galaxies

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Editorial

Workshop Summary "The Power of Faraday Tomography"

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Abstract: This article summarizes the work presented at the workshop "The Power of Faraday Tomography: towards 3D mapping of cosmic magnetic fields", held in Miyazaki, Japan, in Spring 2018. We place the various oral and poster presentations given at the workshop in a broader perspective and present some highlight results from every presenter.

Keywords: cosmic magnetism; Faraday tomography; galactic magnetic fields; MHD

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1. Introduction

Magnetic fields play a vital role on all scales throughout the Universe: allowing the creation of stars and exoplanets, affecting the gas flows in the interstellar medium, forming galactic and AGN jet structures, accelerating cosmic rays, and permeating the cosmic web and galaxy clusters. However, the origin of these cosmic magnets and the mechanisms of field amplification and ordering over the history of the Universe are still largely unsolved.

"Cosmic Magnetism" is recognized as one of the key science topics for the largest radio facilities such as the Low-Frequency Array (LOFAR), the Karl G. Jansky Very Large Array (JVLA), and Atacama Large Millimeter/submillimeter Array (ALMA), as well as the Square Kilometre Array (SKA) and its precursors Murchison Widefield Array (MWA), Hydrogen Epoch of Reionization Array (HERA), the Australian SKA Pathfinder (ASKAP), and MeerKAT. We are now entering the era of these sensitive and high-resolution facilities, which are expected to uniquely solve many outstanding questions in cosmic magnetism. Theoretical and numerical predictions will become much more important in this era.

One of the technological breakthroughs in modern radio telescopes is wide bandwidth in frequency. It improves, for example, the sensitivity, the spectral index estimation, and depolarization analysis. Moreover, it brings us an innovative data analysis method called Faraday Tomography. Here, wide frequency coverage means a "big data" challenge: computational cost is a major issue which should be addressed now to resolve it by the time when the future largest projects run.

The Japanese workshop organizers, part of the Japan SKA Consortium (SKA-JP) Cosmic Magnetism Science Working Group, actively address the (future) capabilities of Faraday tomography [1,2]. The organizers recently had an opportunity to start a collaboration between the SKA-JP and a group in the Netherlands, and put minds from both groups to the problems described above.

This collaboration resulted in the workshop "The Power of Faraday Tomography: towards 3D mapping of cosmic magnetic fields", held in Miyazaki, Japan, from 28 May to 2 June 2018. The goal of the workshop was to present and discuss new results on cosmic magnetism research, with an emphasis on the analysis method of Faraday Tomography. The workshop was meant to be interactive and partly educational: presentations ranged from instructive reviews by senior scientists to new results to tutorials on various analysis methods [3]. A meeting of the POlarisation Sky Survey of the Universe's Magnetism (POSSUM) meeting was held at the workshop, which is not included in these proceedings.

The workshop had 64 participants. The biggest group of these were Japanese (24); there were 19 from Europe (6 Germany, 4 Netherlands, 4 Italy, 2 UK, 1 France, and 1 Spain); 8 from North America (5 Canada and 3 US); 8 from Australia; and 4 from other Asian countries (2 South-Korea, 1 Russia, and 1 India). A relatively large part of these were young researchers: 28 postdocs, 12 PhD students and 2 MSc students.

We emphasize that this article does *not* contain a full discussion of the scientific fields discussed, but only describes the contributions to the various fields made in this workshop. In addition, we do not try to summarize all scientific results in every contribution, but give a few highlights and try to embed the topic into the bigger picture. We encourage the reader to turn to the full proceedings article of any contribution that catches your interest in this summary.

2. Summary of the Conference

The workshop contributions were ordered in seven sessions on related scientific topics. In this section, we briefly introduce the topic and discuss the presentations given in each of these sessions.

