Role of Magnetic Fields in Fueling Seyfert Nuclei

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Abstract

Molecular gas is believed to be the fuel for star formation and nuclear activity in Seyfert galaxies. To explore the role of magnetic fields in funnelling molecular gas into the nuclear region, measurements of the magnetic fields embedded in molecular gas are needed. By applying the new velocity gradient technique (VGT) to CO isotopolog data from the Atacama Large Millimeter/submillimeter Array and the Plateau de Bure Interferometer Arcsecond Whirlpool Survey, we obtain the first detection of CO-associated magnetic fields in several nearby Seyfert galaxies and their unprecedented high-resolution magnetic field maps. The VGT-measured magnetic fields in molecular gas globally agree with those inferred from existing HAWC+ dust polarization and Very Large Array synchrotron polarization. An overall good alignment between the magnetic fields traced by VGT-CO and by synchrotron polarization may support the correlation between star formation and cosmic-ray generation. We find that the magnetic fields traced by VGT-CO have a significant radial component in the central regions of most Seyferts in our sample, where efficient molecular gas inflows or outflow may occur. In particular, we find local misalignment between the magnetic fields traced by CO and dust polarization within the nuclear ring of NGC 1097, and the former aligns with the central bar’s orientation. This misalignment reveals different magnetic field configurations in different gas phases and may provide an observational diagnostic for the ongoing multiphase fueling of Seyfert activity.

Unified Astronomy Thesaurus concepts: Extragalactic magnetic fields (507); Interstellar medium (847); Galaxy nuclei (609); Interstellar synchrotron emission (856)

1. Introduction

Magnetic fields, as the major component of interstellar media (ISM; Beck et al. 2005; Beck & Wielebinski 2013), impact star formation (McKee & Ostriker 2007), gas flows in spiral arms and bars (Abbate et al. 2020), and the formation and evolution of spiral galaxies (Beck & Wielebinski 2013; Lopez-Rodriguez 2020; Borlaff et al. 2021). The study of magnetic fields in one of the two classes of active galaxies, Seyfert galaxies, is essential for identifying their role in funneling the circumnuclear molecular gas (Krolik & Melksin 1990; Kim & Stone 2012), which holds the key for understanding the energy source of Seyferts and the connection between the enhanced star formation and Seyfert activity (Maiolino et al. 1997). However, progress is hampered by a lack of measurements of the magnetic fields directly associated with (extragalactic) molecular gas, which is the potential fuel powering the nuclear starburst and Seyfert activities.

The plane-of-the-sky (POS) magnetic field distribution is traditionally measured using polarization. Synchrotron polarization (Beck et al. 2005; Fletcher et al. 2011; Mulcahy et al. 2017; Stein et al. 2019, 2020) has recently been augmented by measurements of polarized dust emission by the Stratospheric Observatory for Infrared Astronomy (SOFIA; Jones et al. 2019; Lopez-Rodriguez et al. 2020, 2021; Lopez-Rodriguez 2021; Borlaff et al. 2021). It is believed that the polarization from dust is weighted with gas density and thus it is biased toward the magnetic fields in high-density media, while the synchrotron polarization depends on the acceleration and propagation of cosmic-ray electrons and samples the magnetic fields in more diffuse media. These two approaches have their limitations. For instance, dust polarization is sensitive to the dust alignment efficiency (Lazarian & Hoang 2007; Andersson et al. 2015), and synchrotron polarization can be distorted by Faraday rotation (Lazarian & Pogosyan 2016). More importantly, neither of them can separate out the magnetic fields associated with molecular gas from multiphase ISM.

In this paper, we employ a novel technique, the velocity gradient technique (VGT; Yuen & Lazarian 2017b; Gonzalez-Casanova & Lazarian 2017; Lazarian & Yuen 2018; Hu et al. 2018), to exclusively trace the magnetic fields in molecular gas. As CO is the best tracer of nuclear gas dynamics (García-Burillo et al. 2003), the application of VGT to the high-resolution CO maps of nearby Seyfert galaxies holds promise for understanding the role of magnetic fields in transporting the potential fuel toward the nuclei and the origin of nuclear activity. The VGT is established based on both observations showing the ubiquity of turbulence (Chepurnov & Lazarian 2010; Henshaw et al. 2020) and the recent progress in understanding the fundamental effects of magnetic fields on turbulence (Goldreich & Sridhar 1995; Lazarian & Vishniac 1999). As demonstrated by both state-of-the-art magnetohydrodynamic (MHD) simulations and in situ measurements in the solar wind (Cho et al. 2002; Hu et al. 2021c; Duan et al. 2021; Sakshee et al. 2022), turbulent motions...
in the presence of magnetic fields are preferentially in the direction perpendicular to the magnetic field due to the minimum resistance in this direction. As a result, the gradients of turbulent velocities are dominantly perpendicular to the local magnetic field. Therefore, by measuring the velocity gradient of the turbulent motions of molecular gas, one obtains maps of POS magnetic fields in the molecular gas phase.

The VGT has been extensively tested by numerical simulations in various astrophysical conditions (Lazarov & Yuen 2018; Hu et al. 2020a; Ho & Lazarian 2021), considering CO self-absorption (Hsieh et al. 2019; González-Casanova et al. 2019; Hu & Lazarian 2021) and self-gravity effects (Yuen & Lazarian 2017a; Hu et al. 2020b), and it has recently been applied to mapping magnetic fields in the Milky Way in different phases, from diffuse H I media (Hu et al. 2020c; Lu et al. 2020; Hu & Lazarian 2020) to dense molecular clouds (Hu et al. 2019, 2021a; Liu et al. 2022a; Alina et al. 2022), as well as the Central Molecular Zone (Hu et al. 2022a, 2022b). The requirement for the application of the VGT is that the turbulent injection scale is resolved, which is about 100 pc for the Milky Way (Chepurnov et al. 2010; Frisch & Dwarkadas 2017) and expected to be similar in other spiral galaxies. Therefore, with high-resolution Atacama Large Millimeter/submillimeter Array (ALMA; Tosaki et al. 2017; Leroy et al. 2021a) and Plateau de Bure Interferometer Arcsecond Whirlpool Survey (PAWS; Hughes et al. 2013) spectroscopic data, the VGT opens a radically new avenue to mapping magnetic fields of nearby galaxies that is complementary to both synchrotron and dust polarization measurements.

