.

4. DISCUSSION

We now present the argument that the detection of OH emission at 1720 MHz toward J1834−087 favors a hadronic origin for the VHE emission. Specifically, the detection of this line is evidence that the SNR W41 is interacting with the adjacent molecular cloud and that the association is not a line of sight coincidence. Ever since the original detection of OH (1720 MHz) masers in the SNR W28 (Frail et al. 1994), this satellite transition of the hydroxyl molecule has become a powerful tool for identifying when a SNR shock is interacting with a molecular cloud (see reviews by Wardle & Yusef-Zadeh 2002; Frail 2011). OH (1720 MHz) masers are found in about 10% of all Galactic SNRs and they are located on or near the synchrotron peaks. Observations of other molecular species have shown that the OH (1720 MHz) masers are found coincident with dense gas with broad line widths, indicative of post-shock gas (Hewitt et al. 2009; Reach et al. 2005; Arikawa et al. 1999; Frail & Mitchell 1998; Koo & Moon 1997). The velocity of the masers matches the systemic velocity of the molecular gas because strong maser amplification favors shocks transverse shocks with long coherent pathlengths (Green et al. 1997).

It is thought that the OH molecule is formed downstream of a non-dissociative, compression-type shock (20–30 km s\(^{-1}\)) that has propagated into a molecular cloud with densities of the order of \(n_\text{H}_2 = 10^4\)–10\(^5\) cm\(^{-3}\) and temperatures of 30–120 K. Under these conditions, a strong collisionally pumped maser transition results for the OH molecule at 1720 MHz (Lockett et al. 1999). Thus the detection of a OH (1720 MHz) maser is unambiguous proof of an interaction, unlike other tracers such as H\(_1\) or CO emission. The OH provides other physically useful information like the gas density, the geometry of the shock, the radial velocity (for kinematic distances), and in some cases the in situ magnetic field.

Claussen et al. (1997) first noted the link between γ-ray bright SNRs (Esposito et al. 1996) and OH (1720 MHz) masers. This correlation has only gotten stronger as the number of TeV/GeV SNRs has grown (Hewitt et al. 2008; Castro & Slane 2010). Prominent SNRs with OH (1720 MHz) masers and bright γ-rays include W28, W44, IC443, W51C, and W30 (see tables in Frail et al. 2007). The physical relationship between OH (1720 MHz) masers and γ-ray bright SNRs may be direct or indirect. In the later case, the OH is produced downstream of the molecular shock by dissociating H\(_2\)O using the thermal X-rays interior to the remnant (Wardle 1999) and hence the maser is just a signpost for the SNR interacting with a molecular cloud. In the latter, it is the enhanced production of the cosmic rays at the SNR shock that dissociates the H\(_2\)O into OH (Hewitt et al. 2008). In this case there is a close one-to-one relationship between OH and cosmic rays. Observations of molecular ions serve as a diagnostic of cosmic ray ionization rates \(\zeta_\text{CR}\) and therefore could test this hypothesis directly. Recent measurements of \(\zeta_\text{CR}\) near SNRs show enhanced values in dense molecular clouds adjacent to the W51C (Ceccarelli et al. 2011) and in diffuse clouds adjacent to IC443 (Indriolo et al. 2010).

For the specific example of J1834−087, the coincidence of TeV emission toward a GMC does not require that the W41 SNR be the particle accelerator (Albert et al. 2006). Likewise, there is no strong evidence that W41 is interacting with the ubiquitous neutral (H\(_1\)) or molecular (CO) gas along the line of sight (Tian et al. 2007). However, with the detection of the OH at the same velocity of the molecular cloud, there is now stronger evidence that support these earlier claims that the SNR is interacting with the GMC. The shock-excited OH (1720 MHz) maser emission requires that the SNR interacts with the same dense molecular gas needed to produce bright γ-ray emission. This interaction produces the observed gamma-ray luminosity provided the W41 SNR was the result of a canonical 10\(^51\) erg explosion giving up a few percent of its energy to cosmic ray acceleration (Tian et al. 2007). W41 joins a group of middle-aged, γ-ray bright SNRs including W44, IC443, W28, and W51C. Their interaction with a clumpy, dense molecular cloud is key to explaining their gamma-ray luminosity (Chevalier 1999; Uchiyama et al. 2010) and other unusual properties, including steep VHE spectra (Caprioli 2011).

Misanovic et al. (2011) argue that the location of J1834−087 within W41 is a challenge for the hadronic model. They expect that the brightest high energy emission would originate from the outer shell of W41 where the synchrotron emission (Figure 1) traces the interaction with the surrounding medium. Note also that the GeV emission from 2FGL J1834.3−0848 does partially overlap with the W41 shell. Either the offsets between the GeV and TeV emission are real, or they originate due to uncertainties in correcting for the diffuse background and the large point spread function of Fermi compared to H.E.S.S. Nonetheless, if we compare W41 to the sample of SNRs that show a correlation between γ-rays and OH (1720 MHz) masers, this offset does not appear to be a significant problem for the model. While OH masers are seen along SNR shells, they are not uncommon interior to SNRs. J1834−087 and the OH masers are found toward a bright, extended synchrotron emission and in this respect the W41 system resembles IC443 in terms of the location of the masers and the GeV/TeV emission (Tavani et al. 2010; Acciari et al. 2009).

We conclude by noting that while these observations give new impetus to hadronic models, they do not diminish the possibility that some of the VHE emission from J1834−087 could be leptonic in origin produced by one or more energetic neutron star candidates. Further radio observations could strengthen the hadronic model, improving the limits on the brightness temperature of the OH emission and perhaps measuring the in situ magnetic field using Zeeman splitting. A refinement in the properties of the dense gas would also be possible by imaging J1834−087 lines such as NH\(_3\) and SiO, for example (Nicholas et al. 2012; Brogan et al. 2013). The detection of OH masers indicates post-shock molecular gas with densities and temperatures over a broad range of order \(n_\text{H}_2 = 10^4\)–10\(^5\) cm\(^{-3}\) and 30–120 K. However, an accurate mapping of dense gas could lead to better quantitative estimates of the expected brightness of the high energy emission produced by W41.

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REFERENCES

Acciari, V. A., Aliu, E., Arlen, T., et al. 2009, ApJL, 698, L133
Ackermann, M., Ajello, M., Allafort, A., et al. 2013, Sci, 339, 807
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006, ApJ, 636, 777
Albert, J., Aliu, E., Anderhub, H., et al. 2006, ApJL, 643, L53