2.1. Faraday Tomography

Faraday tomography is a relatively new tool to study magnetic fields in galaxies, which allows decomposing various synchrotron emission components along a line of sight into their various Faraday rotation contributions. At the conference, **Shinsuke Ideguchi** presented simulated Faraday spectra of face-on varying turbulent field coherence lengths [4]. He showed that the width of the Gaussian Faraday spectrum of the turbulent fields varies with coherence length of the field, and that its shape is altered with varying regular fields. Therefore, measuring the moments of Faraday components in a spectrum gives information on the magnetic field in a spiral galaxy.

Broadband data are extremely important for Faraday Tomography for both Faraday depth resolution and sensitivity to Faraday thickness; **Yoshimitsu Miyashita** showed that, while in a limited radio band the data and a model can agree, they can diverge widely outside a narrow observed band [5], giving rise to false trust in well-fitting but wrong results.

2.1.1. Alternative Methods for Radio-Polarimetric Data Analysis

Shinsuke Ideguchi reviewed and explained the method of *QU-fitting* [6,7], in which the observed wavelength dependent behavior of Stokes Q and U is compared to various models of components of the Faraday-rotating magnetized gas.

Dmitry Sokoloff combined Faraday Tomography with wavelet analysis to study Faraday depth fluctuations at varying resolutions to render coherent fields in spiral arms visible in Faraday depth maps with dominating small scale Faraday depth variation [8]. With these combined methods, it is possible to identify typical magnetic arms (in the stellar interarm regions) as observed in some nearby spiral galaxies.

2.1.2. Other Advances in Radio (Spectro-Polarimetry) Calibration Techniques

Wasim Raja emphasized the importance of polarization calibration, especially off-axis. He introduced the Australian Square Kilometre Array Pathfinder (ASKAP) and demonstrated a new calibration scheme for its phased array feeds, using an on-dish calibration system and self-calibration.

Philipp Arras explained Bayesian Radio Aperture Synthesis, which reconstructs radio images of the sky using Bayesian inference. This is only possible using prior assumptions to reconstruct the sky [9]. He further developed the software package RESOLVE, and showed that, even with a bad uv-coverage or considerable noise, the algorithm returns valid sky maps of example source Cygnus A.

2.2. Cosmology, Large-Scale Structure, and Galaxy Clusters

Much of the magnetism in the Universe is believed to be amplified and/or maintained by some dynamo process. However, these dynamo processes need tiny magnetic fields, called *seed fields*, to amplify the observed field strengths and configurations. These seed fields could have been created in the early Universe by various processes such as the Biermann battery, cosmological defects and others as described below. Magnetic fields created in this era are called *primordial magnetic fields*. Alternatively, it is possible that the Universe was magnetized only later, e.g., at the time of the reionization of the Universe.

Seed fields are of exceedingly small strength ($\sim 10^{-10}$–10^{-20} G), thus will have to be amplified to the cosmic magnetic fields we can observe today by a dynamo. Both the process of the magnetization of the Universe and its occurrence in time are still unknown, as are the exact dynamo processes in various sources. Several theories for creating and amplifying cosmic magnetic fields were discussed at this conference, as well as the possibility of observing primordial magnetic fields.

2.2.1. Generation of Cosmic Magnetic Fields

Mathieu Langer described a mechanism to create seed fields during the Epoch of Reionization. In the first Strömgren spheres created around the first generation of ionizing sources in the Universe, energetic photons will escape the spheres and create a local electric field. Inhomogeneities in the medium will induce a rotational component in the electric field, which generates magnetic fields [10,11]. Ionizing sources can be the first (Pop III) stars, ionizing galaxies or quasars, which would ionize on kpc to Mpc scales. Therefore, this process can contribute to the large-scale magnetization of the Universe.

Detection of intergalactic magnetic fields could prove an early magnetization of the Universe. **Teppei Minoda** discussed a possible observational signature of primordial magnetic fields in Cosmic Microwave Background (CMB) anisotropies, induced by the thermal Sunyaev–Zel'dovich effect [12]. He calculated the evolution of gas temperature and density in the dark ages including magnetic fields and finds a potentially detectable imprint of primordial magnetic fields on the CMB at large multipoles $\ell \sim 10^5$–10^6.

