MAGNETIC FIELDS STUDIES IN THE NEXT DECADE

EAO SUBMILLIMETRE FUTURES PAPER SERIES, 2019

Ray S. Furuya*1 • Kate Pattle2 • Simon Coudé3 • Tao-Chung Ching4 • Steve Mairs5
Sarah Sadavoy6,7 • Peter Scicluna8 • Archana Soam3 • Chakali Eswaraiah4 • Samar Safi-Harb9

1Institute of Liberal Arts and Sciences, Tokushima University, Minami Jousanajima-machi
I-1, Tokushima 770-8502, Japan
2Institute of Astronomy and Department of Physics, National Tsing Hua University,
Hsinchu 30013, Taiwan, R.O.C.
3SOFIA Science Center, USRA NASA Ames Research Center Moffett Field, CA 94035, U.S.A.
4CAS Key Laboratory of FAST, National Astronomical Observatories, Chinese Academy of Sciences,
Datun Road, Chaoyang District, Beijing 100101, People’s Republic of China
5East Asian Observatory (JCMT) 660 N. A’ohoku Place, Hilo, HI, 96720, U.S.A.
6Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA, 02138, USA
7Department for Physics, Engineering Physics and Astrophysics, Queen’s University,
Kingston, ON, K7L 3N6, Canada
8Academia Sinica Institute of Astronomy and Astrophysics, AS/NTU Astronomy-Mathematics Building,
No 1. Sec. 4 Roosevelt Rd, Taipei, Taiwan
9Dept of Physics and Astronomy, Faculty of Science, University of Manitoba, Winnipeg, MR R3T 2N2 Canada

ABSTRACT

Magnetic fields are ubiquitous in our Universe, but remain poorly understood in many branches of astrophysics. A key tool for inferring astrophysical magnetic field properties is dust emission polarimetry. The James Clerk Maxwell Telescope (JCMT) is planning a new 850 \( \mu \)m camera consisting of an array of 7272 paired Microwave Kinetic Inductance Detectors (MKIDs), which will inherently acquire linear polarization information. The camera will allow wide-area polarization mapping of dust emission at 14"-resolution, allowing magnetic field properties to be studied in a wide range of environments, including all stages of the star formation process, Asymptotic Giant Branch stellar envelopes and planetary nebula, external galaxies including starburst galaxies and analogues for the Milky Way, and the environments of active galactic nuclei (AGN). Time domain studies of AGN and protostellar polarization variability will also become practicable. Studies of the polarization properties of the interstellar medium will also allow detailed investigation of dust grain properties and physics. These investigations would benefit from a potential future upgrade adding 450 \( \mu \)m capability to the camera, which would allow inference of spectral indices for polarized dust emission in a range of environments. The enhanced mapping speed and polarization capabilities of the new camera will transform the JCMT into a true submillimetre polarization survey instrument, offering the potential to revolutionize our understanding of magnetic fields in the cold Universe.

1 Introduction

Our Universe is threaded by magnetic fields (also known as \( B \)-fields), whose presence is deduced from their effects on the astrophysical generation of electromagnetic radiation, or on the propagation of that radiation through the interstellar or intergalactic media (ISM and IGM respectively) [e.g. 1], and so through observation of polarized astrophysical signal. Magnetic fields can significantly affect the dynamics of all phases of the ISM, being coupled to the neutral material by Alfvenic flux freezing (“frozen in”) [2]. These magnetic fields may be primordial [3] or generated or amplified by dynamo effects [1], and can be dissipated by magnetic reconnection [4]. In order to address some of the most pressing questions in modern astrophysics and cosmology we require knowledge of the structure and strength of magnetic fields in the ISM and IGM, the physical roles that they play, and the conditions under which they affect gas dynamics.

*rsf@tokushima-u.ac.jp
Submillimetre emission polarimetry is a key tool for deducing magnetic field properties in cold ($\lesssim 100$ K) gas. Polarized continuum emission arises from non-spherical dust grains aligned with their major axes perpendicular to their local magnetic field [5]: a powerful tracer of plane-of-sky ISM magnetic field direction, as dust makes up 1% of the ISM by mass [6], and is widely used as a proxy for molecular hydrogen [7]. Emission polarimetry is unique in its dynamic range and wide mapping area. Polarized signal is down to column densities $\sim 10^{20} \text{cm}^{-2}$ in space-based observations [8], while submillimetre dust emission remains optically thin at even the highest ISM gas densities [7]. Dust polarization fraction ranges from a maximum of $\sim 20\%$ in the diffuse ISM [8] to $\lesssim 1\%$ in the densest parts of molecular clouds [e.g. 9], and so polarization observations require a sensitivity $\gtrsim 10^2$ times better than is needed in unpolarized light.

Methods for quantifying the dynamic importance of magnetic fields inferred from emission polarimetry are well-established. Plane-of-sky magnetic field strength is inferred using the Davis-Chandrasekhar-Fermi (DCF) method [10, 11], which takes deviations in magnetic field angle to result from Alfvénic distortion by non-thermal motions. The dynamic importance of the magnetic field relative to gravity is assessed using the mass-to-flux ratio, the critical value of which indicates a structure too massive to be supported by its internal magnetic field, while importance relative to non-thermal ISM motions is assessed using the Alfvén Mach number, the ratio of gas velocity dispersion to Alfvén velocity [2]. The dynamic importance of magnetic fields can also be characterised through their morphology [e.g. 12].

The James Clerk Maxwell Telescope (JCMT) is a 15 m telescope operating in the wavelength range $450 - 1100 \mu m$, with a resolution of $14''$ at $850 \mu m$, near the summit of Mauna Kea in Hawaii. The JCMT has for decades been a world leader in submillimetre emission polarimetry, hosting the UKT Polarimeter [13], the SCUPOL polarimeter [14, 15] on the SCUBA camera [16], and now the POL-2 polarimeter [17, 18] on the SCUBA-2 camera [19]. Each of these has measured polarization by inserting a half-wave plate into a camera’s light path, progressing from a sensitivity of $\sim 200 \text{mJy beam}^{-1}$ in a single pixel [UKT Polarimeter, 13], to $\sim 1 \text{mJy beam}^{-1}$ over $> 5000$ pixels [POL-2, 18, 20]. The JCMT has made the first detections of magnetic fields in protostellar envelopes with the UKT Polarimeter [21, 22]; in the centre of a starburst galaxy [23] and in a starless core [24] with SCUPOL; and in a photoionized column with POL-2 [25]. The JCMT has made most DCF measurements of magnetic field strength in the ISM to date [26].

Other recent advances have been the Planck Space Observatory [8] all-sky polarization maps, and the polarimetric capabilities of the Atacama Large Millimeter/submillimeter Array (ALMA) [e.g. 27]. The $5''$-resolution Planck all-sky maps reveal the large-scale polarization structure of the Milky Way, but at best coarsely resolve molecular clouds. Conversely, ALMA can map detailed magnetic fields around individual compact objects but, with a maximum observable size scale $\sim 1''$, cannot provide larger-scale context. With a resolution $\sim 10''$, the JCMT bridges this gap (see Figure 1), flexibly providing information on how Galactic-scale magnetic fields couple to fields on the smallest scales in the ISM, through both wide-area surveys [20] and high-sensitivity mapping of individual sources [e.g. 28].

The JCMT is planning a major instrumentation upgrade. First light for a new $850 \mu m$ camera is planned for October 2022, with $450 \mu m$ capability added in 2024. A new large heterodyne array is planned for 2026. The new camera will have a $12''$ field of view, twice that of SCUBA-2, with a focal plane filled with 3636 pixels, each comprising two Microwave Kinetic Induction Detectors (MKIDs), measuring orthogonal linear polarizations from a single scan observation without a half-wave plate. Native observation of polarized signal, and the improved capabilities of MKIDs over the SCUBA-2 bolometers, will result in a guaranteed $20 \times$ increase in polarization mapping speed over POL-2, and an aspirational $40 \times$ increase. As shown in Figure 2, this will allow entire molecular clouds to be mapped in the time currently required to map a single POL-2 field. This will transform the JCMT into a true polarimetric survey instrument, while retaining its ability to map sources of particular scientific interest to unprecedented depth in polarized light.

In this white paper we present potential science goals for the new JCMT camera. While we primarily focus on the $850 \mu m$ polarimetric capabilities of the camera, we also discuss how the proposed studies could be enhanced by $450 \mu m$ polarimetric data. Where relevant we discuss time-domain magnetic field studies. Section 2 considers star formation and the Galactic ISM; Section 3, evolved stars and stellar remnants; Section 4, magnetic fields in external galaxies, our own Galactic centre, and active galactic nuclei; Section 5, dust grain physics; Section 6, potential synergies with heterodyne instruments; and Section 7, synergies with other polarimeters. Section 8 summarizes the white paper.

