A 330 MHz SURVEY FOR PULSARS AND SUPERNOVA REMNANTS IN M31

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Abstract

In the radio band, supernova remnants (SNR) and pulsars are best identified at low frequencies due to their steep spectra. Motivated by this fact, we have carried out a deep 330 MHz observation of M31 using the VLA. Achieving a sensitivity of 0.6 mJy at 6″ resolution over the entire optical disk of M31, we identified 405 distinct radio sources. While most of these are unresolved background radio galaxies, we found five SNR candidates, three pulsar wind nebula (PWN) candidates, and three pulsar candidates in our source list. The properties of these sources are discussed.

1 Introduction

M31, at a distance of only 780 kpc (Stanek & Garnavich, 1998), is the nearest spiral galaxy to our own Milky Way and therefore is both a natural place to search for extragalactic supernova remnants (SNRs), and serves as a point of comparison for our galaxy. In an attempt to better understand the radio population of M31, particularly the steep-spectrum population, we mapped M31 at ν = 330 MHz (λ = 90 cm) using the Very Large Array (VLA) A-array with a resolution of 6″ and better than mJy sensitivity across the entire field of view. Since the primary beam of the VLA is $> 2°$ at 330 MHz, we were able to map the entire optical disk of M31 in just one pointing. Out of the 405 radio sources detected, five were identified as SNR candidates, three as pulsar wind nebula (PWN) candidates, and three as pulsar candidates.

2 Candidate sources

The SNR, PWN, and pulsar candidates discovered in this survey were identified using the following criteria – the source had to be inside the optical disk of M31, unresolved or marginally resolved in our images, and either be:

- coincident with an optical SNR candidate in M31 (Criterion A in Table 1),
- coincident with an optical H II region candidate in M31 and have radio spectral index $\alpha < -0.1$ (defined such that $S_\nu \propto \nu^\alpha$, Criterion B in Table 1),
- have a radio spectrum that steepens at low frequencies – the possible signature of a SNR/H II-region complex (Criterion C in Table 1),
- have an X-ray counterpart with a soft spectrum that has not been identified as a radio galaxy based on optical observations (Criterion D in Table 1),
- or a counterpart in the ROSAT 2nd PSPC survey of M31 (Supper et al., 2001) that has been classified as a SNR based on previous work (Criterion E in Table 1).

While not all radio SNR, PWN, and pulsars in M31 satisfy these requirements, this set of criteria are effective at rejecting background radio galaxies. Eleven sources met this criteria, and were separated into SNR, PWN, and pulsar candidates by their radio spectral index α. A source was classified as a SNR candidate if it satisfied the above criteria and had $-1.0 \leq \alpha \leq -0.$, as a PWN candidate if it had a spectral index $\alpha > -0.3$,

Table 1: M31 SNR, PWN, and pulsar candidates

Name	Criterion	Size [pc]	L_R [erg s^{-1}]
GLG020	A	<23 × <20	2.33×10^{34}
GLG037	A	37 × <20	2.13×10^{34}
GLG056	B	<21 × <18	2.33×10^{34}
GLG123	A	<20 × <17	8.95×10^{34}
GLG193	D	<20 × <19	2.06×10^{34}
GLG011	A	<20 × <18	1.22×10^{36}
GLG068	A E	<21 × <19	9.68×10^{34}
GLG198	C	<23 × <17	5.80×10^{35}
GLG014	D	...	...
GLG036	B	...	...
GLG205	B	...	...

and as a pulsar candidate if it had a spectral index $\alpha < -1.0$. These sources are listed in Table 1 - the first five sources in this table are the SNR candidates, the second three are the PWN candidates, and the last three are the pulsar candidates. The radio luminosity L_R of these sources was calculated over the frequency range of 10 MHz to 10 GHz assuming that the radio spectrum had no curvature.

Supernova Remnant Candidates: For comparison purpose, we calculated the 325 MHz flux densities (S_{325}) and major axis (θ_M) of known SNRs in the Milky Way (MW; Green (2002); Case & Bharracharya (1998)), Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC) (Berkhuijsen, 1986) and M33 (Gordon et al., 1999) if they were at the distance of M31. Figure 1 shows the 325 MHz flux density S_{325} versus major axis θ_M for these SNRs, as well as for the SNR candidates in M31 identified above. The GLG SNR candidates fall within the locus of points defined by SNRs in these other galaxies, implying that they are most likely not background sources. However the sample of known SNRs in the MW, LMC, SMC, and M33 are subject to a myriad of selection effects, and there are GLG sources not classified as SNR candidates that have similar S_{325} and θ_M. From Fig. 1, the SNR candidates detected in our survey – if they indeed are SNRs – appear to be the brightest, and therefore probably youngest, SNRs in M31. These SNR candidates are brighter than known radio SNRs in M31, e.g., Sjouwerman & Dickel (2001), which were not detected in our survey. While some of these candidates have additional evidence that they are SNRs, e.g., the X-ray spectrum GLG020 is best explained by a Raymond-Smith model with parameters typical of SNRs (Trudolyubov et al., 2004), higher resolution radio imaging as well as deeper X-ray imaging is needed to verify that they are SNRs and to better determine their properties.

