Contents

Collaborative research: Connecting galaxy, molecular cloud, and star formation with magnetic fields

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1. Objectives and Summary

The universe is threaded with magnetic fields that permeate galaxies, molecular clouds, and stars, and which connect these objects together in complex ways. Observations show that galaxies at $z \simeq 2$ (one-third of the present age of the universe) have magnetic fields that are both organized on large scales and of substantial magnitude. Organized, dynamically important magnetic fields are also ubiquitous in the interstellar medium of present-day galaxies. The molecular clouds that are the sites of star formation in nearby galaxies form out of this magnetized plasma, and measurements show that these clouds have substantial magnetic fields as well. These magnetic fields are possibly quite important for star formation, which remains one of the most important unsolved problems in astrophysics. While magnetic fields have been observed in all of these astrophysical regimes, and there is a clear sequence of events – galaxies form molecular clouds, which in turn are the sites of star formation – the ways in which magnetic fields tie galaxies to molecular clouds, and thus potentially affect star formation and the initial stellar mass function, are poorly understood theoretically. **In this proposal, we hypothesize that feedback of magnetic fields from stellar explosions, and subsequent dynamo activity, is responsible for magnitizing the universe. We will test this hypothesis by running a suite of cosmological and isolated galaxy simulations, and comparing the results to galactic and extra-galactic observations.** Care will be taken to quantify limitations due to observational constraints (noise, sensitivity, projection effects) and numerical effects (resolution and input assumptions).

Our long-term goals are to create a predictive model for the evolution of magnetic fields in the universe, from intergalactic scales down to that of individual stars, and to self-consistently understand both the effects of magnetic fields on star formation as well as the ways in which magnetic fields are ejected from stars into their host galaxies. Our objective *in this proposal* is to understand how galactic-scale magnetic fields affect the formation and evolution of molecular clouds, and in turn how magnetic fields ejected from stars are amplified and ordered within galaxies. Our rationale is that an improved understanding of how magnetized molecular clouds form within galaxies will lead to more accurate initial conditions for targeted studies of star formation, and will provide an opportunity to model that critical process in a more realistic way. The team we have assembled contains experts in magnetohydrodynamic (MHD) simulations of cosmological structure formation and of star formation, is united in our use of a sophisticated and high-dynamic-range numerical tool that can seamlessly connect the cosmological and stellar scales (the Enzo code), and is strongly connected to observations of both extragalactic and local magnetic fields through our collaborators.

In this project, we will use high resolution MHD simulations of cosmological structure formation, along with newly developed sub-grid models for star formation, feedback, and the injection of magnetic fields from stellar populations into the interstellar medium, to model the evolution of magnetic fields over the age of the universe. These calculations will provide the initial conditions for simulations of the interstellar medium in idealized, isolated galaxies, where we will follow the formation of magnetized molecular clouds and determine the impact of magnetic fields on their lifetime, evolution, and bulk star formation properties. Finally, we will model how feedback from stellar populations injects magnetic fields back into the interstellar medium, potentially affecting the behavior of the large-scale magnetic fields in galaxies.

The end result of this project will be a deep understanding of the connection between galaxies and molecular clouds, and of the properties of the magnetic fields that permeate these objects. This project is innovative due to its connection of cosmological structure (i.e., galaxies and their environments) to molecular clouds and the star formation that occurs therein, and the modeling of both of these classes of objects in a unified theoretical and numerical framework. The understanding gained by doing this will be transformative in terms of our ability to more accurately model star formation through cosmic time, and will directly connect to current and future observations of magnetic fields in a range of astrophysical situations.

2. Scientific Motivation

The universe is magnetized on nearly every scale – magnetic fields can be seen in the intergalactic and interstellar medium; in molecular clouds; and in stars. The universe also appears to be magnetized over a wide range of cosmic time, with evidence for magnetic fields observed at high redshift as well as in the local universe. Magnetic fields are dynamically important in many of the observed astrophysical environments, having energy densities that are comparable to (or in equipartition with) other available energy sources, including heat, turbulence, cosmic rays, and radiation. Furthermore, even in situations where magnetic fields are dynamically irrelevant (such as the intergalactic plasma in clusters of galaxies), they are critical for processes such as thermal conduction and particle acceleration. In some extremely diffuse plasmas, magnetic fields are the only mechanism that causes particles to behave as a fluid! In addition, magnetic fields are a useful probe of astrophysical plasma physics, but are often challenging to use as an observational diagnostic due to fundamental uncertainties in measurements (e.g., the need to assume a coherence length to interpret Faraday rotation measure observations).

In the following sections, we describe what is known about magnetic fields in the universe, both observationally and theoretically, and highlight some of our gaps in understanding. **In general, while magnetic fields have been measured in virtually all astrophysical regimes, and while there is a clear sequence of events – galaxies form molecular clouds, which in turn are the sites of star formation – the ways in which magnetic fields tie galaxies to molecular clouds, and thus potentially affect star formation and the stellar initial mass function, are poorly understood theoretically.**

2.1. The high-redshift universe and intergalactic medium

There is evidence that magnetic fields have existed over much of the age of the universe. Observations of high-redshift quasar absorption line spectra show that MgII absorption lines are associated with large Faraday rotation measures, requiring that organized magnetic fields of strengths comparable to those observed in galaxies today ($\sim \mu$G) must have existed by $z \approx 1.3$, less than half of the age of the universe Bernet et al. (2008); Joshi & Chand (2013); Farnes et al. (2014). In related observations, Kronberg et al. (2008) use observations of rotation measures in a large sample of quasars that extends to $z \simeq 3.7$ to show that the distribution of rotation measures broadens with redshift (despite the expected cosmological 'dilution' of high redshift rotation measures expected by the expanding universe), and that at increasing redshift progressively fewer sources are found with small rotation measures in the observer frame. The implications of this observation are that the environments of high-redshift ($z \sim 2-3$) galaxies were significantly magnetized, with the possibility that magnetic field strengths in galaxies at this epoch – a few billion years after the Big Bang – are comparable to those seen in present-day galaxies. This work broadly agrees with earlier observations of $z \sim 2-3$ radio galaxies Athreya et al. (1998), which showed different rotation measures between the two radio lobes of the observed galaxies. The most obvious interpretation of this difference is that it comes from the radio galaxy itself, and the inferred magnetic fields have strengths on the order of a few μG.

In addition to existing in galaxies over a wide span of time, the presence of magnetic fields has been inferred on cosmological scales in the intergalactic medium. At megaparsec scales, Neronov & Vovk (2010) show that the lack of measured GeV gamma-rays in the direction of TeV gamma-ray sources observed by the Fermi Large Area Telescope yields a *lower bound* of $\mathrm{B} \geq 3 \times 10^{-16}$ G, with the lower bound increasing as $\propto \lambda_B^{-1/2}$ if the magnetic field correlation length λ_B is significantly smaller than a megaparsec. Different analyses of data from the same instrument by Dermer et al. (2011); Tavecchio et al. (2010), with varied assumptions, results in lower limits for the strength of large-scale magnetic fields in the low redshift intergalactic medium that range from $\geq 10^{-18}$ G to $\geq 5 \times 10^{-15}$ G. None of these observations provides direct measurements of the coherence lengths of the fields in question, though they are inferred to be on the order of megaparsecs or greater. Also, it should be noted that these are lower limits on the large-scale intergalactic magnetic field and not a direct measurement. An upper limit can also be determined by using the cosmic microwave background (CMB) – specifically, measurements of CMB temperature anisotropies and polarization put strong upper limits on a mean pre-recombination magnetic field strength $\simeq 10^{-9}$ G Barrow et al. (1997); Widrow et al. (2012); Durrer & Neronov (2013), and in the near future results from the Planck satellite may put further constraints on both this upper limit and on the coherence lengths of cosmological magnetic fields. We note that the CMB-derived upper limit is more stringent than the limits coming from Big Bang Nucleosynthesis, where measurements of the ratios of primordial species (including H, D, and He), as well as the baryon-to-photon ration η, give a strong upper limit for primordial magnetic field strengths of 10^{-7} G.