In this work, we apply the VGT for the first time to extragalactic environments. We employ the VGT for five nearby Seyfert galaxies, M51 (Hughes et al. 2013), NGC 1068 (Tosaki et al. 2017), NGC 1097 (Lopez-Rodriguez et al. 2021), NGC 3627 (Soida et al. 2001), and NGC 4826 (García-Burillo et al. 2003), by using molecular emission line data of CO isotopologs obtained from ALMA and PAWS archive (Hughes et al. 2013; Tosaki et al. 2017; Leroy et al. 2021a, 2021b). We compare our results on the first four galaxies with the dust polarization data from the SOFIA legacy program (Lopez-Rodriguez et al. 2020, 2021; Borlaff et al. 2021) and synchrotron polarization data from the Very Large Array (VLA; Beck et al. 2005; Fletcher et al. 2011). We also use the VGT to produce the first magnetic field map of NGC 4826, for which no polarization data are available yet.

This paper is organized as follows. In Section 2, we briefly describe the PAWS, ALMA, VLA, and HAWC+ data used in this work. In Section 3, we review the basic concepts of MHD turbulence and introduce the pipeline of the VGT. We apply the VGT to five Seyfert galaxies and present the results in Section 4. We discuss the implications for the magnetic fields’ role in fueling Seyfert nuclei and the galactic dynamo in Section 5. We summarize our results in Section 6.

### 2. Observational Data

#### 2.1. Emission Lines

The $^{12}$CO ($J = 1–0$), $^{13}$CO ($J = 1–0$), and $^{12}$CO ($J = 2–1$) emission lines used in this work come from the PAWS (Hughes et al. 2013), ALMA NGC 1068 project (Tosaki et al. 2017), and the Physics at High Angular Resolution in Nearby Galaxies (PHANGS)–ALMA survey (Leroy et al. 2021a), respectively. A summary of the data sets is presented in Table 1.

| Galaxy     | Distance | Resolution | Emission Line | Data Source   | $\Delta v$   | Polarization               |
|------------|----------|------------|---------------|---------------|--------------|---------------------------|
| M51        | 7.6 Mpc  | 37.0 pc    | $^{12}$CO($J = 1–0$) | PAWS          | 5.0 km s$^{-1}$ | HAWC+ 154 $\mu$m and VLA 6.2 cm |
| NGC 1068   | 14.4 Mpc | 98.0 pc    | $^{12}$CO($J = 1–0$) | ALMA          | 1.5 km s$^{-1}$ | HAWC+ 89 $\mu$m          |
| NGC 1097   | 17.0 Mpc | 82.0 pc    | $^{12}$CO($J = 2–1$) | PHANGS-ALMA   | 2.5 km s$^{-1}$ | HAWC+ 89 $\mu$m and VLA 3.5 cm |
| NGC 3627   | 9.6 Mpc  | 47.0 pc    | $^{12}$CO($J = 2–1$) | PHANGS-ALMA   | 2.5 km s$^{-1}$ | HAWC+ 154 $\mu$m          |
| NGC 4826   | 5.3 Mpc  | 26.0 pc    | $^{12}$CO($J = 2–1$) | PHANGS-ALMA   | 2.5 km s$^{-1}$ | ...                       |

*Note.* $\Delta v$ represents the velocity resolution of emission lines. PAWS: Hughes et al. (2013). ALMA: Tosaki et al. (2017). PHANGS–ALMA: Leroy et al. (2021a, 2021b). HAWC+: Borlaff et al. (2021); Lopez-Rodriguez et al. (2020, 2021). VLA: Fletcher et al. (2011); Beck et al. (2005).

### 2.2. Polarization Measurement

We use the High-resolution Airborne Wideband Camera Plus (HAWC+) polarization measurement obtained from HAWC+ archival database (Harper et al. 2018; Lopez-Rodriguez et al. 2020; Borlaff et al. 2021). The magnetic field orientation is defined as $\phi_B = \phi + \pi/2$, where $\phi$ is the polarization angle. We use the band D measurement (154 $\mu$m, FWHM $\approx 13^\circ$6) for galaxies M51 and NGC 3627, and the band C measurement (89 $\mu$m, FWHM $\approx 7^\circ$8) for NGC 1068 and NGC 1097. We also adopt the VLA radio observation (combined with the Effelsberg telescope) at wavelength 6.2 cm (FWHM $\approx 8^\circ$0) for M51 (Fletcher et al. 2011) and at 3.5 cm (FWHM $\approx 3^\circ$0) for NGC 1097 (Beck et al. 2005). We consider only pixels with $p/\sigma_p > 2$, where $p$ is the polarization fraction and $\sigma_p$ is its uncertainty. The polarization data are not smoothed further but regridded to match data from the VGT-measured magnetic field orientation.
3. Methods

3.1. Anisotropy of MHD Turbulence and Velocity Gradients

The method of tracing magnetic fields through velocity gradients is rooted in the theories of MHD turbulence (see Goldreich & Sridhar 1995, hereafter GS95) and turbulent reconnection (see Lazarian & Vishniac 1999, hereafter LV99). In what follows, we briefly explain the essentials.

The prophetic study of GS95 proposed that the turbulent eddy is anisotropic, i.e., the eddy is elongating along the magnetic field. Or in other words, the maximum velocity fluctuation appears in a direction perpendicular to the magnetic field. This anisotropy can be derived from the “critical balance” condition: the cascading time \((k_{∥}v_{∥})^{-1}\) equals the wave period \((k_{∥}v_{A})^{-1}\). Considering that the velocity fluctuation is scale-dependent, for instance, the Kolmogorov-type turbulence \(v_{l} \propto l^{1/3}\). Here \(k_{∥}\) and \(k_{⊥}\) are wavevectors parallel and perpendicular to the magnetic field, respectively. \(v_{l}\) is turbulent velocity at scale \(l\) and \(v_{A}\) is Alfvén speed. The corresponding GS95 anisotropy scaling is then

\[
k_{∥} \propto k_{A}^{2/3}
\]

which reveals the anisotropy increases as the scale of turbulent motions decreases. However, this derivation is drawn in Fourier space, in which the local spatial information is not available, so the anisotropy is measured with respect to the mean magnetic field, which builds up the global reference frame. In this frame, anisotropy of larger eddies dominates over small eddies (Cho & Vishniac 2000). Consequently, one can only observe a scale-independent anisotropy, which is dominated by the largest eddy (Cho & Vishniac 2000; Hu et al. 2021c).