Kerstin Kunze presented numerical simulations of cosmological magnetic fields and their influence on the reionization history of the Universe [13,14]. She showed that high primordial magnetic field values cause reionization to happen earlier. In the particular examples studied, primordial magnetic fields would leave observational traces in the 21 cm line signal at frequencies above 120 MHz, which could be observable with the Square Kilometre Array (SKA).

2.2.2. Amplification of Cosmic Magnetic Fields

Amplification of cosmic seed fields to the values that we currently observe requires a dynamo, converting various other sources of energy into magnetic energy. The exact mechanisms, drivers, energy balance and time scales are still under discussion.

Dongu Ryu presented numerical simulations of turbulent dynamo action in galaxy clusters, and showed that this gives a coherence length of maximally ∼50 kpc. Coherent magnetic fields in clusters are observed to scales of ∼1 Mpc, so that another dynamo mechanism is needed to transport magnetic energy to larger spatial scales. A possibility explored is *sporadically driven* turbulent dynamo, which only flares up during galaxy mergers. This will increase the injection length somewhat, but still cannot explain the largest observed scales.

Jennifer Schober discussed the amplification of magnetic fields due to the Chiral Magnetic Effect. This effect can amplify magnetic fields due to unequal numbers of left-handed and right-handed fermions, which happens in special circumstances such as in proto-neutron stars, in heavy-ion collisions in Earth-based colliders, or in the first second of the Universe. Her numerical simulations show initial exponential amplification of small-scale magnetic fields, followed by a slower evolution of fields on significantly larger spatial scales by turbulence developing [15].

Julius Donnert argued that current large cosmological numerical simulations need to be expanded. Magnetic fields amplified by the turbulent dynamo grow from small scales to large scales, thus one needs to resolve the smallest scales (∼3 kpc), which is sub-grid for many current cosmological models. He introduced the Wombat software, which is a complete redesign of a cosmological code that runs massively parallel on a supercomputer, developed in collaboration with Cray Supercomputers [16].

2.2.3. Magnetic Fields in Galaxy Clusters

Radio emission is ubiquitous in clusters, and can typically be divided into two components: (1) radio halos in the centers of clusters, which are roughly co-located with thermal X-ray emission and generally unpolarized; and (2) radio relics at the outskirts of clusters, which are highly polarized and believed to be created by large-scale shocks due to galaxy mergers in the cluster.

Soonyoung Roh investigated if numerical simulations can reproduce observed radio halos and relics. The similarity between radio and X-ray power spectrum slopes in halos suggests a direct correlation between the thermal and non-thermal emission, indicating re-acceleration of electrons. She probed various energy relations and found that a cosmic ray energy density comparable to the magnetic energy density reproduces radio halos the best. Her simulations of relics reproduce shock regions with enhanced synchrotron emission.

Francesca Loi simulated full-Stokes radio emission from galaxy clusters including discrete foreground and background sources, to investigate detectability of polarization in the clusters with the SKA [17]. She found that the behavior of cluster radio halos is a dominant factor significantly influences the Faraday depth spectrum, and that Faraday screens and additional sources introduce ambiguities in the Faraday spectrum which complicates interpretation.

Valentina Vacca presented advanced techniques for the study of magnetic fields in the large scale structure of the Universe, using radio halos to study magnetic field strength and structure on scales up to several hundreds of kpc. In addition, new 1.4 GHz polarimetric observations with the Sardinia Radio Telescope show a new population of diffuse synchrotron sources fainter and larger than known cluster sources, potentially associated with magnetic fields in the cosmic web [18]. Lastly, decomposition methods using Faraday rotation of background radio galaxies allow statistical distinction among the Faraday rotation due to the Milky Way, filaments, galaxy clusters, voids, and sheets, and consequently investigation of extragalactic magnetic field properties [19].