Intergalactic magnetic fields on smaller scales have also been observed. Rotation measure

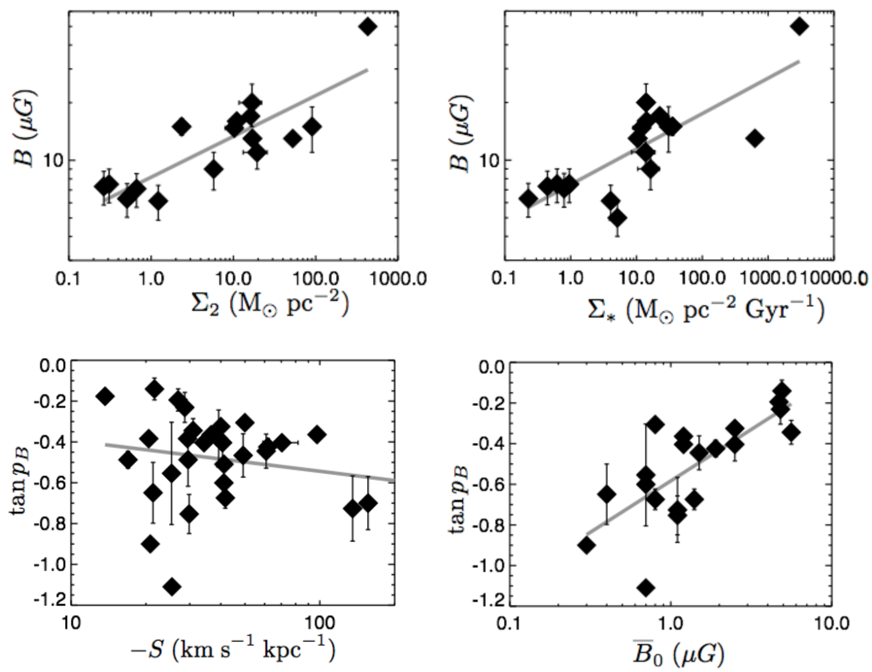

Fig. 1.— Magnetic field properties from a sample of 20 nearby spiral galaxies from Van Eck et al. (Van Eck et al. 2014, panels taken from Figures 4 and 9). Top row: Total magnetic field strength vs. H_2 surface density (left) and vs. star formation rate surface density (right). Bottom row: Pitch angle of mean magnetic field vs. rotational shear rate (left) and vs. axisymmetric component of the large-scale magnetic field (right). While Van Eck et al. (2014) find close correlations between a variety of properties, not all are easily explicable via galactic dynamo theory.

observations of the intracluster medium – that is, the intergalactic plasma in clusters of galaxies – show that it is threaded by magnetic fields that are on the order of $0.1 - 10$ μG (depending on cluster location) Carilli & Taylor (2002); Enßlin et al. (2005); Vogt & Enßlin (2005), with patches of much higher magnetization (~ 40 μG) observed. Furthermore, “cool core” clusters tend to have stronger fields by a factor of roughly 2 than non-cool core clusters. The same observations show that magnetic fields are not regularly ordered on cluster scales, but instead have coherence lengths that range from a few kpc to tens of kpc. It is very difficult to discern the volume filling fraction of magnetic fields in the intracluster medium due to the paucity of background sources that can be used to observe rotation measures – however, essentially all background sources show some magnetization.

2.2. Low-redshift galaxies

Observations of magnetic fields in nearby galaxies provide an important complement to measurements of magnetic fields in both the intergalactic medium and at high redshift. Recent work by Van Eck et al. Van Eck et al. (2014) consolidates data on the properties of the magnetic fields and interstellar media of 20 local spiral galaxies, with selected results shown in Figure 1. All galaxies have detectable magnetic fields with ordered field strengths on the order of $1 - 10$ μG, and total field strengths roughly 5 times larger, $5 - 50$ μG, which is roughly in equipartition with the cosmic ray and kinetic energy densities (a result that has been confirmed elsewhere; Mao et al. (2012); Beck & Wielebinski (2013)), and which are coherent on large scales. Clear correlations exist between the total magnetic field strength and molecular gas density, as well as the star formation rate. Furthermore, the magnetic pitch angle correlates well with the mean axisymmetric magnetic field strength, but not with the local rotational shear rate. The authors also compare these results with predictions from galactic dynamo theory, and note that while some of the observations agree with these predictions, there is clear need for further theoretical work.

Measurements of magnetic field properties in other types of local galaxies have been made as well. Field strengths in local elliptical galaxies may be on the order of $5-10$ μG, comparable to local spirals, although with much smaller coherence lengths – far smaller than the size of the galaxy itself Wielebinski & Krause (1993); Moss & Shukurov (1996), though to date no conclusive measurement has been made. Field strengths in dwarf galaxies have been measured to have total field strengths ranging from $5-15$ μG and ordered fields having strengths of $1-8$ μG, generally a few times weaker than local spirals, depending on the galaxy in question Chyży et al. (2000, 2011); Roychowdhury & Chengalur (2012); Mao et al. (2012); Nikiel-Wroczyński et al. (2013); Jurusik et al. (2014). We do note that dwarf galaxies with lower masses do tend to have lower total and ordered magnetic field strengths than larger dwarfs and spirals, and galaxies with higher star formation rates also tend to have higher magnetic field strengths (as was seen in spirals in Van Eck et al. (2014)). Furthermore, it seems that, for dwarf galaxies where the structure of the magnetic field strength can be measured, the ordered component is about 20% as strong as the total magnetic field, which is comparable to much more massive local spiral galaxies.

2.3. The Milky Way

The best candidate for obfuscating the picture of magnetic fields in galaxies is our own Milky Way. The proximity to the source means that high resolution measurements can be made, but our location within the galactic disk means that comparing to other galaxies is difficult. Faraday rotation and polarization of other galaxies measures the field strength integrated through the entire thickness of the disk, while similar measurements of our own galaxy only sample fractions of the field. Further, many local radio features make it difficult to disentangle fields due to the galaxy itself.

The magnetic field in the Milky Way can be broken broadly into two components: a large scale magnetic field that has a coherence length on the order of the size of the Galaxy itself, and a small scale field that is either completely random or somewhat correlated with the large scale field. Synchrotron radio emission indicates that the large scale field strength is roughly 10 μG at a Galactocentric radius of 3 kpc, and decreases to 6 μG near the Sun. This is consistent with Zeeman measurements of nearby molecular clouds (see Section 2.4). Estimates of the strength of the random magnetic field component varies from $B_{\rm rand} \gtrsim 1.3\ \mu$G (Gaensler et al. 2001) to 4 μG (Fauvet et al. 2011). The most complete survey of dust polarization was performed by the *Planck* satellite (Planck Collaboration et al. 2015), which can be seen in the right panel of Figure . Clearly structure can be seen on a range of scales throughout the galactic disk.