Pulsar Wind Nebula Candidates: While not the brightest PWN, the quintessential PWN in the Milky Way is the Crab nebula, with a radio luminosity L_R of 1.8×10^{35} erg s^{-1} (Helfand & Becker, 1987). As shown in Table 1 two of the three PWN candidates detected in the GLG survey, GLG011 and GLG198, have higher radio luminosities than the Crab nebula by a factor of a few. This is surprising but does not necessarily disqualify these sources from being PWN. GLG011 and GLG068 have X-ray counterparts with luminosities and X-ray to radio luminosity ratios similar to that of the galactic PWN (Helfand & Becker, 1987). The X-ray spectrum for GLG011 is best fit by a power-law model typical of most PWN (Sergey Trudolyubov, private communication), while the X-ray spectrum of GLG068 is best fit by a thermal-bremsstrahlung spectrum more typical of SNR shells (Albert Kong, private communication). This discrepancy between the radio and X-ray emission could be explained if the radio emission originated from the central PWN and the X-ray emission from the outer SNR shell. Deeper X-ray observations are required to determine if this is the case.

Pulsar Candidates: All three GLG sources identified as pulsar candidates, if placed at the distance of M31, would be several orders of magnitude more luminous than any known galactic pulsar. Therefore, it is unlikely that these sources are pulsars in M31. However, radio sources with spectrum as these are rare and are interesting – and they can be extremely variable sources, high-z radio galaxies, relic radio galaxies, or possibly pulsars in the halo of the Milky Way or in between M31 and the Milky Way. Additional observations at radio and optical wavebands are needed to determine the nature of these sources.

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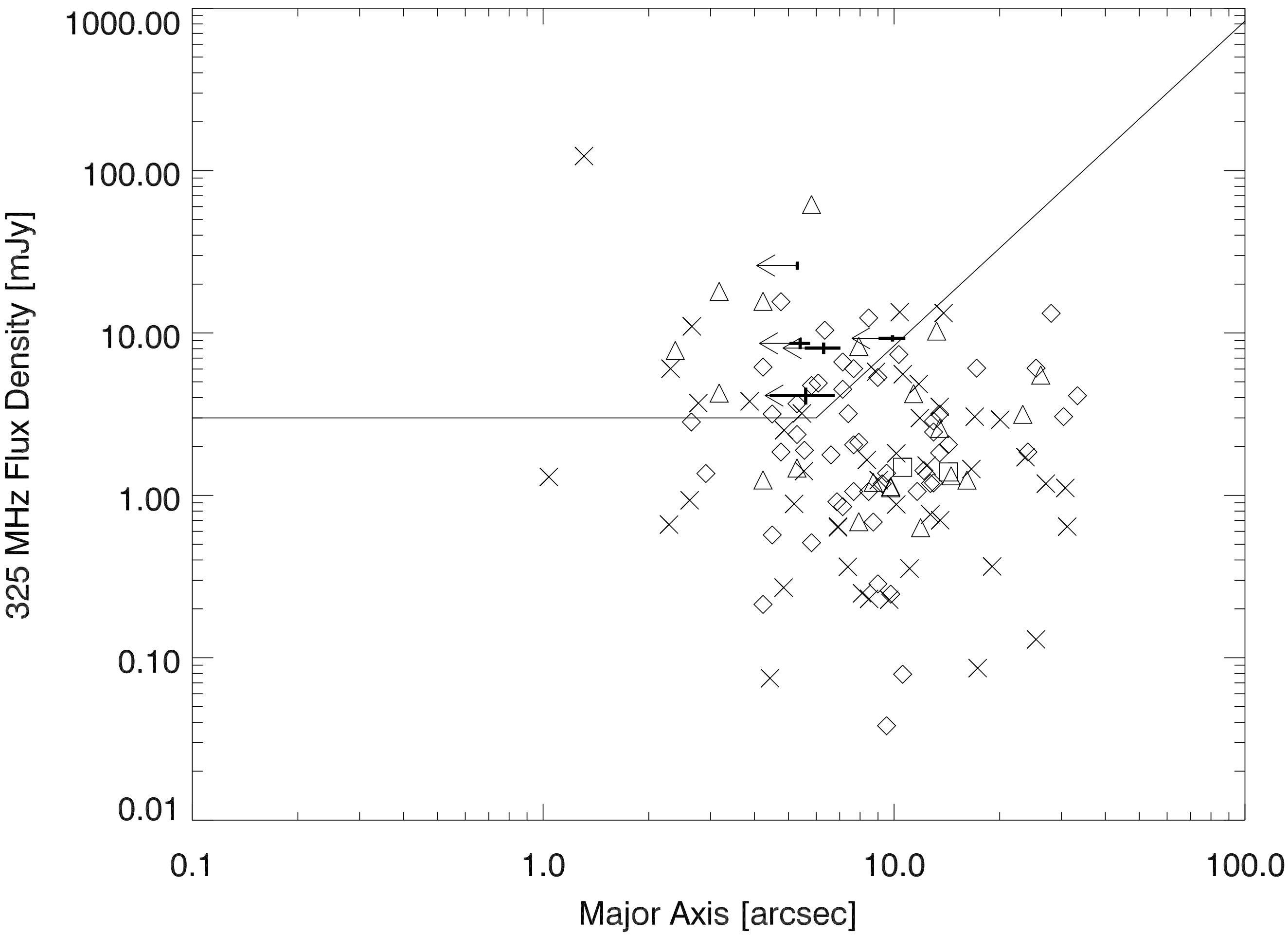

Figure 1: S_{325} versus θ_M of Milky Way ($\times$'s), M33 (diamonds), LMC (triangles), and SMC (squares) supernova remnants if placed at the distance of M31. SNR candidates in the GLG sources are denoted by the thick "+" signs. Arrows indicate the upper limit on θ_M for GLG SNR candidates. The line represents the observational limits of the GLG survey – only SNRs with a flux density $S_{325} > 3$ mJy beam^{-1} will be detected.

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