Hiroki Akamatsu discussed the synergy between X-ray and radio observations in galaxy clusters. He determined Mach numbers of shocks in radio relics from the temperature profile across the shock, as observed, e.g., in the Sausage relic with the Suzaku satellite. Assuming that diffuse shock acceleration is the dominant electron acceleration process in these shocks, one can derive the Mach number from radio observations too. In the Sausage, the two estimates of the Mach number are in agreement. However, diffusive shock acceleration cannot accelerate the electrons to the required energies, which indicates that reacceleration of the electrons must play a role.

This was also shown by **Motokazu Takizawa**, who concluded that the Mach numbers derived from X-ray and radio emission in the Toothbrush relic do *not* agree with each other. He also reported the detection of a surface brightness edge in the cluster RXC J1053.7+5453, which he suggested may be due to a contact discontinuity [20–22].

Detailed analysis on small-scale structure in the "handle" of the Toothbrush relic was presented by **Matthias Hoeft**. The ridge of the shock is frequency dependent and therefore cannot be due to a magnetic enhancement but must instead be due to a traveling shock front which cools. The narrowness of the peak combined with the turbulence indicates that magnetic fields here are lower than average.

The fact that the Toothbrush relic is still highly polarized at 3.6 cm Effelsberg observations (with very low resolution) indicates that the field across the relic is very regular.

2.2.4. Intergalactic Magnetic Fields

Intergalactic space is believed to be magnetized to some level as well. In addition to theoretical estimates, the first tentative detections of magnetic fields in intergalactic space and/or filaments of the cosmic web are being discussed. Various ways to constrain or predict intergalactic magnetic fields were discussed.

Takuya Akahori studied the optimum frequency range to detect intergalactic magnetic fields with Faraday tomography. He concluded that for fairly small bandwidths around the optimum 500–600 MHz, intergalactic Faraday depths of $\sim$5 rad m^{-2} should become detectable [23,24].

Vikram Ravi reviewed Fast Radio Bursts (FRBs) and discussed how their rotation measures can help constrain progenitor models and probe intergalactic space. Dispersion measures of FRBs measure the baryon content of the intergalactic medium. Current observations can put an upper limit of extragalactic magnetic fields of $\sim$20 nG.

Justin Bray used arrival directions of Ultra-High Energy Cosmic Rays (UHECRs) as probes to constrain intergalactic magnetic fields. Assuming various plausible source populations for the UHECRs, and neglecting deviations due to the Galactic magnetic field, he arrived at a conservative upper limit for the intergalactic magnetic field in cosmic voids of $\sim$0.1 nG, which is lower than the current CMB limits [25].

Shane O'Sullivan re-imaged polarized point sources detected in the HETDEX field (see Section 2.4) at high resolution with LOFAR. He found small Faraday depth differences between lobes in radio galaxies on Mpc scales. This can be explained by an intergalactic magnetic field with an rms strength $B_{rms} \sim 0.3$ μG. However, the poorly constrained small-scale fluctuations in the Faraday depth of the Milky Way limit the analysis [26,27].

2.3. Galaxies and AGN

2.3.1. AGN

Shane O'Sullivan presented millimeter-spectropolarimetry results of high Faraday depths ($\sim 10^5$ rad m^{-2}) from the radio jet of 3C 273 using Atacama Large Millimeter Array (ALMA) observations (project led by Talvikki Hovatta [28]).

Craig Anderson demonstrated that the thermal plasma in radio galaxy lobes can be probed using Faraday Tomography [29]. Observations of Fornax A at 1–3 GHz with the Australia Telescope Compact Array (ATCA) show complex Faraday depth structure, with frequent small-scale reversals of Faraday depth sign. Ruling out both Kelvin–Helmholtz and Rayleigh–Taylor instabilities, he found that the most likely explanation for these structures is material advected from the host galaxy NGC 1316. He also presented a polarization map of part of the Southern lobe of Centaurus A with the Australia SKA Pathfinder (ASKAP), which shows complex depolarization structure.