The morphology of the magnetic field in external spirals is generally parallel to spiral arms, as shown in the left panel of Figure 2. This is likely the case with the Milky Way. However, unlike other galaxies, the Milky Way seems to additionally harbor at least one reversal in the direction of the magnetic field (Thomson & Nelson 1980; Jaffe et al. 2011). Many models exist to match the data (see the recent review by Haverkorn 2014), including an antisymmetric spiral (similar to other galaxies), a bisymmetric spiral (which would account for reversals), a ring structure, and some superposition of these. The vertical component of the Galactic magnetic field is similarly difficult to measure. Using rotation measure from more than 1,000 extragalactic radio sources, Mao et al. (2010) find that there is no symmetry in the vertical component at the radius of the sun, with the Galactic north field showing a field consistent with zero, and the Galactic south field of $0.31 \pm 0.03\mu$G. On the other hand, Jansson & Farrar (2012) find that, modeling the synchrotron intensity from WMAP, the field is consistent with an "X" shaped magnetic field. Unfortunately, none of the existing measurements are consistent with expected observations and a coherent dynamo. This is possibly due to the fact that the timescale for the coherent $\alpha - \Omega$ dynamo is longer than the age of the Galaxy, or if tidal interactions or injection of small scale magnetic fields continually disrupt the symmetry (Moss et al. 2012).

2.4. Connecting galaxies to molecular clouds

Molecular Clouds and Giant Molecular Clouds are cold (10 K) and have masses anywhere from $10^4 - 10^7$ M$_\odot$. From the limited number of Zeeman splitting measurements in cold molecular clouds, field strengths in molecular clouds range from 1 μG in low density gas ($\simeq 100$ cm^{-3}), and increase to a few mG in higher density gas ($\simeq 10^7$ cm^{-3}) (Crutcher 2012). Star formation is controlled by some combination of gravity, turbulence, and magnetic fields (McKee & Ostriker 2007), and the relative importance of each is the subject of significant debate (compare, e.g., Padoan et al. 2013; Li et al. 2014). The ratio of magnetic to kinetic energy is typically parameterized by the Alfvén Mach number, $\mathcal{M}_{\rm A} = v/v_{\rm A}$, where $v_{\rm A} = B/4\pi\sqrt{\rho}$ is the signal speed along a magnetic field line. Values of $\mathcal{M}_{\rm A} > 1$, so-called super-Alfvénic flow, indicates a weak magnetic field relative to kinetic energy, while $\mathcal{M}_{\rm A} < 1$, or sub-Alfvénic flow, indicates that magnetic fields dominate energetically. The ratio of gravitational to magnetic energy is typically parameterized by the mass-to-flux ratio, $\mu = M/\Phi$, where Φ is the magnetic flux threading a cloud of mass M, in units of the critical field strength for collapse. The actual values of $\mathcal{M}_{\rm A}$ and μ are difficult to measure observationally due to the challenge in measuring magnetic field strengths directly over large scales (Crutcher 2012). Thus, statistical and morphological arguments are made, often with different results. From measurements of column density power spectra and extinction measure distribution in molecular clouds, Padoan & Nordlund (1999) and Padoan et al. (2004) argue that super-Alfvénic turbulence

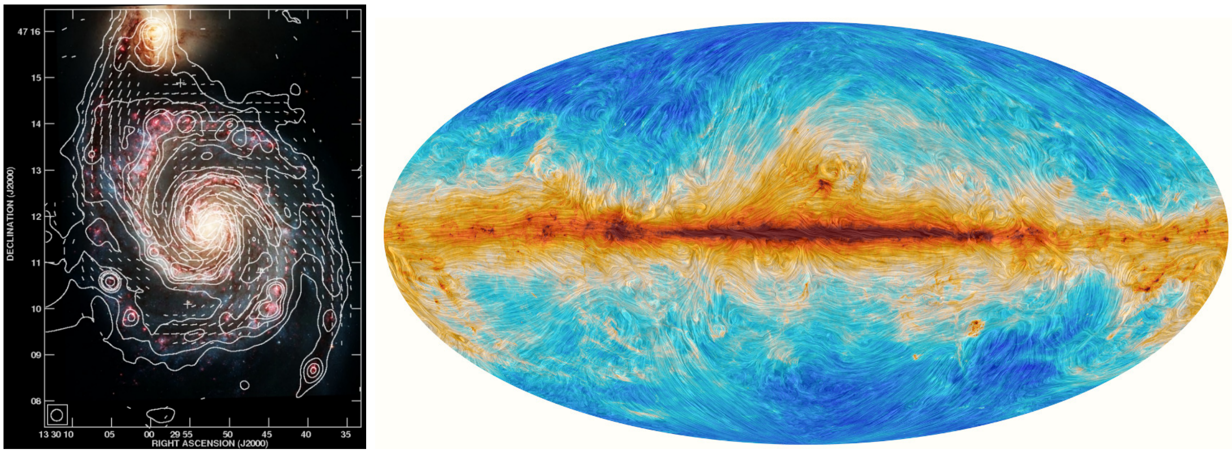

Fig. 2.— Coherent magnetic structure is seen in many disk galaxies. (*Left*) The magnetic field from polarized $\lambda = 3, 6$ and 20 cm radio emission (vectors) along with total emission (contours) in M51. From Fletcher et al. (2011). Optical background from *Hubble Space Telescope* (image credit: NASA, ESA, S. Beckwith (STScI) and The Hubble Heritage Team (STScI/AURA)). This shows the well-ordered nature of the magnetic field along the spiral arms. (*Right*) The *Planck* polarization map showing the 353 GHz dust intensity convolved with the direction of polarization (Planck Collaboration et al. 2015). This shows coherent structrue on a range of scales throughtout the Milky Way.

is more consistent with molecular cloud measurements than the statistics of sub-Alfvénic models. On the other hand, Heyer & Brunt (2012) have shown that a difference in the slope of the velocity power spectrum between two orthogonal directions indicates that $\mathcal{M}_{\rm A} \approx 1$. Simulations (de Avillez & Breitschwerdt 2005; Kritsuk et al. 2011c) indicate that $\mathcal{M}_{\rm A} > 1$ for clouds that formed from the warm neutral medium. Polarization measurements indicate that fields are parallel to the long axis of low mass filaments, perpendicular to the long axis of high mass filaments (Li et al. 2013) (see the left panel of Figure 3), and exhibit coherent alignment between large and small scales (Li et al. 2009), all of which indicate $\mathcal{M}_{\rm A} < 1$. Zeeman measurements of methanol masers in star forming region indicate that the magnetic field order is imprinted on even small-scale structures over kpc scales. (Green et al. 2012). However, turbulence substantially impacts the structure of molecular clouds (see, e.g., Elmegreen & Scalo 2004; Mac Low & Klessen 2004), and statistical properties indicate that turbulent kinetic energy is comparable to, if not dominant over, magnetic energy (Padoan & Nordlund 2004; Heyer & Brunt 2012), indicating $\mathcal{M}_{\rm A} \gtrsim 1$.