## 2 Magnetic fields in star formation

**Molecular clouds:** Stars form in molecular clouds, the gas dynamics of which are regulated by a, interplay between turbulent pressure, magnetic fields and self-gravity [e.g. 33]. These cold molecular clouds form out of the warm ISM, which is heated both by supernova shocks and by cosmic rays trapped by the galactic magnetic field [34]. Proposed formation mechanisms include multiple-shock compression of atomic clouds embedded in a weak galactic-scale magnetic field [35], or colliding flows in a magnetized warm ISM [36], among other models. Thus, galactic-scale magnetic fields may be integral to setting the initial conditions for the formation of stars within molecular clouds.
Figure 1: A comparison of JCMT, Planck and ALMA polarization observations. All vectors are rotated by 90° to trace magnetic field direction. Left: Planck observations of the Orion Molecular Cloud [8]. Centre: JCMT observations of the OMC-1 region in the centre of Orion [29]. Note the significant deviations from the large-scale field morphology. The total area observed with the JCMT is shown as a black circle on the left-hand panel. Lower right: ALMA observations of the Serpens SMM 1 protostar [30], located at comparable distance to Orion [31, 32]. The extent of the ALMA observations is shown as a black square on the central panel (Serpens MM1 is not located in the marked region). Upper right: The resolutions of Planck [8, 37] and extinction polarimetric observations [38] suggest that large-scale magnetic fields in molecular clouds are bi-modal, being preferentially aligned either parallel or perpendicular to the major axis of the cloud. The relationship between magnetic fields and filamentary structure within clouds remains uncertain. Recent observations of the Vela C complex by BLAST-Pol [39] and of IRDCs by POL-2 [40], along with optical and NIR extinction polarimetric results [e.g. 41, 42], show that magnetic fields on the peripheries of self-gravitating filaments are generally perpendicular to the filaments’ major axes (see Figure 3). However, these magnetic fields may be aligned with low-density substructures (sometimes called ‘striations’) which are themselves perpendicular to the filaments’ major axes [42]. These striations may comprise material being accreted onto filaments along magnetic field lines [43]. These observations tell us about overall field-filament alignment within molecular clouds, but do not provide sufficient resolution to determine the the behaviour of magnetic field inside filaments. Conservation of magnetic flux requires that magnetic fields either pass through filaments [e.g. 44] or wrap around them [ e.g. 45]. Sensitive high-resolution polarization observations would distinguish between these cases, informing the role of magnetic fields in filamentary accretion and fragmentation.

POL-2 observations of nearby molecular clouds suggest that within dense filaments, relationships between field and filament direction can become more complex. For example, the centre of the OMC-1 molecular cloud – the nearest region of high-mass star formation – shows a field geometry that may have been significantly distorted by large-scale motion of material under gravity [29, see Figure 1]. However, the surface-brightness limitation and relatively small extent of a POL-2 observation [18] and the insensitivity of SCUBA-2 to large-scale structure [47] limits our current ability to deduce the properties of magnetic fields within filamentary structure, particularly in low-density non-self-gravitating filaments. To determine the existence or otherwise of magnetically-supported filaments, higher-sensitivity polarization observations with < 0.1 pc linear resolution are needed [48]. The new 850-µm camera will allow entire molecular clouds to be mapped in polarized light at 14″ resolution, equivalent to ~ 0.01 pc in nearby molecular clouds.

Feedback from massive stars drives the dynamics and regulates the evolution of the molecular clouds in which they form [49]. Intense UV radiation and/or winds from OB stars as well as supernova feedback drive the expansion of HII regions, creating structures such as photoionized columns (also known as pillars or elephant trunks) in the photodissociation regions (PDRs) at the interface between molecular and ionized material. The role of magnetic fields in PDR evolution remains poorly constrained [e.g. 50, 51]. POL-2 has recently made the first map of magnetic fields within the famous ‘Pillars of Creation’ in M16 [25, see Figure 4], finding that the magnetic field is dynamically important, but unable to
prevent the columns’ destruction by the oncoming ionization front. However, the improved mapping speed of the new camera will allow the entire PDR associated with an open HII region to be mapped in the time currently required to map individual columns, allowing investigation of the role of magnetic fields in the large-scale evolution of HII regions.

**Time estimate:** Given a 20× increase in mapping speed, with 14 hours of observing time in Band 2 weather, 0.6 square degrees of the sky could be observed to a depth of 1.5 mJy/beam, as shown in Figure 2. This would allow mapping of full molecular clouds to the depth currently achieved in single pointing observations by the BISTRO (B-Fields in Star-forming Region Observations) Survey [20], fulfilling the science goals described above.

**Starless and prestellar cores:** A key indicator of the relative importance of magnetic fields in the gravitational collapse of cores to form YSOs, and of the magnetic fields in YSOs themselves, is the strength and morphology of magnetic fields in starless cores. Starless cores are overdensities in star-forming regions which, if gravitationally bound (a ‘prestellar core’ [52]), will go on to form an individual star or system of stars [53]. A detailed understanding of how starless cores form and evolve is necessary in order to understand the functional form of the Initial Mass Function [54].

Being extended, low-surface-brightness objects, starless cores remain particularly challenging to observe. The JCMT has been responsible for nearly all polarimetric observations of starless cores to date, both with SCUPOL [55] and more recently with POL-2 [e.g. 56]. Isolated starless cores generally appear to have a smooth and well-ordered magnetic field, with detectable polarization across the cores [e.g. 57]. An example of a starless core observed with POL-2 is shown in Figure 4. Despite being gravitationally unstable [e.g. 58], none of the prestellar cores so far observed unambiguously show the ‘hourglass’ magnetic field which would indicate ambipolar-diffusion-driven collapse [59]. The role of magnetic fields in the physics of prestellar core formation and collapse thus remains unclear. However, very few starless cores have been observed in polarized light, due to the prohibitive amount of time required for a detection, and observations are strongly biased towards the very highest-surface-brightness cores. With 20× increased mapping speed, the new JCMT camera would allow at least an order of magnitude increase in the number of starless cores detectable, and would allow investigation of whether the uniform fields seen in bright cores are the norm, and to systematically search for cores showing signs of magnetically regulated collapse.

Debate continues over whether high-mass stars form from the monolithic collapse of prestellar cores, analogously to low-mass stars, or through competitive accretion or other dynamic processes [49]. If high-mass prestellar cores exist, they are likely to require significant magnetic support [e.g. 62]. Archival data from the SCUPOL Legacy Catalogue toward a set of bright massive cores in the G 11.11-0.12 region has been used to propose that one of these sources is a magnetically supported high-mass starless core [62]. Most detections of high-mass star-forming cores to date have been made using interferometric observations [e.g. 63, 64] in which any extended lower-density periphery will be resolved out. The new JCMT camera will allow entire IRDCs to be surveyed in polarized light, searching for polarization geometries consistent with magnetic support, and for existing high-mass core candidates to be surveyed systematically, allowing the debate over magnetically-supported high-mass starless cores to be put onto a statistical footing.
Figure 3: Examples of magnetic fields in molecular clouds. **Left:** Plane-of-sky magnetic field structure observed with POL-2 in the nearby (∼300 pc) Perseus B1 low-mass star-forming region [60]. Image shows 850 µm intensity; contours show $^{12}$CO J=3-2 integrated intensity (10 and 20 K km s$^{-1}$) measured with HARP [47]. Embedded YSOs are marked with star symbols. **Right:** Plane-of-sky magnetic field morphology observed with BLAST-Pol in the early-stage molecular cloud Vela C (∼700 pc) [61].

**Time estimate:** Given a 20× increase in mapping speed, the well-studied prestellar core L1544 (peak 850µm brightness ∼300 mJy/beam) could be observed to a sensitivity of 0.5 mJy/beam with 5 hours of Band 1 observations, allowing 3-σ detection of 0.5% polarization on-peak. A survey of 20 such cores would thus require only 100 hours of observing time.

**Protostellar systems:** Protostellar cores, dense cores with a size ∼0.1 pc containing embedded hydrostatic objects, either young stellar objects (YSOs) or their precursors, are generally warmer, brighter and more centrally condensed than their starless counterparts, and so are less challenging to observe. Protostellar cores, containing complex internal structures (discs, accretion flows, etc.), are good interferometric targets [65]. However, single-dish observations provide information on the environments of these cores unobtainable with interferometers. The new JCMT camera offers the opportunity to perform unbiased surveys of the magnetic environments of protostellar cores in nearby molecular clouds.

Recent interferometric observations suggest that the dynamic importance of magnetic fields in protostellar cores may vary widely: the majority have outflows randomly oriented with respect to the magnetic field direction (on scales ∼10$^2$ – 10$^3$ AU), suggesting a weak magnetic field, while a minority show parallel outflow and field directions, suggesting a dynamically important field [65]. A large dust polarization survey could investigate whether this behaviour persists on core-to-filament scales (∼0.1 pc), and whether there is a difference in large-scale magnetic environment between the two populations of protostellar cores. Such a survey would offer a strong legacy set of data, and would identify targets for interferometric follow-up. Studying magnetic fields from core scales down to the scales of disks (∼10$^2$ AU) is vital to understand the origin of those disks and the formation of jets and outflows, in order to determine whether field misalignment, turbulence, or non-ideal magnetohydrodynamic (MHD) processes are at play [e.g., 66, 67, 68].