The scale-dependent anisotropic property of sub-Alfvénic MHD turbulence was later derived by LV99. LV99 explained that the scale-dependent anisotropy is only observable in the local reference frame, which is defined in real space with respect to the mean magnetic field passing through the eddy at scale \(l\). In this frame, spatial information is available to define the local magnetic field. As local magnetic fields gives minimal resistance along the direction perpendicular to the magnetic field, it is easier to mix the magnetic field lines instead of bending them. Consequently, the turbulent cascading is channelled in the direction perpendicular to the magnetic field. Again, for instance, considering the Kolmogorov-type turbulence, the motion of eddies perpendicular to the local magnetic field direction obeys the Kolmogorov law \(v_{L} \propto l_{⊥}^{1/3}\). Here \(l_{∥}\) and \(v_{l∥}\) are the perpendicular components of the eddies’ scale and velocity with respect to the local magnetic field, respectively. With the “critical balance” in the local reference frame, \(v_{l∥}l_{∥}^{-1} \approx v_{L}l_{⊥}^{-1}\), one can obtain the scale-dependent anisotropy scaling:

\[
l_{∥} = L_{inj}\left(\frac{l_{⊥}}{L_{inj}}\right)^{2/3} M_{A}^{-4/3}, \quad M_{A} \leq 1
\]

where \(l_{∥}\) is the parallel component of the eddies’ scale. \(L_{inj}\) is the turbulence injection scale and \(M_{A}\) is the Alfvén Mach number. This scale-dependent anisotropy in the local reference frame was demonstrated numerically (Cho & Vishniac 2000; Maron & Goldreich 2001) and observed in situ in the solar wind (Wang et al. 2016; Matteini et al. 2020; Duan et al. 2021).

Super-Alfvénic MHD turbulence (i.e., \(M_{A} > 1\)) is typically isotropic. The super-Alfvénic motions at the injection scale are hydrodynamic due to the relatively weak backreaction of the magnetic field. However, the kinetic energy of turbulent motions follows the nearly isotropic turbulent cascade. The importance of magnetic backreaction gets stronger at smaller scales. Eventually, at the scale \(l_{c} = L_{inj}M_{A}^{-3}\), the turbulent velocity becomes equal to the Alfvén velocity so that the turbulence is anisotropic (Lazarian 2006).

In particular, the corresponding anisotropy scaling for velocity fluctuations and the amplitude of velocity fluctuations’ gradient are (Lazarian & Vishniac 1999)

\[
\nabla v_{l} \propto v_{L} \left(\frac{l_{⊥}}{L_{inj}}\right)^{-2/3} M_{A}^{1/3}
\]

where \(v_{inj}\) is the injection velocity. The direction of \(\nabla v_{l}\) indicates the direction of the maximum changes in velocity fluctuations, i.e., perpendicular to the local magnetic field.

A vital property of turbulence’s gradient induced by turbulence is the increase in gradient amplitude with decreasing scale (Hu et al. 2022a), which is not usually true for a large-scale gradient of nonturbulent nature, for instance, galactic differential rotation. When dealing with Seyfert galaxies, it is therefore necessary that the observation resolves the turbulence’s injection scale to \(\sim 100\) pc so that the turbulent gradient dominates, although this does not exclude that in some observations gradients cannot arise for other reasons.

3.2. The VGT

The VGT is the main analysis tool in the work. As introduced above, it is theoretically rooted in the advanced MHD turbulence theory (Goldreich & Sridhar 1995) and fast turbulent reconnection theory (Lazarian & Vishniac 1999). Here we follow the VGT recipe proposed in Hu et al. (2022a), employing thin velocity channel maps Ch(x, y) to extract velocity information in position–position–velocity (PPV) cubes via the velocity caustics effect. The concept of the velocity caustics effect was proposed by Lazarian & Pogosyan (2000) to signify the effect of the distortion of density structure due to turbulent and shear velocities along the line of sight (LOS).

Since a density structure with different velocities is sampled into different velocity channels, it is significantly modified. The statistics of the intensity fluctuations in PPV and their relations to the underlying statistics of turbulent velocity and density are formulated in Lazarian & Pogosyan (2000). The study showed that the velocity fluctuations are most prominent in thin channel maps (Lazarian & Pogosyan 2000; Hu et al. 2021b). In particular, the thin channel and the thick channel can be distinguished by

\[
\Delta v < \sqrt{\delta (v^2)}, \quad \text{thin channel},
\]

\[
\Delta v > \sqrt{\delta (v^2)}, \quad \text{thick channel},
\]

where \(\Delta v\) is the velocity channel width and \(\sqrt{\delta (v^2)}\) is the velocity dispersion. The choice of channel thickness is intended to increase the relative weight of velocity-induced fluctuations compared to density-induced ones (Lazarian & Pogosyan 2000).
This is important because, due to the properties of MHD turbulence, velocity fluctuations are better aligned with magnetic field than their density counterparts. The validity of the velocity caustics effect in the multiple-phase medium of neutral hydrogen H I was questioned by Clark et al. (2019). However, their arguments were exposed by Yuen et al. (2019) with the analysis of observational data in Yuen et al. (2021). That demonstrates the importance of velocity caustics in multiphase galaxy H I.

To calculate velocity gradients, each thin channel map is convolved with 3×3 Sobel kernels\(^7\) to calculate the pixelized gradient map \(\psi_g^i(x, y)\) of
\[
\begin{align*}
\nabla_x Ch_i(x, y) &= G_x \ast Ch_i(x, y), \\
\nabla_y Ch_i(x, y) &= G_y \ast Ch_i(x, y), \\
\psi_g^i(x, y) &= \tan^{-1}\left(\frac{\nabla_y Ch_i(x, y)}{\nabla_x Ch_i(x, y)}\right),
\end{align*}
\]
where \(\nabla_x Ch_i(x, y)\) and \(\nabla_y Ch_i(x, y)\) are the x and y components of gradient, respectively, and \(*\) denotes convolution. To suppress the effect of noise in the spectroscopic data, we mask out the raw gradient whose corresponding intensity is less than three times the rms noise level.