The catalog of rotation measures (RM) of polarized NVSS sources [30] contains a few dozen sources at high latitudes with anomalously high RMs. **Yik Ki (Jackie) Ma** investigated the cause of these anomalously high RMs using follow-up observations at 1–2 GHz with the VLA. Some of these RMs were caused by wrongly evaluated $n\pi$-ambiguities. He suggested using the variation in RM in a radius of 3° as a diagnostic to find sources with a wrong evaluation of the $n\pi$-ambiguity.

Alice Pasetto performed spectro-polarimetric imaging of 14 polarized AGN with high RMs (RM > 500 rad m^{-2}), using the Jansky Very Large Array (JVLA) at 4 and 12 GHz. These sources show widely varying total intensity synchrotron spectra and polarization behavior. QU-fitting reveals multiple Faraday depth components with Faraday depths from 100 s to 1000 s of rad m^{-2}. These high-Faraday depth components could be, e.g., due to jet winds, or a clumpy medium very close to the central black hole.

The role of magnetic fields in dust tori around Active Galactic Nuclei (AGN) was discussed by **Yuki Kudoh**, who showed that numerical simulations of AGN tori need both high order accuracy and high resolution in order to determine the role of the magneto-rotational instability in the torus [31].

Tomohisa Kawashima investigated the influence of spin on the shadow of the supermassive black hole in the center of M87, which will be imaged by the Event Horizon Telescope (EHT). His general relativistic MHD (GR-MHD) simulations show that very high spins may be detectable by a slight increase in shadow radius.

2.3.2. Spiral Galaxies

Radiopolarimetric observations of a large selection of edge-on spiral galaxies, as part of the CHANG-ES project [32], were shown by **Marita Krause**. She presented estimates of radio scale heights for this sample, and concluded that gravitationally influenced galactic winds are ubiquitous in spiral galaxies [33]. She showed that the scale heights of the polarized halos depend mainly on the diameter of the radio disks of the galaxies. Lack of frequency dependence of scale heights implies that cosmic ray transport is dominated by escape through Galactic winds.

Numerical magnetohydrodynamical simulations of spiral galaxies by **Mami Machida** show that weak fields amplified by the magneto-rotational instability (MRI) become turbulent and eventually form outflows driven by magnetic pressure [34]. Therefore, a dynamo is created produced by the MRI and the Parkes instability. She calculated observable Faraday depths and polarized intensity from the simulation results, including depolarization effects. The butterfly pattern as in the RM map from the Northern VLA Sky Survey [30] can be reproduced, as well as magnetic arms and low-frequency depolarization in the disk.

Hiroyuki Nakanishi derived RMs for six bright galaxies at inclination angle $i < 70^\circ$ from VLA data at 1.4 GHz and 4.8 GHz. He combined the magnetic field direction information from the RMs with polarization vector orientations from synchrotron polarization maps to obtain maps of integrated magnetic field vectors across these galaxies. In all galaxies, small (or meso-)scale structure in magnetic field can be seen, with abundant field reversals.

Kohei Kurahara showed that the directions of magnetic field vectors in nearby galaxy NGC 6946 as derived from radiopolarimetric maps show reversals in field directions on meso-scales, which cannot be explained by recent numerical simulations of galactic magnetic fields developing from an axisymmetric magnetic field configuration [35].

Sarrvesh Sridhar presented his work on the curious galaxy NGC 4258, which shows anomalous arms in radio, X-rays and Hα that are offset from the star forming disk. His Westerbork Synthesis Radio Telescope (WSRT) continuum and HI observations and LOFAR data show the anomalous arms. He found a $\sim$6% increase in polarized intensity at a location of an HI hole in the western anomalous arm, suggesting interaction between the polarizing gas and the star forming disk. This leads him to propose a model where the western arm is located in the plane of the star forming disk, but the eastern arm is protruding at an angle form the disk.