A further unanswered question is of the role played by magnetic fields in the formation of brown dwarfs [69]. The improved sensitivity and mapping speed of the new JCMT camera will allow for systematic investigation of cloud cores hosting very low luminosity objects (VeLLOs; integrated luminosity <∼0.1 L$_{\odot}$), potential progenitors of either proto-brown dwarfs or very low-mass YSOs [e.g. 70]. A large sample of VeLLOs could include first hydrostatic cores (FHSCs) – the much-searched-for adiabatic first kernel of mass which precedes a core’s collapse to make a YSO. Regardless of whether VeLLOs are FHSCs or very young YSOs, their outflows are too weak to affect the magnetic fields in their host cores, and so they offer the possibility of mapping the initial field structure in protostellar cores [71].

**Time-domain science:** A long-standing question in star formation is of the rate at which a YSO gains mass from its surroundings [73], and of the role of magnetic fields in regulating this process. While YSOs are inherently variable objects [e.g., 74, 75], sporadic episodes of elevated mass accretion can be observed at the earliest stages of a YSO’s life at far-infrared (FIR) and submillimetre wavelengths [76]. The frequency and amplitude of this variability give insight into the physical drivers of unsteady accretion. The JCMT Transients Survey first showed that submillimetre protostellar variability is robustly observable [77, 78, 79]. When a YSO enters a burst phase, the surrounding material...
reprocesses the excess energy and the submillimetre flux increases with dust temperature [76, 79]. Monitoring potential changes in the magnetic field in the accreting material over timescales of weeks to years will give insight into the physical conditions of these systems. Radio observations have also shown short-timescale (hours) synchrotron flares associated with T Tauri stars [e.g. 80, 81]. The JCMT recently made the first submillimetre observation of a similar event in the JW 566 T Tauri Binary System [82], thought to be the most powerful of its kind recorded. Fast-followup target-of-opportunity polarimetric observations of the dusty regions associated with such flares will be compared with archival data to note any significant changes in magnetic field properties, even over short timescales.

**Time estimate:** For a YSO with peak 850\(\mu\)m brightness \(\sim 1000\) mJy/beam (such as the variable source EC53 [83]), a sensitivity \(\sim 3.3\) mJy/beam would be required in order to make a 3-\(\sigma\) detection of 1\% changes in polarization. Given a 20\(\times\) increase in mapping speed, this could be achieved in approximately 10 minutes of Band 2 observing time. This would make both wide-area YSO polarization surveys covering entire molecular clouds and long-term and target-of-opportunity monitoring of protostellar variability feasible.

**450\(\mu\)m science:** Comparison of 450\(\mu\)m and 850\(\mu\)m measurements of polarization in molecular clouds and cores will allow study of differing polarization structures in warm and cold dust populations along the line of sight, thereby producing quasi-three-dimensional magnetic field models [e.g. 67]. The potential of such studies is demonstrated by recent FIR polarimetric observations of Orion A, showing that the magnetic field structure observed at 850\(\mu\)m (Figure 1) gives way in the FIR to a polarization structure that traces the bipolar structure produced by the BN/KL explosion [84]. The 450\(\mu\)m capabilities of the new camera will allow such comparisons to be made as a matter of course.

### 3 Late-stage Stellar Evolution

**AGB stars and planetary nebulae:** The new JCMT camera will significantly improve our knowledge of magnetic fields in asymptotic giant branch (AGB) stars and planetary nebulae by allowing the study of magnetic fields in circumstellar material, and so of the typical magnetic field geometry within a circumstellar envelope, how magnetic fields regulate mass-loss phenomena in AGB stars (or vice versa), and of the relationship between stellar and circumstellar magnetic fields. Cool evolved stars have significant magnetic fields both at their surfaces [85] and in their envelopes [e.g. 86, 87], measurements of which currently use Zeeman splitting either of atomic lines from the stellar photosphere or of maser transitions of molecules in the circumstellar material. However, these measurements sample only a small fraction of the gas associated with the stars, while photospheric lines may be affected by starspots, and masers inherently sample only high-density, population-inverted, molecular gas in the inner outflow. An overall view of magnetism in evolved stars requires observations of the overall magnetic field structure of the circumstellar envelope.

Debate continues as to whether magnetic fields in AGB stars are produced by angular-momentum transfer from a companion. Statistics of the presence and morphology of the large-scale field will allow comparison to models of the expected population of companions, and with known binary stars. Comparison between field morphology and mass-loss history will reveal whether magnetic fields play any role in shaping the outflow. Correlating magnetic field properties with evolutionary stage will explore how fields evolve with the stars, and if they play a role in the changes that occur as
stars evolve off the AGB. Moreover, along with supernovae, AGB stars have been considered as major sites of dust grain production. Data provided by the new camera would thus provide new observational constraints on dust grain physics.

**Time estimate:** ALMA observations of IRC+10216, the brightest AGB star in the submillimetre [88], suggest that POL-2 might need ~30 hours of Band 1 weather to detect 5%-polarized emission in the outer envelope. A 20× increase in speed would make the brightest sources observable in 1–2 hours each. A large program could thus observe tens or hundreds of evolved stars and map the polarization in their envelopes, particularly if informed by the results of the ongoing Nearby Evolved Stars Survey (NESS) Large Program, or by future continuum mapping with the new camera.

**Supernova remnants:** ISM properties control galactic evolution by regulating star formation rate, while stars return much of their material to the ISM through dense winds or supernova explosions at the end of their lives. These supernovae send shock waves into the ISM, producing supernova remnants (SNRs) which disperse heavy elements, while also compressing and seeding magnetic field lines [e.g., 89, 90]. The origin of magnetic fields in SNRs and their link to the magnetic field of their host galaxy is an important open question, with few objects studied in detail [e.g., 91, 92]. While submillimetre observations offer a new, independent way of probing magnetic fields, only a few SNRs have been mapped in submillimetre polarization to date. With the 20× increase in mapping speed of the new JCMT camera, 850 μm polarization observations of SNRs will be achievable for large numbers of objects, opening a new field of study for the JCMT. A polarization survey of the nearby galaxies M31 and M33 will help link our understanding of the global view of their star formation with their magnetic field morphology: while most extragalactic SNRs will be very compact, their high polarization fractions mean they should be detectable with the new JCMT camera.

The new camera will also enable novel studies in the field of pulsar wind nebulae (PWNe), a subclass of core-collapse supernovae. These are non-thermal, polarized synchrotron bubbles inflated by the loss of rotational energy from fast-spinning neutron stars. It is believed that dust grains are able to penetrate into the nebula given the low pulsar velocity, thus making circumpulsar disks [93]. Future observations of a large sample of PWNe (in their different stages of evolution) will open a new window into the discovery of circumpulsar disks in which planets may form.

SNR magnetic field studies are important not only to understand the particle acceleration mechanism operating in SNR shocks, but also to address the larger questions of cosmic magnetism and the origin of cosmic rays driving future large radio telescopes such as the Square Kilometer Array and thenext generation VLA (ngVLA), and the γ-ray Cherenkov Telescope Array. Observations made with the new JCMT camera will serve as pathfinder science for these instruments.

**Time estimate:** 850μm polarization is detected in 9 hours of mixed Band 1/2 POL-2 commissioning observations of the Crab Nebula SNR. A similar detection would thus be achievable in approximately 30 minutes with a 20× increase in mapping speed. Fainter SNRs would thus be detectable with a few hours of observing time.

### 4 Galactic-scale magnetic fields

**Spiral Galaxies:** The disk of our galaxy is threaded by a large-scale magnetic field, mostly parallel to its spiral arms [e.g., 8, 94]. Similar fields have also been observed in nearby galaxies [95, 96], indicating that these fields are closely tied to the dynamics of spiral galaxies [97], and are likely sustained by a dynamo effect created by differential rotation and star formation occurring within them [e.g., 98]. However, Faraday rotation measures have shown the existence of a field reversal in the inner region of our galaxy [e.g., 99], which has not yet been observed elsewhere, and which could indicate anisotropic turbulence in galactic magnetic fields, or perturbation by satellite galaxies [97].

Submillimetre dust polarization observations in nearby spiral galaxies will allow insight into the magnetic properties of the high-density gas, which will serve as templates to better understand our galaxy’s magnetic field [8]. Several of these nearby galaxies were successfully detected at 450 μm and 850 μm by the JINGLE survey using the SCUBA-2 camera on the JCMT [100], and so the new camera will have the required sensitivity to detect polarization in these objects. The new camera’s larger field of view will allow the first 850 μm polarization surveys of the M31 and M33 galaxies, as discussed above. These extragalactic polarization data sets can be analyzed similarly to those of molecular clouds, providing information about the magnetic and turbulent properties of galactic-scale magnetic fields [101].

**Time estimate:** M31 occupies approximately 3 square degrees on the sky. To map this area to 1.5 mJy/beam sensitivity in 850μm polarized light with the new camera would require approximately 70 hours of Band 2 time, making polarization surveys of nearby spiral galaxies eminently feasible.

