The magnetic environment in the central region of nearby galaxies

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Abstract. The central regions of galaxies harbor some of the most extreme physical phenomena, including dense stellar clusters, non-circular motions of molecular clouds and strong and pervasive magnetic field structures. In particular, radio observations have shown that the central few hundred parsecs of our Galaxy has a striking magnetic field configuration. It is not yet clear whether these magnetic structures are unique to our Milky Way or a common feature of all similar galaxies. Therefore, we report on (a) a new radio polarimetric survey of the central 200 pc of the Galaxy to better characterize the magnetic field structure and (b) a search for large-scale and organized magnetized structure in the nuclear regions of nearby galaxies using data from the Very Large Array (VLA) archive. The high angular resolution (∼5") of the VLA allows us to study the central 1 kpc of the nearest galaxies to search for magnetized nuclear features similar to what is detected in our own Galactic center. Such magnetic features play an important role in the nuclear regions of galaxies in terms of gas transport and the physical conditions of the interstellar medium in this unusual region of galaxies.

1. Introduction

Magnetic fields play crucial roles in the interstellar environments of galaxies and are observed on a number of scales in galaxies, up to scale lengths of 8 kpc for the regular, organized fields in the disks (e.g., Beck 2004, Beck and Gaensler 2006). Radio synchrotron observations are one of the best ways to probe magnetic fields across galaxies as radio waves are not subject to interstellar extinction. In addition to revealing maps of the magnetic field structure, radio observations give estimates for the mean equipartition magnetic field strengths in galaxies from ∼10-20 µG in galactic spiral arms, and ∼40 µG in galactic nuclear regions. The central regions of galaxies harbor some of the most extreme physical phenomena, including dense stellar clusters, non-circular motions of molecular clouds and strong and pervasive magnetic field structures. In addition, studies across the electromagnetic spectrum reveal that galactic nuclei are major sites of episodic and energetic phenomena related both to active galactic nuclei (AGN) and also to intense bursts of star formation.

Recently, studies of the circumnuclear regions of several galaxies have revealed that magnetic fields in this part of the galaxy may help to transport materials into the nuclear region (which then may fuel a starburst or AGN). In the barred galaxies, NGC1097 and NGC1365, radio emission is enhanced along the bar regions, indicating the presence of a shock front. Further, magnetic stresses in the circumnuclear ring can then drive mass inwards at rates high enough to feed nuclear activity (Beck et al 1999; 2005). In the spiral ringed galaxy M 94 (NGC 4736)
the polarized radio emission reveals a pattern of ordered magnetic field arising from the central regions of the galaxy that may be where magnetic amplification occurs (Chyży and Buta 2008). In addition, the expulsion of materials from the nucleus may also be regulated by magnetic fields. Energetic events arising from star-burst or AGN activity in the nucleus often result in explosive vertical “fountains” of million degree gas, rising 1–2 kiloparsec (kpc) above galactic nuclear regions (e.g., NGC 1569 and NGC 4631; Heckman et al. 1995). These fountains may well be related to vertical magnetic field structures and outflow from the galactic disk (e.g., NGC 4631; Golla and Hummel 1994).

Detailed knowledge of the violent interplay between stellar and magnetized interstellar components is limited for most galactic nuclei because of their great distances, even for the most sophisticated observational instrumentation. At a distance of only 8.0 kpc, the center of our Milky Way galaxy provides an excellent laboratory for detailed studies of the interplay of massive stars, gas and, importantly, magnetic fields. Because of the nearly 30 magnitudes of visual extinction toward this region of our Galaxy, studies at radio wavelengths have proved to be fruitful in understanding the details of the magnetized interstellar medium and for understanding the nuclei of nearby, normal galaxies.