As the orthogonal relative orientation between velocity gradients and the magnetic field appears only when the sampling is statistically sufficient, each raw gradient map \(\psi_g^i(x, y)\) is further processed by the sub-block averaging method (Yuen & Lazarian 2017b). The sub-block averaging method takes all gradient orientations within a sub-block of interest and then plots the corresponding histogram. A Gaussian fitting is then applied to the histogram. The Gaussian distribution’s peak value gives the statistically most probable gradient orientation within that sub-block.

By repeating the gradient’s calculation and the sub-block averaging method for each thin velocity channel, we obtain a total of \(n_v\) processed gradient maps \(\psi_g^i(x, y)\) with \(i = 1, 2, \ldots, n_v\). In analogy to the Stokes parameters of polarization, the pseudo \(Q_g\) and \(U_g\) of gradient-inferred magnetic fields are defined as
\[
\begin{align*}
Q_g(x, y) &= \sum_{i=1}^{n_v} Ch_i(x, y) \cos(2\psi_g^i(x, y)), \\
U_g(x, y) &= \sum_{i=1}^{n_v} Ch_i(x, y) \sin(2\psi_g^i(x, y)), \\
\psi_g(x, y) &= \frac{1}{2} \arctan\left(\frac{U_g}{Q_g}\right).
\end{align*}
\]

The pseudo polarization angle \(\psi_g\) is then defined correspondingly. Similar to the Planck polarization, \(\psi_B = \psi_g + \pi/2\) gives the POS magnetic field orientation. In this work, we do not make a selection of velocity range but use all emissions from the galaxies. The use of the velocity caustic effect and pseudo-Stokes parameters distinguishes the VGT from a typical structure or edge detection algorithm by the gradient used in imaging processing. Due to the velocity caustic effect, the gradient of the emission in thin channels does not necessarily detect real density structures in the galaxy. By integrating the pseudo-Stokes parameters along the LOS, the VGT reflects the emission’s dynamic information rather than the emission’s total intensity contours.

4. Results

The input for the VGT is the high-resolution spectroscopic cubes of molecular tracers \(^{12}\)CO and \(^{13}\)CO. We follow the established VGT procedures (see Section 3) to trace the POS magnetic fields. Estimates of the statistical uncertainties of VGT measurements are provided in Appendix B (Figure 11).

To compare our magnetic field maps to those inferred from polarization obtained with HAWC+ as well as the VLA. The correlation between cosmic-ray generation and star formation is suggested by the “far-infrared–radio correlation” (Matthews et al. 2021). Thus radio synchrotron radiation is expected around star-forming regions, but with a much larger scale height due to the cross-phase diffusion of turbulent magnetic fields and diffusion of cosmic-ray electrons (Planck Collaboration et al. 2014; Hu et al. 2022c; Xu & Lazarian 2022). Dust polarization is expected to trace the magnetic fields in cold dense media according to Planck results for the Milky Way (Planck Collaboration et al. 2014).

The correspondence of the POS magnetic field orientations obtained with the VGT-CO and polarization measurements is quantified by the alignment measure (AM; Gonzalez-Casanova & Lazarian 2017): AM = 2(cos\(^2\)\(\theta_e\) − \(\frac{1}{2}\)), where \(\theta_e\) is the angle between the two magnetic field vectors. If the two measures provide identical results, then AM = 1. If the two measures are perpendicular to each, i.e., misaligned, we have AM = −1.

4.1. M51

Figure 1 presents the morphology of magnetic fields toward M51 measured by the VGT, \(^{12}\)CO, HAWC+ 154 \(\mu\)m dust polarization (Bolli et al. 2021), and VLA radio 6.2 cm polarization (Fletcher et al. 2011). For the VGT measurement, we average the gradients over each sub-block of 20×20 pixels, which is an optimal block size used in earlier VGT studies (Hu et al. 2020a), and smooth the gradient map \(\psi_g\) with a Gaussian filter of FWHM \(\sim 6\)”, which is equivalent to the sub-block’s size, to reduce the gradient’s uncertainty caused by the Gaussian fitting. The resulting magnetic field map has a higher resolution than those of HAWC+ (\(\sim 13\)”) and VLA (\(\sim 8\)”). From Figure 1, we see that in spiral arms, the global magnetic structure traced by the VGT and polarization are in good agreement, with the inferred magnetic fields closely following the spiral arm pattern. On average, the AMs of the two methods are in the range of 0.75–1.00 (see Figure 10 in Appendix A), with a peak value at AM \(\approx 1\). Noticeably, the misalignment (i.e., negative AM) between VGT and VLA measurements appears in the central region. However, as shown in Appendix B, the VGT measurement in regions of low CO intensity is typically associated with high uncertainty due to the poor signal-to-noise ratio. Such misalignment in low-intensity regions may not be caused by physical reasons. A radial component of magnetic field is only significant in CO (see Figure 12 in Appendix C), accompanying the molecular gas inflow driven by the two-armed spiral toward the nucleus of M51 (Querejeta et al. 2016).

In general, the star formation rate (SFR) is not homogeneous across spiral galaxies. A high SFR means a more active
star-forming process, indicating more substantial turbulence in the ISM injected by supernova explosions and stellar winds. Given that the VGT is rooted in the physics of MHD turbulence, these turbulence injection mechanisms can potentially cause the correlation between the VGT-traced magnetic field and SFR. Using the available SFR data from Leroy et al. (2019), we plot the correlation of SFR and AM for the M51 galaxy in Figure 2.