**Starburst Galaxies:** Galactic magnetic field strengths ~100 μG are observed in starburst (intensely star-forming) galaxies [e.g., 102]. In comparison, the Milky Way’s large-scale field strength is ~ 5 μG, similar to M31 and M33 [97]. While the origin of starburst galaxies’ strong magnetic fields is not well-understood, their interaction with galactic outflows may have magnetized the IGM in the early universe [e.g., 103]. The new JCMT camera will significantly
expands our knowledge of the magnetic field structure in the densest regions of starburst galaxies, helping to explain the nature of these fields and how they are maintained in environments of intense stellar feedback [e.g., 23, 97, 104].

**Time estimate:** The starburst galaxy M82 has a peak 850\(\mu\)m brightness of 1400 mJy/beam and a median polarization fraction of 2.8% [23]. A 5-\(\sigma\) detection of this polarization fraction could be achieved in less than 3 minutes in Band 2 weather with the new camera, and fainter starbursts could be observed in minutes or hours.

**Super-Massive Black Holes and Active Galactic Nuclei:** The role of magnetic fields in galactic evolution can be investigated through observations of Sagittarius A*, the super-massive black hole (SMBH) at the centre of our galaxy. While Sgr A* is currently quiescent, its accretion behaviour provides information on AGN physics, such as jet launching mechanisms and galactic-scale feedback, unobtainable in more distant sources. Similarly to AGN such as Cygnus A [105], Sgr A* hosts a circumnuclear disc (CND) with a rotating molecular torus housing ionized streamers [106, 107]. POL-2 observations of the CND (Figure 4) show that the magnetic field and the CND align on larger scales, while the innermost field lines align with the streamers [72, 108], suggesting that the CND and the streamers are an inflow system. Observations with the new JCMT camera will allow the large-scale magnetic environment of the Galactic centre and Sgr A* to be mapped in unprecedented detail. These combined with observations of Sgr A* itself from the Event Horizon Telescope [109, 110], of which the JCMT is a part, will revolutionize our understanding of how SMBHs acquire mass, and so how magnetic fields influence the galactic-scale feedback effects that regulate galactic evolution.

**Time estimate:** The POL-2 polarization vectors of the Galactic Centre shown in Figure 1 were achieved in \(\sim\) 14.5 hours of mixed Band 1/2 time, with a sensitivity \(\sim\) 1.6 mJy/beam [72]. With the new camera, such an observation could be made in \(\sim\) 45 minutes, making a deep, wide-area survey of the Galactic Centre quickly practicable.

**Time-domain science:** Among the most extreme environments in which magnetic fields have been detected are jets launched from accretion events onto SMBHs in radio-loud AGN [e.g. 111]. The 850 \(\mu\)m emission of these objects is dominated by highly-polarized synchrotron radiation from relativistic electrons accelerated along magnetic field lines [e.g. 112], and the turbulent nature of the magnetized medium found within shocks along these relativistic jets may cause their observed temporal variability in polarized intensity [e.g. 113, 114].

**Time estimate:** Variable AGN polarization is detected between 40-minute Band 2 850 \(\mu\)m POL-2 observations (sensitivity \(\sim\) 7 mJy/beam) [18]. The new camera would decrease the observing time per measurement to 2 minutes, making a daily observing campaign possible. Such high-cadence measurements would provide a statistically-significant AGN variability data set on timescales of days, and would allow precise measurements of intra-day variability [e.g. 115].

**450 \(\mu\)m science:** The smaller beam size of the JCMT at 450 \(\mu\)m may help to detect polarized emission from radio-loud AGN by reducing the effect of beam dilution on the measured signal. More importantly, while synchrotron emission is typically the main source of emission in these AGN, their 850 \(\mu\)m polarization can be contaminated by dust emission, [116]. This dust component would typically be an order of magnitude brighter than the synchrotron emission at 450 \(\mu\)m, thus lifting the degeneracy between the thermal and non-thermal components at 850 \(\mu\)m. Combined 450 \(\mu\)m and 850 \(\mu\)m polarimetric data of flat-spectrum radio-loud AGN such as blazars can also be used to probe the electron density and magnetic field properties in the inner components of relativistic jets launched by SMBHs [e.g. 113, 115, 117].

## 5 Dust grain physics and alignment mechanisms

For polarization observations to trace magnetic fields, a fraction of the ISM dust population must consist of non-spherical grains with major axes preferentially aligned perpendicular to the local magnetic field direction [5]. The most promising theory for how this occurs is the Radiative Alignment Torques (RATs) paradigm [119], in which irregular grains are spun up by anisotropic radiation [120]. If grain alignment is driven by an incident radiation field, its effectiveness should decrease with increasing extinction [119, 120]. A systematic decrease in polarization fraction towards high-extinction lines of sight (often called a ‘polarization hole’) is indeed commonly observed [e.g. 9, 60, 121], implying loss of grain alignment, an effect most pronounced in starless cores which have no internal source of photons [122, 123]. However, non-Gaussian noise properties of polarization measurements can lead to a predisposition for a lack of grain alignment to be inferred at low-to-intermediate signal-to-noise [124]. Higher-sensitivity observations will allow observation of starless and protostellar cores in a wider range of environments, elucidating the conditions under which grains lose alignment with the magnetic field, and so constraining the size distribution of grains in high-density regions.

Simple models predict an approximately flat submillimetre polarization spectrum (the variation of polarization fraction with wavelength) in molecular clouds [125]. However, polarization spectra have been found to have a minimum at 350 \(\mu\)m [e.g. 125, 126]. While this is possible in the RAT paradigm [127], the predicted variation in polarization fraction with wavelength is too small to explain the apparent 350 \(\mu\)m minimum. However, recent work combining BLAST-Pol 250–500 \(\mu\)m and Planck 850 \(\mu\)m observations have shown a polarization spectrum which is flat to within 10–20% across the submillimetre in nearby molecular clouds [128, 129]. Comparing polarization spectra observed on
450$\mu$m science: Replacing Planck’s 5′ beam with the JCMT’s 12′′ resolution will produce detailed submillimetre polarization spectra through synthesis with BLAST-TNG [130] and SOFIA [131], with 36′′-resolution (BLAST 500 $\mu$m). The upgrade to include 450 $\mu$m imaging could replace BLAST-TNG’s 500 $\mu$m band, further improving the resolution.

6 Synergy with molecular line magnetic field observations

Zeeman Effect: The most direct measurement of astrophysical magnetic field strength is through Zeeman splitting of paramagnetic spectral lines. Such line-of-sight field strength measurements, using either thermal lines (e.g., HI, OH and CN) or maser lines (e.g., H$_2$O), have only been achieved toward a limited number of sources [e.g. 132]. Although magnetic field strengths inferred from dust emission using DCF analysis are comparatively indirect, they can, through wide-area mapping, simultaneously provide both the field structure and its strength in the plane of the sky [e.g. 26]. While Zeeman and DCF measurements probe different magnetic field components, the two are broadly consistent with and complement each other (Figure 5) [26], and can be combined to estimate total magnetic field strength [58]. A more complex approach is to combine polarization, Zeeman and ion-to-neutral molecular line width ratios in order to determine the angle of the magnetic field with respect to the line of sight [133, 134].

With its enhanced sensitivity, the new JCMT camera will allow estimates of magnetic field strengths to be obtained even in the lower-density periphery of molecular clouds. We will therefore have a more complete knowledge of magnetic field strengths over a larger range of gas densities, as shown in Figure 5. Polarization maps made using the new camera will thus provide a valuable reference for the planning of future measurements of the Zeeman effect as well as providing opportunities to infer three-dimensional magnetic field properties, and driving associated theoretical studies.

Goldreich-Kylafis effect: Molecular line polarization can arise from the Goldreich-Kylafis (GK) effect [135], in which molecular line emission may in certain circumstances be linearly polarized either parallel or perpendicular to the plane-of-sky magnetic field. The GK effect can complement emission polarimetry, occurring in regions where polarized dust emission is to faint to detect: for example, dust polarization can be used to probe magnetic fields in the high-column-density circumstellar material around YSOs, while fields in the low-column-density lobes of molecular outflows can be probed using the GK effect. Spectropolarimetric observations can also be used to probe the structure of magnetic fields in position-position-velocity space in order to, for example, disentangle the magnetic field of the galactic spiral arms. Wide-field Galactic plane observations made using the new JCMT camera, complemented with targeted observations of the GK effect with the forthcoming heterodyne array, might for the first time reveal the magnetic field structures of individual spiral arms, and the connection between galactic-scale and cloud-scale magnetic fields.
7 Synergies with other polarimeters

As discussed in Section 1, and elsewhere above, the resolution, field of view and mapping speed of the JCMT makes it an excellent bridge between Planck all-sky polarization maps and interferometric polarization imaging with ALMA and other similar instruments such as the Submillimeter Array (SMA). The new JCMT camera will both perform targeted high-resolution follow-up of Planck observations and undertake wide-area surveys from which targets for interferometric follow-up can be selected. The new JCMT camera will also perform pathfinder science for forthcoming large radio telescopes such as the Square Kilometer Array (SKA) and the next generation VLA (ngVLA).