2. Our Galactic Center

2.1. The Magnetized Environment

One of the most striking aspects of the radio continuum image of our Galactic center (GC) shown in Fig. 1 is the presence of the narrow linear features oriented essentially perpendicular to the orientation of the Galactic plane. First detected with the VLA by Yusef-Zadeh, Morris and Chance (1984), the 8 well-known non-thermal filaments (NTFs) have the following properties (Gray et al. 1995; Yusef-Zadeh et al. 1997; Lang et al. 1999a): (1) show strong linear polarization (30–50% in most cases) and (2) have intrinsic magnetic field orientations aligned along their lengths, indicating that they may trace a large-scale poloidal magnetic field (e.g., Morris and Serabyn 1996). The magnetic field traced by these NTFs is opposite to the orientation of the magnetic field in the galactic disk, which is azimuthal and follows the spiral arms. Several theories have explored the origin and stability of such a field structure (Chandran, Cowley and Morris 2000; Chandran 2001). One idea is that the magnetic field may be pervasive throughout the GC, with the NTFs representing sites of relativistic particles (Morris 1994). More recently, many new NTFs have been detected with lower surface brightnesses, shorter extents and many different orientations (Lang et al. 1999b; LaRosa et al. 2004; Yusef-Zadeh et al. 2004) and the overall structure of the magnetic field has yet to be fully uncovered. La Rosa et al. (2005) suggest that the numerous weak and randomly-oriented filamentary structures suggest a much weaker, more local and dynamic field configuration in this region of the Galaxy.

The magnetic pressure for field strengths of 0.1–1 mG (which is what is estimated for the magnetic field in the GC) corresponds to 4 ×10^{-10} to 4 ×10^{-9} erg cm^{-3} and is likely to be balanced by the pressure from the hottest interstellar components. Careful comparisons between diffuse X-ray emission and radio features can provide insight on this balance. The results of Wang, Gotthelf and Lang (2002) show that the diffuse X-ray emission is consistent with T\sim10^7 K hot gas, which corresponds to a pressure in the hot component of \sim1–5\times10^{-10} erg cm^{-3} for a particle density of 0.1–0.5 cm^{-3}. Therefore, the correlation between the diffuse, hot X-ray emission and the magnetic fields in the GC region has important implications for the confinement of hot gas, and the ultimate transport of such energetic ISM components out of the nuclear region of the Galaxy (e.g., Shibata and Uchida 1987).
2.2. Large-scale VLA 4.9 GHz Polarimetric Survey

Although a number of lower frequency surveys of the GC have recently been made (Nord et al 2004; Yusef-Zadeh et al 2004), uniform coverage at a higher frequency (> 1.4 GHz) has not been carried out until this work. In particular, large rotation measures (> 1000 rad m$^{-2}$) toward the GC (Yusef-Zadeh et al 1997; Lang et al 1999a,b) cause complete depolarization at 1.4 GHz, which is why this 4.9 GHz survey is ideally suited for detecting polarized intensity from magnetized features in the GC, including the enigmatic new “streaks” (NTF-candidates) (Nord et al 2004; Yusef-Zadeh et al 2004). Determining whether the new NTF-candidate sources are polarized may allow us to uncover an underlying magnetic field structure in the GC and will greatly increase the number of NTF sources in this region.

We have begun to construct the first 4.9 GHz mosaic of the GC region made from 90 pointings in D-configuration and 50 pointings in C-configuration with the VLA in order to study extended structures in total and polarized intensity. Observations were made during 2003-2006, and data calibration for all fields in both configurations is nearly completed. The quality of the data is very high and the total integration time on source is ~75 minutes per pointing. The combination of data from these two configurations should provide sensitivity to diffuse large-scale structures.
but also have a final angular resolution of <10′′. Mosaicking such a large and complex region in full Stokes mode (i.e., both total and polarized intensity) has proven to be a challenge. The Multi-Scale Clean algorithm available in CASA, the new software package being developed by the National Radio Astronomy Observatory is designed for fields like our GC mosaic, which have a substantial diffuse component in addition to numerous compact sources.