Maja Kierdorf presented S-band (2–4 GHz) JVLA polarimetric data of nearby spiral M51, complementing existing data at $\sim$1.5 GHz, 5 GHz and 8 GHz. This intermediate frequency band is ideal to probe the disk-halo interaction in M51. She showed that her data cannot be fit well with published depolarization models for M51 [36], thus a more complex interpretation is needed.

2.4. Magnetic Fields in the Milky Way

2.4.1. Magnetic Fields in the General Interstellar Medium

Cameron Van Eck discussed LOFAR Faraday Tomography of a $\sim$300 square degree region at high latitudes, probing the nearby interstellar medium (ISM) [37]. He found ubiquitous and large-(angular-)scale polarized emission at various low Faraday depths. His calculations of depolarization in Faraday thick media show that Gaussian shapes get depolarized rapidly at low frequencies. The turbulent ionized medium can be represented by a Gaussian in Faraday space, leading him to the conclusion that LOFAR is only sensitive to polarized emission building up in neutral (Faraday-thin) clouds.

The Global Magneto-ionic Medium Survey (GMIMS, [38]) consists of six individual surveys together covering two hemispheres and full frequency coverage between $\sim$300 MHz and $\sim$1800 MHz. Two of these surveys have been finished to date and their results were discussed in this meeting.

Firstly, **Alex Hill** presented the GMIMS-North-High Band study (1300–1800 MHz). He studied a highly polarized region in the outer Galaxy called the Fan Region. Although it was long believed that the Fan Region was local (a few 100 pc), depolarization of part of the Fan region by the supernova remnant W4 now places (part of) the Fan region firmly in and/or behind the Perseus Arm. Modeling (de-)polarization due to large-scale magnetic field models confirms the presence of this region [39]. He introduced the new Canadian Hydrogen Intensity Mapping Experiment (CHIME) instrument, including a first preliminary image of the whole northern sky.

The second GMIMS presentation focused on HII regions in the GMIMS-South-Low survey (300–480 MHz). **Alec Thomson** showed that HII regions may completely depolarize background emission, or not depolarize at all, depending on their distance and thermal electron density. Depolarized HII regions can be used to estimate the emissivity of their foregrounds.

To translate Faraday depth measurements to magnetic field knowledge, a good model for thermal electron density in the Milky Way is crucial. Dispersion Measures (DMs) of pulsars are an important probe, which is often hampered by large uncertainties in their distances. **Osamu Kameya** discussed differential VLBI to determine parallax distances. Using these, he found that the thermal electron density in the solar neighborhood is quite complex and not accurately represented in the NE2001 galactic electron density model.

Polarization of near infrared and optical starlight is an independent tracer of the Galactic magnetic field. This method was discussed by **Tetsuya Zenko**, who observed 52 Cepheids towards the inner Galaxy using the Infrared Survey Facility (IRSF) and added 14 Cepheids from the literature. In a field towards the inner Galaxy, he could reconstruct a global magnetic field parallel to the plane, but also detected small-scale variations.

Understanding the interstellar medium includes understanding the fragmentation of gas. Planary structures (filaments) exist at all scales and epochs, oftentimes magnetic field induced. Their clumpy fragmentation has been described numerically, but is analytically a tough problem to solve. **Jean-Baptiste Durrive** presented his method to solve the fourth-order gravitational instability, by reducing it to an iterative second order problem. His solution agrees very well with the numerical results.

2.4.2. Magnetic Fields in Galactic Objects

The Local Bubble is a superbubble blown by a collection of supernovae a few million years ago, in which our sun is embedded. By deriving an analytical model for the magnetic field in the shell of the Local Bubble, represented by an inclined spheroid off-centred from the sun, and comparing its predicted dust polarization to that measured by Planck at high Galactic latitudes, **Marta Alves** found that the magnetic field in the local interstellar medium has been highly deformed by the Local Bubble [40].