The details of the initial conditions, boundary conditions, and equation of state have profound impact on molecular cloud lifetimes and collapse rates (Federrath & Klessen 2012; Collins et al. 2012; Rey-Raposo et al. 2014). Furthermore, even in models of star-forming clouds where magnetic fields play a subordinate role their effect is still non-negligible. Figure 3 shows a snapshot of molecular cloud collapse from Collins et al. (2012) and also the star formation rate as a function of mean magnetic field. In the pictured simulations, even though the mass-to-flux ratio and kinetic-to-magnetic energy ratio are both larger than unity, the increased magnetic field decreases the

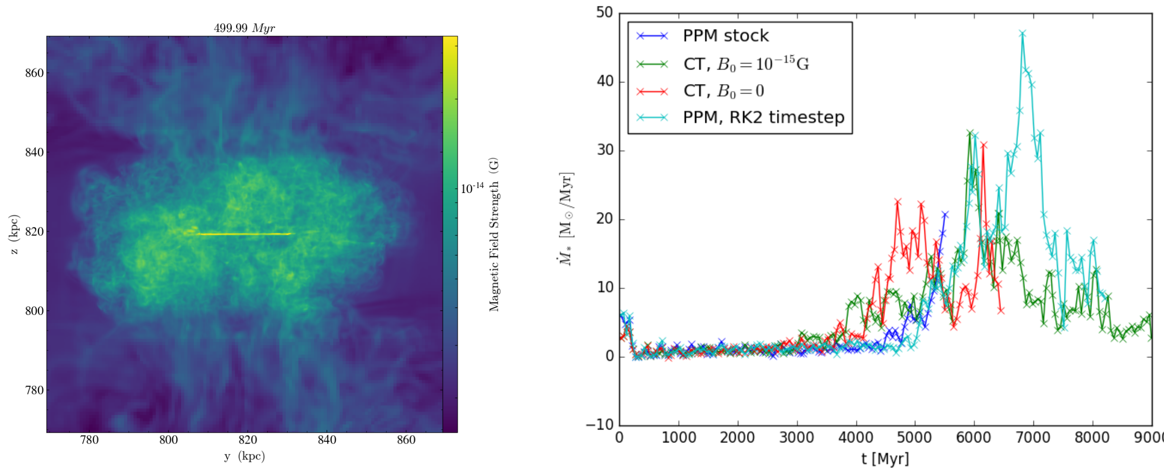

Fig. 3.— Two images from preliminary work on galaxy-scale simulations: *(Left)* From an initial uniform field of 10^{-15}G, a Milky Way sized galaxy (seen edge-on) produces fields up to 10^{-13}G at 20 kpc from the disk within 500 Myr. This simulation has an under-resolved ISM in the galaxy, but a realistic density profile, and unrealistic initial conditions. We will improve on these conditions with this proposal. *(Right)* Star formation rate from simulations that explore several numerical parameters (the third order Piecewise Parabolic Method with two time-step criteria and the second-order CT method with two field strenghts) shows that subtle changes in numerics can have significant impact on the star formation, which will in turn impact magnetic field generation. From Collins et al. (2012).

star formation rate by a substantial amount, and the morphology of the magnetic field follows the filamentary structure. Thus it is clear that for a detailed understanding of star formation, magnetic fields must be included. In order to capture these conditions self-consistently, **we will perform extremely high resolution simulations of isolated galaxies, extracted from cosmological initial conditions, that resolve the formation of a wide mass range of molecular clouds.**

2.5. The origin and amplification of magnetic fields in the universe

As discussed in Section 2.1, magnetic fields appear to exist everywhere in the intergalactic medium, albeit at a very low level. The physical regimes where they appear to reside – on mega-parsec scales and above, and in both intergalactic filaments and in voids – argue against a galactic origin. So, then, what is the likely origin of these fields, and what theoretical constraints can we utilize?

Widrow Widrow (2002); Widrow et al. (2012) provides a host of possible origins for the observed cosmological magnetic fields, which we briefly summarize. Magnetic fields could be generated during the inflationary epoch, during the hadronic or electroweak phase transitions, or in the radiation-dominated era prior to recombination. Depending on the nature of the effect, theoretical predictions for a minimum field strength vary hugely, from a minimum value of B $\sim 10^{-32}$ G to substantially more than a Gauss (values given at the present day). Generally speaking, theory dictates that a minimum magnetic field strength of 10^{-19} G (present-day value) and with coherence lengths on megaparsec scales must exist; the maximum theoretically-predicted value is vastly higher than the observational upper limits from the CMB of $\bar{B} \simeq 10^{-9}$ G (Section 2.1).

Given the minuscule magnetic field strengths that must have been generated prior to structure formation, and the relatively high ($> 10\ \mu$G) fields observed in both galaxies and the cores of galaxy clusters, an obvious question arises: how are such high magnetic fields generated from such weak seed fields? Straightforward adiabatic collapse of the gas (and corresponding compression of the fields) suggests an increase in magnetic field from the initial value of $\delta^{2/3}$, where δ is the ratio of maximum to original density. Given the characteristic density of the Milky Way's interstellar medium, this implies an adiabatic amplification of $\simeq 10^4 - 10^5$ times the primordial value – far too small of a value to explain the roughly 13 order of magnitude difference between the minimum inferred value in the lowest-density regions of the universe and the field strength observed in the interstellar medium.

This observation leads inexorably to the conclusion that there must be some sort of dynamo process at work that amplifies the magnetic field by using kinetic energy from the various processes associated with structure formation (i.e., gravitational collapse, rotational motion, etc.). There are two dominant modes of amplification. The *fluctuating* dynamo draws small scale turbulent energy into small scale magnetic energy. While this mechanism has growth times of 10^7 years, fast enough to generate substantial fields from extremely weak seed fields, it does not produce fields that are ordered on large scales. The second amplification mechanism is the $\alpha - \Omega$ dynamo, wherein differential rotation and buoyancy work together to add helicity to the fluid, thus amplifying the field on the large scales associated with the rotation of the galaxy. This is a slower process, which limits the large scale field available to more massive galaxies. (See Brandenburg & Subramanian (2005) for a detailed review of both dynamo processes.) Either of these processes can easily magnify a seed field to the galactic field strength of 10^{-6} G Beck & Wielebinski (2013), and compression by gravitational collapse further amplifies the galactic field strength and is responsible for the further magnification of the field to the 10^{-3} G level observed in high-density star forming regions Collins et al. (2011b). We note that further seeds beyond the weak primordial field may be necessary to reach the observed magnetic field strengths in galaxies, particularly for the earliest galaxies – observations of strong magnetic fields at high redshift imply that dynamos have a relatively short time to operate! If that is the case, two plausible mechanisms for magnetic field generation are supernova remnants Widrow (2002) and the jets from supermassive black holes Hoyle (1969); Daly & Loeb (1990), both of which produce strong magnetic fields with substantial coherence lengths.

3. Proposed Work

In this project, we will use high dynamic range magnetohydrodynamical (MHD) simulations to understand how galactic-scale magnetic fields affect the formation and evolution of molecular clouds, and to identify the characteristics of these magnetized clouds that pertain to star formation. Specifically, we will use a targeted series of high resolution MHD simulations of galaxy formation, both in a cosmological context (Section 3.1.1) and as isolated, idealized objects (Section 3.1.2), to explore the evolution of magnetic fields through cosmic time. In our cosmological and isolated galaxy calculations, we will use subgrid models for molecular cloud behavior and for the injection of magnetic fields into the interstellar medium through supernovae and galactic winds, which will supplement the standard models of star formation and feedback. These calculations will ultimately provide initial and boundary conditions for simulations of the formation, evolution, and eventual destruction of individual star-forming molecular clouds and their environments. These calculations will be run with the Enzo code (Section 4) using computing time secured through the XSEDE and PRAC allocation processes (Section 3.1.4), and at all times will be guided by, and compared to, a range of observations of magnetic fields (Section 3.2). This will be done through close collaboration between an expert in simulations of cosmological structure formation (O'Shea), an expert in simulations of molecular clouds and star formation (Collins), an expert in observations of magnetic field structure (Mao), and two graduate students, as described in Section 7.