As expected, high SFR preferentially corresponds to positive AM, which indicates a good agreement of the VGT and polarization. This correspondence is more apparent in dust polarization, which is tightly associated with star formation activity. The correspondence of negative AM and high SFR in synchrotron polarization is contributed by the misalignment observed in the central area of M51.
4.2. NGC 1068

In the Seyfert and starburst galaxy NGC 1068, molecular gas is abundant along the star-forming spiral arms and in the central region. Figure 3 shows the POS magnetic fields toward NGC 1068 mapped by applying the VGT (FWHM $\sim 5''$) to $^{13}$CO ($J = 1-0$) emission, in comparison with HAWC+ 89 $\mu$m polarization (beam size $\sim 7''$). The two measurements are globally compatible with each other, except in the interface regions between the bar and the spiral arms. In the interface regions, strong inward radial flow of molecular gas is also detected and attributed to the combined action of the bar and the spiral arm (García-Burillo et al. 2014). Beginning from the bar-arm transition regions, VGT reveals a significant radial component of magnetic fields in CO along the bar (see Figures 12 and 13 in Appendix C). The remarkable coincidence between the inflow (García-Burillo et al. 2014; Lopez-Rodriguez et al. 2020) and radial magnetic fields seen in molecular gas suggests that magnetic fields play an
important role in transporting CO to the central reservoir of molecular gas and powering star formation in the kiloparsec-scale starburst ring. However, readers should note that in this work we do not explicitly distinguish inflow or outflow. For a region dominated by gravity, we expect to observe accretion and inflows associated with molecular material.

4.3. NGC 3627

For this interacting galaxy (Haynes et al. 1979), the magnetic fields traced by $^{12}$CO ($J = 2–1$) closely follow the bar and asymmetric spiral structures, with FWHM $\sim 8/70$ (see Figure 3). By comparing with HAWC+ $154$ $\mu$m polarization (FWHM $\sim 13/76$), we see a good alignment between the two measurements in the western arm and the bar. The misalignment (i.e., negative AM) appears at the end of the southern bar and in the eastern arm. An unusual magnetic field component crossing the dust lane in the southeast disk was earlier found by radio polarization measurements (Soida et al. 2001). A recent collision with a dwarf galaxy may be responsible for the enhanced star formation in the eastern arm and the distortion of the southeast region (Weżgowiec et al. 2012). The different magnetic field configurations seen in CO and dust support this scenario and may reflect distinct pre- and post-collision flows of different phases induced by the interaction. Tidal interaction with the neighboring galaxy NGC 3628 can significantly affect its subsequent dynamical evolution and trigger efficient radial inflow toward the nucleus (Zhang et al. 1993).

4.4. Circumnuclear Region of NGC 1097

4.4.1. A Molecular Ring in the Nucleus and Dust Lanes in the Bar

As an efficient driver of gas inflow, a strong bar with prominent dust lanes along it is present in NGC 1097. The orbiting gas loses angular momentum at the dust-lane shocks and falls toward the galactic center (Athanassoula 1992). Despite the high density of gas due to shock compression, the formation of molecular clouds and stars is suppressed in the bar because of the strong shear along it (Athanassoula 1992). The inflowing gas settles in the nuclear ring (see Figure 13 in Appendix C), serving as the raw material for molecular cloud and star formation when the velocity shear is mitigated. In addition to the large shear along the dust lane, another possible cause of the different distribution between dust and molecular gas is temperature. When temperature increases, the shock front along the bar moves closer to the bar’s major axis, and the central ring that connects the inner ends of the bar becomes more elongated along the bar’s major axis (Englmaier & Gerhard 1997; Patsis & Athanassoula 2000). This means that the colder molecular gas traced by CO (and dust) and the warmer gas traced by dust can have different distributions and flow configurations.

4.4.2. Magnetic Fields Traced by CO

As shown in Figure 4, at the inner ends of the bar, the magnetic fields mapped with CO (VGT; FWHM $\sim 10^{4}$) are curved into the central circumnuclear ring. Magnetic fields can be compressed by shocks and stretched by shear in the dust lanes along the bar. The tension force of bent magnetic fields can cause further removal of the angular momentum of gas both at dust-lane shocks and within the nuclear ring (Krolik & Meiksin 1990). MHD simulations of barred galaxies suggest that the presence of magnetic fields leads to a more centrally concentrated ring and enhanced mass inflow rate to the galactic center (Kim & Stone 2012). As an important characteristic for one to identify the role of magnetic fields, we clearly see that the magnetic fields mapped with CO are bent into an “L” shape within the nuclear ring as expected from simulations (Kim & Stone 2012). We also see that the magnetic fields within the ring have a radial component (see Figures 12 and 13 in Appendix C) following the secondary bar of NGC 1097 reported by Quillen et al. (1995). The magnetic fields threading the secondary bar are expected to impose a magnetic braking effect on the gas spiraling into the innermost region and to further remove its angular momentum, as suggested in Kim & Stone (2012). Our observed magnetic field morphology in CO indicates that, in addition to the gravitational torques from the bars, magnetic fields introduce additional torques, which contribute to the removal of angular momentum and transport of gas from the galactic disk to its innermost region.

4.4.3. Magnetic Fields Traced by Dust

We see from Figure 4 that the magnetic fields measured by $89$ $\mu$m HAWC+ dust polarization ($\sim 7/8$; Lopez-Rodriguez et al. 2021) extend into the ring. Unlike the magnetic fields traced by CO, there is no significant bending of field lines traced by dust within the ring. There is a clear correlation between the regions with misalignment and radial field (see Figure 5), showing the radial magnetic fields across the ring along the primary large-scale bar seen in dust polarization. The misalignment between the magnetic fields traced by CO and dust may be attributed to their different distributions in the strong bar and inner ring system. If there is a warmer phase that is preferentially traced by dust, the morphology of magnetic fields with AM $\sim −1$ reflects the more elongated shape of the central concentration of warmer gas rather than that of colder gas. This misalignment suggests the two-phase gas inflows along the bar and within the ring.

Figure 5 displays the distributions of negative AM (i.e., misalignment between the VGT and HAWC+ polarization) and negative HAWC+’s PM (i.e., radial field) toward the starburst ring of NGC 1097. PM is defined as the pitch angle measurement: $PM = \cos(\theta_{p})$, where $\theta_{p}$ is the pitch angle of the magnetic field. The spatial distribution of misalignment (i.e., negative AM) coincides with the negative PM in statistics. In particular, we plot the correlation of AM and PM. The PM is averaged over uniformly spaced bins. Therefore, the misalignment between the VGT and HAWC+ polarization is mainly contributed by the radial field within the ring measured by HAWC+.