Supernova remnants (SNRs) are believed to be the main Galactic sources for acceleration of electrons to cosmic-ray energies. The most plausible model used is Diffusive Shock Acceleration (DSA). However, there are still many open questions, one of which is the unknown cosmic ray acceleration efficiency. Hα emission from SNR shock fronts probe shock acceleration physics, argued **Satoru Katsuda**. In particular, a difference in polarization degree in narrow and broad Hα line may be proportional to the acceleration efficiency. He measured Hα polarization in broad and narrow Hα lines in the young Tycho SNR, known to be a very efficient particle accelerator. He found equal polarization in broad and narrow lines, consistent with interstellar polarization. **Jiro Shimoda** studied correlation functions in 1.5 GHz VLA synchrotron total intensity in the Tycho SNR, which is correlated to the magnetic field power spectrum. The outer shell is consistent with a Kolmogorov magnetic field power spectrum, but the inner edge of the shell is not. He suggested that this is due to the contact discontinuity that is located there.

SS 433 is a (so far) unique galactic object consisting of a stellar jet protruding through the SNR W50. **Haruka Sakemi** obtained ATCA observations at 2.3–3.0 GHz of SS 433 and showed that there is a strong polarized filament behind the SS 433 jet head, and weaker filaments behind it possibly indicating a helical magnetic field [41]. Faraday Tomography reveals a complex pattern of Faraday depth components from 0 to $\sim$300 rad m^{-2}. This structure is compared to the two-temperature MHD simulations of astrophysical jets presented by **Takumi Ohmura**, which is the first jet simulation to use separate electron and ion temperatures. She found that the electron temperature is 1–2 orders of magnitude lower than the ion temperature at the jet hotspot, where the magnetic field is amplified by the termination shock [42].

Mariko Nomura explained the "Bullet" in W44, a Y-shaped bright emission feature in the SNR W44, by a bow shock from an isolated stellar-mass black hole through the molecular cloud associated with W44. Her MHD simulations show that only a magnetic field of 0.5 mG or more can create a feature that agrees with the size and shape of the observed feature. Three observed Compact High Velocity Clouds near the Galactic Center may also have been created this way. Searching for their interactions with molecular clouds may thus be a way to uncover the hidden population of Galactic stellar-mass black holes.

Hiroyuki Takahashi presented GR-MHD simulations of supercritical accretion (i.e., accretion above the Eddington limit) onto a magnetized neutron star by a binary companion star. He showed the formation of a magnetosphere in these simulations and presented a theoretical model of the magnetosphere radius and spin-up rate of the central neutron star, consistent with the GR-MHD results.

Kenji Nakamura presented 2D MHD simulations of the transitions of X-ray binaries between accretion states. Simulations including thermal conduction formed a low-temperature, high-density accretion disk similar to simulations without thermal conduction, but in addition produced a warm accretion flow around this accretion disk [43].

2.4.3. Large-Scale Models of the Galactic Magnetic Field

There are a fair number of global galactic magnetic field models, either 2D (only the disk) or 3D (including the gaseous halo). These models are mostly fitted to synchrotron total intensity, polarized intensity and/or RMs from pulsars and/or extragalactic sources. The quality of fit of the latest models is somewhat comparable, and a model sufficiently reliable to use for ISM studies or foreground subtraction is not available yet. Improvements to these models were discussed in the form of adding tracers and diagnostics, or improving the modeling method.

Jennifer West searched for non-zero helicity in the Milky Way, which is predicted to cause skewness of the distribution in the RM vs. polarized intensity distribution. For this, she compared predictions from dynamo models containing different modes [44], with synchrotron polarization data from the Planck satellite.

An other independent tracer of galactic magnetic fields are OH masers, found in many environments. However, when using them as probes of the galactic magnetic field, it is best to look in star forming regions, where OH masers form at the outer edges.