3.1. Simulating the Magnetized Universe

3.1.1. Cosmological simulations

As described in Section 2, there is a great deal of observational evidence that magnetic fields exist in galaxies over a wide variety of masses and redshifts, and also in intergalactic space. Furthermore, it appears that the magnetic fields in star-forming galaxies build up relatively quickly, based on observations of $z \simeq 2-3$ galaxies which show that the magnetic fields measured in their interstellar medium (ISM) are roughly in equipartition with other sources of ISM energy. We will explore the evolution of magnetic fields in the universe, both over time and in a wide range of environments, by using a carefully-chosen series of cosmological simulations. At present, a collaboration of galaxy modelers (led by PI O'Shea) is in the midst of running two sets of large-volume cosmological simulations using the Enzo code – one of a 25 Mpc volume, and the other 75 Mpc, both with 1024^3 root grid cells and particles, and with multiple sets of physics in each set of calculations and moderate physical resolution ($\Delta x \simeq 400$ pc). Taken together, these sets of calculations resolve the formation of galaxies over three orders of magnitude in mass, from $\simeq 10^{10}$ to 10^{13} $M_\odot$, which encompasses galaxies ranging in size from the Small Magellenic Cloud through the largest ellipticals. These simulations will be completed by the time that the grant period for this project begins, and we will mine these datasets to find approximately a dozen galaxies whose masses, morphologies, and formation histories probe the regimes of interest for understanding magnetic field behavior, and which we will resimulate at high resolution. We will include the following galaxies in our list of follow-up simulations, which will enable us to target essentially the entire range of observations listed in Sections 2.1 and 2.2:

1. Four spiral galaxies of roughly Milky Way mass ($M_{gal} \simeq 1-2 \times 10^{12}$ $M_\odot$) that have a range of formation histories, including galaxies that have rapid early merger rates as well as those with smoother formation histories. In particular, we will include at least one galaxy with a history similar to the Milky Way, with no major mergers after $z \sim 2$. These will be compared to observations of local spiral galaxies (e.g., Van Eck et al. 2014) and to the magnetic fields in the ISM of our own Milky Way.
2. At least two galaxies that grow rapidly at early times and are large enough in terms of stellar mass that they can be directly compared to observations of magnetic fields in galaxies at $z \simeq 2-3$ (e.g., Bernet et al. 2008; Kronberg et al. 2008; Athreya et al. 1998).
3. Four dwarf galaxies of masses $\simeq 10^{10}$ and 10^{11} $M_\odot$ at $z = 0$, with one galaxy of each mass experiencing star formation at the present epoch and one that is relatively quiescent. These will be compared with observations of local dwarf galaxies Chyży et al. (2000, 2011); Roychowdhury & Chengalur (2012); Mao et al. (2012); Nikiel-Wroczyński et al. (2013); Jurusik et al. (2014).
4. Two galaxies that are massive ellipticals (having essentially no star formation) at $z = 0$, which will be compared to local ellipticals Wielebinski & Krause (1993); Moss & Shukurov (1996).

Once these galaxies are selected from the pilot calculations, we will re-generate the initial conditions for these galaxies at much higher mass and spatial resolution using the MUSIC cosmological IC code Hahn & Abel (2011), and then re-run the calculations to the redshift of interest (typically the present day) at very high spatial resolution ($\Delta x_{min} \simeq 100$ pc) using prescriptions for metal-dependent radiative cooling, star formation and feedback, and AGN feedback. This is the state of the art for physics-rich cosmological galaxy formation simulations, and results in galaxies with reasonable $z = 0$ properties (e.g., Scannapieco et al. 2012; Vogelsberger et al. 2014; Hopkins et al. 2014). In addition, we will include the equations of ideal magnetohydrodyamics using a cosmologically-motivated seed field initialized to $B \simeq 10^{-15}$ G at $z \simeq 100$ when the simulations begin.

One of the virtues of this type of cosmological simulation is that they are relatively inexpensive (see Section 3.1.4), which allows us to experiment with variations in physical models to understand the effect that model choice may have on our results. For some subset of these galaxies, in addition to our standard calculation we will try varying the strength and configuration of the initial seed field (which is unlikely to make a difference in larger halos (e.g., Xu et al. 2010, 2011), though it is unclear if this is true in smaller halos), will experiment with magnetic field generation using the Biermann Battery (e.g., Xu et al. 2008b; Graziani et al. 2014), and explore multiple models for magnetic field injection from stellar populations and from AGN (in particular, varying the total energy and configuration of the magnetic fields injected).

The cosmological simulations alone will allow us to answer several questions: How do magnetic fields develop in galaxies as a function of cosmic time, mass, formation history, and morphology?

Does the initial seed field's strength or configuration ultimately make a difference in the properties of observable magnetic fields in galaxies? How are star formation rate and magnetic field properties related over cosmic time? And, finally, how (and to what distance) are magnetic fields communicated into the intergalactic medium, and can the inferred intergalactic magnetic fields (e.g., Kronberg et al. 1999; Neronov & Vovk 2010) come from galaxies alone? With this latter question, and assuming that most magnetic fields in the intergalactic medium come from galactic winds, we can potentially draw connections between metal absorbers in the intergalactic and circumgalactic medium with magnetic fields – connections that can be probed by the Jansky VLA, ALMA, and future long-wavelength telescopes such as the Square Kilometer Array. Observational diagnostics will be discussed further in Section 3.2

3.1.2. Galactic Simulations

While the cosmological simulations will be able to directly address a range of observationally-motivated questions about magnetic fields in galaxies, their relatively limited ($\Delta x \simeq 100$ pc) spatial resolution means that they only marginally resolve larger molecular clouds, and are far too coarsely resolved to directly simulate star formation. To this end, we will use our cosmological galaxy simulation data as initial conditions for idealized calculations of isolated disk, elliptical, and dwarf galaxies. For these calculations, we will extract the target galaxies from Section 3.1.1 and embed them in isolated, non-cosmological boxes. This will allow us to increase the resolution to $\simeq 1$ pc and follow both molecular cloud formation as well as more carefully follow star formation and feedback processes, albeit over substantially less than a Hubble time. This will allow us to explore the relationship between large-scale galactic magnetization and the properties of individual molecular clouds over a wider cloud mass scale. In addition, these isolated calculations will allow us to explore in greater detail the effects that varied energy and magnetic field injection mechanisms from stellar populations (from stellar winds and Type Ia and Type II supernovae) and from AGN have on magnetic field generation, and also on the possible effect that resolution might have on dynamo amplification of magnetic fields in both spiral and elliptical galaxies (an effect that was shown to be important in high-redshift halos; Sur et al. 2010; Schleicher et al. 2013).

In these simulations we will focus resolution on the cold molecular gas and follow the injection of kinetic energy from supernovae, and the subsequent dynamo. This will be done for one of each of the four categories of galaxies: one spiral, one high z galaxy, one dwarf, and one massive elliptical. The massive elliptical, having no star formation or molecular content, may be omitted based on the magnetic activity seen in the cosmological phase. These simulations will allow us to refine the star formation and feedback algorithms by more finely resolving the sampled IMF and more finely resolving the turbulence and dynamo action. They will also allow us to explore the creation and destruction of molecular clouds in a magnetized environment, which has had little study to date (Dobbs & Price 2008; Kim & Ostriker 2015), and the connection between the magnetic field of individual clouds to the galaxy itself. The simulations described here will likely require a more detailed treatment of H_2 formation – including dust grain formation, photoelectric heating, the effect of non-trivial optical depths on cooling rates, and others – which are already contained in the ENZO chemistry solver (see, e.g., Tasker 2011; Meece et al. 2014). In roughly half of the simulations we will inject magnetic fields from supernovae explosions, by adding it in a divergence-free manner as was done in Li et al. (2006); Nakamura et al. (2006); Xu et al. (2008a), modeling the injection of magnetic energy into the ISM by supernovae. This will be compared to simulations that have no injection and only allow the small- and large-scale dynamos to operate, as in (Beck et al. 2012).