Figure 2 shows preliminary images from both the D- and C-configuration data in total and polarized intensity. The preliminary results are promising, revealing newfound detail in several areas: (1) numerous compact and extended features in the region between Sgr A and Sgr C, shown in Fig. 2 (lower left), have not been previously studied in the radio continuum with such high resolution. A number of these sources appear to have shell-like morphology which indicates they may be tracing massive star-forming activities. Several of these sources have mid-IR counterparts in recently published Spitzer images (Stolovy et al in prep.); (2) the survey has begun to reveal polarized intensity from several candidate NTFs, and upon further polarization corrections, we hope to uncover many more polarized counterparts to candidate NTFs. Figure 2 (lower right) shows strong polarized intensity from four of the well-known NTFs; finally, (3) the C-configuration data show a large number of new compact sources which will assist in understanding the true radio point source population in the GC and the nature of these sources (e.g., pulsars, extragalactic, etc.). When completed, by combining the D- and C-configuration data and producing a complete source catalog for total and polarized intensity, this survey should be able to address the following questions: (1) Are the numerous NTF-candidates polarized, and if so, do they trace out an underlying complex magnetic field structure, (2) Is the magnetic field in the GC region strong and pervasive or weak and diffuse with enhancements? (3) How do massive stars impact the ISM? and (4) What is the radio point-source population at the GC?

3. Nearby Galactic Nuclei

Our results from the GC indicate that the magnetic field is strong and well-organized in this region and plays an important role in the transport of plasma and energy out of the nuclear region. We have therefore begun an archival investigation of the central regions of the nearest, normal-type galaxies (analogs to the Milky Way). A search for similarly coherent magnetized features in nearby galaxies will allow us to better understand the role and uniqueness of the magnetic fields in the GC of the Milky Way.

3.1. Target Criteria

The best targets for such a study are located at distances < 10 Mpc, so that 1′′ (which is a typical resolution of the VLA) resolution corresponds to no more than about 50 pc. In addition, potential targets should be normal galaxies not thought to be undergoing a large starburst episode (although may have in the past). The study of extended, polarized features in M81 illustrates that the nuclear regions of other normal galaxies may be rich in magnetized and filamentary features similar to those found in our own Galactic center (Kaufman et al 1996). These authors used the VLA in all its configurations at both 1.4 and 4.9 GHz to obtain 1′′ and better spatial resolution. Kaufman et al (1996) identify a large-scale (up to 1 kpc) magnetized “arc” within the inner 1 kpc of the galaxy, indicating that the interstellar magnetic field in this region is well-organized. In addition, the compact source in the center of M81 (M81*: Brunthaler et al 2001) has been found to be one of the best analogs to the GC compact source Sgr A*. Sjouwerman et al (2005) have used a large number of 4.9 GHz multi-configuration, archival, VLA observations of the nuclear regions of M31 and identified a non-thermal filamentary structure at very weak flux levels in the central kpc of the galaxy. Using the VLA archive, we identified multi-configuration, multi-frequency radio continuum observations of the nuclear regions of the above galaxies at 1.4 or 4.9 GHz in the A, B and C array configurations.
Figure 2. (Top) Preliminary 4.9 GHz mosaic image using D-array data only (resolution \(\sim 20''\)).
(Lower left): Inset of C-array mosaic in the vicinity of SgrC showing numerous compact and shell-like features indicating the presence of massive star forming activities with resolution \(\sim 6''\).
(Lower right): Inset of polarized intensity from the C-array mosaic, with 4 NTFs at positive Galactic latitudes labeled with white arrows.

3.2. Archival Imaging & Results

Table 1 lists the galaxies for which we found data at 1.4 and 4.9 GHz with sufficient angular resolution \((<5'')\) and high sensitivity (rms levels < 0.1 mJy) in the VLA archive. Figures 3–
| Galaxy | Distance (Mpc) | Scale (arcsec) | Reference/Archive Code |
|--------|----------------|----------------|------------------------|
| M 31   | d=0.7          | 1"=3 pc        | Sjouwermann et al (2005) |
| M 33   | d=0.8          | 1"=4 pc        | this paper/ AK140       |
| M 81   | d=3.5          | 1"=17 pc       | Kaufman et al (1996)    |
| M 83   | d=4.5          | 1"=22 pc       | this paper/ AW418        |
| M 94   | d=4.5          | 1"=22 pc       | this paper/ AD145        |
| M 51   | d=8.0          | 1"=40 pc       | this paper/ AC147        |

**Table 1.** Nearby Galactic Nuclei Properties

Figure 3. Nuclear region of M 33 at 4.9 GHz (resolution: 7.17" × 6.16").