4.4.4. Magnetic Fields Traced by Synchrotron

In Figure 4, we see an overall good alignment between the magnetic fields traced by CO and synchrotron. The molecular ring of NGC 1097 coincides with the starburst ring (Quillen et al. 1995; Davies et al. 2009; van de Ven & Fathi 2010). This supports the correlation between star formation and cosmic-ray generation (Vollmer et al. 2022). In particular, Liu et al. (2022b) found that in NGC 3627, the magnetic field inferred from synchrotron polarization agrees more with the magnetic fields traced by VGT-CO rather than the one traced by VGT-H$\alpha$, suggesting that synchrotron electrons are well mixed with CO in star-forming regions. However, one should note that the acceleration and propagation of relativistic electrons responsible for synchrotron polarization in the centers of active galaxies is not a well-understood process. Therefore, the interpretation of
synchrotron polarization angle as perpendicular to the POS magnetic field component can also be misleading.

4.5. Prediction of Magnetic Field Morphology toward NGC 4826:

We apply the VGT to obtain the first magnetic field map of NGC 4826, for which polarization measurements are not yet available. Figure 6 shows the VGT-predicted magnetic field orientations using the $^{12}$CO emission line and HAWC$^+$ polarization at 89 $\mu$m (Lopez-Rodriguez et al. 2021; colored segments). The magnetic fields are overaid onto the HST WFC3/F814W ultraviolet image (Lee et al. 2022). Coincidentally, streaming motions in CO were also observed in the inner disk (García-Burillo et al. 2003).

5. Discussion

5.1. Dynamo Activity

The VGT-measured magnetic field morphology can help us understand the dynamo process in galaxies. For instance, preferentially tangential/spiral magnetic fields, which follow the shear caused by differential rotation, are believed to be a product of the dynamo mechanism (Beck et al. 1996). Such a globally spiral field is observed in M51, NGC 1068, NGC 1097’s starburst ring, and NGC 3627’s spiral arms (see Figures 12 and 13 in Appendix C). However, in the transition region from the inner bar to the outskirt, NGC 1097, NGC 1068, and NGC 3627 exhibit a preferentially radial magnetic field configuration. This change from tangential to radial magnetic field configuration indicates that the gas’s streaming motion becomes more important (see Figures 12 and 13 in Appendix C). In addition, dynamo studies in barred galaxies suggest dynamically more important magnetic fields and a closer alignment between magnetic and velocity fields than in normal spiral galaxies (Moss et al. 2001). The VGT-measured magnetic fields in CO show similar transition features, indicative of their dynamically important role in enhancing the molecular gas inflow in Seyfert galaxies.

5.2. Implications of the Observed Alignment

The overall agreement between the magnetic field orientations measured with the VGT-CO and polarization reveals the coherence of magnetic fields across different gas phases, including the molecular phase traced by CO, denser phases...
traced by dust (Andersson et al. 2015), and the warm diffuse phase traced by synchrotron radiation. This alignment seen in Seyfert galaxies is also observed in our normal barred spiral galaxy, the Milky Way (Alina et al. 2022; Tram et al. 2022; Zhao et al. 2022). The observed coherence suggests that the magnetic fields threading the multiphase gas with an extended range of densities all participate in the evolution of the galactic dynamic and undergo dynamo amplification (Vishniac & Cho 2001) and turbulent reconnection diffusion (Lazarian & Vishniac 1999). This supports the idea that molecular clouds are a part of the unified magnetic ecosystem in spiral galaxies and that magnetic fields in diffuse and molecular phases have a coherent structure. This finding can have very important implications for many multiscale processes, e.g., star formation (Ching et al. 2022) and cosmic-ray propagation (Padovani & Galli 2011; Xu & Lazarian 2022).

5.3. Implications of the Observed Misalignment

Despite the alignment seen for the global magnetic structure especially in spiral arms, the nearby Seyfert galaxies feature misalignment between the magnetic fields mapped with VGT-CO and polarization in regions with significant molecular gas inflows or, less likely, outflows. This is particularly seen in the central part of M51, the bar–spiral interface of NGC 1068, and the nucleus of NGC 1097. In these regions with misalignment predominant radial magnetic fields in CO are also identified with the VGT. In NGC 3627, the misalignment probably marks the distortions in the molecular disk induced by a recent

Figure 6. Morphology of magnetic fields revealed by the VGT (streamlines) using the $^{12}$CO ($J = 2-1$) emission line toward the NGC 4826 galaxy. The magnetic field is overlaid with the Hubble Space Telescope WFC3/F814W ultraviolet image (Lee et al. 2022). The black circle represents the beamwidth of observation.
Galaxy interactions are both drivers of gas inflow and collision. As non-axisymmetric instabilities such as bars and galaxy interactions are both drivers of gas inflow toward the nuclei (Wada 2004), our findings reveal the active role of magnetic fields in removing the angular momentum of molecular gas in the galactic disk and transporting it toward the nuclei of nearby Seyferts.

5.4. Contribution from Systematic Gradients

Galaxies may possess systematic gradients that are imposed by other conditions, for instance the galactic differential rotation and CO’s bulk motion. The systematic gradients can contribute to the measured velocity gradients. However, the ALMA and PAWS data resolve the galaxies down to a scale <100 pc, at which the turbulence effect is already significant. The CO emission must have the imprint of MHD turbulence.

The calculation of velocity gradient employs the concept of a thin velocity channel based on the velocity acoustic effect (Lazarian & Pogosyan 2000). The intensity structure observed in the thin velocity channel is dominated by turbulent velocity fluctuations once the turbulence’s scale of ∼100 pc is resolved (Lazarian & Pogosyan 2000). The most important aspect is that the amplitude of the turbulence’s velocity gradient is scale-dependent. The amplitude increases when the spatial scale decreases, but this is not the case for the bulk motion or the shear velocity’s gradient (see the Appendix in Hu et al. 2022a).

Therefore, although there are contributions from non-turbulence velocity gradients, we expect that at scales where turbulence can be resolved its contribution is dominant.