3.1.3. Connecting Star Formation Theory and Galaxy Formation

Simulations of galaxy formation and star formation in a cosmological context rely, by necessity, on ad-hoc prescriptions for star formation. For instance, the oft-used method of Cen & Ostriker (1993) requires that material is above a certain threshold and has negative velocity divergence (i.e., converging gas flow), then turns a fraction of gas in a resolution element into stars. This type of algorithm has a number of free parameters that are typically normalized by their ability to reproduce observed star formation properties of star forming galaxies. Meanwhile, a substantial amount of work has gone into understanding the rate and mass fraction of star formation at the molecular cloud (MC) level. In the proposed work, we will bridge the gap between the local and cosmologial models by developing a new star formation algorithm that incorporates developments in molecular cloud dynamics. Ad-hoc star formation algorithms have done reasonably well in reproducing observable quantities such as the redshift evolution of stellar mass in galaxies. However, the tight, linear correlation between total gas mass and star formation rate, even at high redshift, implies that the details of the giant molecular clouds are essential in determining star formation rates (Genzel et al. 2010; Shapley 2011; Lada et al. 2012; Lada 2014). **We will develop a new star formation algorithm for use in cosmological simulations that takes advantage of molecular cloud physics.** This development will happen in conjunction with both molecular cloud and cosmological simulations.

Predictions of the mass distribution and rate of star formation can be made based on the statistics of the turbulence at the molecular cloud level. We will follow the pioneering work of (Padoan & Nordlund 2002; Krumholz & McKee 2005) and the later extensions by (Hennebelle & Chabrier 2008; Padoan & Nordlund 2011; Hennebelle & Chabrier 2011; Federrath & Klessen 2012) to formulate a new star formation procedure that incorporates the magnetic field of the galaxy and molecular cloud properties.

One of the most fortuitous events in the study of supersonic turbulence is the fact that the density probability distribution function (PDF) tends to form a lognormal. This has been exploited by several star formation models, and we will do the same in this project. The width of the PDF is related in turn to the Mach number $\mathcal{M} = v_{\rm rms}/c_{\rm s}$: higher $\mathcal{M}$ yields higher compression, thus wider PDFs. Using the standard turbulent and magnetic scaling laws, one can formulate an analytic expression based solely on the mean Mach number, magnetic field strength, and cloud mass. Several variations of this have been done, and we will explore each in turn. A similar model was recently developed with the code Nyx (Braun & Schmidt 2015), wherein it was demonstrated that this technique is successful in reproducing observed star formation laws. We will extend this work by additionally incorporating magnetic fields, in order to directly incorporate MHD effects into our cosmological simulations

3.1.4. Computing time

Zoom-in cosmological simulations of a single Milky Way-type galaxy using Enzo, with $\simeq 400$ pc resolution, require approximately 100,000 CPU-hours on TACC's Stampede resource Hummels & Bryan (2012); Joung et al. (2012); Hummels et al. (2013), or slightly less on NCSA's Blue Waters. The addition of MHD roughly doubles the computational cost, and increasing the particle mass resolution by a factor of 8 (to 5×10^5 $M_\odot$) will help to resolve early structure formation, but will increase the computational time by another factor of approximately four (rather than 8, due to judicious choices made during the creation of initial conditions, which will reduce the overall number of particles). Increasing spatial resolution will result in approximately a factor of two increase in cost. Together, this suggests that a high resolution, physics-rich Milky Way-type simulation will cost roughly 1.6 million CPU-hours on Stampede or Blue Waters – expensive, but not impossibly so. Dwarf galaxy simulations and galaxies that stop at $z \simeq 2$ will require substantially less time. Isolated disk simulations will be comparably inexpensive – at most 50,000 CPU-hours apiece on either Stampede or Blue Waters. Taken together, we estimate that we will need 8-10 million CPU-hours per year on a machine like Stampede or Blue Waters for the cosmological and isolated disk calculations required for this proposal.

Dr. O'Shea and Dr. Collins have had significant success in procuring computing time on XSEDE resources as PIs and Co-PIs of numerous large allocation – they have over 25 million combined CPU-hours of XSEDE computing time over the past five years, most recently on XRAC allocations TG-AST090040 and AST140008. In addition, Dr. O'Shea was the PI of a Blue Waters PRAC allocation that ended in March 2015 consisting of 124 million CPU-hours, and Drs. O'Shea and Collins are co-PIs of a new Blue Waters allocation (starting in April 2015, continuing through March 2017) of roughly 100 million CPU-hours. Both their XSEDE and Blue Waters allocations will be devoted in part to the project described in this proposal, and the level of resources obtained is more than adequate for the proposed science.

3.2. Observational Comparisons

We will use the mock radio observation tools that are a part of the publicly-available yt package (built as a part of Skillman et al. (2013)) to create synthetic observations of our simulated galaxies and molecular clouds. These synthetic observations will include rotation measures, synchrotron emission, Zeeman splitting, and polarization at a variety of wavelengths (including optical, far IR, and in the radio), and will enable us to (1) compare our simulations directly to a range of observations and (2) to make predictions for measurements that will be made by both current and future observatories.

3.2.1. Extragalactic Observations

We will compare our simulations to Faraday rotation measures from observations of high-redshift galaxies Bernet et al. (2008); Kronberg et al. (2008); Athreya et al. (1998), the field magnitude and arrangement in local dwarf galaxies, Chyży et al. (2000, 2011); Roychowdhury & Chengalur (2012); Mao et al. (2012); Nikiel-Wroczyński et al. (2013); Jurusik et al. (2014), field strength, structure and coherence in nearby elliptical Wielebinski & Krause (1993); Moss & Shukurov (1996) and spiral galaxies Van Eck et al. (2014). We will also use measurements of large-scale intergalactic magnetic fields as a constraint Neronov & Vovk (2010). Recently techniques have been developed to combine polarized synchrotron emission with Faraday Rotation depths to probe the full magnetic configuration (Heald et al. 2009; Mao et al. 2015). We will make predictions for (and thus motivate) future observations of magnetic field arrangement, coherence length, and magnitude as observed in the radio and optical that will target magnetic fields in galaxies, galactic outflows, and the intergalactic medium from the Jansky VLA, ALMA, and LOFAR, and in the further future the Square Kilometer Array pathfinder telescopes and the SKA itself.

An extremely useful probe of the correlation of magnetic field properties and star formation is the correlation between the Far Infrared Radiation (FIR) flux and the Radio Continuum (RC). A surprisingly tight correlation between these two fluxes has been studied for several decades (Helou et al. 1985). Both radiation sources are indirectly related to star formation, and we will aim to probe this correlation as a function of redshift. The FIR comes from re-heating of dust near sites of massive star formation, while the RC comes form synchrotron radiation of cosmic rays (Helou & Bicay 1993; Niklas & Beck 1997). Murphy et al. (2006) model the radio profiles as smoothed version of the FIR profiles, indicating that for the most part the RC can be seen as a diffusive flux of cosmic rays. However, accurate measurement of this relation has not been reproduced in cosmological simulations. Modeling the FIR is done in post-production after the simulations have finished, by measuring the mass distribution in stars at a given time and using radiative transfer to measure the optical depth to FIR. Modeling the RC requires following the cosmic ray spectrum and the competition between radiation terms. These include inverse Compton scattering, ionization of neutral gas, and bremsstrahlung in addition to the synchrotron that is observable in the RC. Schleicher & Beck (2013) propose that at high redshift, inverse Compton may begin to dominate over synchrotron and the FIR-RC correlation will break down around $z = 2 - 4$, depending on the strength of the field and the star formation rate. Several of our simulations will include the cosmic ray treatment incorporated into Enzo and described in Salem et al. (2014); Salem & Bryan (2014), suitably modified to incorporate cosmic ray losses by the aforementioned processes. This will allow us to predict future observations by ALMA and LOFAR and to explore the utility of the RC as a probe of highly extincted star formation.