Chikaedu Ogbodo presented Zeeman splitting measurements of the 1720 MHz transition of hydroxyl masers as part of the MAGMO project [45], and discussed polarimetric properties and derived magnetic field strengths.

Jimi Green discussed current and future polarimetric OH (hydroxyl) maser surveys to detect magnetic fields in star forming regions through Zeeman splitting. He also introduced the CH (carbine) maser as a tracer of a gas phase between CO and atomic H, which enables measuring the so-called "dark magnetism".

Marijke Haverkorn presented the Interstellar MAGnetic field INference Engine (IMAGINE), which is a software package to model the Galactic magnetic field using Bayesian inference, as well as the associated (open) collaboration of researchers in various fields interested in Galactic magnetism [46,47].

2.5. Amazing Magnetism Projects

A few of the exciting instruments or surveys expected to enable breakthroughs in cosmic magnetism in the near future were discussed.

Bryan Gaensler presented the first results from Wide Field Polarization Surveys. Firstly, the ASKAP POlarisation Sky Survey of the Universe's Magnetism (POSSUM) survey is an all-southern sky polarimetric survey at 1.1–1.4 GHz at 10 arcsecond resolution and down to $\sim$20 μJy/beam sensitivity. Secondly, the Very Large Array Sky Survey (VLASS) will survey the northern sky from 2 to 4 GHz at 2.5 arcsec resolution to a sensitivity of $\sim$70 μJy/beam. A major goal of these surveys is the creation of a RM Grid of extragalactic point sources, which allows study of magnetic fields in the Milky Way, external galaxies, AGN, clusters, and the intergalactic medium.

Tessa Vernstrom gave an overview of the Murchison Widefield Array (MWA), and a wide variety of MWA science results including limits on synchrotron radiation from the cosmic web [48] or absorption studies of Galactic HII regions [49]. She presented the GaLactic and Extragalactic All-Sky MWA Survey (GLEAM, [50]) catalog, visualization, science results, and follow-up surveys.

George Heald presented both the LOFAR Multifrequency Snapshot Sky Survey (MSSS) and GLEAM survey, which together form a truly all-sky polarimetric source catalog at low frequencies. He showed early MSSS results and discussed the survey's upgrade to 45 arcsec resolution. The polarization analysis of the MSSS data, the MSSS All-sky Polarization Survey (MAPS), was presented by **Jamie Farnes**. The GLEAM results include ongoing analysis of polarized point sources, the GLEAM source catalog and the MWA's upgrade to longer baselines.

Jamie Farnes also presented the the SKA Science Data Processor Integration Prototype (SIP), which is an end-to-end prototype of the major components of the Science Data Processor of the SKA. He discussed inclusion of the MAPS data pipeline into SIP including Faraday Tomography, and showed early results of MAPS data as processed with SIP [51].

3. Conclusions

This highly successful workshop saw presentations of broad and varied scientific results on many aspects of cosmic magnetism, based on observations, simulations, and theory. New results on cosmic magnetism from stellar scales to large-scale structure formation, and from the magnetic field generation in the early Universe to magnetism in nearby galactic objects were presented and discussed.

As the Japanese part of the Scientific Organizing Committee (SOC) was a representation of the Japan SKA Consortium (SKA-JP) Cosmic Magnetism Science Working Group, an important topic in the workshop was the future of radio astronomy and radio-polarimetry in particular, as addressed in many presentations. The audience was presented with exciting new observations of various new or upgraded radio telescopes and instruments, such as the CHIME, LOFAR, SRT, MWA, and ASKAP telescopes and VERA, ATCA-CAB and Parkes PAF receivers. In addition to observational advances, developments in computing are equally important. Updates were presented on numerical methods to process and (statistically) analyze complex datasets, computing hardware and software developments for the SKA, and to prepare for the era of exascale computing.

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