The new JCMT camera will also synergize with other current and forthcoming single-dish polarization instruments [26]. HAWC+ [131], currently operating on the airborne SOFIA observatory, is an FIR polarimeter operating in the wavelength range 53–214\(\mu m\) with resolution 4.8–18.2\". HAWC+ is optimized to observe a warmer dust population than the JCMT; as discussed in Section 3, synthesis of polarization observations across the FIR/submillimetre regime is essential to understanding how dust properties and magnetic fields vary with gas temperature and density. BLAST-TNG [136], a balloon-borne polarimeter planned to fly from Antarctica in December 2019, operates at 250–500\(\mu m\) with resolutions 30–60\". Flight in Antarctica mean that BLAST-TNG can observe a limited number of Southern-sky targets, with declinations largely not observable by the JCMT, making the two instruments complementary.

ToiTEC [137], the camera currently being commissioned at the LMT, will operate at wavelengths 1.1–2.1mm, with resolution 5.0–9.8\". NIKA-2 [138], a camera currently being commissioned at the IRAM 30m telescope, will operate at 1.2 and 2.0mm with resolutions of 11 and 18\". Both cameras will offer a polarization mode. Synthesis of JCMT 850\(\mu m\) and 450\(\mu m\) observations with these data will further add to polarization spectra across the wavelength range of dust continuum emission, while the higher surface brightness of cold dust at 450\(\mu m\) and 850\(\mu m\) will enhance the JCMT’s ability to detect cold and dense sources over that of millimetre cameras. Moreover, comparison of millimetre and submillimetre observations of sources with significant nonthermal emission will allow the effects of synchrotron radiation to be disentangled from continuum emission (c.f. Section 4). The A-MKID camera [139], currently being commissioned at APEX, will operate at 350\(\mu m\) and 850\(\mu m\) with resolutions of 8 and 19\", and will offer a polarization mode. Observing declinations < +50\(\circ\), A-MKID may prove to be an effective Southern-sky counterpart to the JCMT.

All of these single-dish polarimeters modulate signal using a half-wave plate or polarizing grid [26]. The new JCMT camera will therefore have an intrinsic advantage in its ability to measure polarization natively, making it unique in its ability to provide polarization information as a standard component of an astrophysical observation.

8 Executive Summary

The James Clerk Maxwell Telescope (JCMT), which has long been at the forefront of submillimetre polarization instrumentation, is proposing a next-generation 850\(\mu m\) camera. In this white paper we have presented the science case for the polarimetric capabilities of this camera. The JCMT’s current POL-2/SCUBA-2 system has provided its user community with an outstanding and unique imaging polarimeter, and has resulted in numerous international collaborations and the global exchange of knowledge and ideas. The science goals and instrumentation requirements described in this work are based on wide-ranging discussions both across and beyond the JCMT community.

The new JCMT camera will be a vital tool with which to address fundamental questions of the role of magnetic fields in galactic astronomy and star formation, and also to pursue such studies beyond the Milky Way by analysing the magnetic field properties of galaxies as a whole. Key questions in such galactic and extra-galactic studies would include that of the role of magnetic fields in determining star formation efficiency and the origin of the Initial Mass Function, and in determining a galaxy’s structure, ISM thermal balance, and global star formation rate. The JCMT is vital to such studies, with a mapping size of tens of arcminutes and an angular resolution of 14\" at 850\(\mu m\), and operating in the optimal wavelength regime for detection of cold and dense material. The new JCMT camera’s enhanced sensitivity and wide field of view will make it unique in its ability to serve as a wide-area survey instrument with which to study the interplay between self-gravity, turbulence and magnetism which drives the evolution of the cold ISM, and so to resolve questions crucial to our understanding of cosmic star-formation history.

References

[1] J. L. Han. Observing Interstellar and Intergalactic Magnetic Fields. Annual Review of Astronomy and Astrophysics, 55(1):111–157, Aug 2017.
[2] H. Alfvén. Existence of Electromagnetic-Hydrodynamic Waves. Nature, 150(3805):405–406, Oct 1942.
[3] D. Grasso and H. R. Rubinstein. Magnetic fields in the early Universe. Phys. Rep., 348(3):163–266, Jul 2001.
[4] Ethan T. Vishniac and A. Lazarian. Reconnection in the Interstellar Medium. *The Astrophysical Journal*, 511(1):193–203, Jan 1999.

[5] L. Davis, Jr. and J. L. Greenstein. The Polarization of Starlight by Aligned Dust Grains. *The Astrophysical Journal*, 114:206, September 1951.

[6] R. C. Bohlin, B. D. Savage, and J. F. Drake. A survey of interstellar H I from Lalpha absorption measurements. II. *The Astrophysical Journal*, 224:132–142, Aug 1978.

[7] R. H. Hildebrand. The determination of cloud masses and dust characteristics from submillimetre thermal emission. *QJRAS*, 24:267–282, Sep 1983.

[8] Planck Collaboration, P. A. R. Ade, N. Aghanim, and others. Planck intermediate results. XIX. An overview of the polarized thermal emission from Galactic dust. *Astronomy & Astrophysics*, 576:A104, Apr 2015.

[9] Jungmi Kwon, Yasuo Doi, Motohide Tamura, and others. A First Look at BISTRO Observations of the ρ Oph-A core. *The Astrophysical Journal*, 859(1):4, May 2018.

[10] Leverett Davis. The Strength of Interstellar Magnetic Fields. *Physical Review*, 81(5):890–891, Mar 1951.

[11] S. Chandrasekhar and E. Fermi. Magnetic Fields in Spiral Arms. *The Astrophysical Journal*, 118:113, Jul 1953.

[12] J. D. Soler, P. Hennebelle, P. G. Martin, and others. An Imprint of Molecular Cloud Magnetization in the Morphology of the Dust Polarized Emission. *The Astrophysical Journal*, 774(2):128, Sep 2013.

[13] Alistair M. Flett and Alexander G. Murray. First results from a submillimetre polarimeter on the James Clerk Maxwell Telescope. *Monthly Notices of the Royal Astronomical Society*, 249:4P, Mar 1991.

[14] A. G. Murray, R. Nartallo, C. V. Haynes, F. Gannaway, and P. A. R. Ade. An Imaging Polarimeter for SCUBA. In A. Wilson, editor, *The Far Infrared and Submillimetre Universe*, volume 401 of *ESA Special Publication*, page 405, Aug 1997.

[15] J. S. Greaves, W. S. Holland, T. Jenness, and others. A submillimetre imaging polarimeter at the James Clerk Maxwell Telescope. *Monthly Notices of the Royal Astronomical Society*, 340(2):353–361, Apr 2003.

[16] W. S. Holland, E. I. Robson, W. K. Gear, and others. SCUBA: a common-user submillimetre camera operating on the James Clerk Maxwell Telescope. *Monthly Notices of the Royal Astronomical Society*, 303(4):659–672, Mar 1999.

[17] P. Bastien, E. Bissonnette, A. Simon, and others. POL-2: The SCUBA-2 Polarimeter. In Pierre Bastien, Nadine Manset, Dan P. Clemens, and Nicole St-Louis, editors, *Astronomical Polarimetry 2008: Science from Small to Large Telescopes*, volume 449 of *Astronomical Society of the Pacific Conference Series*, page 68, Nov 2011.

[18] Per Friberg, Pierre Bastien, David Berry, and others. POL-2: a polarimeter for the James-Clerk-Maxwell telescope. In *Proceedings of the SPIE*, volume 9914 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 991403, Jul 2016.

[19] W. S. Holland, D. Bintley, E. L. Chapin, and others. SCUBA-2: the 10 000 pixel bolometer camera on the James Clerk Maxwell Telescope. *Monthly Notices of the Royal Astronomical Society*, 430(4):2513–2533, Apr 2013.

[20] Derek Ward-Thompson, Kate Pattle, Pierre Bastien, and others. First Results from BISTRO: A SCUBA-2 Polarimeter Survey of the Gould Belt. *The Astrophysical Journal*, 842(1):66, Jun 2017.

[21] N. R. Minchin, D. Ward-Thompson, and G. J. White. A submillimetre continuum study of S 140/L 1204: the detection of three new submillimetre sources and a self-consistent model for the region. *Astronomy & Astrophysics*, 298:894, Jun 1995.

[22] Motohide Tamura, J. H. Hough, and Saeko S. Hayashi. 1 Millimeter Polariometry of Young Stellar Objects: Low-Mass Protostars and T Tauri Stars. *The Astrophysical Journal*, 448:346, Jul 1995.

[23] J. S. Greaves, W. S. Holland, T. Jenness, and T. G. Hawarden. Magnetic field surrounding the starburst nucleus of the galaxy M82 from polarized dust emission. *Nature*, 404:732–733, Apr 2000.

[24] Derek Ward-Thompson, J. M. Kirk, R. M. Crutcher, and others. First Observations of the Magnetic Field Geometry in Prestellar Cores. *The Astrophysical Journal Letters*, 537(2):L135–L138, Jul 2000.

[25] Kate Pattle, Derek Ward-Thompson, Tetsuo Hasegawa, and others. First Observations of the Magnetic Field inside the Pillars of Creation: Results from the BISTRO Survey. *The Astrophysical Journal Letters*, 860(1):L6, Jun 2018.