6. Summary

In this work, we present the first application of the VGT to trace the POS magnetic fields in five nearby Seyfert galaxies, M51, NGC 1068, NGC 1097, NGC 3627, and NGC 4826. The application is achieved by using high-resolution (<100 pc) molecular emission line data of CO isotopologs obtained from ALMA and PAWS archives. We demonstrate that the synergy of the VGT using gas tracers and polarization presents valuable information on magnetic fields in different gas phases and their role in fueling nuclear activity in Seyferts. Our main findings are:

1. By comparing with existing dust and synchrotron polarization data obtained from HAWC+ and VLA, we demonstrate the VGT’s validity and accuracy in tracing extragalactic magnetic fields.
2. An overall good alignment between the magnetic fields traced by the VGT-CO and synchrotron supports the correlation between star formation and cosmic-ray generation.
3. We find that the magnetic fields traced by VGT-CO have a more significant radial component in the central regions of most Seyferts in our sample, where efficient molecular gas inflows are expected.
4. We find a misalignment between the magnetic fields traced by VGT-CO and dust polarization within the nuclear ring of NGC 1097, and the former follow the secondary central bar. This reveals different magnetic field configurations in different gas phases and may provide an observational diagnostic for the ongoing multiphase fueling of Seyfert activity. The magnetic field morphology revealed by VGT-CO supports the theoretical expectation (Krolik & Meiksin 1990; Kim & Stone 2012) on the effect of magnetic fields in removing the angular momentum of molecular gas and fueling nuclear activities.

5. We expect the misalignment between the magnetic fields traced by VGT-CO and dust polarization in the eastern arm of NGC 3627 is likely affected by a recent collision with NGC 3628. This misalignment revealed by VGT-CO can be important for studies on environmental effects on galaxy evolution.

6. For NGC 1068, the coincidence between the inflow and radial magnetic fields traced by VGT-CO suggests that magnetic fields play an important role in transporting CO to the central molecular reservoir.

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Software: Julia (Bezanson et al. 2012).

Appendix A

Distribution of AM

We present the distribution maps of AM value (AM = (cos^2 θ₁ - 1/2), where θ₁ is the angle between the two magnetic field vectors) in Figures 7 and 8. AM = 1 means two vectors are in the same direction, while AM = −1 suggests two vectors are perpendicular to each. In general, the magnetic fields traced by the VGT are globally compatible with the polarization measurements (i.e., AM ∼ 1). Although discrepancy exists, a good agreement suggests turbulence’s role is important. Turbulence’s intrinsic properties may contribute to the discrepancy, because super-Alfvénic turbulence is isotropic. It is possible that the telescope does not resolve the scale l_A in some super-Alfvénic regions (see Section 3), so we observe a disagreement of the VGT and polarization. In addition, dust is
Figure 7. Distribution of AM (between the VGT and polarization) toward M51 (top) and NGC 1097 (bottom left: dust polarization; bottom right: synchrotron polarization) galaxies. All plots share the same color bar and are overlaid on maps of CO emission intensity.
well mixed with all the interstellar phases, including both molecular and atomic gas (Andersson et al. 2015). The dust size distribution, alignment, as well as the magnetic field direction, can change in different phases. For instance, shocks and radiative torque disruption change the size distribution of dust. This affects dust alignment. (Lazarian & Hoang 2021). Therefore, the polarization from dust depends on the intensity of radiation in a wavelength comparable with the size of the grains. The alignment of dust has never been studied in the environment of active galaxies. Therefore, it may not be surprising that we see the differences between the dust polarization sampling aligned dust in very different conditions along the LOS, and the VGT-CO.

As both the VGT and HAWC+ sample the magnetic field in the cold-gas phase, their agreement is expected, as observed in M51, NGC 1068, and NGC 3627. However, strikingly in NGC 1097, the VGT significantly differs from HAWC+ dust polarization but agrees with VLA synchrotron polarization, which measures the ionized gas phase. To investigate this unexpected discrepancy, we blanked out the pixels in which the AM of VGT–VLA alignment is negative. As shown in Figure 9, the discrepancy mostly appears in the central disk region, including the upper and lower parts of the starburst ring.

Figure 10 shows the histograms of AM (between the VGT and polarization) toward the four galaxies. While the
distribution spans from $-1$ to $1$, the majority is still concentrated in the range $0.75$–$1.0$. This suggests a globally compatible agreement between the VGT and polarization.

**Appendix B**

**Uncertainty of the Magnetic Field Direction Measured by the VGT**

The two significant uncertainties of the magnetic field can come from the systematic error in the observational map and the VGT algorithm. For the latter, the VGT takes a subregion and fits a corresponding Gaussian histogram of the gradient’s orientation. It then outputs the angle of orientation corresponding to the peak value of the Gaussian fitting histogram. The uncertainty therefore can be considered as the error $\sigma_{\psi_p}(x, y, v)$ from the Gaussian fitting algorithm within the 95% confidence level.

Considering the noise $\sigma_n(x, y, v)$ in velocity channel $\chi(x, y, v)$ and error propagation, the uncertainties $\sigma_q(x, y)$ and $\sigma_U(x, y)$ of the pseudo-Stokes parameters $Q_g(x, y)$ and $U_g(x, y)$ can be obtained from

$$
\sigma_{\cos}(x, y, v) = |2 \sin(2\psi_p(x, y, v))\sigma_{\psi_p}(x, y, v)|
$$
$$
\sigma_{\sin}(x, y, v) = |2 \cos(2\psi_p(x, y, v))\sigma_{\psi_p}(x, y, v)|
$$
$$
\sigma_{q}(x, y, v) = |\chi \times \cos(2\psi_p)|\sqrt{(\sigma_n/\chi)^2 + (\sigma_{\cos}/\cos(2\psi_p))^2}
$$
$$
\sigma_{u}(x, y, v) = |\chi \times \sin(2\psi_p)|\sqrt{(\sigma_n/\chi)^2 + (\sigma_{\sin}/\sin(2\psi_p))^2}
$$
$$
\sigma_{q}(x, y) = \sqrt{\sum_{v} \sigma_{q}(x, y, v)^2}
$$
$$
\sigma_{u}(x, y) = \sqrt{\sum_{v} \sigma_{u}(x, y, v)^2}
$$
$$
\sigma_{\psi_p}(x, y) = \frac{|U_g/Q_g|\sqrt{(\sigma_q/Q_g)^2 + (\sigma_U/U_g)^2}}{2[1 + (U_g/Q_g)^2]}
$$

where $\sigma_{\psi_p}(x, y)$ gives the angular uncertainty of the resulting magnetic field direction. The uncertainty maps of the galaxies are presented in Figure 11. The median value is listed in Table 2.
Appendix C
Pitch Angle