Another important correlation is the "Star Formation Main Sequence" (SFMS) of galaxies Daddi et al. (2007); Speagle et al. (2014). This relation between star formation rate and stellar mass is a power law that is essentially constant over time, with a normalization that falls with time. This can be interpreted as a relatively quiescent, steady-state star formation process with cosmic time. Recent simulation efforts have reported good agreement with the SFMS at low redshift, but reduced star formation rate at intermediate redshifts (Sparre et al. 2015). We will measure this for not only the highly resolved galaxies, but also the entire population of galaxies formed from the cosmological simulation. This will be compared to both the low redshift behavior Brinchmann et al. (2004) and high redshift Daddi et al. (2007). This measurement itself is not a probe of magnetic fields, but as star formation depends on field strength we will correlate the slope and normalization of this linear relation with magnetic field strength in the constituent galaxies.

3.2.2. Galactic Observations

One of the primary goals in this work is understanding the relationship between the large scale magnetic field of the galaxy and the magnetic fields in molecular clouds. As discussed in Section 2.4, there is clear evidence of coherent magnetic fields in galactic structure, but the importance in molecular cloud structure and dynamics is ambiguous.

The primary question is: Over what scales are the magnetic field aligned, and how does this alignment imprint on the molecular gas and impact its dynamics? To properly answer this question, we will focus on three measurements, ensuring consistency with earlier observational work and exploring field properties that have not been measured. These properties are: the properties of individual molecular clouds; the correlation between field directions at two points; and correlations between field direction and material gradients.

Molecular Cloud Properties. The mean magnetic field strength in molecular clouds is challenging to measure, but potentially of critical importance in star formation theory. We will reconcile molecular cloud properties with observational molecular clouds by comparing synthetic ^{13}CO maps with linewidth-size and mass-size relations as measured by the Galactic Ring survey (Jackson et al. 2006; Roman-Duval et al. 2010). We will then predict the mean field strength vs. linewidth and size, and discuss the expected mass-to-flux and kinetic-to-magnetic energy distributions.

Field-Field Correlation. We will use synthetic polarization and Faraday rotation measure to measure the correlation length in the galactic scale simulations. We will also measure the distribution of alignments of magnetic fields between and within individual molecular clouds, and between each molecular cloud and the three-dimensional, kpc-scale mean field. These will be compared to the well-correlated alignment seen within molecular clouds (Li et al. 2009) and along galactic spiral arms (Fletcher et al. 2011). This will allow us to ensure the validity of the fields in our galaxies, and predict the probability of alignment between any pair of molecular clouds.

Field-Mass Correlation. We will also explore the relation between field strength and material. This has garnered recent attention as magnetic field tends to align with low density HI as seen in the GALFA-HI survey (Clark et al. 2014), and tends to lie perpendicular to higher density structure (Planck Collaboration et al. 2014). We will perform synthetic dust emission and synthetic HI maps to examine these properties. Dust polarization results will be compared to the histogram of relative orientation between polarization angle and column density gradient. For consistent comparison with the HI measurements, we will perform the Rolling Hough Transform (Clark et al. 2014) on the synthetic HI map to determine the linear structure, and correlate that with the polarization map. These measurements will assess the validity of the data. We will also explore the alignment of clouds themselves on the large scale patterns, and measure the probability of finding a cloud at a certain distance along the large scale field. This will measure the interaction of magnetic field and structure on the 100-1000 pc scale.

4. Tools

The Enzo code. The calculations described in this proposal will be performed using the Enzo code. Enzo is a publicly available Cartesian adaptive mesh renement code used for the simulation of cosmological and astrophysical phenomena (Bryan et al. 2014, `http://enzo-project.org`). Enzo uses a block-structured adaptive mesh refinement scheme Berger & Colella (1989) to achieve high spatial and temporal resolution, and combines an N-body adaptive particle-mesh solver for dark matter dynamics with a Piecewise Parabolic Method (PPM) hydro solver that has been extensively modified for cosmological applications and hypersonic flows Bryan et al. (1995). In addition, the code includes a range of other physics, including both equilibrium and nonequilibrium chemistry and cooling models, radiative cooling using a Raymond-Smith model and Cloudy emissivity tables Smith et al. (2008), and prescriptions for the formation and feedback of both stellar populations and black holes. Enzo also includes modules for magnetohydrodynamics (both the Dedner divergence-cleaning method and a constrained transport method; Wang & Abel (2009); Wang et al. (2010); Collins et al. (2010)) and radiation transport using a ray-casting method and flux-limited diffusion Wise & Abel (2011); Reynolds et al. (2009). Enzo has been used to model a wide variety of cosmological and astrophysical phenomena – most relevant to this proposal, Enzo has been used heavily to study high- and low-redshift cosmological structure formation Abel et al. (2002); Turk et al. (2009); O'Shea & Norman (2007); Wise et al. (2012); Smith et al. (2008); Hummels & Bryan (2012); Egan et al. (2014); Simpson et al. (2013), the intergalactic and circumgalactic medium Hallman et al. (2007); Smith et al. (2011); Hummels et al. (2013); Joung et al. (2012), and the properties of star-forming molecular clouds Kritsuk et al. (2011b,a); Collins et al. (2011b,a, 2012); Schmidt et al. (2013).

The Enzo code has been selected by the NSF to be part of the Petascale Computing Resource Allocation (PRAC) program under three separate allocations totaling approximately 300 million core-hours, and was one of the handful of codes that were first used on Blue Waters when it was first made available for science runs in early 2012. Near-perfect scaling of the code in its unigrid (non-AMR) mode has been demonstrated to more than 90,000 CPU cores. Calculations using AMR do not scale as well, although reasonable performance at up to several thousand CPU cores can be expected for large, well-balanced, and physics-rich AMR runs. Given that the simulations needed for this project are well below this scale, Enzo will easily handle the calculations that are necessary for the proposed work.

The yt code. Our simulations will be analyzed and visualized with the yt package (Turk et al.

2011, http://yt-project.org), which is an open source analysis and visualization toolkit for grid- and particle-based simulations. YT was originally developed to work with ENZO, but now supports numerous simulation codes, including both grid-based and particle-based astrophysical codes (i.e., FLASH, ART, Gadget, Gasoline). Among the capabilities of YT are slices and projections (both on and off the Cartesian axes); volume renderings; halo finding and profiling; 1, 2, and 3 dimensional profiles; light-cone projections; synthetic QSO sight lines (i.e., absorption line spectra); contouring; and clump-finding. We will use YT to perform many of these analysis tasks – all of which are parallelized – and will furthermore use YT to make a variety of mock observations of galaxies using tools that have been developed and used by our collaboration. YT can be used as a standalone code and is also callable from within an ENZO simulation, allowing analysis to be performed on in-memory datasets (a capability that will be very helpful for analysis of our larger simulations). YT is highly parallel and scales well on XSEDE computing resources.