[26] Kate Pattle and Laura Fissel. Submillimeter and far-infrared polarimetric observations of magnetic fields in star-forming regions. *Frontiers in Astronomy and Space Sciences*, 6:15, 2019.
[27] C. L. H. Hull, P. Mocz, B. Burkhart, and others. Unveiling the Role of the Magnetic Field at the Smallest Scales of Star Formation. *The Astrophysical Journal Letters*, 842:L9, June 2017.

[28] Hsi-Wei Yen, Bo Zhao, I. Ta Hsieh, and others. JCMT POL-2 and ALMA Polarimetric Observations of 6000-100 au Scales in the Protostar B335: Linking Magnetic Field and Gas Kinematics in Observations and MHD Simulations. *The Astrophysical Journal*, 871(2):243, Feb 2019.

[29] Kate Pattie, Derek Ward-Thompson, David Berry, and others. The JCMT BISTRO Survey: The Magnetic Field Strength in the Orion A Filament. *The Astrophysical Journal*, 846(2):122, Sep 2017.

[30] Charles L. H. Hull, Josep M. Girart, Łukasz Tychoniec, and others. ALMA Observations of Dust Polarization and Molecular Line Emission from the Class 0 Protostellar Source Serpens SMM1. *The Astrophysical Journal*, 847(2):92, Oct 2017.

[31] Marina Kounkel, Lee Hartmann, Laurent Loinard, and others. The Gould’s Belt Distances Survey (GOBELINS) II. Distances and Structure toward the Orion Molecular Clouds. *The Astrophysical Journal*, 834(2):142, Jan 2017.

[32] Gisela N. Ortiz-León, Sergio A. Dzib, Marina A. Kounkel, and others. The Gould’s Belt Distances Survey (GOBELINS). III. The Distance to the Serpens/Aquila Molecular Complex. *The Astrophysical Journal*, 834(2):143, Jan 2017.

[33] Mordecai-Mark Mac Low and Ralf S. Klessen. Control of star formation by supersonic turbulence. *Reviews of Modern Physics*, 76(1):125–194, Jan 2004.

[34] M. G. Wolfire, D. Hollenbach, C. F. McKee, A. G. G. M. Tielens, and E. L. O. Bakes. The Neutral Atomic Phases of the Interstellar Medium. *The Astrophysical Journal*, 443:152, Apr 1995.

[35] Shu-ichiro Inutsuka, Tsuyoshi Inoue, Kazunari Iwasaki, and Takashi Hosokawa. The formation and destruction of molecular clouds and galactic star formation. An origin for the cloud mass function and star formation efficiency. *Astronomy & Astrophysics*, 580:A49, Aug 2015.

[36] Fabian Heitsch, James M. Stone, and Lee W. Hartmann. Effects of Magnetic Field Strength and Orientation on Molecular Cloud Formation. *The Astrophysical Journal*, 695(1):248–258, Apr 2009.

[37] Planck Collaboration, P. A. R. Ade, N. Aghanim, and others. Planck intermediate results. XXXV. Probing the role of the magnetic field in the formation of structure in molecular clouds. *Astronomy & Astrophysics*, 586:A138, Feb 2016.

[38] Hua-bai Li, Min Fang, Thomas Henning, and Jouni Kainulainen. The link between magnetic fields and filamentary clouds: bimodal cloud orientations in the Gould Belt. *Monthly Notices of the Royal Astronomical Society*, 436(4):3707–3719, Dec 2013.

[39] Dylan L. Jow, Ryley Hill, Douglas Scott, and others. An application of an optimal statistic for characterizing relative orientations. *Monthly Notices of the Royal Astronomical Society*, 474(1):1018–1027, Feb 2018.

[40] Tie Liu, Pak Shing Li, Mika Juvela, and others. A Holistic Perspective on the Dynamics of G035.39-00.33: The Interplay between Gas and Magnetic Fields. *The Astrophysical Journal*, 859(2):151, Jun 2018.

[41] Kohji Tomisaka. Magnetohydrostatic Equilibrium Structure and Mass of Filamentary Isothermal Cloud Threaded by Lateral Magnetic Field. *The Astrophysical Journal*, 785(1):24, Apr 2014.

[42] Jason D. Fiege and Ralph E. Pudritz. Helical fields and filamentary molecular clouds - I. *Monthly Notices of the Royal Astronomical Society*, 311(1):85–104, Jan 2000.

[43] C. J. Salji, J. S. Richer, J. V. Buckle, and others. The JCMT Gould Belt Survey: constraints on prestellar core properties in Orion A North. *Monthly Notices of the Royal Astronomical Society*, 449(2):1769–1781, May 2015.

[44] S. I. Sadavoy, J. Di Francesco, D. Johnstone, and others. The Herschel and JCMT Gould Belt Surveys: Constraining Dust Properties in the Perseus B1 Clump with PACS, SPIRE, and SCUBA-2. *The Astrophysical Journal*, 767:126, April 2013.
[48] D. Arzoumanian, Ph. André, P. Didelon, and others. Characterizing interstellar filaments with Herschel in IC 5146. Astronomy & Astrophysics, 529:L6, May 2011.
[49] J. C. Tan, M. T. Beltrán, P. Caselli, and others. Massive Star Formation. In Henrik Beuther, Ralf S. Klessen, Cornelis P. Dullemond, and Thomas Henning, editors, Protostars and Planets VI, page 149, Jan 2014.
[50] William J. Henney, S. Jane Arthur, Fabio de Colle, and Garret Melley. Radiation-magnetohydrodynamic simulations of the photoionization of magnetized globules. Monthly Notices of the Royal Astronomical Society, 398(1):157–175, Sep 2009.
[51] Jonathan Mackey and Andrew J. Lim. Effects of magnetic fields on photoionized pillars and globules. Monthly Notices of the Royal Astronomical Society, 412(3):2079–2094, Apr 2011.
[52] D. Ward-Thompson, P. F. Scott, R. E. Hills, and P. Andre. A Submillimetre Continuum Survey of Pre Protostellar Cores. Monthly Notices of the Royal Astronomical Society, 268:276, May 1994.
[53] P. J. Benson and P. C. Myers. A Survey for Dense Cores in Dark Clouds. The Astrophysical Journal Supplement, 71:89, Sep 1989.
[54] F. Motte, P. Andre, and R. Neri. The initial conditions of star formation in the rho Ophiuchi main cloud: wide-field millimeter mapping. Astronomy & Astrophysics, 336:150–172, Aug 1998.
[55] Brenda C. Matthews, Christie A. McPhee, Laura M. Fissel, and Rachel L. Curran. The Legacy of SCUPOL: 850 µm Imaging Polarimetry from 1997 to 2005. The Astrophysical Journal Supplement, 182(1):143–204, May 2009.
[56] Junhao Liu, Keping Qiu, David Berry, and others. The JCMT BISTRO Survey: The Magnetic Field in the Starless Core ρ Ophiuchus C. The Astrophysical Journal, 877(1):43, May 2019.
[57] Richard M. Crutcher, D. J. Nutter, D. Ward-Thompson, and J. M. Kirk. SCUBA Polarization Measurements of the Magnetic Field Strengths in the L183, L1544, and L43 Prestellar Cores. The Astrophysical Journal, 600(1):279–285, Jan 2004.
[58] J. M. Kirk, D. Ward-Thompson, and R. M. Crutcher. SCUBA polarization observations of the magnetic fields in the pre-stellar cores L1498 and L1517B. Monthly Notices of the Royal Astronomical Society, 369(3):1445–1450, Jul 2006.
[59] T. C. Mouschovias. Nonhomologous contraction and equilibria of self-gravitating, magnetic interstellar clouds embedded in an intercloud medium: star formation. II. Results. The Astrophysical Journal, 207:141–158, Jul 1976.
[60] Simon Coudé, Pierre Bastien, Martin Houde, and others. The JCMT BISTRO Survey: The Magnetic Field of the Barnard 1 Star-forming Region. The Astrophysical Journal, 877(2):88, Jun 2019.
[61] L. M. Fissel, P. A. R. Ade, F. E. Angièl, and others. Balloon-Borne Submillimeter Polarimetry of the Vela C Molecular Cloud: Systematic Dependence of Polarization Fraction on Column Density and Local Polarization-Angle Dispersion. The Astrophysical Journal, 824:134, June 2016.
[62] T. Pillai, J. Kauffmann, J. C. Tan, and others. Magnetic Fields in High-mass Infrared Dark Clouds. The Astrophysical Journal, 799(1):74, Jan 2015.
[63] Ya-Wen Tang, Paul T. P. Ho, Patrick M. Koch, Stephane Guilloteau, and Anne Dutrey. Dust Continuum and Polarization from Envelope to Cores in Star Formation: A Case Study in the W51 North Region. The Astrophysical Journal, 763(2):135, Feb 2013.
[64] Tao-Chung Ching, Shih-Ping Lai, Qizhou Zhang, and others. Magnetic Fields in the Massive Dense Cores of the DR21 Filament: Weakly Magnetized Cores in a Strongly Magnetized Filament. The Astrophysical Journal, 838(2):121, Apr 2017.
[65] Charles L. H. Hull and Qizhou Zhang. Interferometric observations of magnetic fields in forming stars. Frontiers in Astronomy and Space Sciences, 6:3, Mar 2019.
[66] P. Hennebelle and S. Fromang. Magnetic processes in a collapsing dense core. I. Accretion and ejection. Astronomy & Astrophysics, 477:9–24, January 2008.
[67] D. Seifried, R. Banerjee, R. E. Pudritz, and R. S. Klessen. Turbulence-induced disc formation in strongly magnetized cloud cores. Monthly Notices of the Royal Astronomical Society, 432:3320–3331, July 2013.
[68] J. Masson, G. Chabrier, P. Hennebelle, N. Vayet, and B. Commerçon. Ambipolar diffusion in low-mass star formation. I. General comparison with the ideal magnetohydrodynamic case. Astronomy & Astrophysics, 587:A32, March 2016.
[69] G. Chabrier, A. Johansen, M. Janson, and R. Rafikov. Giant Planet and Brown Dwarf Formation. In Henrik Beuther, Ralf S. Klessen, Cornelis P. Dullemond, and Thomas Henning, editors, Protostars and Planets VI, page 619, Jan 2014.