In Figures 12 and 14, we plot the pitch angle as a function of the distance to the galactic center. We follow the recipe used in Borlaff et al. (2021) for calculating the pitch angle. We generate a zero-pitch-angle template by computing the radius $r$ and zero pitch angle, which is perpendicular to the radial direction, of every pixel in galactocentric coordinates. Then we transform the zero pitch angle and radius back to the observer’s coordinates, i.e., the POS. The pitch angle is calculated as the difference between the measured position angle of the magnetic field and the template in the IAU convention. The pitch angle is averaged at each annulus from the galactic center with linearly spaced radial bins. The essential calculation parameters are listed in Table 2.

We find M51 has a mean pitch angle around $\sim 25^\circ$, and the difference between the three measurements is not significant except in the outer $r > 5$ kpc region, which is also reported by Borlaff et al. (2021). NGC 1097’s three measurements exhibit
significantly different pitch angles. Dust polarization appears at a smaller pitch angle. The difference between the VGT and synchrotron polarization at $r \sim 1$ kpc is mainly contributed by the contact region of the shock front and inner bar, while they are more similar along the dust lanes. An apparent difference in the VGT and dust polarization in NGC 1068 is observed. Like Lopez-Rodriguez et al. (2020), we find a mean pitch angle $\sim 20^\circ$ at $r < 1.5$ kpc. Notably, the VGT’s pitch angle decreases to $\sim 0$ at $r > 2.0$ kpc due to the south tail’s contribution. NGC 3627 shows a similar pitch angle for both the VGT and dust observation at $r > 4.0$ kpc. As for NGC 4826, a change in the sign of pitch angle is observed at $r < 0.25$ kpc.

To quantify the morphology of magnetic field, like the definition of AM, we introduce the pitch angle measurement: $\text{PM} = \cos(2\theta_p)$, where $\theta_p$ is the pitch angle of the magnetic
Figure 13. The distribution of PM in M51 (a), NGC 1097 (b), NGC 3627 (c), and NGC 1068 (d) galaxies. PM > 0 indicates a preferentially tangential field and PM < 0 suggests a preferentially radial field. Approximated locations of the inner bar are labeled by green segments, and yellow arrows indicate the direction of inflows. The background images and contours are maps of CO emission intensity.
field. Also, we average the PM at each annulus from the galactic center. Unlike the averaged pitch angle, PM has a clear physical meaning: PM > 0 indicates a preferentially tangential field, while PM < 0 represents a preferentially radial field. The difference between PM and pitch angle can be easily understood based on the fact that the angular average of two pitch angles 45° and −45° is 0, while these two angles are neither tangential nor radial, i.e., PM = 0 in this case.

The PM as a function of the distance to the galactic center is presented in Figures 12 and 14. We find that M51, NGC 1068, and NGC 3627 have tangential fields spanning almost all scales. For M51, a negative PM of the VGT at a large distance (r > 5 kpc) may come from the effect of noise. In addition, NGC 1097 and NGC 4826 exhibit radial fields at small scales (r < 0.5 kpc for NGC 1097 and r < 0.75 kpc for NGC 4826) but a tangential field at large scales. In particular, Figure 13 presents the spatial distribution of PM. We find the negative PM usually appears in the positions of inflow. The references used to locate the inner bars and inflows for Figure 13 and Figure 14 include: (i) M51 (Meidt et al. 2013; Querejeta et al. 2016); (ii) NGC 1097 (Quillen et al. 1995; Davies et al. 2009; van de Ven & Fathi 2010); (iii) NGC 1068 (García-Burillo et al. 2014; Lopez-Rodriguez et al. 2020); (iv) NGC 3627 (Haan et al. 2009; Beuther et al. 2017). We find the tangential fields are most apparent in the positions of inflows. A similar trend is also observed in NGC 4826, in which the VGT measurement is radial at r < 0.75 kpc. However, the radial fields cover the entire central region of NGC 4826, instead of only the transition region.

Moreover, we calculate the AM of the VGT measurement and polarization as a function of the distance to the galactic center. We can see that for M51 the VGT agrees with both synchrotron and dust polarization. However, in NGC 1097, the VGT aligns with synchrotron polarization better than dust.
The inclination ($i$) of the galaxy disk is measured with respect to the POS, and the position angle (P.A.) of the major axis of the projected galaxy disk in the sky plane is measured in the IAU convention. $\sigma_{\theta_g}$ represents the median uncertainty of the VGT measurement and $\langle \theta_g \rangle$ is the mean pitch angle.

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| Galaxy | R.A.(J2000) | Decl.(J2000) | $i$ | P.A. | $\sigma_{\theta_g}$ | $\langle \theta_g \rangle$ (VGT, HAWC+, VLA) |
|--------|-------------|-------------|-----|------|-----------------|----------------------------------|
| M51    | 200°24'69"  | 47°19'5"   | 20°3 | 12°0 | 14°99          | 24°98 ± 0°12, 26°54 ± 1°34, 28°32 ± 0°38 |
| NGC 1068 | 40°67°    | -0°013    | 48°1 | 52°0 | 10°50          | 16°26 ± 0°14, 31°28 ± 1°11, |
| NGC 1097 | 41°57°    | -30°275   | 45°0 | -45°5 | 12°37          | -30°60 ± 0°35, -8°80 ± 1°98, -38°47 ± 0°35 |
| NGC 3627 | 17°063    | 12°991    | 65°0 | 17°0 | 11°30          | 11°48 ± 0°12, 17°3 ± 1°31, |
| NGC 4826 | 19°4182   | 21°683    | 60°0 | 112°0 | 8°92          | 14°11 ± 0°24, |
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