Figure 4. Nuclear region of M 83 at 4.9 GHz (resolution: 1.40" × 1.32").

6 show images of the central kpc or less in each of the galaxies for which we found archival observations. In all cases, there was sufficient (u,v) coverage and integration time to do polarization calibration.

**M 33:** The 4.9 GHz image of M 33 in Fig. 3 shows the central few hundred parsecs of M 33. There is diffuse emission in an 'arc'-like configuration surrounding the nucleus. This emission extends for approximately 1.5' total (350 pc at 0.8 Mpc), or ~150 pc on either side of the nucleus (indicated by a cross). Using a similar-resolution 1.4 GHz image, the spectral index of the radio emission was found to vary between $\alpha = -0.2$ and $-0.4$, roughly consistent with non-thermal emission. Total intensity in this diffuse arc is faint (100–300 $\mu$Jy beam$^{-1}$) and the rms level in the image is $\sim 25$ $\mu$Jy beam$^{-1}$. Therefore, for even 50% polarization ($\sim 50$–150 $\mu$Jy beam$^{-1}$), which is optimistic, the sensitivity in this dataset is not high enough to make a confident detection of polarized intensity.

**M 83:** Figure 4 shows radio emission at 4.9 GHz arising from the central 1 kpc of M 83 with ~1" resolution. Diffuse radio emission is present over the entire nuclear region, with peaks near the
very center of the galaxy. The extended emission has a spectral index between 4.9 and 1.4 GHz of $\sim-0.5$ to $-0.9$. There is no detectable polarization arising from the brightest regions of total intensity ($\sim2-4$ mJy beam$^{-1}$), where it is possible to detect down to $\sim10\%$ polarization; however, for some of the weaker structures, it may not be possible to detect polarization with these archive data.

**M 94:** Figure 5 shows the central 300 pc of the nucleus of M 94 with a resolution of $\sim2''$. The radio emission shows a non-thermal spectral index in this region with $\alpha=-0.5$. Weak polarization (signal-to-noise of $\sim3$) was detected at 4.9 GHz in the central regions of the source, but was not detected at 1.4 GHz, so we cannot confirm that the archival data show polarization. However, recent VLA observations in D-configuration at 8 and 5 GHz with 10–15” resolution show that the nuclear region is strongly magnetized with a well-ordered circumnuclear field on slightly larger scales (Chyzy and Buta 2008).

**M 51:** A 1” image of the central regions of M 51 is shown in Fig. 6. The nuclear source is the bright point source in the center of the image. The nuclear source does not show polarization at 4.9 GHz, with rms noise levels of 15 $\mu$Jy. The source to the north of the nucleus has a loop-like morphology and is strongly suggestive of an outflow (Maddox et al 2007). In Fig. 6, this source has very weak radio emission (20 $\mu$Jy or so), and appears to be non-thermal in nature; however, these data do not have high enough sensitivity to reliably detect a polarized intensity counterpart for the loop-like structure.

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**Figure 5.** Nuclear region of M 94 at 4.9 GHz (resolution: $1.89'' \times 1.53''$).

**Figure 6.** Nuclear region of M 51 at 4.9 GHz (resolution: $0.55'' \times 0.45''$).
4. Future Work & Instrumentation

The Vlal archive search was a useful first attempt and allowed us to determine that existing observations are not sensitive enough to do a study of the polarization properties of diffuse emission in the central hundreds of parsecs to 1 kpc in nearby galaxies. Since sensitivity appears to be the main challenge, this project is ideally suited for the Expanded VLA (ELVLA). This upgrade to the VLA is currently in progress and expected to be fully available by 2012; in the meantime, there are many opportunities for shared-risk observing as the receivers are upgraded and correlator tested, and eventually replaced. The ELVLA is expected to have a factor of 10 improvement in sensitivity, especially in the 1-10 GHz range. This will be crucial for a study like this one, where we are hoping to obtain high-sensitivity images of nearby nuclei.

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