[70] T. Liu, Q. Zhang, K.-T. Kim, and others. Planck Cold Clumps in the λ Orionis Complex. I. Discovery of an Extremely Young Class 0 Protostellar Object and a Proto-brown Dwarf Candidate in the Bright-rimmed Clump PGCC G192.32-11.88. The Astrophysical Journal Supplement, 222:7, January 2016.

[71] A. Soam, Jugmi Kwon, G. Maheswar, Motohide Tamura, and Chang Won Lee. First Optical and Near-infrared Polarimetry of a Molecular Cloud Forming a Proto-brown Dwarf Candidate. The Astrophysical Journal Letters, 803(2):L20, Apr 2015.

[72] P. Y. Hsieh, P. M. Koch, W. T. Kim, and others. Magnetized Inflow Accretion. In C. Matulonis and H. Parsons, editors, East Asian Observatory News, volume 4, pages 12–14, Sep 2018.

[73] Lee Hartmann, Gregory Herczeg, and Nuria Calvet. Accretion onto Pre-Main-Sequence Stars. Annual Review of Astronomy and Astrophysics, 54:135–180, Sep 2016.

[74] II Evans, Neal J., Michael M. Dunham, Jes K. Jørgensen, and others. The Spitzer c2d Legacy Results: Star-Formation Rates and Efficiencies; Evolution and Lifetimes. The Astrophysical Journal Supplement Series, 181(2):321–350, Apr 2009.

[75] Jan Forbrich, Mark J. Reid, Karl M. Menten, and others. Extreme Radio Flares and Associated X-Ray Variability from Young Stellar Objects in the Orion Nebula Cluster. The Astrophysical Journal, 844(2):109, Aug 2017.

[76] Doug Johnstone, Benjamin Hendricks, Gregory J. Herczeg, and Simon Bruderer. Continuum Variability of Deeply Embedded Protostars as a Probe of Envelope Structure. The Astrophysical Journal, 765(2):133, Mar 2013.

[77] Gregory J. Herczeg, Doug Johnstone, Steve Mairs, and others. How Do Stars Gain Their Mass? A JCMT/SCUBA-2 Transient Survey of Protostars in Nearby Star-forming Regions. The Astrophysical Journal, 849(1):43, Nov 2017.

[78] Steve Mairs, Doug Johnstone, Helen Kirk, and others. The JCMT Transient Survey: Identifying Submillimeter Continuum Variability over Several Year Timescales Using Archival JCMT Gould Belt Survey Observations. The Astrophysical Journal, 849(2):107, Nov 2017.

[79] Doug Johnstone, Gregory J. Herczeg, Steve Mairs, and others. The JCMT Transient Survey: Stochastic and Secular Variability of Protostars and Disks In the Submillimeter Region Observed over 18 Months. The Astrophysical Journal, 854(1):31, Feb 2018.

[80] Ray S. Furuya, Hiroko Shinnaga, Kouichiro Nakanishi, Munetake Momose, and Masao Saito. A Giant Flare on a T Tauri Star Observed at Millimeter Wavelengths. Publications of the Astronomical Society of Japan, 55:L83–L87, Dec 2003.

[81] J. Forbrich, K. M. Menten, and M. J. Reid. A 1.3 cm wavelength radio flare from a deeply embedded source in the Orion BN/KL region. Astronomy & Astrophysics, 477(1):267–272, Jan 2008.

[82] Steve Mairs, Bhavana Lalchand, Geoffrey C. Bower, and others. The JCMT Transient Survey: An Extraordinary Submillimeter Flare in the T Tauri Binary System JW 566. The Astrophysical Journal, 871(1):72, Jan 2019.

[83] Hyunju Yoo, Jeong-Eun Lee, Steve Mairs, and others. The JCMT Transient Survey: Detection of Submillimeter Variability in a Class I Protostar EC 53 in Serpens Main. The Astrophysical Journal, 849(1):69, Nov 2017.

[84] D. T. Chuss, B.-G. Andersson, J. Bally, and others. HAWC+/SOFIA Multiwavelength Polarimetric Observations of OMC-1. The Astrophysical Journal, 872:187, February 2019.

[85] A. Lèbre, M. Aurière, N. Fabas, and others. Search for surface magnetic fields in Mira stars. First detection in χ Cygni. Astronomy & Astrophysics, 561:A85, Jan 2014.

[86] H. Herpin, A. Baudry, C. Thum, D. Morris, and H. Wiesemeyer. Full polarization study of SiO masers at 86 GHz. Astronomy & Astrophysics, 450(2):667–680, May 2006.

[87] W. H. T. Vlemmings, E. M. L. Humphreys, and R. Franco-Hernández. Magnetic Fields in Evolved Stars: Imaging the Polarized Emission of High-frequency SiO Masers. The Astrophysical Journal, 728(2):149, Feb 2011.

[88] Thavisha E. Dharmawardena, Francisca Kemper, Peter Scicluna, and others. Extended Dust Emission from Nearby Evolved Stars. Monthly Notices of the Royal Astronomical Society, 479(1):536–552, Sep 2018.

[89] M. R. M. Leão, E. M. de Gouveia Dal Pino, D. Falceta-Gonçalves, C. Melioli, and F. G. Geraissate. Local star formation triggered by supernova shocks in magnetized diffuse neutral clouds. Monthly Notices of the Royal Astronomical Society, 394(1):157–173, Mar 2009.
[90] J. L. West, S. Safi-Harb, T. Jaffe, and others. The connection between supernova remnants and the Galactic magnetic field: A global radio study of the axisymmetric sample. Astronomy & Astrophysics, 587:A148, Mar 2016.

[91] J. Rho, H. L. Gomez, A. Boogert, and others. A dust twin of Cas A: cool dust and 21 $\mu$m silicate dust feature in the supernova remnant G54.1+0.3. Monthly Notices of the Royal Astronomical Society, 479(4):5101–5123, Oct 2018.

[92] Brian J. Williams and Tea Temim. Infrared Emission from Supernova Remnants: Formation and Destruction of Dust, page 2105. 2017.

[93] O. Löhmer, A. Wolszczan, and R. Wielebinski. A search for cold dust around neutron stars. Astronomy & Astrophysics, 425:763–766, Oct 2004.

[94] Pablo Fosalba, Alex Lazarian, Simon Prunet, and Jan A. Tauber. Statistical Properties of Galactic Starlight Polarization. The Astrophysical Journal, 564(2):762–772, Jan 2002.

[95] A. Fletcher, R. Beck, A. Shukurov, E. M. Berkhuijsen, and C. Horellou. Magnetic fields and spiral arms in the galaxy M51. Monthly Notices of the Royal Astronomical Society, 412(4):2396–2416, Apr 2011.

[96] Rainer Beck. Magnetic fields in the nearby spiral galaxy IC 342: A multi-frequency radio polarization study. Astronomy & Astrophysics, 578:A93, Jun 2015.

[97] A. Ordog, J. C. Brown, R. Kothes, and T. L. Landecker. Three-dimensional structure of the magnetic field in the disk of the Milky Way. Astronomy & Astrophysics, 603:A15, Jul 2017.

[100] A. Saintonge, C. D. Wilson, T. Xiao, and others. JINGLE, a JCMT legacy survey of dust and gas for galaxy evolution studies - I. Survey overview and first results. Monthly Notices of the Royal Astronomical Society, 481:3497–3519, December 2018.

[101] Martin Houde, Talayeh Hezareh, Scott Jones, and Fereshte Rajabi. Non-Zeeman Circular Polarization of Molecular Rotational Spectral Lines. The Astrophysical Journal, 764(1):24, Feb 2013.

[102] B. Adebaehr, M. Krause, U. Klein, and others. <ASTROBJ>M 82</ASTROBJ> - A radio continuum and polarisation study. I. Data reduction and cosmic ray propagation. Astronomy & Astrophysics, 555:A23, Jul 2013.