5. Significance of Proposed Work

Magnetic fields are essential components of galactic structure, but the nature of their growth and morphology is elusive to understand from a theoretical and numerical standpoint. The challenge in doing so lies in the difficulty of devising a consistent treatment of initial and boundary conditions, of including the necessary physics, and in interpreting observations. The proposed project will model the origin and evolution of galactic magnetic fields, and their impact on star-forming molecular clouds, from cosmological initial conditions to the present day. We will also create synthetic observations for JVLA, ALMA, and other telescopes, which will be crucial to interpretating existing and upcoming observations. In addition, we will use these tools to explore the possibilities of future observations that will be made by the next generation of radio telescopes. This work will result in a deep understanding of the connection between galaxies and molecular clouds, and of the magnetic fields that permeate these objects. This project is innovative due to its connection of cosmological structure (i.e., galaxies and their environments) to molecular clouds and the star formation that occurs therein, and the modeling of both of these classes of objects in a unified theoretical and numerical framework. The understanding gained by doing this will be transformative in terms of our ability to more accurately model star formation through cosmic time, and will directly connect to current and future observations of magnetic fields in a range of astrophysical situations.

6. Results from prior NSF Support

Dr. David C. Collins has never been a PI or co-PI on an NSF grant.

Dr. Brian W. O'Shea: is currently the PI or co-PI of multiple NSF-funded projects. The grant most relevant to this project is an NSF Division of Advanced Cyberinfrastructure Petascale Computing Resource Allocation grant (PRAC; ACI 0832662; "Formation of the First Galaxies: predictions for the next generation of observatories," PI: Brian O'Shea, $40K, 5/2009-4/2013. **Intellectual merit:** This grant examined high-redshift galaxy formation using extremely sophisticated cosmological simulations that included both radiation transport and detailed treatments of star formation and feedback, and made detailed predictions about the transition between metal-free and metal-enriched star formation as well as the properties of populations of high redshift galaxies. Publications from this grant include **??**Chen et al. (2014); Smith et al. (2015); O'Shea et al. (2015); Ahn et al. (2015), with additional papers currently in the refereeing process. **Broader Impacts:** This project helped to improve the accuracy of simulations of galaxy formation, which is crucial to making predictions for a variety of ground- and space-based observational campaigns. It helped to train multiple graduate students and postdoctoral researchers, and to make substantial infrastructure improvements to the Enzo and yt codebases, which will benefit the user communities of those tools. Also, public talks relating to high redshift galaxies and their importance to astronomy and astrophysics were given by several of the investigators.

7. Collaboration management plan and timeline

The Team. Dr. Brian O'Shea (PI) is an expert in cosmological simulations of structure formation, and has modeled galaxy evolution from the earliest galaxies through present-day galaxy clusters. He is an expert on the sub-grid modeling of astrophysical processes in the Enzo code, and is wholly or partially resonsible for several of Enzo's most critical modules for this project, including the star formation and feedback and AGN feedback algorithms. In this work, Dr. O'Shea and his research group at Michigan State University will be responsible for the cosmological simulations of galaxy formation, and will lead the design and analysis of idealized elliptical and dwarf galaxy simulations.

Dr. David Collins (Co-PI) is an expert in numerical MHD methods and simulations of star forming clouds, and has participated in simulations of MHD turbulence in a variety of contexts, including first stars, and galaxy clusters. He was primarily responsible for the development of the MHD solver that will be used for this work. In the proposed work, Dr. Collins and his research group at Florida State University will be responsible for simulations at the galaxy scale and below, focusing on the formation and collapse of molecular clouds, and the strength and topology of the galactic magnetic field. They will also be responsible for the development of the new MHD-based star formation and feedback algorithm, and will lead the design and analysis of idealized disk galaxy simulations.

Dr. Sui Ann Mao (external collaborator; group leader at the Max Planck Institute for Radio Astronomy in Bonn, Germany) is an expert in the measurement of magnetic field structure in the Milky Way, the Large Magellanic Cloud, Local Volume galaxies, and in more distant galaxies. She will offer guidance regarding synthetic observations of simulations at all scales, suggest additional measurements beyond those described in this proposal, and will verify that the behavior of simulated fields in the simulations described in this proposal are consistent with current observations. Our work will also inform her observational campaign by predicting observational quantities.

Plan and Timeline. PI O'Shea (MSU) and co-PI Collins (FSU) jointly have responsiblity for carrying out the research described in this proposal and for reporting progress and results to the NSF. They individually are responsible for overseeing the grant budget and for mentoring the graduate student at their respective institutions.

At the scientific and technical level, Dr. O'Shea and the MSU graduate student are responsible for designing, running, and analyzing the cosmological galaxy formation simulations and, in collaboration with Dr. Mao, comparing the simulations to extragalactic observations of magnetic fields. The MSU and FSU contingents will work together to extract initial conditions for the galaxy-level simulations from cosmological calculations, and will the FSU group will focus on the study of magnetic field evolution in isolated galaxy simulations under a variety of circumstances and on the formation of molecular cloud-based star formation and feedback algorithms. Both the FSU and MSU research groups, as well as Dr. Mao, will work together to further develop the synthetic observing capabilities in YT as they pertain to magnetic field observations, and on comparing simulations with observations at all physical scales.

The timetable and milestones for this project are listed below. We assume for planning purposes that the work done as a part of this project will start in August 2016.

- **Year 1** (2016-17): Run first round of cosmological MHD zoom-in simulations of all galaxies. Extract initial conditions for first isolated galaxy calculations. Begin data analysis of cosmological simulations. Run first isolated galaxy simulations. *Milestones*: Complete first round of cosmological simulations.
- **Year 2** (2017-18): Finish data analysis of first round of cosmological simulations. Run first round of isolated galaxy calculations, informing improved subgrid star formation and feedbakc models. Run and analyze zoom-in cosmological simulations with physics variations. Analyze molecular cloud simulations and create improved subgrid stellar feedback model. *Milestones*: Completed data analysis for first set of cosmological simulations and first round of isolated galaxy simulations. Creat subgrid stellar feedback model with MHD.
- **Year 3** (2018-19): Run and analyze final round of zoom-in cosmological simulations and isolated galaxy simulations, using new subgrid MHD stellar feedback model. *Milestones*: Completed final round of cosmological simulations and isolated galaxy simulations (including data analysis).
- **End of grant**: Public release of all new Enzo modules, as well as all yt mock observation tools and example scripts. Public release of all simulation data and data products.

8. Intellectual merit and broader impacts

Intellectual merit: This project is novel because it will use high resolution magnetohydrodynamics simulations to self-consistently follow the evolution of plasma over a huge range of astrophysically important length, density, and temporal scales, thus bridging the gap between the cosmological structure formation that results in galactic-scale magnetic fields and the star-forming molecular clouds that form out of the magnetized interstellar medium. This is crucial because an improved understanding of how magnetized molecular clouds form within galaxies will lead to more accurate initial conditions for targeted studies of star formation, and will provide an opportunity to model that critical process in a more realistic way. The results of this project will facilitate our interpretation of observations of magnetic fields in the intergalactic medium, in both high redshift and nearby galaxies, and in the Milky Way galaxy itself.

Broader impacts: Our proposed work will have significant impact on scientists in training, who will learn to use cutting-edge numerical tools at the largest possible scale. We will involve undergraduate students at Michigan State University (through MSU's REU program, which targets women and under-represented minorities) and graduate students at MSU and FSU in our research efforts. Scientific results from this program will be visualized by members of our collaboration, and will be disseminated to the public via our pre-existing collaborations with planetaria and museums, and via the Internet. In addition, these visualizations will be used as part of outreach talks and "Ask a Scientist" events that involve members of this project. The simulation data produced as a result of this project will be used in computational science courses at Michigan State, where it will be used to train students in scientific visualization and data analysis techniques. Similarly, this data will be used at Florida State in undergraduate-level "Hydrodynamics for astrophysics" and "Extragalactic astrophysics" courses, and will use the results obtained in this project to incorporate active research into the education of undergraduate physics and astrophysics majors. The resulting curricular materials will be made available to the public via the World Wide Web.

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