[103] Serena Bertone, Corina Vogt, and Torsten Enßlin. Magnetic field seeding by galactic winds. Monthly Notices of the Royal Astronomical Society, 370(1):319–330, Jul 2006.

[104] T. J. Jones, C. D. Dowell, E. Lopez Rodriguez, and others. SOFIA Far-infrared Imaging Polarimetry of M82 and NGC 253: Exploring the Supergalactic Wind. The Astrophysical Journal Letters, 870:L9, January 2019.

[105] E. Lopez-Rodriguez, R. Antonucci, R.-R. Chary, and M. Kishimoto. The Highly Polarized Dusty Emission Core of Cygnus A. The Astrophysical Journal Letters, 861:L23, July 2018.

[106] F. H. Vincent, W. Yan, O. Straub, A. A. Zdziarski, and M. A. Abramowicz. A magnetized torus for modeling Sagittarius A* millimeter images and spectra. Astronomy & Astrophysics, 574:A48, Jan 2015.

[107] F. H. Vincent, M. A. Abramowicz, A. A. Zdziarski, and others. Multi-wavelength torus-jet model for Sagittarius A*. Astronomy & Astrophysics, 624:A52, Apr 2019.

[108] Pei-Ying Hsieh, Patrick M. Koch, Woong-Tae Kim, and others. A Magnetic Field Connecting the Galactic Center Circumnuclear Disk with Streamers and Mini-spiral: Implications from 850 $\mu$m Polarization Data. The Astrophysical Journal, 862(2):150, Aug 2018.

[109] Event Horizon Telescope Collaboration, Kazunori Akiyama, Antxon Alberdi, and others. First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole. The Astrophysical Journal Letters, 875(1):L1, Apr 2019.

[110] S. Issaoun, M. D. Johnson, L. Blackburn, and others. The Size, Shape, and Scattering of Sagittarius A* at 86 GHz: First VLBI with ALMA. The Astrophysical Journal, 871(1):30, Jan 2019.

[111] A. P. Marscher. Relativistic Jets in Active Galactic Nuclei. In P. A. Hughes and J. N. Bregman, editors, Relativistic Jets: The Common Physics of AGN, Microquasars, and Gamma-Ray Bursts, volume 856 of American Institute of Physics Conference Series, pages 1–22, September 2006.

[112] E. I. Robson, J. A. Stevens, and T. Jenness. Observations of flat-spectrum radio sources at $\lambda$850 $\mu$m from the James Clerk Maxwell Telescope - I. 1997 April to 2000 April. Monthly Notices of the Royal Astronomical Society, 327:751–770, November 2001.
[113] S. G. Jorstad, A. P. Marscher, J. A. Stevens, and others. Multiwavelength Polarimetric Observations of 15 Active Galactic Nuclei at High Frequencies: Correlated Polarization Behavior. *The Astronomical Journal*, 134:799–824, August 2007.

[114] A. P. Marscher. Turbulent, Extreme Multi-zone Model for Simulating Flux and Polarization Variability in Blazars. *The Astrophysical Journal*, 780:87, January 2014.

[115] J. W. Lee, S.-S. Lee, S. Kang, D.-Y. Byun, and S. S. Kim. Detection of millimeter-wavelength intraday variability in polarized emission from S5 0716+714. *Astronomy & Astrophysics*, 592:L10, August 2016.

[116] E. Lopez-Rodríguez, A. Alonso-Herrero, T. Diaz-Santos, and others. The origin of the mid-infrared nuclear polarization of active galactic nuclei. *Monthly Notices of the Royal Astronomical Society*, 478(2):2350–2358, Aug 2018.

[117] S.-S. Lee, S. Kang, D.-Y. Byun, and others. First Detection of 350 Micron Polarization from a Radio-loud AGN. *The Astrophysical Journal Letters*, 808:L26, July 2015.

[118] R. M. Crutcher, B. Wandelt, C. Heiles, E. Falgarone, and T. H. Troland. Magnetic Fields in Interstellar Clouds from Zeeman Observations: Inference of Total Field Strengths by Bayesian Analysis. *The Astrophysical Journal*, 725:466–479, December 2010.

[119] A. Lazarian and Thiem Hoang. Radiative torques: analytical model and basic properties. *Monthly Notices of the Royal Astronomical Society*, 378(3):910–946, Jul 2007.

[120] B. G. Andersson, A. Lazarian, and John E. Vaillancourt. Interstellar Dust Grain Alignment. *Annual Review of Astronomy and Astrophysics*, 53:501–539, Aug 2015.

[121] Archana Soam, Kate Pattle, Derek Ward-Thompson, and others. Magnetic Fields toward Ophiuchus-B Derived from SCUBA-2 Polarization Measurements. *The Astrophysical Journal*, 861(1):65, Jul 2018.

[122] T. J. Jones, M. Bagley, M. Krejny, B. G. Andersson, and P. Bastien. Grain Alignment in Starless Cores. *The Astronomical Journal*, 149(1):31, Jan 2015.

[123] T. J. Jones, Michael Gordon, Dinesh Shenoy, and others. SOFIA Mid-infrared Imaging1 and CSO Submillimeter Polarimetry Observations of G034.43+00.24 MM1. *The Astronomical Journal*, 151(6):156, Jun 2016.

[124] Kate Pattle, Shih-Ping Lai, Tetsuo Hasegawa, and others. JCMT BISTRO Survey observations of the Ophiuchus Molecular Cloud: Dust grain alignment properties inferred using a Ricean noise model. *arXiv e-prints*, page arXiv:1906.03391, Jun 2019.

[125] R. H. Hildebrand, J. L. Dotson, C. D. Dowell, D. A. Schleuning, and J. E. Vaillancourt. The Far-Infrared Polarization Spectrum: First Results and Analysis. *The Astrophysical Journal*, 516(2):834–842, May 1999.

[126] John E. Vaillancourt, C. Darren Dowell, Roger H. Hildebrand, and others. New Results on the Submillimeter Polarization Spectrum of the Orion Molecular Cloud. *The Astrophysical Journal Letters*, 679(1):L25, May 2008.

[127] T. J. Bethell, A. Chepurnov, A. Lazarian, and J. Kim. Polarization of Dust Emission in Clumpy Molecular Clouds and Cores. *The Astrophysical Journal*, 663(2):1055–1068, Jul 2007.

[128] Natalie N. Gandilo, Peter A. R. Ade, Francesco E. Angilè, and others. Submillimeter Polarization Spectrum in the Vela C Molecular Cloud. *The Astrophysical Journal*, 824(2):84, Jun 2016.

[129] Jamil A. Shariff, Peter A. R. Ade, Francesco E. Angilè, and others. Submillimeter Polarization Spectrum of the Carina Nebula. *The Astrophysical Journal*, 872(2):197, Feb 2019.

[130] B. J. Dober, P. A. R. Ade, P. Ashton, and others. The next-generation BLASTpol experiment. In *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VII*, volume 9153 of *Proc. SPIE*, page 91530H, July 2014.

[131] D. A. Harper, M. C. Runyan, C. D. Dowell, and others. HAWC+, the Far-Infrared Camera and Polarimeter for SOFIA. *Journal of Astronomical Instrumentation*, 7:1840008–1025, 2018.

[132] Richard M. Crutcher. Magnetic Fields in Molecular Clouds. *Annual Review of Astronomy and Astrophysics*, 50:29–63, Sep 2012.

[133] Martin Houde, John E. Vaillancourt, Roger H. Hildebrand, Shadi Chitsazzadeh, and Larry Kirby. Dispersion of Magnetic Fields in Molecular Clouds. II. *The Astrophysical Journal*, 706(2):1504–1516, Dec 2009.

[134] M. Houde. Magnetic Fields in Three Dimensions. In Pierre Bastien, Nadine Manset, Dan P. Clemens, and Nicole St-Louis, editors, *Astronomical Polarimetry 2008: Science from Small to Large Telescopes*, volume 449 of *Astronomical Society of the Pacific Conference Series*, page 213, Nov 2011.

[135] P. Goldreich and N. D. Kylafis. On mapping the magnetic field direction in molecular clouds by polarization measurements. *The Astrophysical Journal Letters*, 243:L75–L78, Jan 1981.
[136] N. Galitzki, P. A. R. Ade, F. E. Angilè, and others. The Next Generation BLAST Experiment. *Journal of Astronomical Instrumentation*, 3:1440001, November 2014.

[137] Sean Bryan, Jason Austermann, Daniel Ferrusca, and others. Optical design of the TolTEC millimeter-wave camera. In *Proc. SPIE*, volume 10708 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 107080J, Jul 2018.

[138] R. Adam, A. Adane, P. A. R. Ade, and others. The NIKA2 large-field-of-view millimetre continuum camera for the 30 m IRAM telescope. *Astronomy & Astrophysics*, 609:A115, Jan 2018.

[139] Luis Esteras Otal. *The Optical System and the Astronomical Potential of A-MKID, a New Camera Using Microwave Kinetic Inductance Detector Technology*. PhD thesis, University of Bonn, 08 2014.